Collaboration. Commitment. Confidence.SM

TPF-5(291) FINAL REPORT:

EVALUATING THE IMPACT OF NON-EXPERIMENTAL FACTORS ON PAVEMENT PERFORMANCE:

Task 1: Agency-Specific Trends
Task 2: Impact of Construction and Materials Issues
Task 3: Review of SPS-2 Early Failures
Task 4: Lessons Learned from State Supplemental Sections

Prepared On Behalf Of:	Date	Project Number
State Pooled Fund Study TPF-5(291)	October 2021	56A0418-008 (TPF 5(291)) 219.03.10 (NCE)

Nicole Dufalla, P.E.
Project Engineer, NCE

Kevin Senn, P.E.
Principal Engineer, NCE

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

The following acronyms are used in this publication:

AC	Asphalt Cement
BTB	Bituminous Treated Base
DGAB	Dense Graded Aggregate Base
FWD	Falling Weight Deflectometer
LCB	Lean Concrete Base
LTPP	Long Term Pavement Performance
PATB	Permeable Asphalt Treated Base
PCC	Portland Cement Concrete
SPS	Specific Pavement Study
SPS-2	Specific Pavement Study – PCC New Construction
w/cm	Water cement ratio

1.0 BACKGROUND

The NCE team was awarded the Transportation Pooled Fund (TPF) Study 5(291) to investigate data from the Long-Term Pavement Performance (LTPP) Specific Pavement Study (SPS)-2 experiment for concrete pavement design factors, with the Washington State Department of Transportation as the Lead State. This pooled fund study included the investigation and proposal of a pavement preservation experiment utilizing existing test site conditions. Upon completion of the initial phase of the study, several SPS-2 Tech Days were conducted to broaden the pavement community's knowledge of the SPS-2 experiment and to garner input on analyses the community would find useful. The Pooled Fund Technical Advisory Committee (TAC) also provided recommendations for additional analyses.

As a result, five additional tasks were focused on SPS-2 test sections:

- Conducting a deterioration rate analysis
- Analyzing performance data
- Investigating sources of non-LTPP data
- Analyzing joint score and area of localized roughness (ALR) impacts on performance
- Updating previous SPS-2 analyses

Upon completion of these tasks, an additional 11 tasks were proposed. The purpose of this supplementary extension of TPF-5(291) was to conduct further analyses of existing data from the LTPP SPS-2 concrete pavement experiment. The focus of this set of tasks was to investigate the impact of non-experimental factors on pavement performance. The following tasks were completed:

- Identifying agency-specific trends
- Analyzing the impact of construction and materials issues
- Reviewing early SPS-2 failures
- Identifying lessons learned from state supplemental sections
- Analyzing the impacts of climate, traffic, and overall condition on deterioration rate
- Comparing SPS-8 and SPS-2 performance
- Assessing diurnal changes in roughness
- Evaluating service life
- Comparing mix-design performance
- Conducting Mechanistic Empirical Pavement Design Guide (MEPDG) sensitivity analysis of portland cement concrete/lean concrete base (PCC/LCB) bond
- Evaluating transverse joint opening width

This report presents the results of the first four proposed additional tasks contain similarities in content, such that original construction information is reviewed and discussed for each of the tasks. A more thorough description of each task follows in Section 2, Task Overview. This report includes the entirety of work for Tasks 1-4.

2.0 TASK OVERVIEW

Task 1 includes a review of SPS-2 experimental sites by agency to investigate agency-specific trends among the test sections. The entire task includes the following scope of work:

- Reviewing all SPS-2 construction and deviation reports
- Reviewing previous work to identify individual agencies where deterioration rates do not follow the trends seen in most other agencies
- Identifying and discussing possible factors at specific test sections or sites that may have influenced deterioration rates to fall outside the generalized trends

Task 2 includes a review of SPS-2 experimental sites by construction and material issues and evaluate trends between these issues and performance. The entire task includes the following scope of work:

- Reviewing all SPS-2 reports and identify issues and the possible causes and impacts they have had.
- Grouping test sections with similar construction or material issues and comparing their performance to test sections without issues.

Task 3 includes a review of SPS-2 experimental sites that have exhibited early failure, comprised of the following scope of work:

- Identifying test sections in the SPS-2 experiment that exhibited early failure
- Reviewing historical construction and deviation reports for these test sections
- Reviewing material testing data and performance trends
- Identifying and categorizing possible cause-and-effect relationships between construction and material issues and pavement performance

Task 4 includes an investigation into the performance of state supplemental experiment sections constructed during the SPS-2 core test section construction, comprised of the following scope of work:

- Identifying the differences in the design and construction of the state's control/supplemental sections from the core experiment sections
- Reviewing historical construction and deviation reports for these supplemental test sections
- Reviewing material testing data and performance trends
- Analyzing and comparing the performance in measured and predicted deterioration rates

.

3.0 METHODOLOGY

To investigate the possible construction and material-related causes of anomalous behaviors of SPS-2 test sections required for Tasks 1 to 4, a standard methodology of investigation was established.

First, the performance of all SPS-2 test sections was quantified across three different distress metrics for each distress survey conducted: roughness (measured as International Roughness Index, IRI), wheel-path faulting (measured in inches), and percent slabs cracked. Next, metrics established as recommended performance thresholds for pavement rating (Visintine et al 2018) were used to establish performance levels. These performance levels and metrics are reproduced in Table 1 below.

Table 1. Recommended Performance Thresholds for Pavement Rating (Visintine et al 2018)

Condition Metric	Performance Level	Threshold
IRI	Good	<95
IRI	Fair	95-170
IRI	Poor	>170
Percent cracking, JPCC	Good	<5%
Percent cracking, JPCC	Fair	5-15%
Percent cracking, JPCC	Poor	>15%
Faulting	Good	<0.10
Faulting	Fair	0.10-0.15
Faulting	Poor	>0.15

Sites were classified as having poor performance if they met the criteria established for poor performance described in Table 1 across any of the three tested metrics for any year that measurements were taken. For example, if a test section obtained an IRI considered "poor" for only one year, this section would still be defined as having "poor" performance. Additionally, plots of performance trends across each of these condition metrics were also included for each state in the Task 1 discussion to indicate performance over time. A line indicating the threshold for poor performance for each of these condition metrics is included in each plot.

Next, original construction and deviation reports for each section were reviewed for relevant information related to these performance issues. This primarily included observations relating to possible construction-related causes of early failure and poor performance as outlined in the construction reports, such as sudden weather events or changes to the intended construction plan. Additionally, any observations relating to possible material-related causes of early section failure, such as significant deviations of the concrete paving mixtures, issues with the base material, or other material-related deviations and issues, were also evaluated.

It should be noted the review of the construction reports was inherently limited as only known construction deviations could be included in the discussion of each report. The depth and detail of original construction reports varied significantly across projects and this may also be reflected in the available data and consequent analysis.

After these specific observations were linked to sections that exhibited poor performance, material testing data and performance trends for these sections were incorporated into this analysis. Additionally, specific materials and construction related variables to help quantify some of these potential issues, such as tested PCC strength, thickness, and other properties, were also investigated for each of the SPS-2 sections exhibiting poor performance. Because these sections were constructed together by each state, the analysis of these results are presented by state so that other possibly complicating factors (weather, traffic, etc.) are controlled.

Finally, in Task 1, these multiple sources of data were then analyzed together to establish possible cause-and-effect relationships between the SPS-2 experimental sections that exhibited poor performance and possible construction and materials related causes of these failures. Observations of performance across each SPS-2 project are then discussed.

For Task 2, the information outlined above is disseminated to establish trends across materials and construction issues that were found to be common through the investigation of construction and deviation reports across different agencies. These include construction-based issues and deviations, such as difficulty with specific base construction, joint sawing, dowel bar insertion, and layer thickness deviations, as well as materials-based deviations such as out-of-spec aggregate gradations, concrete strength, or unstable subgrade materials.

For Task 3, an investigation of SPS-2 test sections that exhibited early failure was conducted. Early failure was defined as achieving a ‘poor’ level of performance within ten years of construction based on the FHWA criteria outlined previously. These multiple sources of data were then analyzed together to establish possible cause-and-effect relationships between the SPS-2 experimental sections that exhibited early failure and possible construction and materials related causes of these failures.

For Task 4, sections were analyzed differently if the project contained only one supplemental test section or if the state agency had chosen to conduct a more thorough supplemental test section experiment. For states with only a single supplemental test section, consistently numbered -0259, this test section was constructed with the typical paving concrete mixture design and structure typical for each participating agency. For these states, the performance of this supplemental test section was compared to the performance of all of the core test sections within the same state and observations were drawn regarding the performance of the standard agency concrete section and the core experimental sections of the SPS-2 experiment.

For states choosing to conduct an entirely separate supplemental experiment, the performance of these test sections was evaluated against each other within the state and against the standard performance of the other core experimental sections in the SPS-2 experiment.

4.0 TASK 1 – AGENCY SPECIFIC TRENDS

This task reviews data and information for SPS-2 experimental sections that exhibited poor performance in each state as outlined previously. This includes possible construction and materials related causes of early failures as discussed in the construction reports, deviation reports, materials testing information, section construction data, and performance trend data.

4.1 Arizona (04)

In 1993, 21 experimental sections for the SPS-2 experiment were constructed in Arizona, a dry-no-freeze climatic region. Of these 21 original test sections, 2 were removed from study in 2018; however, these two sections represented state supplemental sections that were surfaced in asphalt concrete.

4.1.1 Traffic and climate deviations

There were no noted traffic or climate deviations. At construction, the intended level of traffic, given as an Average Annual Daily Traffic (AADT) for these sections was 15,900 while the measured KESALs per year, as of 2021, was 1610. Additionally, the freezing index of this area was measured to be 0 freezing days per year and the average annual precipitation was 7.5 inches, well within the designation for a dry-no-freeze climatic region.

4.1.2 Construction related deviations

The construction report for the Arizona SPS-2 sections listed many possible construction related deviations for several test sections.

There was significant difficulty in constructing the lean concrete base (LCB) sections: the concrete mixture was too dry and was cured inadequately (late and with spotty application). Test section 040217 required a follow-up curing as the original curing was completed during a light rain. During the construction of the PATB layer, there was difficulty wrapping the filter fabric around the layer's edge to prevent soil infiltration in the drain, so this was not completed. During the construction of the PATB layer of test section 040224, it was noted that the paver's auger broke down after 1 pass of paving. This caused a stoppage of 3 hours before restarting, which was then shut down after an additional hour due to lack of materials. It was noted that both hard rain and a dust storm occurred during the construction of this test section.

During the PCC paving of the test sections, several construction difficulties were noted. During the paving of test section 040213, all dowel bars had to be inserted by hand following the breaking of the dowel bar inserter. During the paving of test section 040215, paving operations stopped several times due to a lack of concrete supply to the paver. Stoppages also occurred during the paving of sections 040218 and 040219 due to issues with the paver itself. The paver leaked oil onto test section 040218 and experienced frequent stoppages during the paving of test section 040219.

During the construction of the supplemental sections, the span saw blew out and the continued joint sawing of this section cut joints that were too wide in test section 040266, which did require epoxy patching. Additionally, the saw blade sparked while sawing joints in test section 040267, which could possibly indicate that the dowels were located too high in the pavement and may have been compromised by the sawing.

4.1.3 MATERIALS RELATED DEVIATIONS

There were several materials related deviations noted in the construction report, most commonly during the construction of the state supplemental sections. The DGAB layer used for test sections 040263, 040264, and 040265 was out of specification due to excess material on the 3/8” sieve.

For the supplied concrete of the supplemental sections, it was found test section 040262 had almost a 3-inch slump, well beyond the specification limits, and was noted to “appear wet”, and the material in test section 040264 was found to have a slump of 4 inches and an air content of 12-13%. Both of these metrics far exceed the target values for this mixture. The measured modulus of rupture values for these test sections is given in Table 2 below. Test sections that exhibited poor pavement performance are indicated with bold type font.

Table 2. Measured Modulus of Rupture for Specific Arizona SPS-2 Test Sections

	Measured modulus of rupture, psi (target 14 day modulus of rupture, psi)		
SHRP ID	14-day	28-day	365-day
040213	**560 (550)**	**630**	**850**
040214	810 (900)	840	
040215	580 (550)	685	945
040216	790 (900)	825	890
040218	**860 (900)**	**925**	**970**
040219	**575 (550)**	**680**	**805**
040220	**810 (900)**	**840**	**975**
040222	**945 (900)**	**950**	**1085**
040224	805 (900)	825	915
040262	**580**	**670**	**845**
040265	**515**	**545**	**890**
040267	570	580	815
040268	520	625	770

It can be seen that many test sections did not meet the 14-day target strength.

4.1.4 TEST SECTION PERFORMANCE

Most test sections generally exhibited good performance across performance metrics, except for slab cracking. Individualized plots of these performance metrics by year are given in Figure 1, Figure 2, and Figure 3 below.

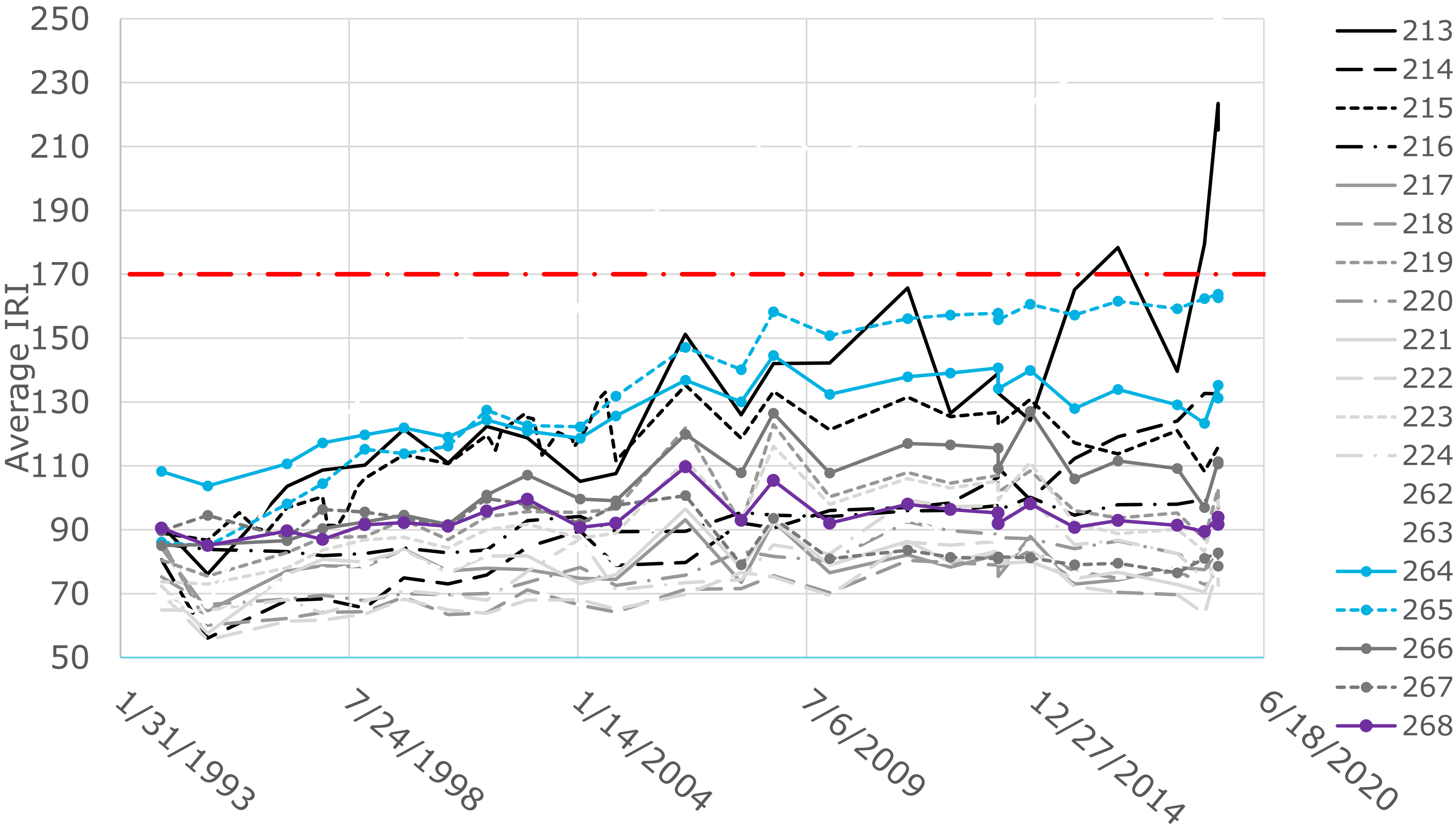

Figure 1. Roughness Measurements (IRI) for Arizona SPS-2 Test Sections

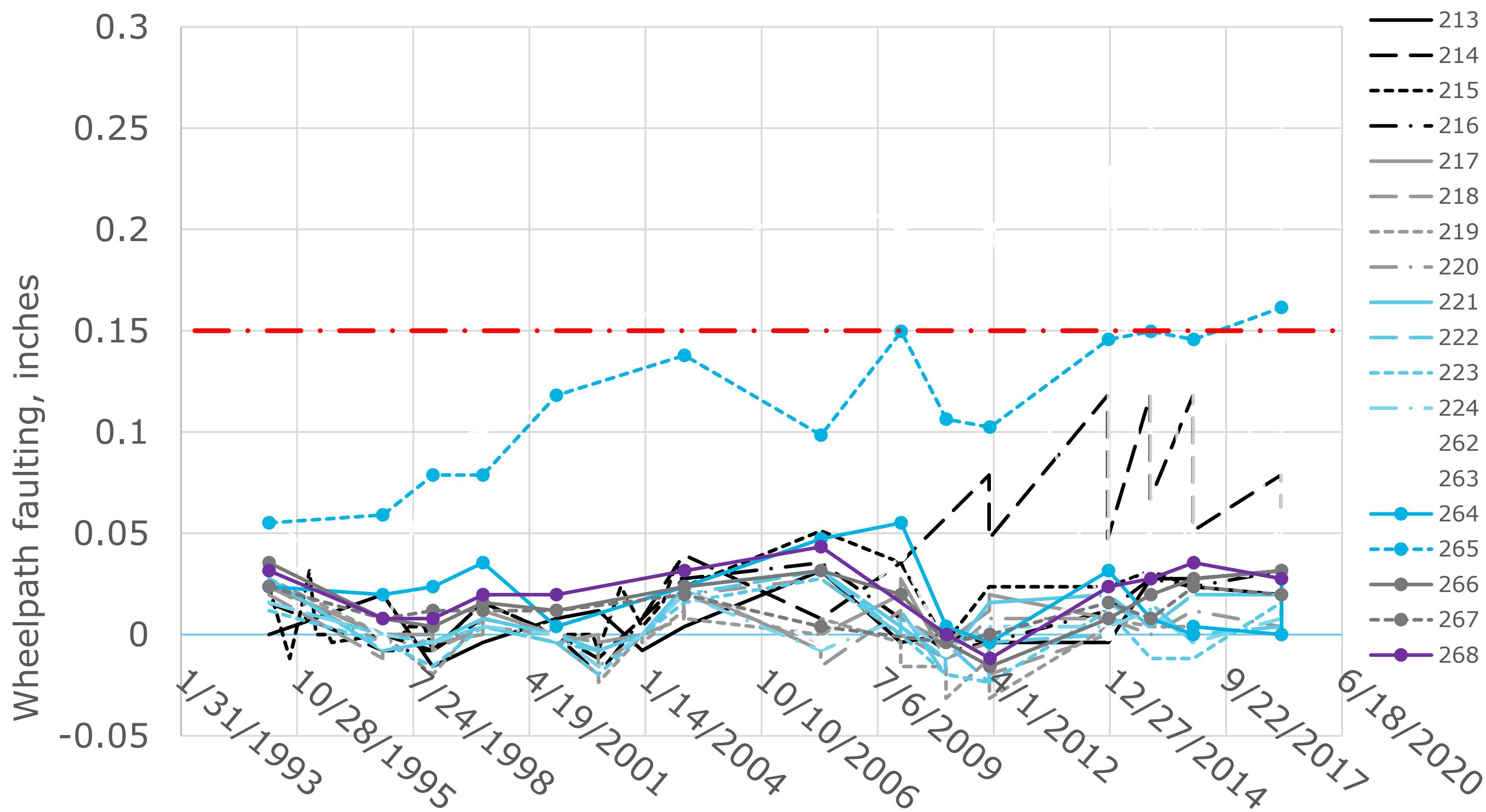

Figure 2. Wheel-Path faulting Measurements (in inches) for Arizona SPS-2 Test Sections

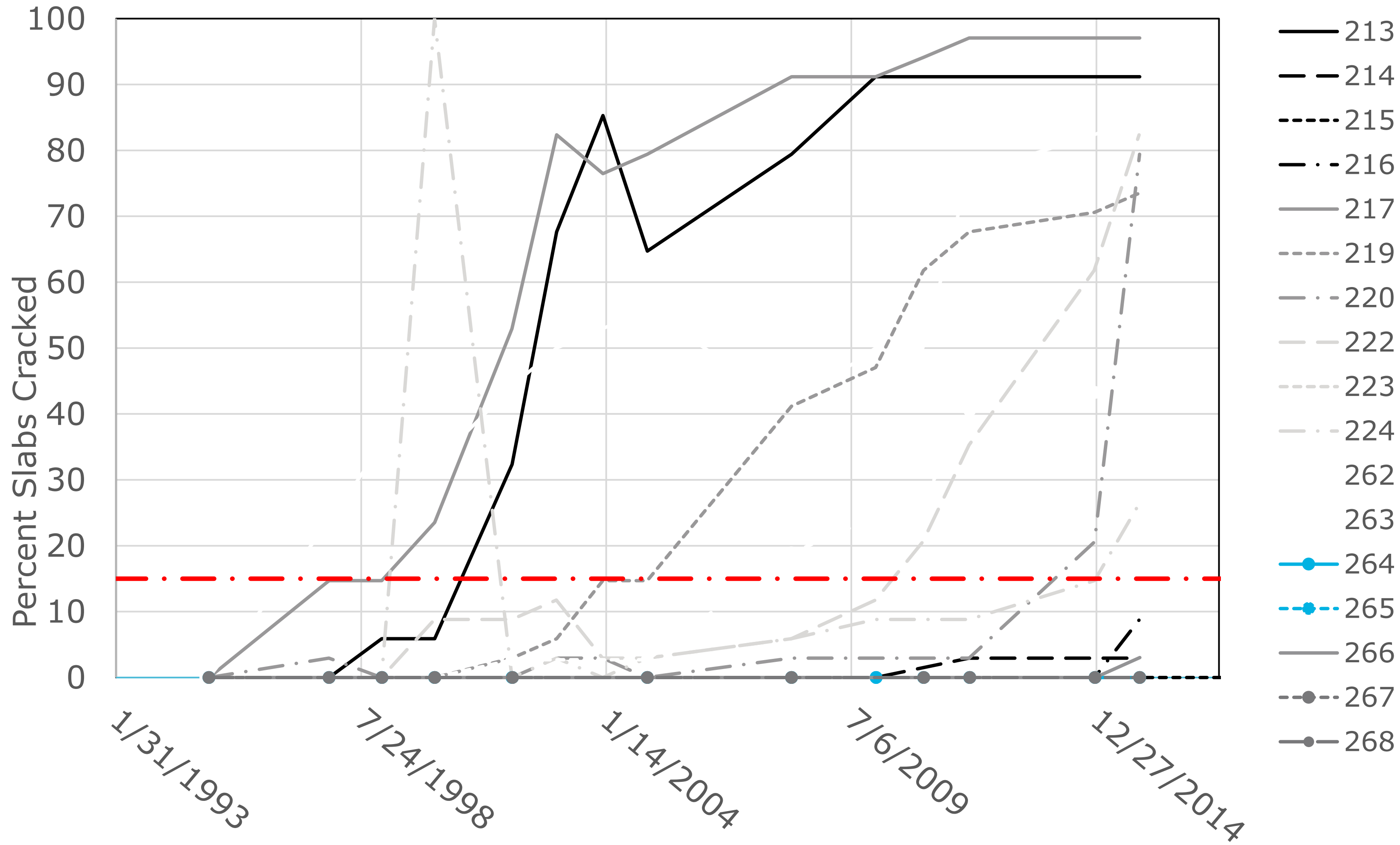

Figure 3. Percent Slabs Cracked for Arizona SPS-2 Test Sections

It can be seen from the plots that several test sections exhibited poor performance across the measured performance metrics. Specifically, test sections 040262 and 040213 exhibited poor levels of roughness with test section 040265 trending upward to poor roughness performance as well. Test sections 040262 and 040265 both exhibited poor performance with regards to wheel-path faulting. Slab cracking was the most common indicator exhibiting poor performance, test sections 040213, 040217, 040218, 040219, 040220, 040222 040224, and 040263 all exhibited poor performance regarding slab cracking. Summarized performance trends of the Arizona SPS-2 test sections are given in Table 3 below.

Table 3. Performance Trends Across Arizona SPS-2 Test Sections

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
040213	POOR	POOR	GOOD
040214	FAIR	GOOD	POOR
040215	FAIR	GOOD	GOOD
040216	FAIR	GOOD	GOOD
040217	FAIR	POOR	GOOD
040218	GOOD	POOR	GOOD
040219	FAIR	POOR	GOOD
040220	GOOD	POOR	GOOD
040221	FAIR	POOR	GOOD
040222	GOOD	POOR	GOOD
040223	FAIR	GOOD	GOOD
040224	FAIR	POOR	GOOD
040259	GOOD	GOOD	GOOD
040260	FAIR	GOOD	GOOD
040261	FAIR	GOOD	GOOD
040262	POOR	POOR	POOR
040263	FAIR	POOR	GOOD
040264	FAIR	GOOD	GOOD
040265	POOR	GOOD	POOR
040266	FAIR	GOOD	GOOD
040267	FAIR	GOOD	GOOD
040268	FAIR	GOOD	GOOD

Consistent with the plot data, the pavement performance for the sections is generally moderate with cracking the most common cause of poor ratings across test sections. In general, faulting is not a problem and roughness is a moderate problem across sections. Specific sections receiving a distress metric that could be classified as poor performance is given in Table 4 below.

Table 4. Arizona SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
040213	2011-2019	2001-2015	
040217		2000-2015	
040218		1997-2015	
040219		2008-2015	
040220		2014-2015	
040221		2001-2015	
040222		2011-2015	
040262	2014 – 2019	2008-2015	2004-2019
040263		2008-2015	
040265	2019		2014-2019

The most significant performance metric for the Arizona SPS-2 test sections is slab cracking. Most test sections have experienced poor performance due to cracking by 2020.

4.1.5 FAILURE SUMMARY

Some trends can be observed between test sections that exhibited poor pavement performance. First, test sections 040217, 040218, 040219 and 040220 all exhibited poor performance due to slab cracking. These four sections were constructed on the LCB base layer. The construction report cited significant issue with constructing the LCB layer due to increased stiffness and dryness which caused significant difficulty during placement. Additionally, the LCB layer was cured inadequately. These construction and materials issues with the LCB layers could contribute to the poor performance experienced by test sections 040217, 040218, 040219 and 040220.

Test section 040213, which experienced poor performance through roughness and cracking, was the only test section constructed without a functional dowel bar inserter and dowels had to be inserted by hand. This was the only deviation specifically relating to this test section. Test sections 040221 and 040222 were thinner sections constructed on the PATB base layer but there were no material and construction deviations specific to these test sections.

The concrete used in the construction of test section 040262 was noted to have excessive moisture and its slump of 3 inches was out of specification limits for construction. The DGAB layer under test sections 040263 and 040265 failed the gradation specification with excess material on the 3/8-inch sieve. Interestingly, these two test sections experienced significant roughness and wheel-path faulting distresses, but not significant slab cracking.

4.2 Arkansas (05)

In 1993, 12 experimental sections for the SPS-2 experiment were constructed in Arkansas, a wet-no-freeze climatic region. Of these 12 original test sections, 1 section (050213) was removed from study in 2008 while the remaining 11 experimental sections were removed from study in 2013.

4.2.1 TRAFFIC AND CLIMATE DEVIATIONS

At construction, the intended level of traffic of this section was 1700 KESALs while the measured KESALs per year, as of 2021, was 3560, indicating the actual traffic load was double the expected traffic load for this experiment. Additionally, the freezing index of this area was measured to be 28 freezing days per year and the average annual precipitation was 53.3 inches, indicating the climate was well within the expected boundaries for this climatic region.

4.2.2 CONSTRUCTION RELATED DEVIATIONS

The original construction and deviation reports contained several construction deviations that applied to all Arkansas SPS-2 test sections. The edge drains from the original highway had not been removed at the time of construction, though these were intended to be removed prior to construction of these test sections. Additionally, none of the longitudinal joints in the test sections were sealed as intended and pumping was observed on all test sections by early 1997, within 4 years of construction.

Specifically, there was an issue with the concrete slip form paver during the construction of test section 050221, when the augers became entangled with the dowel bar assembly. This was repaired but was a construction deviation.

Additionally, in terms of specific construction location deviations, there was substantial water flow observed from the edge drains, indicating it was possible that a spring was located below the test sections. This would substantially increase the subsurface moisture in the section.

4.2.3 MATERIALS RELATED DEVIATIONS

The most significant material deviation for the Arkansas test sections, which was a consistent deviation across all sites, was the modulus of rupture for the concrete fell below the targeted values. This was especially true for the 900 psi targeted mixture as seen in the measured average modulus of rupture values from test specimens given in Table 5.

Table 5. Average Modulus of Rupture Values for Arkansas SPS-2 Test Sections

	Target 14-day strength	Average 14-day strength
Low strength sections (odd numbered sections)	550 psi	545 psi
High strength sections (even numbered sections)	900 psi	825 psi

The measured modulus of rupture values for these test specimens indicate that the provided mix was close to the specification. In the case of the high strength mix, the tested strength was 75 psi below the target modulus of rupture. The modulus of rupture testing data that was taken specifically for the sections that failed early is given in Table 6 below. It can be seen that all tested sections were significantly below the target modulus of rupture value for each section. Oddly, the test specimens exhibited significantly lower 28-day strength than 14-day strength, suggesting that something was done incorrectly in measuring the strength or in handling the specimens calling into question the validity of the test data. Test sections exhibiting poor performance are indicated with bold type font.

Table 6. Specific Modulus of Rupture Values for Arkansas SPS-2 Test Sections

SHRP ID	14-day modulus of rupture, psi	28-day modulus of rupture, psi	365-day modulus of rupture, psi
050213	**568 (550)**	**414**	**585**
050217	**564 (550)**	**491**	**630**
050218	**825 (900)**	**557**	
050219	506 (550)	439	
050221	521 (550)	555	625
050223	568 (550)	493	
050224	506 (900)	752	814

4.2.4 TEST SECTION PERFORMANCE

Most test sections exhibited fair performance across performance metrics, with the exception of slab cracking in 3 sections. Individualized plots of these performance metrics by year are given in Figure 4, Figure 5, and Figure 6 below.

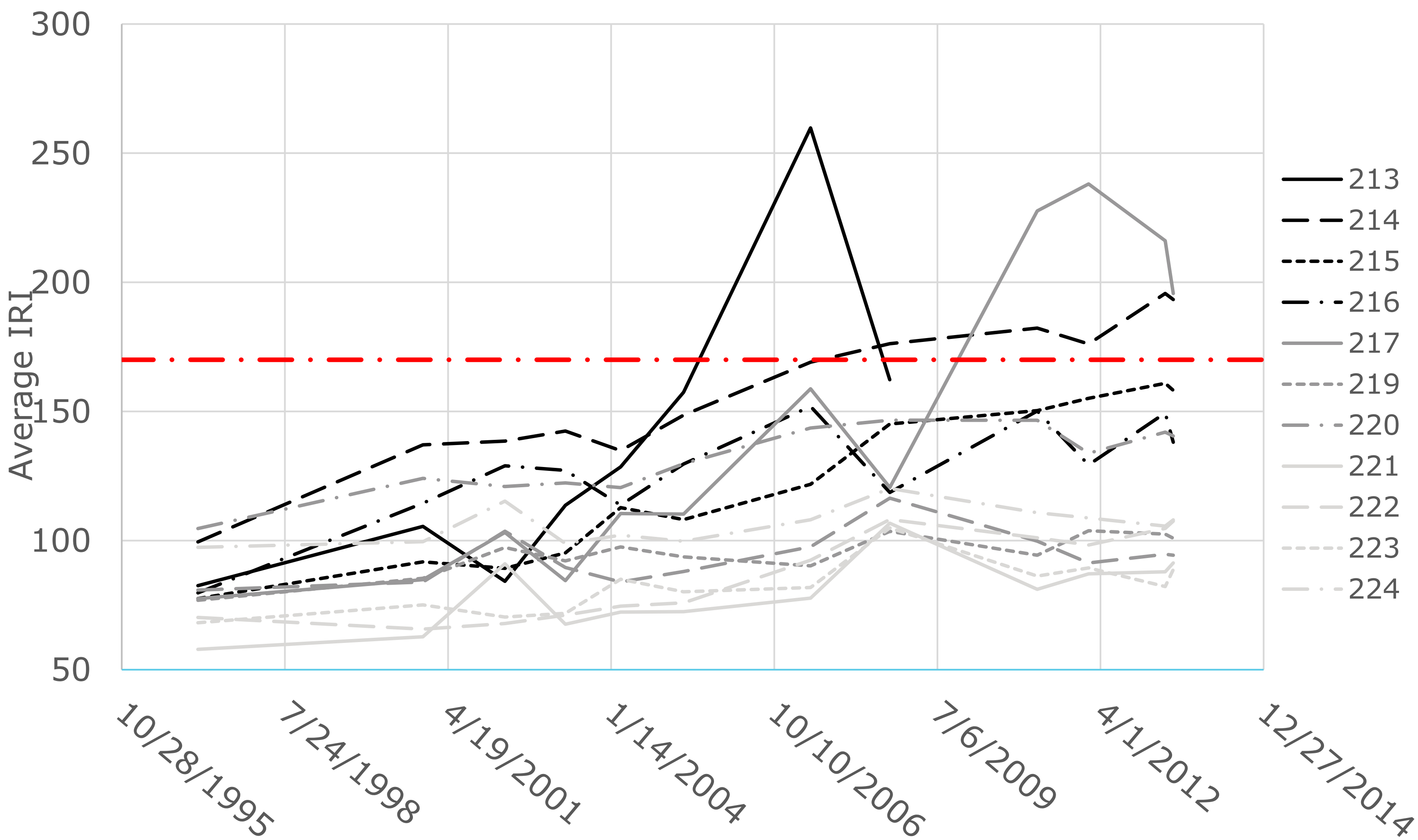

Figure 4. Average Measured Roughness (in IRI) for Arkansas SPS-2 Test Sections

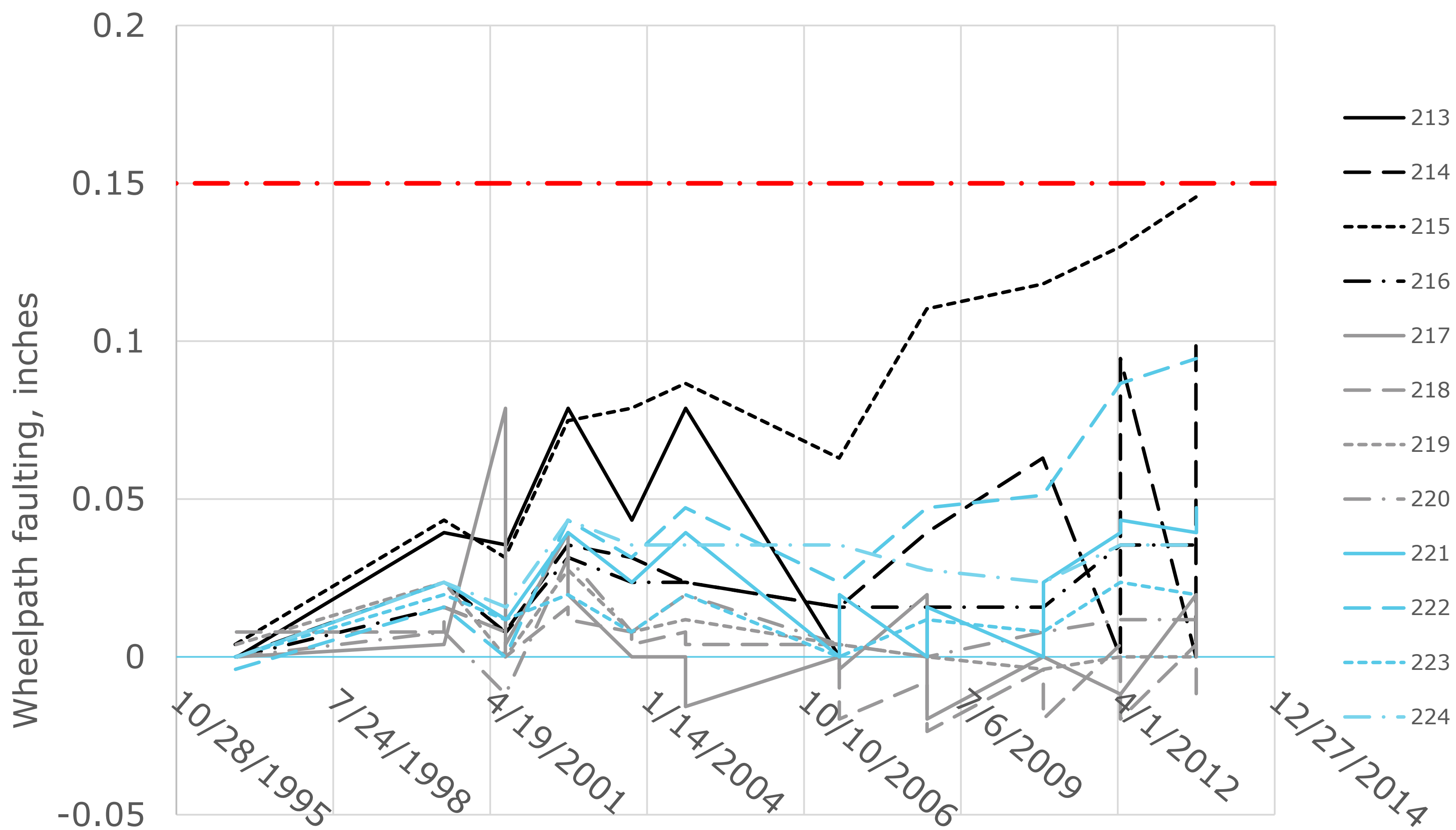

Figure 5. Average Wheel-Path faulting (in inches) for Arkansas SPS-2 Test Sections

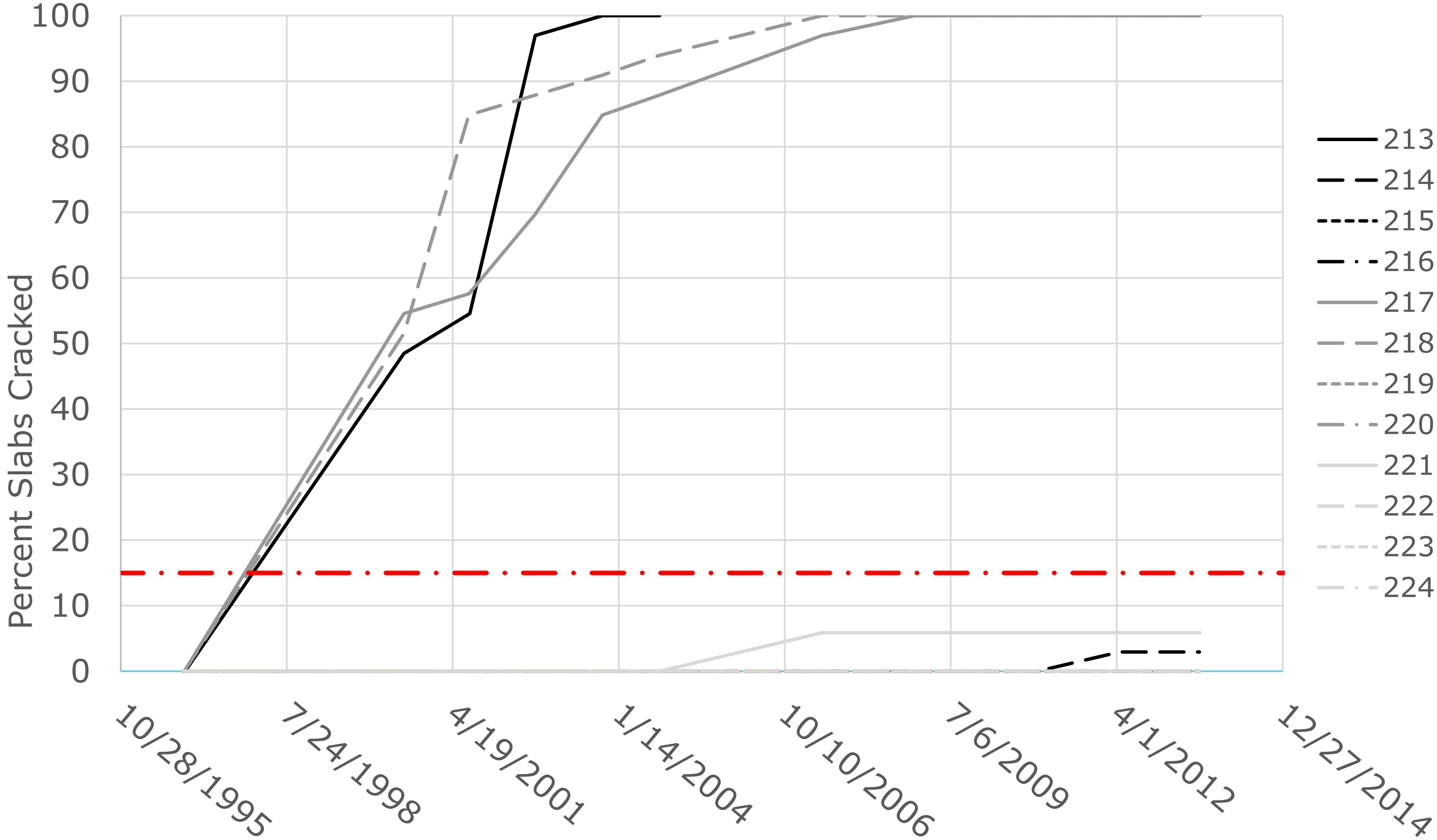

Figure 6. Average Percentage of Slabs Cracked for Arkansas SPS-2 Test Sections

The summarized performance of the test sections is given in Table 7 below.

Table 7. Performance Trends Across Arkansas SPS-2 Test Sections

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
050213	POOR	POOR	GOOD
050214	POOR	GOOD	GOOD
050215	FAIR	GOOD	FAIR
050216	FAIR	GOOD	GOOD
050217	POOR	POOR	GOOD
050218	FAIR	POOR	GOOD
050219	FAIR	GOOD	GOOD
050220	FAIR	GOOD	GOOD
050221	FAIR	FAIR	GOOD
050222	FAIR	GOOD	GOOD
050223	FAIR	GOOD	GOOD
050224	FAIR	GOOD	GOOD

The section performance was generally moderate with the most issues occurring as a result of surface roughness that measured fair in all but 3 sections where poor IRI values were measured. Test sections that specifically exhibited poor performance across any of these three metrics are given in Table 8 below.

Table 8. Arkansas SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
050213	2007	2000-2004	
050214	2007-2013		
050217	2011-2013	2000-2013	
050218		2000-2013	

It can be seen that four test sections received ratings of poor performance for both surface roughness and for percent cracking during the life of the pavement. This is corroborated with the plots, which indicate that test sections 050213, 050214, and 05217 exhibited poor performance with respect to roughness while no test sections exhibited poor performance due to wheel-path faulting, though test section 050215 was trending upward to the poor performance threshold. However, test sections 050213, 050217, and 050218 all exhibited excessive slab cracking, achieving 100% slabs cracked within ten years of construction.

4.2.5 FAILURE SUMMARY

The four test sections specifically experiencing poor performance included test sections 050213, 050214, 050217 and 050218. These test sections did not have material or construction deviations that were specific to these test sections. Rather, these test sections were still affected by the relatively low strength that affected all mixtures and the increased subsurface moisture that likely affected all test sections.

Notable trends between these test sections include two were constructed on the DGAB base while two were constructed on the LCB base layer and two were low strength and two were high strength test sections. However, all four of these test sections were constructed with the thinner (8”) PCC surface layer. Given the extremely high traffic levels of these test sections, these four thinner sections were under designed. The other 8” thick PCC test sections were over 8” of base, as opposed to the 6” of base that the thinner sections were constructed on. Therefore, the four sections experiencing poor performance had the thinnest pavement structure of all test sections.

4.3 California (06)

In 1999, 12 experimental sections for the SPS-2 experiment were constructed in California, a dry-no-freeze climatic region. Of these 12 original test sections, 2 sections (060201 and 060204) were removed from study in 2017.

4.3.1 TRAFFIC AND CLIMATE DEVIATIONS

At construction, the intended level of traffic of this section was 2405 KESALs while the measured KESALs per year, as of 2021, was 1870, indicating the actual traffic was slightly less than the expected traffic for this experiment. There was no deviation from the expected climatic conditions and the freezing index of this area was measured to be 0 freezing days per year and the average annual precipitation was 10.9 inches, well within the designation for a dry-no-freeze climatic region.

4.3.2 CONSTRUCTION RELATED DEVIATIONS

The original construction and deviation reports contained several construction deviations that applied to all California SPS-2 test sections. The PATB base layer, utilized in test sections 060209, 060210, 060211 and 060212, was found to have a variable thickness due to the amount of material placed in the paving windrow. As paving of the PATB continued, blading techniques were used to improve the thickness consistency. Additionally, during construction of the LCB layers, curing compound was applied inadequately and cracking was observed on the surface of the LCB layer prior to placement of the PCC.

Finally, there was a temporary stoppage of paving to repair the tie bar inserter and several voids left behind the paver throughout the project. However, these voids were able to be repaired during construction and did not appear to leave any lasting distresses on any test sections.

4.3.3 MATERIALS RELATED DEVIATIONS

There were several materials-related deviations from the experimental study in the California SPS-2 test sections. First, the subgrade was noted to be too soft and failed the LTPP requirements: four of the sections ultimately achieved a subgrade deemed 'stable' but 8 test sections were constructed on 'unstable' subgrade. The test sections that had appropriate 'stable' subgrade deflection measurements were 060203, 060206, 060207, and 060208. All other test sections had subgrade deflection measurements that exceeded the allowable deflection for this experiment.

The LCB base layer, utilized in test sections 060205, 060206, 060207 and 060208, was found to have some issues during construction, likely due to mix discrepancies in the LCB material itself. Two plants were used to supply LCB to the project: an on-site concrete plant and an off-site concrete plant; however, there were noticeable differences in quality between these two mixtures. The LCB layer from the on-site plant was found to develop cracks after placement and appeared to have a larger fraction of coarse aggregate than the mix from the off-site plant. Therefore, more aggregate segregation of the LCB layer was observed in the mix produced from the on-site plant.

4.3.4 TEST SECTION PERFORMANCE

Most test sections exhibited fair performance across performance metrics, with the exception of slab cracking. Individualized plots of these performance metrics by year are given in Figure 7, Figure 8, and Figure 9 below.

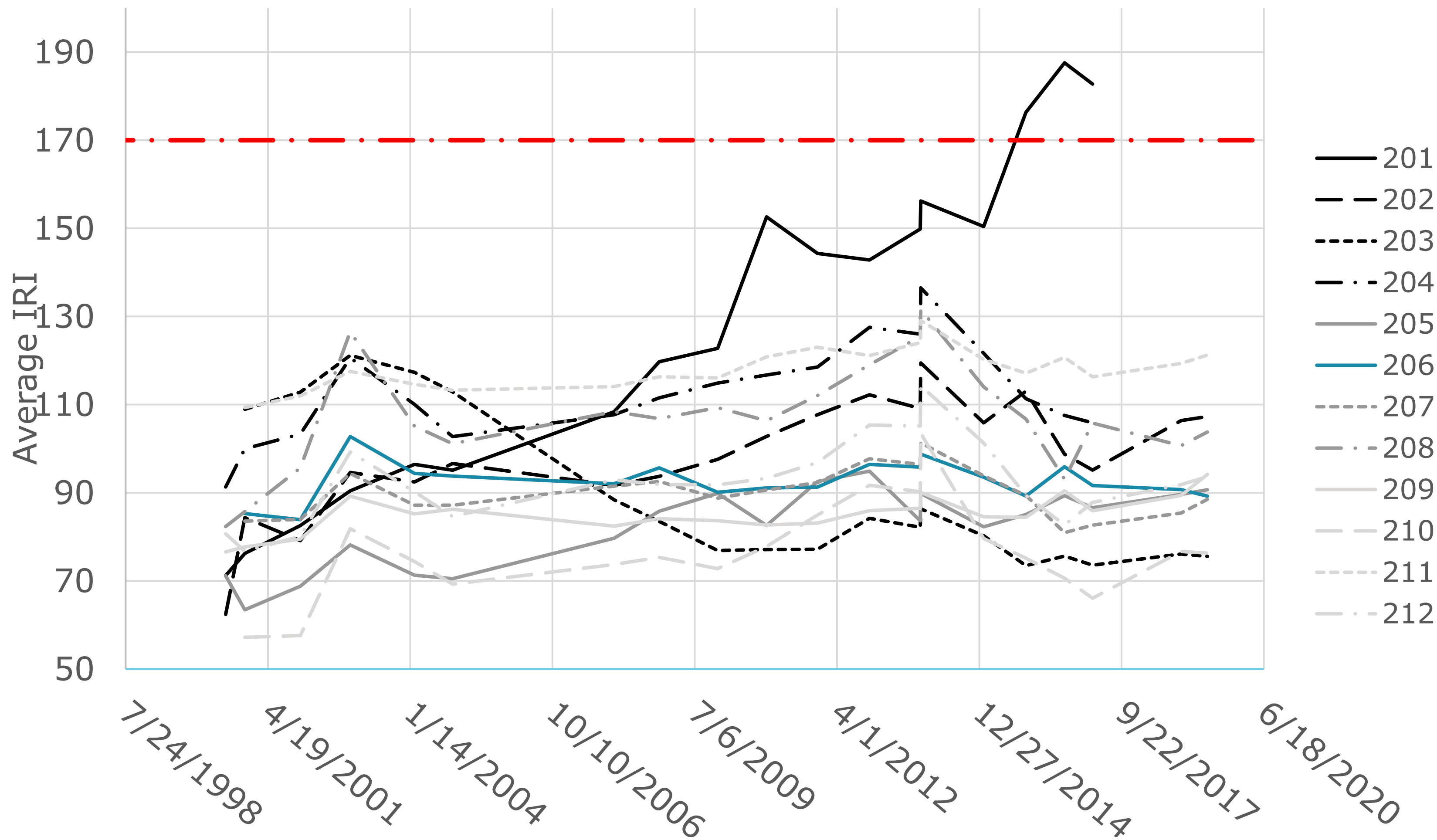

Figure 7. Average Measured Roughness (in IRI) for California SPS-2 Test Sections

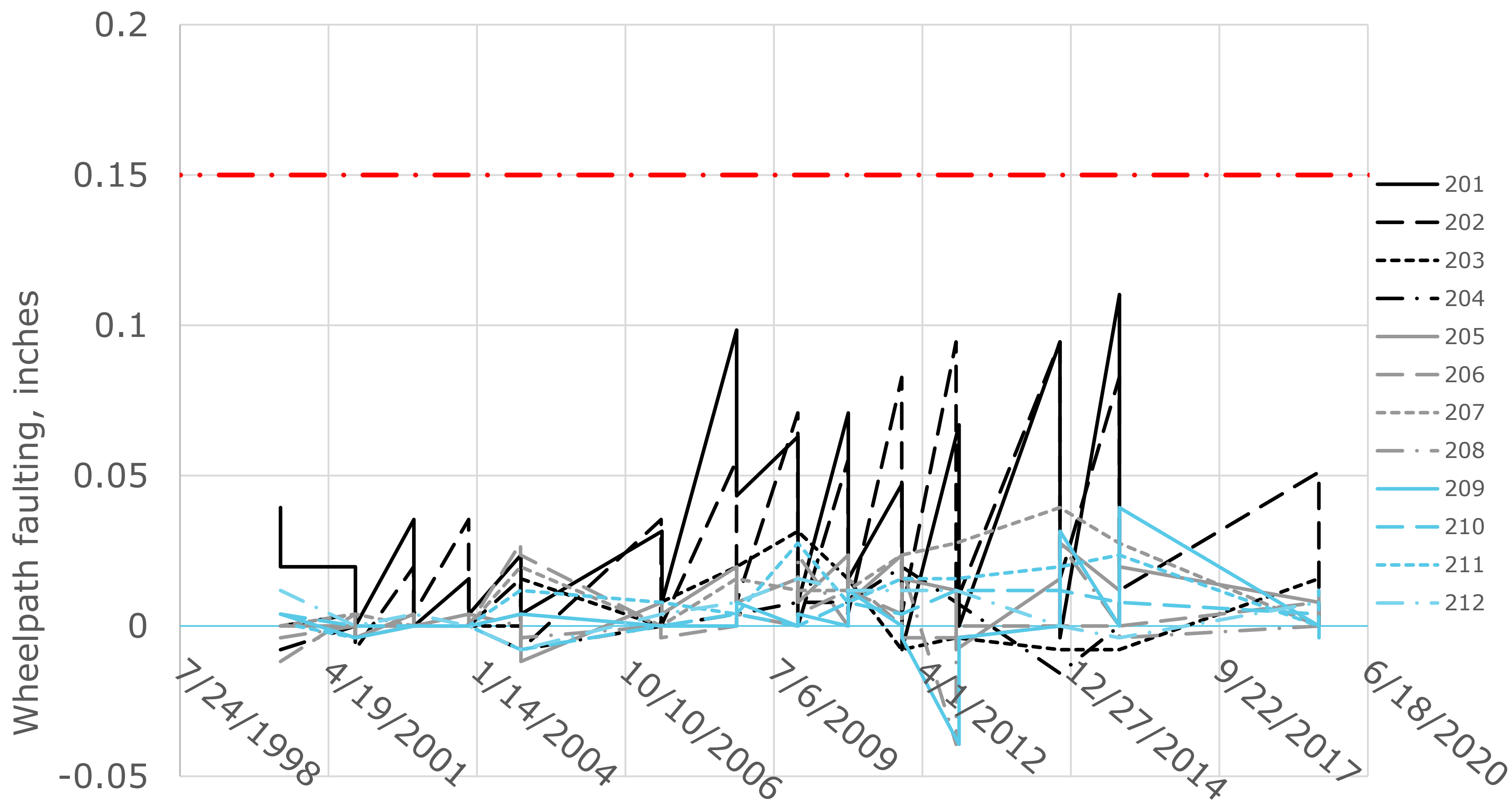

Figure 8. Average Wheel Path Faulting (in inches) for California SPS-2 Test Sections

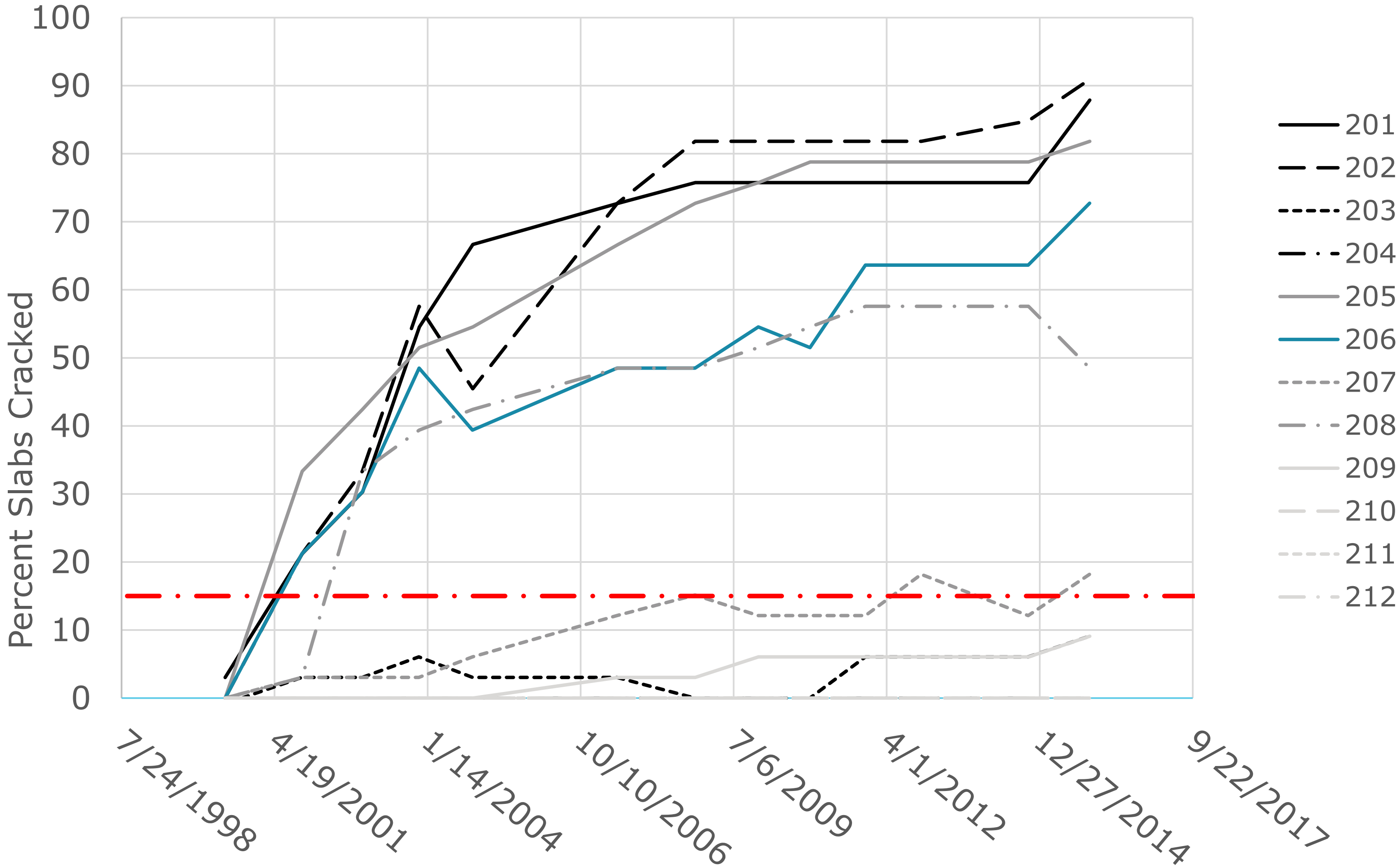

Figure 9. Average Percentage of Slabs Cracked for California SPS-2 Test Sections

A summary of performance trends of California SPS-2 test sections is given in Table 9.

Table 9. Performance Trends Across California SPS-2 Test Sections

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
060201	POOR	POOR	FAIR
060202	FAIR	POOR	GOOD
060203	FAIR	FAIR	GOOD
060204	FAIR	GOOD	GOOD
060205	FAIR	POOR	GOOD
060206	FAIR	POOR	GOOD
060207	FAIR	POOR	GOOD
060208	FAIR	POOR	GOOD
060209	FAIR	FAIR	GOOD
060210	FAIR	GOOD	GOOD
060211	FAIR	GOOD	GOOD
060212	FAIR	GOOD	GOOD

The sections are performing moderately, with cracking being the most common reasons sections receive a poor performance rating. In general, the sections have very little faulting and only moderate roughness. Specific test sections receiving a poor performance rating across any of the 3 performance metrics is given in Table 10 below.

Table 10. California SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
060201	2015-2017	2000-2015	
060202		2001-2015	
060205		2001-2015	
060206		2001-2015	
060207		2004-2015	
060208		2001-2015	

Cracking is the most common issue with the SPS-2 test sections in California with nearly half of all test sections exhibiting poor performance due to observed cracking.

Specifically, from the plots, only test section 060201 exhibited poor performance with respect to roughness while no test sections exhibited poor performance with respect to wheel-path faulting. However, test sections 060201, 060202, 060205, 060206, 060207, and 060208 all exhibited poor performance with respect to slab cracking, experiencing cracking that exceeded the threshold of poor performance within several years of construction.

4.3.5 Failure summary

All four test sections constructed with an LCB layer as the base experienced a poor rating due to cracking. The construction report noted some issues with the construction of the LCB layer, including that two different plants were used to supply LCB to the project and there was a noticeable quality difference between the two sites with noticeable segregation in one of the LCB mixes that was used across all four test sections. In addition to this segregation, it was noted that the LCB layer was cured inadequately and cracking was observed on the surface of the LCB layer before the placement of the PCC layer. Therefore, the poor performance due to cracking for test sections 060205, 060206, 060207 and 060208 may be related to construction and material issues with the LCB layer itself.

No direct construction or materials related deviations were noted that apply to test sections 060201 and 060202. However, these two sections were placed on the DGAB layer and were the two thinnest sections; therefore, having the thinnest bound layer section of the test section, they would be expected to have lower performance.

4.4 Colorado (08)

In 1993, 13 experimental sections for the SPS-2 experiment were constructed in Colorado, a dry-freeze climatic region. Of these 13 original test sections, 1 section (080217) was removed from study in 2014 and 2 additional sections (080215 and 080221) were removed from study in 2017.

4.4.1 Traffic and climate deviations

At construction, the intended level of traffic of this section was 780 KESALs while the measured KESALs per year, as of 2021, was only 390, indicating the actual traffic was less than the expected traffic for this experiment. Additionally, the freezing index of this area was measured to be 302 freezing days per year and the average annual precipitation was 14.3 inches, well within the designation for a dry-freeze climatic region.

4.4.2 Construction related deviations

The construction and deviation reports indicated many deviations from the intended construction of these test sections. First, in terms of site location deviations, test section 080215 contained a 24-inch diameter concrete pipe approximately 10-13 feet below the surface.

Next, there were several subgrade-related construction deviations throughout the Colorado sections. The subgrade thickness was found to vary and test sections 080213, 080214, 080215, 080216, 080221 and 080222 were all constructed on fill material while test sections 080217, 080218, 080219, 080220, 080223 and 080224 were constructed on cut material. Additionally, the subgrade on test section 080215 was comprised of 10 ft of old highway fill with 2 ft of sand (a fine cover material) that appeared to be well-compacted but was inconsistent with the subgrade of other test sections.

The subgrade of test section 080221 received more compaction than all other sections since this was used as a haul road during construction. However, this test section was also found to have a 4-inch pipe protruding at the surface that was sawed off, capped, and paved over. Additionally, it was observed that test section 080217 was constructed in a "'wetland-like' area, which contains a high water table". Two soft spots from the subgrade were removed and the area was replaced with fine sand fill and compacted.

There were also several base-related construction deviations throughout the Colorado sections for all three types of base layers used. First, the DGAB layer for test sections 080221, 080222, 080223 and 080224 were all constructed during heavy rain.

During the construction of the LCB layer for test section 080217, pumping was noted across the travel lane, possibly due to issues with the high water table as previously discussed. To remedy this, CDOT inspectors on site required the subgrade be compacted with a steel wheel roller immediately in front of the LCB dump trucks. Paving of the LCB layer continued, though the construction report notes that this additional steel-wheel compaction did not sufficiently repair the observed poor subgrade and no additional repairs were completed. Pumping was also observed during the LCB placement in test section 080220 which had similar subgrade issues. Transverse cracking, segregation, and depressions were observed on the LCB layers of both sections within one week of placing the LCB layer.

During the paving of the PATB of test section 080221, part of the PATB layer sunk 2 inches on the day following the initial paving. This section required additional PATB to be placed to bring the section to the correct grade level. It was theorized to be a result of the additional compaction this section received due to serving as a haul road, as mentioned previously.

Finally, there were several PCC-layer related construction deviations for test sections in Colorado. During the paving of the PCC layer of test section 080221, a dowel basket was pulled out of the passing lane and not replaced. During the PCC paving of section 080217, the spreader sank on the outside edge of the lane due to heavy rain during construction.

4.4.3 MATERIALS RELATED DEVIATIONS

According to the construction report, both sections 080220 and 080217 were constructed on a subgrade with a high moisture content and some pumping was evident. The average modulus of rupture values for the SPS-2 test sections in Colorado is given in Table 11 below. Sections exhibiting poor performance are indicated with bold font type.

Table 11. Measured Modulus of Rupture Values for Colorado SPS-2 Test Sections

	Measured modulus of rupture, psi		
SHRP ID	14-day	28-day	365-day
080213	520 (550)	630	710
080214	**930 (900)**	**950**	**950**
080215	510 (550)	580	650
080216	**900 (900)**	**925**	**870**
080217	**508 (550)**	**588**	**680**
080218	**810 (900)**	**950**	**840**
080219	515 (550)	640	655
080220	925 (900)	988	950
080221	475 (550)	470	620
080222	950 (900)	952	1008
080223	**595 (550)**	**578**	
080224	815 (900)	700	1050

No deviations in concrete strength were noted in the construction report; however, the test sections with the lower design strength mix design (550 psi) often failed to meet that target strength.

4.4.4 Test section performance

Most test sections generally exhibited fair performance across performance metrics, with the exception of slab cracking. Individualized plots of these performance metrics by year are given in Figure 10, Figure 11, and Figure 12 below.

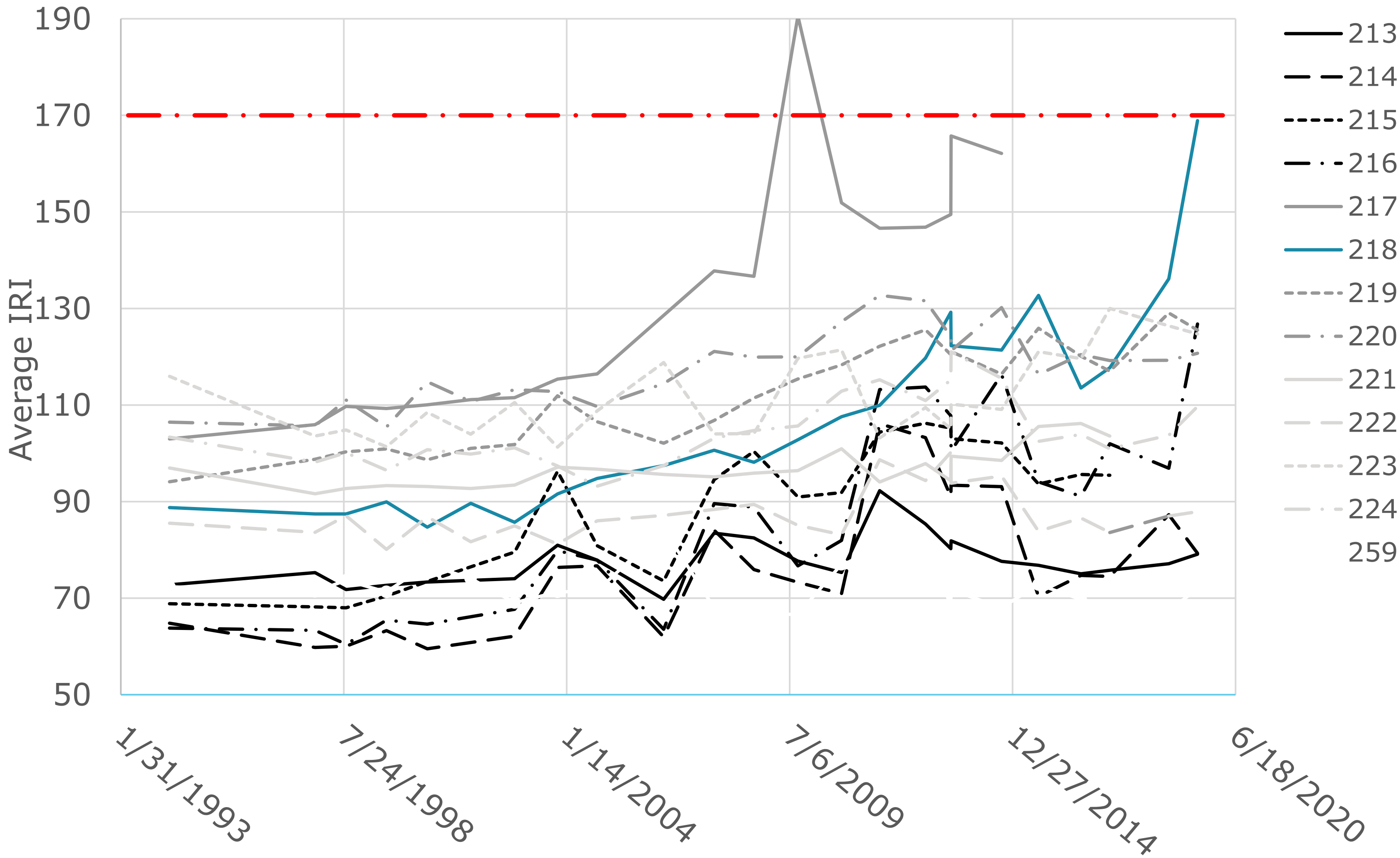

Figure 10. Average Measured Roughness (in IRI) for Colorado SPS-2 Test Sections

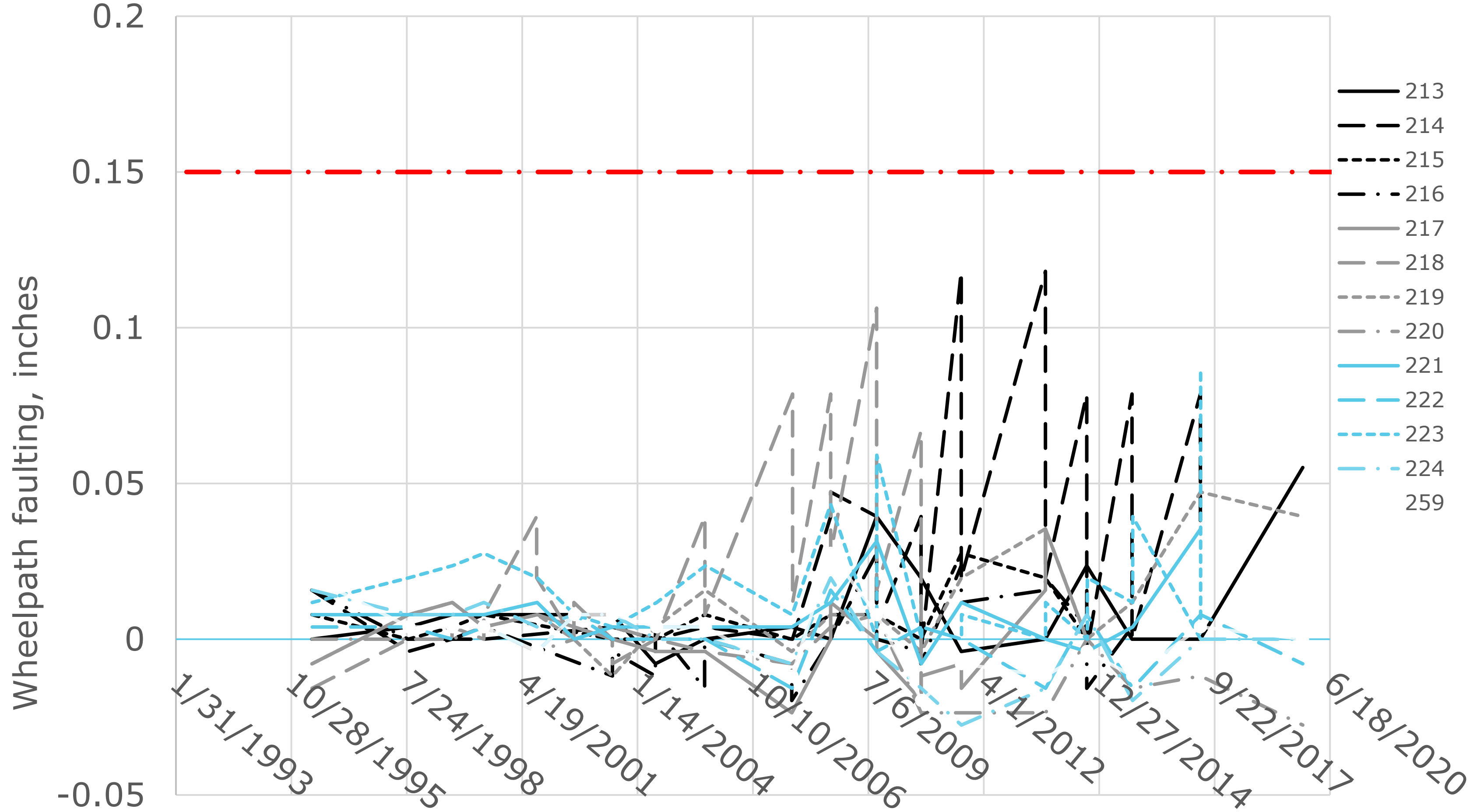

Figure 11. Average Wheel-Path faulting (in inches) for Colorado SPS-2 Test Sections

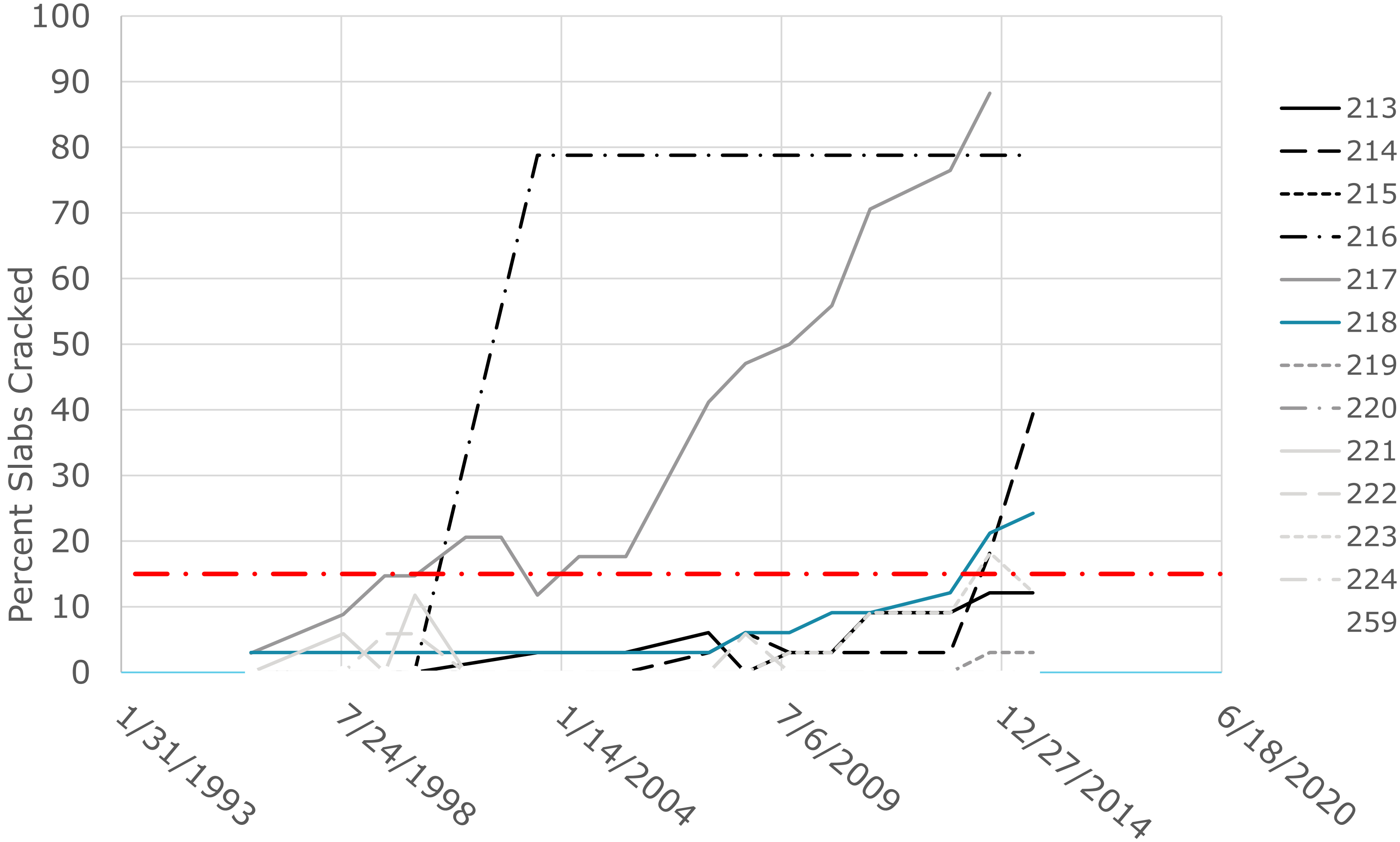

Figure 12. Average Percentage of Slabs Cracked for Colorado SPS-2 Test Sections

Only test sections 080217 and 080218 exhibited poor performance with respect to roughness while no test sections exhibited poor performance with respect to wheel-path faulting. However, test section 080214, 080216, 080217, 080218, and 080223 all exhibited poor performance with respect to slab cracking. A summary of the performance of the test sections are given in Table 12 below.

Table 12. Performance Trends Across Colorado SPS-2 Test Sections

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
080213	GOOD	FAIR	GOOD
080214	FAIR	POOR	FAIR
080215	FAIR	GOOD	GOOD
080216	FAIR	POOR	GOOD
080217	POOR	POOR	GOOD
080218	POOR	POOR	POOR
080219	FAIR	GOOD	GOOD
080220	FAIR	GOOD	GOOD
080221	FAIR	FAIR	GOOD
080222	FAIR	FAIR	GOOD
080223	FAIR	POOR	GOOD
080224	FAIR	GOOD	GOOD
080259	GOOD	GOOD	GOOD

Most sections are generally performing well but the most consistent poor performance is for the percent cracking metric, with 5 sections rated as having poor performance. The test sections receiving poor performance ratings are given in Table 13 below.

Table 13. Colorado SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
080214		2014-2015	
080216		2003-2015	
080217	2009-2014	2001-2014	
080218	2019	2014-2015	2017
080223		2014	

4.4.5 FAILURE SUMMARY

Despite the many construction and material related deviations throughout this project, there are only 5 test sections exhibiting poor performance, only 1 of which has been removed from study. However, there is little consistency in the test sections currently exhibiting poor performance, not being continuous, of consistent thickness, lane width, strength, or constructed on the same base type.

Test section 080217 was taken out of study first and was 1 of 2 test sections to be constructed in the high water table area with multiple soft spots due to the saturated conditions. Despite their efforts to repair these sections, this saturated subgrade is the most likely cause of early distress of this section. The observation of the high water table and pumping observed during the construction of the LCB layer indicate that the subgrade was certainly a problem. Additionally, a blow up was observed in the nearby transition section, a distress that can indicate significant changes in moisture and temperature, or that a joint has locked with moisture or debris.

Test section 080220 also experienced pumping and was the other Colorado test section constructed in the high water table area and also had pumping and cracking of the LCB layer prior to the placement of the PCC layer; however only test section 080217 was removed from study early. In terms of original experimental design, both of these test sections had 14 ft lane widths. However, test section 080217 was constructed with an 8 inch PCC thickness of only 550 psi flexural strength whereas test section 080220 was constructed with an 11 inch PCC thickness with 900 psi flexural strength. This increase in thickness and PCC pavement flexural strength likely contributed to the increased longevity of test section 080220, despite both sections having soft, saturated subgrade and LCB deviations and issues.

4.5 Delaware (10)

In 1992, 14 experimental sections for the SPS-2 experiment were constructed in Delaware, a wet-freeze climatic region. Of these 14 original test sections, all were removed from study in 2016.

4.5.1 TRAFFIC AND CLIMATE DEVIATIONS

At construction, the intended level of traffic was 203 KESALs while the measured KESALs per year, as of 2021, was 250, indicating the actual traffic was slightly more than expected. The freezing index of this area was measured to be 87 freezing days per year and the average annual precipitation was 45.8 inches, well within the designation for a wet-freeze climatic region.

4.5.2 CONSTRUCTION RELATED DEVIATIONS

The construction and deviation reports for the Delaware test sections indicate many possible construction and material issues that could have contributed to early failures. It was observed that the low strength sections (550 psi strength) of 100205, 100201 and 100209 experienced excessive shrinkage cracking. These were originally placed in June 1995 and were replaced in October 1995. Test sections 100206 and 100202 also experienced excessive shrinkage cracking and were replaced in November 1995. When test sections 100201 and 100202 were

removed, the underlying DGAB layer was disturbed, which required more DGAB to be added and the surface was reworked before placement.
Across the test sections, the bases did not extend the full width of the shoulders and the edge drains were not placed at the required minimum of 3 ft from the edge of the pavement or shoulder. The test sections with LCB (100205, 100206, 100207, and 100208) experienced difficulty in the construction of the LCB layer. The LCB paver stopped several times and caused slight depressions. Shrinkage cracking was noticed and developed in all observed depressions. High spots were milled before the paving of the PCC layer.

The high strength test sections 100202, 100206 and 100210 exhibited transverse cracking the day after PCC layer placement and test section 100206 also exhibited longitudinal cracking. The Delaware DOT theorized that this cracking was due to the sawing operation of the contractor.

4.5.3 MATERIALS RELATED DEVIATIONS

The test sections 100205, 100201, and 100209 were cast together and finishing of these sections was noted to be very difficult with shrinkage cracking was already evident after finishing. The Delaware DOT believed the shrinkage cracking to be caused by the very low cement content of the concrete mix. A different concrete mixture, the Delaware DOT Type B mixture (with a flexural strength of 650 psi) was used for test sections 100201, 100203, and 100207. The mixture designs used for the test sections is given in Table 14 below. The original low-strength mixture had an extremely high w/cm of 0.63. These sections were removed and replaced due to excessive shrinkage cracking.

Table 14. PCC Layer Mix Designs for Delaware SPS-2 Test Sections

SHRP ID	Date	MOR[1], psi	CA[1], lbs/CY	FA[1], lbs/CY	Cement, lbs/CY	Slag, lbs/CY	Water, gals	w/cm	Air %	SL[1], in	AE[1]	WRA[1]
100260	06/95	650	1899	1281	564[2]		30.5	0.45	5.5			2
100205[3], 100201[3], 100209[3]	06/95	550	1875	1470	400[2]		30	0.63	6.5	2	0.7	
100205, 100201, 100209	10/95	650	1812	1257	367	197	30.5	0.45	6.5			2
100211, 100203, 100207	06/95	650	1899	1281	564[2]		30.5	0.45	5.5			2
100206[4], 100202[4], 100210	06/95	900	1838	1239	397[2]	214	30.5	0.42	6.5			3
100206, 100202	11/95	900	1945	1114	487	257	32	0.36	6.5	2	1.9	2.5
100212, 100208, 100204	07/95	900	1945	1114	735[2]		32	0.36	6.5	2	1.9	2.5
100259	07/95	650	1812	1257	367	197	30.5	0.45	6.5			2

[1] MOR (modulus of rupture), CA (coarse aggregate), FA (fine aggregate), SL (slump), AE (air entraining admixture), WRA (water reducing admixture) [admixtures dosed in oz/100 lbs cementitious material]
[2] Low alkali cement used in these mixtures
[3] Sections 100201, 100205, and 100209 were replaced in October 1995 with the mix presented below the original mix
[4] Sections 100206 and 100202 were replaced in November 1995 with the mix presented below the original mix

Unsurprisingly, these mixtures did not fulfill the target requirements, especially for the low strength mix, which as seen above, was replaced by the standard Delaware DOT 650 psi strength mix. Further, slag cement was not included in the concrete mix for every test section. The average strength results for the test sections are given in Table 15.

Table 15. Average Measured Modulus of Rupture Across All Delaware SPS-2 Test Sections

	Target 14-day strength	Average 14-day strength	Average 28-day strength	Average 365-day strength
Low strength sections (odd numbered sections)	550 psi	657 psi	767 psi	797 psi
High strength sections (even numbered sections)	900 psi	757 psi	883 psi	837 psi
Supplementary section (100259)		750 psi	840 psi	770 psi
Supplementary section (100260)		710 psi	730 psi	

It can be seen that the tested strength far exceeded the original target strength for the low strength mixtures and the tested strength for the high strength sections did not meet the target strength for these sections and was approximately 150 psi too low. The specific strength results for each section are given in Table 16 below.

Table 16. Measured Modulus of Rupture for Specific Delaware SPS-2 Test Sections

	Measured modulus of rupture, psi (target 28 day modulus of rupture, psi)		
SHRP ID	14-day	28-day	365-day
100202	920 (900)	1190	1120
100205	750 (550)	930	
100207	550 (900)	650	680
100208	620 (900)	730	680
100211	670 (550)	720	740
100212	730 (900)	730	710
100259	750	840	770
100260	710	730	970

Test section 100202 met the strength target, but no other high strength section tested came close to meeting the target strength of 900 psi. The low strength mixtures exceeded the planned target strength by approximately 100-200 psi in each section as well. Most mixtures exhibited unusual strength gain behavior (Table 16) with many sections gaining little strength, or even losing strength, over the course of the year.

Air content data taken on site during construction indicates the average air content for low-strength mixes that were tested was 8.3% while the average air content for high-strength mixes was 6.7%. Given the target air content of 5.5%.

4.5.4 TEST SECTION PERFORMANCE

Most test sections generally exhibited fair performance across performance metrics. Individualized plots of these performance metrics by year are given in Figure 13, Figure 14, and Figure 15 below.

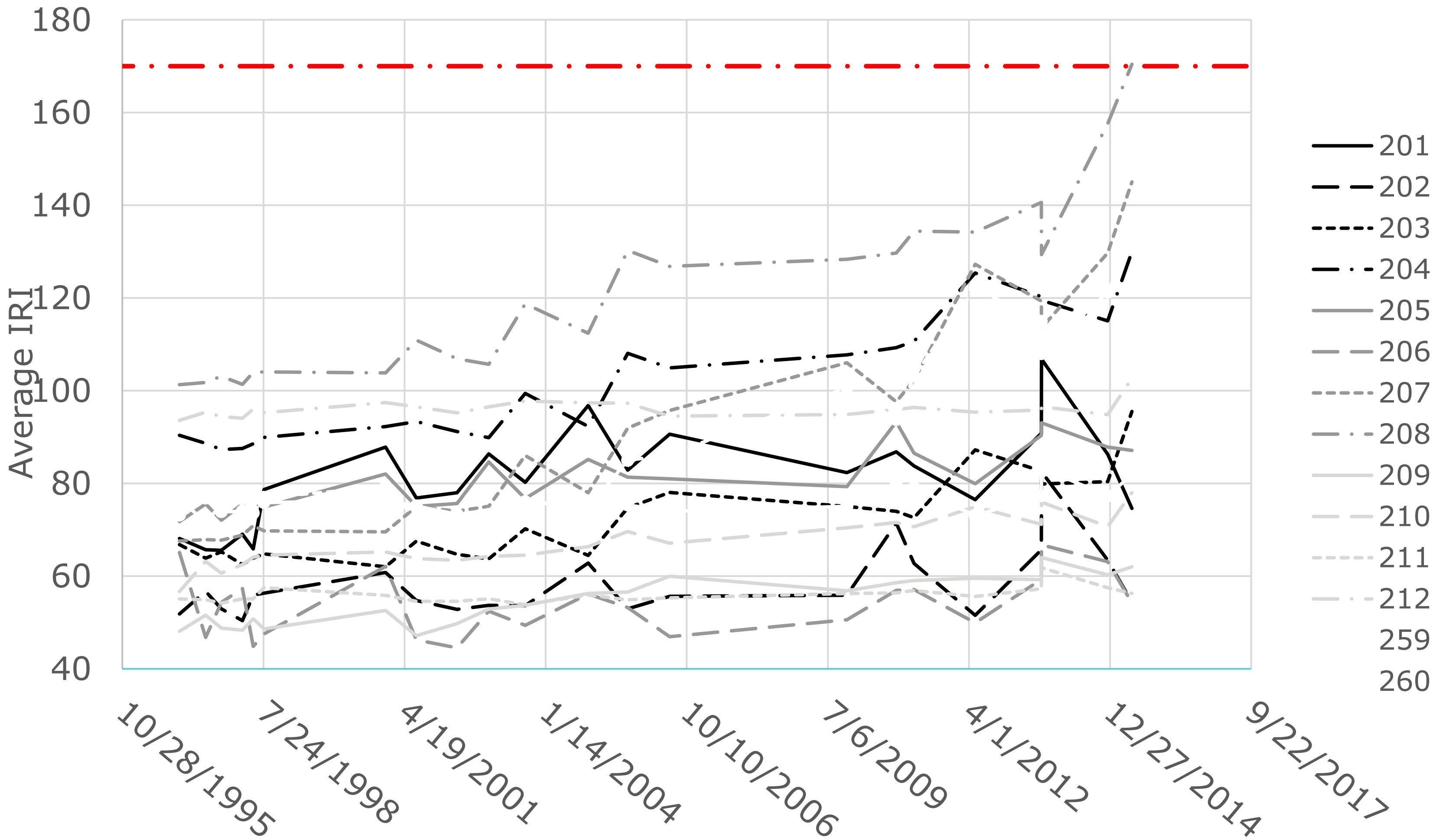

Figure 13. Average Pavement Roughness (in IRI) for Delaware SPS-2 Test Sections

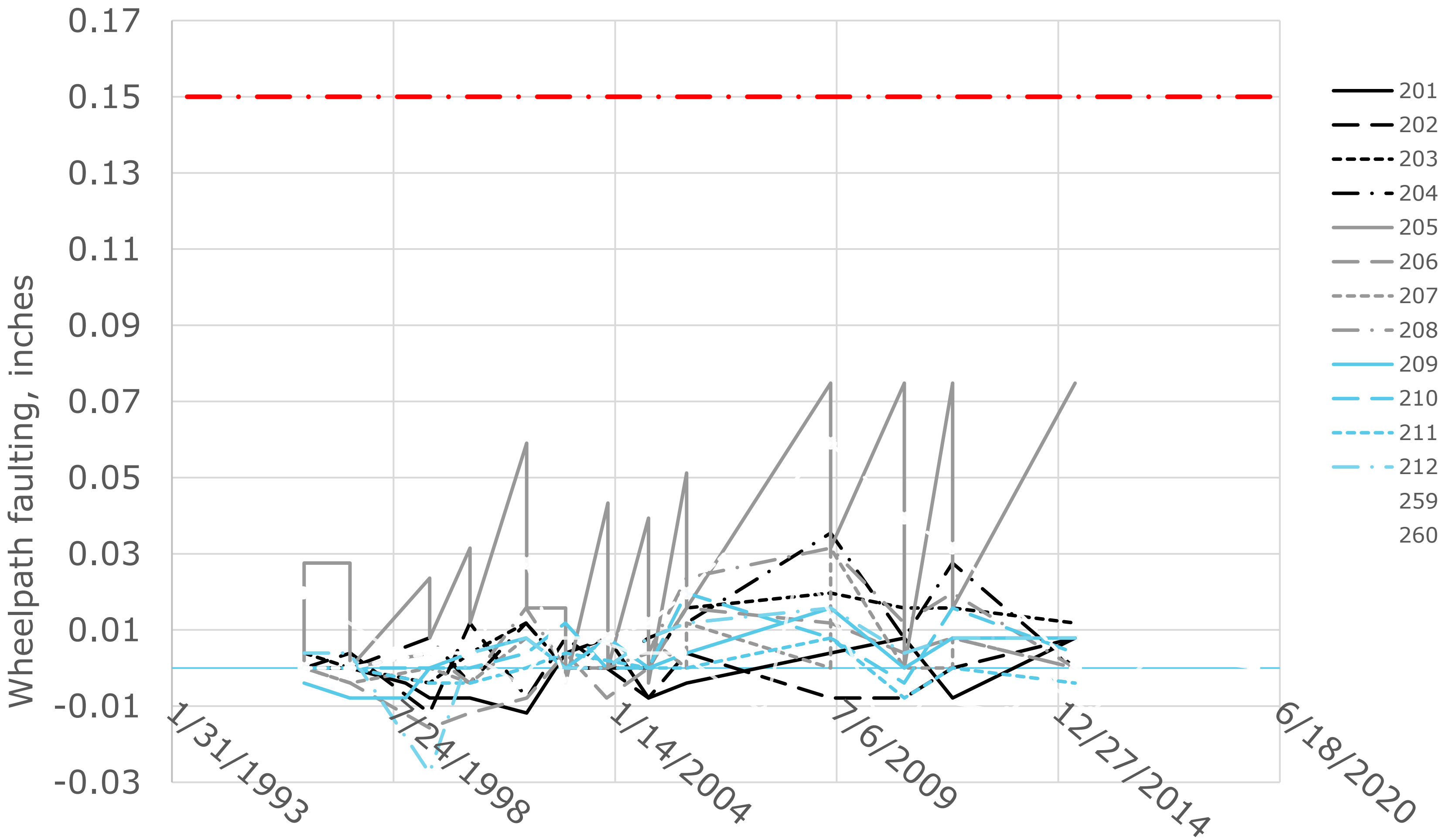

Figure 14. Average Wheel-Path faulting (in inches) for Delaware SPS-2 Test Sections

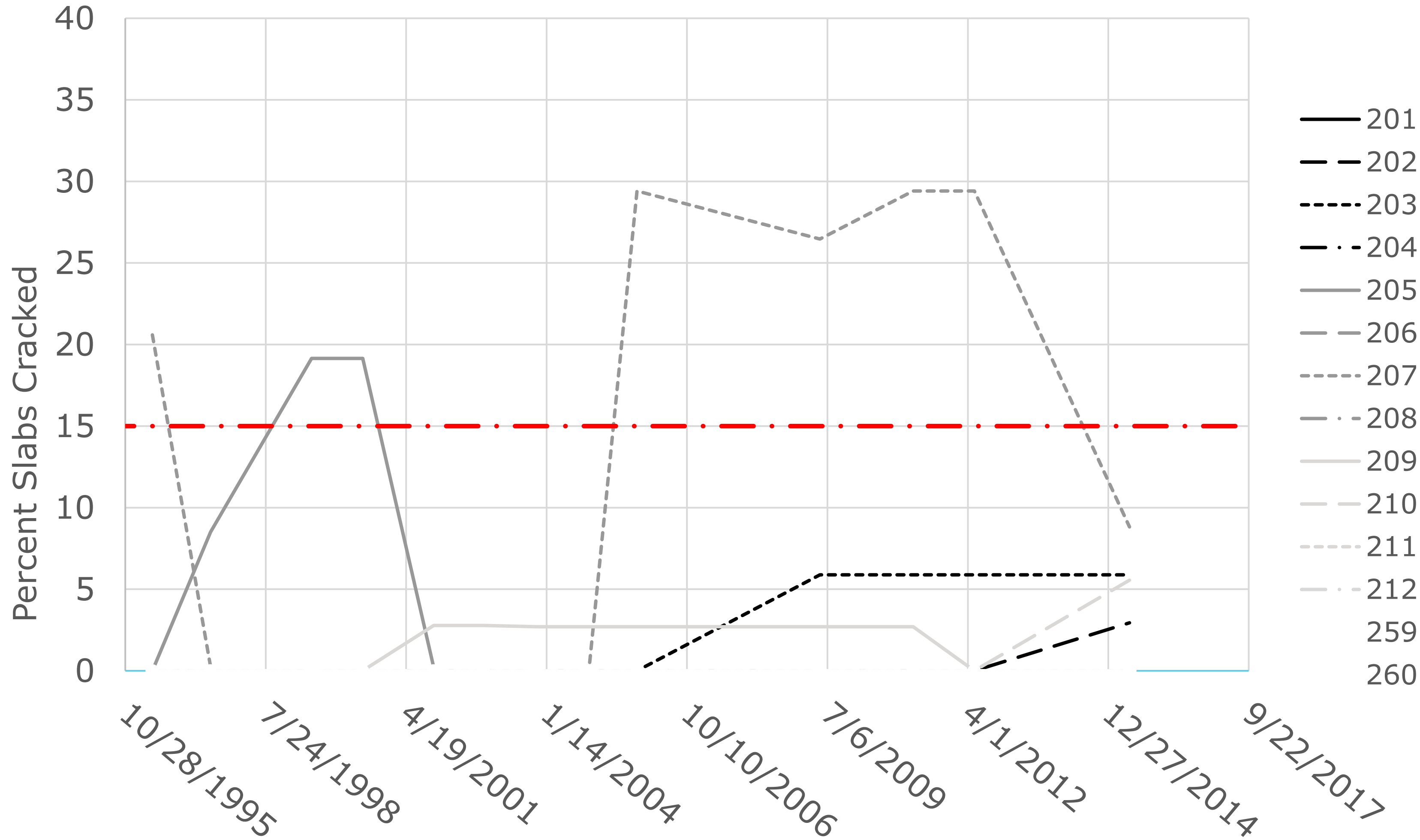

Figure 15. Average Percent Slabs Cracked for Delaware SPS-2 Test Sections

Only test section 100208 exhibited poor performance with respect to surface roughness while all test sections were well below the poor performance threshold in wheel-path faulting. Test sections 100205 and 100207 exhibited poor performance with respect to slab cracking. A summary of the noted performance trends for Delaware SPS-2 test sections is given in Table 17.

Table 17. Performance Trends Across Delaware SPS-2 Test Sections

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
100201	FAIR	GOOD	GOOD
100202	GOOD	GOOD	GOOD
100203	FAIR	FAIR	GOOD
100204	FAIR	GOOD	GOOD
100205	FAIR	POOR	FAIR
100206	GOOD	GOOD	GOOD
100207	FAIR	POOR	GOOD
100208	POOR	GOOD	GOOD
100209	GOOD	GOOD	GOOD
100210	GOOD	FAIR	GOOD
100211	GOOD	GOOD	GOOD
100212	FAIR	GOOD	GOOD
100259	FAIR	GOOD	GOOD
100260	FAIR	GOOD	GOOD

Despite being removed from study, many of the Delaware SPS-2 test sections were generally performing well. Specific test sections that received poor performance ratings while in study are given in Table 18 below.

Table 18. Delaware SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
100208	2013-2015		
100205		1999-2000	
100207		2005-2015	

4.5.5 FAILURE SUMMARY

The Delaware SPS-2 test sections contained many deviations from the intended construction and materials. However, the three specific sections exhibiting poor performance, test sections 100205, 100207, and 100208 did have some similar deviations across these test sections. These test sections all had inconsistent strength from planned, as discussed previously (Table 8). Test sections 100207 and 100208 were both paved on LCB base and their strength values were significantly lower (200 psi) than the target strength of 900 psi. While test section 100205 was a low strength section, its strength was significantly higher than anticipated. Additionally, all three of these test sections were constructed on the LCB layer, which had noted construction challenges during placement that may have contributed to poor performance.

4.6 Iowa (19)

In 1995, 13 experimental sections for the SPS-2 experiment were constructed in Iowa, a wet freeze climatic region. These test sections remain in study and have overall moderate performance.

4.6.1 TRAFFIC AND CLIMATE DEVIATIONS

At construction, the intended level of traffic of this section was 329 KESALs while the measured KESALs per year, as of 2021, was 570, indicating the actual traffic load was significantly higher than expected. The freezing index of this area was measured to be 548 F days and the average annual precipitation was 35.6 inches, indicating the climate was well within the expected boundaries for this climatic region.

4.6.2 CONSTRUCTION RELATED DEVIATIONS

There were several deviations noted in the construction report for the Iowa test sections. First, construction of the test section was delayed due to an extremely rainy spring season and there were construction delays throughout the project due to rainy weather.

During the construction of test section 190222, dowel baskets were placed incorrectly resulting in this test site being removed and replaced by the contractor. This changed the boundaries of the test section.

Finally, 1 ft of the filter fabric was removed across the longitudinal edge drains in test sections 190221, 190222, 190223, and 190224. There were some variations in constructed thickness of the sections, which are given in Table 19 below. Sections that exhibited poor performance are indicated with bold type font.

Table 19. Summary of Construction Factors for Iowa SPS-2 Test Sections

SHRP ID	Base Type and Thickness	Lane Width	PCC thickness	
			Design	Built
190217	6 "LCB	**14**	**8**	**7.9**
190218		**12**	**8**	**8.2**
190219		12	11	11.2
190220		14	11	11.3
190215	6" DGAB	12	11	11.9
190216		**14**	**11**	**11.8**
190213		14	8	8.7
190214		**12**	**8**	**8.7**
190259		14	11	
190221	4" PATB 4"DGAB	14	8	9.4
190222		12	8	8.5
190223		12	11	11.9
190224		14	11	11.5

4.6.3 MATERIALS RELATED DEVIATIONS

There were several materials related deviations for the Iowa SPS-2 test sections. The high strength mixture did not achieve the targeted flexural strength with the average 14-day modulus of rupture being 150 psi below the target (750 psi instead of 900 psi). In response, the mix was altered by adding 50 extra pounds of cement per cubic yard (without redesign) and this was paved. However, modulus of rupture testing indicates that target strength was still not met for the high strength test sections as seen in Table 20 below.

Table 20. Measured Modulus of Rupture for Specific Iowa SPS-2 Test Sections

	Measured modulus of rupture, psi (target 14 day modulus of rupture, psi)		
SHRP ID	14-day	28-day	365-day
190213	500 (550)	590	590
190214	700 (900)	770	770
190219	440 (550)	530	610
190220	770 (900)	720	890
190223	460 (550)	520	680
190224	790 (900)	750	930

4.6.4 TEST SECTION PERFORMANCE

Most test sections generally exhibited fair performance across performance metrics. Individualized plots of these performance metrics by year are given in Figure 16, Figure 17, and Figure 18 below.

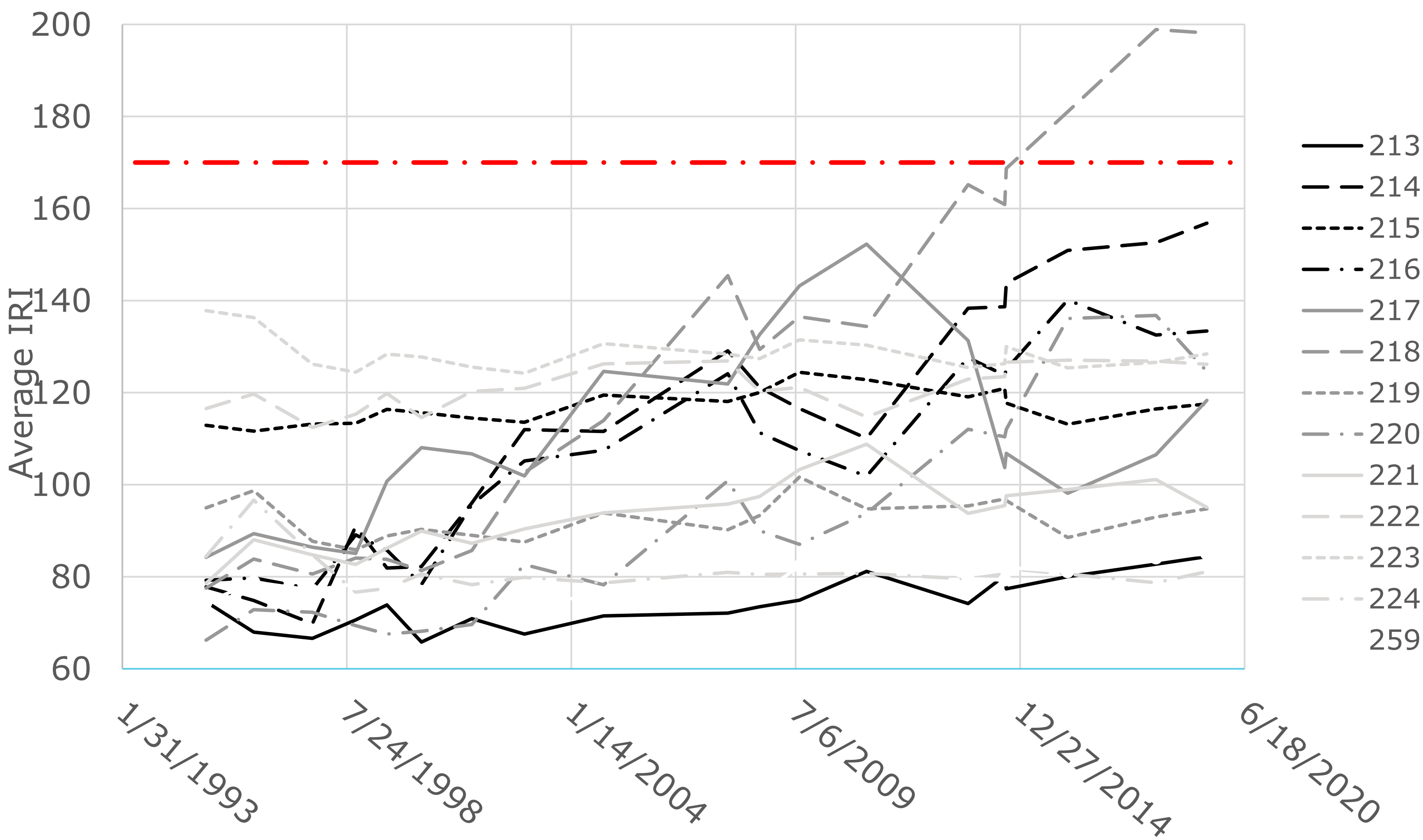

Figure 16. Average Roughness (in IRI) of Iowa SPS-2 Test Sections

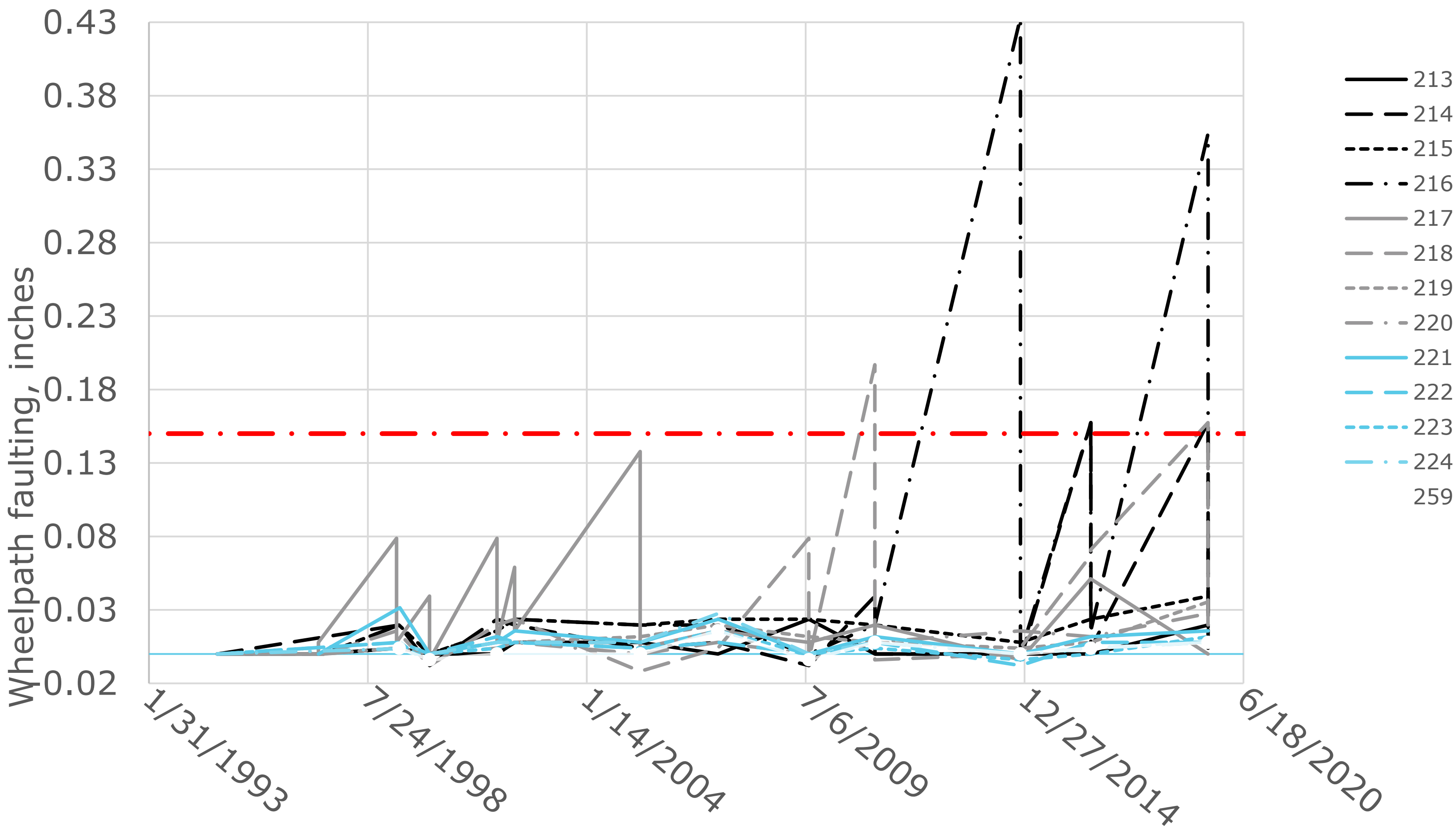

Figure 17. Average Wheel-Path faulting (in inches) of Iowa SPS-2 Test Sections

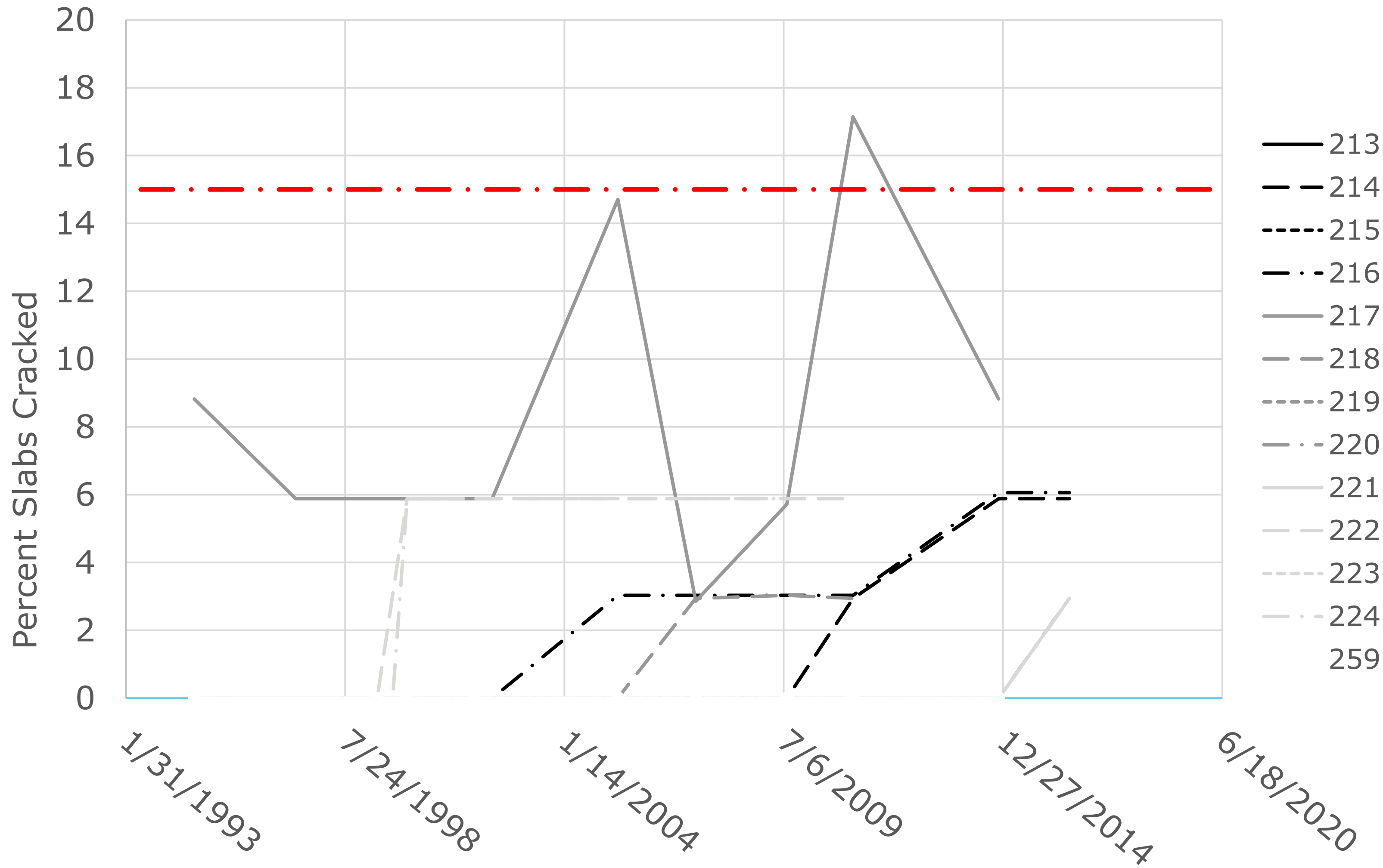

Figure 18. Average Percent Slabs Cracked of Iowa SPS-2 Test Sections

Many test sections exhibited fair performance across roughness with only test section 190218 exhibited poor performance with respect to roughness. Test sections 190216 and 190218 both exhibited poor performance with respect to wheel-path faulting and test section 190217, while exhibiting fair performance, was extremely close to the threshold for poor performance with respect to wheel-path faulting. Test section 190217 exhibited poor performance with respect to slab cracking. The performance trends of the Iowa SPS-2 test sections are summarized in Table 21 below.

Table 21. Performance Trends Across Iowa SPS-2 Test Sections

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
190213	GOOD	GOOD	GOOD
190214	POOR	FAIR	POOR
190215	FAIR	GOOD	GOOD
190216	FAIR	FAIR	POOR
190217	FAIR	POOR	FAIR
190218	POOR	GOOD	POOR
190219	FAIR	GOOD	GOOD
190220	FAIR	GOOD	GOOD
190221	FAIR	GOOD	GOOD
190222	FAIR	FAIR	GOOD
190223	FAIR	GOOD	GOOD
190224	FAIR	FAIR	GOOD
190259	GOOD	GOOD	GOOD

In general, the performance of these test sections is moderate with several test sections obtaining "poor" performance ratings across all three performance metrics. The specific test sections which received metrics during distress surveys which correlated to "poor" performance are given in Table 22 below.

Table 22. Iowa SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
190214			2016-2019
190216			2014-2019
190218	2014-2019		2011-2019
190217	2019	2011	

Generally, it can be seen that most poor performance was due to faulting with only two test sections experiencing poor performance ratings for roughness and only one section experiencing poor performance due to cracking.

4.6.5 FAILURE SUMMARY

There were some significant variations from the intended construction practices and material parameters that could affect the performance of the Iowa SPS-2 test sections, including significant variances in thickness and strength. Table 23 summarizes some construction and material properties for the test sections that are experiencing poor performance.

Table 23. Summary of Construction and Material Properties of Iowa SPS-2 Test Sections with Poor Performance

SHRP ID	Base Type and Thickness	Lane Width	PCC thickness		PCC 14-day modulus of rupture, psi	
			Design	Built	Design	Built
190217	6″ LCB	14	8	7.9		
190218	6″ LCB	12	8	8.2		
190216	6″ DGAB	14	11	11.8		
190214	6″ DGAB	12	8	8.7	900	700

Three of the four test sections experiencing poor performance utilized the high strength mix (targeting 900 psi flexural strength at 14 days), which consistently failed to meet the strength requirement. Additionally, most poorly performing sections have the thinner PCC thickness with half placed on DGAB and the other half placed on the LCB base layer.

4.7 Kansas (20)

In 1992, 13 experimental sections for the SPS-2 experiment were constructed in Kansas, a wet-freeze climatic region. These test sections remain in study and have overall fair performance.

4.7.1 TRAFFIC AND CLIMATE DEVIATIONS

At construction, the intended level of traffic of this section was estimated to be 1300 KESALs while the measured KESALs per year, as of 2021, was 720, indicating the actual traffic load was significantly less than expected. Additionally, the freezing index in the area was measured to be 252 F days per year and the average annual precipitation was 33.4 inches, indicating the climate was well within the expected boundaries for this climatic region.

4.7.2 CONSTRUCTION RELATED DEVIATIONS

There were several construction related deviations during the construction of the Kansas SPS-2 test sections. First, there were unexpected site conditions with 7 test sections constructed on top of underground structures. Most prominently, there was a box culvert located below test sections 200204, 200208, 200209, and 200211. Additionally, the transverse drain for the PATB layer ran below test section 200210 and a median drain ran below test section 200211.

Construction was initially delayed due to an exceptionally rainy season and there were delays throughout construction due to continually rainy weather during construction. Type C fly ash was used to dry subgrade soil prior to construction of the stabilized aggregate subbase.
There were many construction issues with construction of the PATB layer and it was ultimately placed too thick and required trimming to the appropriate thickness following initial placement.

4.7.3 MATERIALS RELATED DEVIATIONS

There were very few materials related distresses outlined in the construction report. It was noted during construction that the PATB layer was impossible to core and material was physically hammered into forms for sampling instead. A summary of the measured modulus of rupture values for the test sections is given in Table 24 below.

Table 24. Measured Modulus of Rupture for Specific Kansas SPS-2 Test Sections

	Measured modulus of rupture, psi (target 14 day modulus of rupture, psi)		
SHRP ID	14-day	28-day	365-day
200201	606 (550)	638	692
200202	803 (900)	911	915
200203	595 (550)	656	744
200204	784 (900)	849	816
200205	702 (550)	706	722
200206	829 (900)	928	904
200207	560 (550)	645	715
200208	855 (900)	1035	883
200209	624 (550)	576	746
200210	924 (900)	839	1002
200211	576 (550)	674	693
200212	865 (900)	990	992
200259	618	677	738

It can be seen from this data that the low strength mix samples regularly exceeded the targeted strength requirement of 550 psi and generally the high strength mix samples failed to meet their minimum strength requirement of 900 psi. In general, the results look very consistent although the mixtures for test sections 200204 and 200205 had the largest deviation from their respective target strengths.

4.7.4 TEST SECTION PERFORMANCE

Most test sections exhibited fair performance across performance metrics. Individualized plots of these performance metrics by year are given in Figure 19, Figure 20, and Figure 21 below.

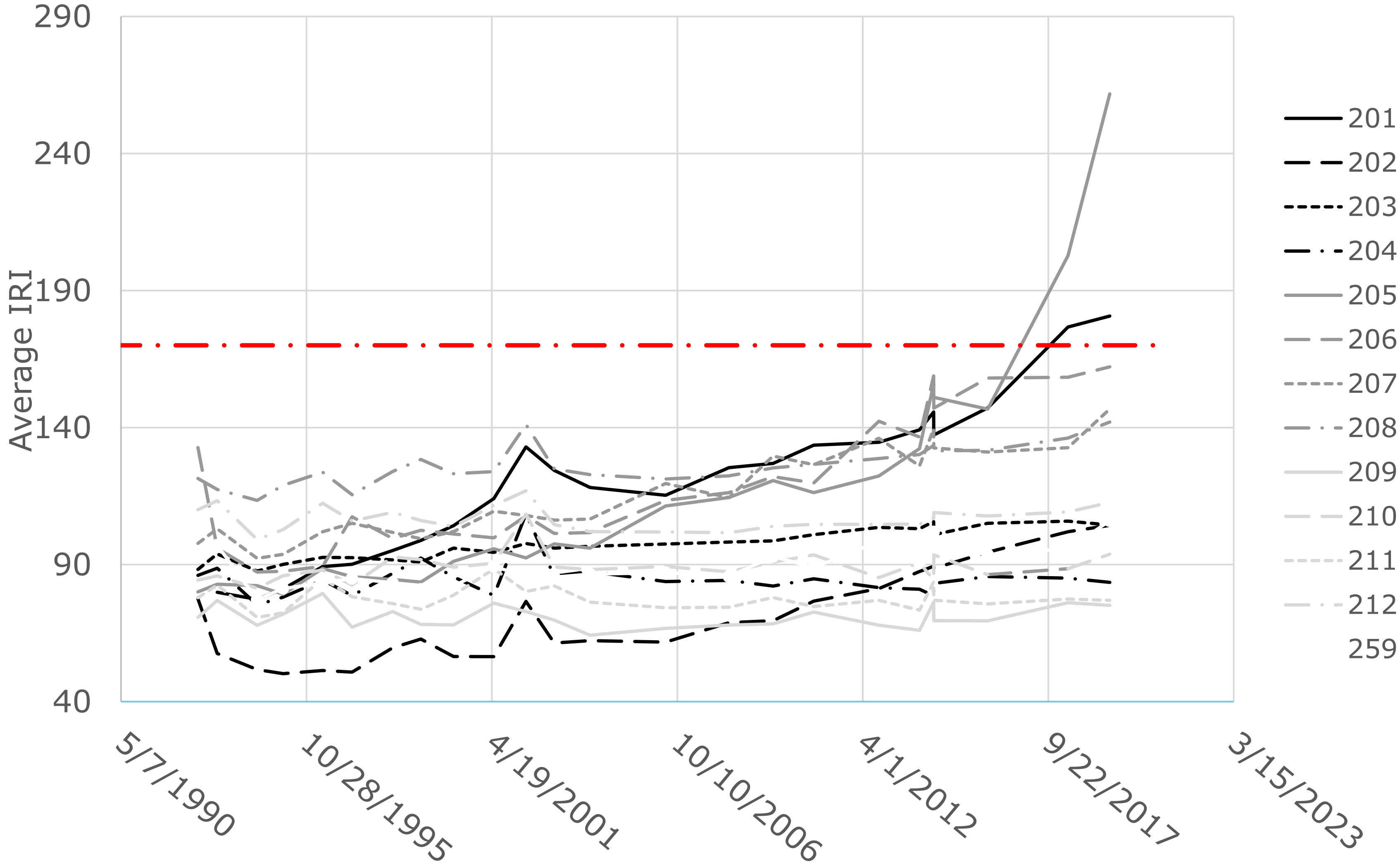

Figure 19. Average Roughness (in IRI) of Kansas SPS-2 Test Sections

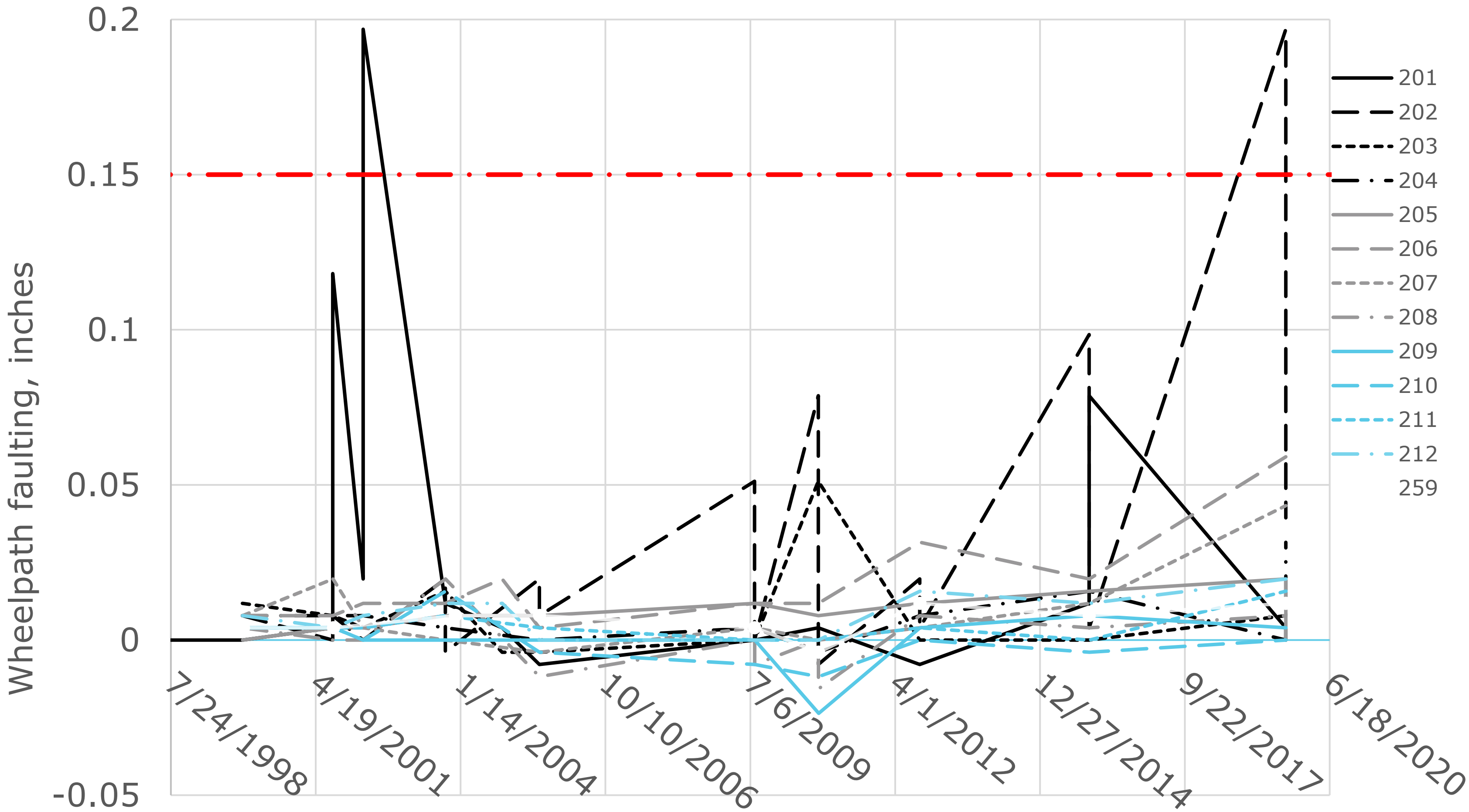

Figure 20. Average Wheel-Path faulting (in inches) of Kansas SPS-2 Test Sections

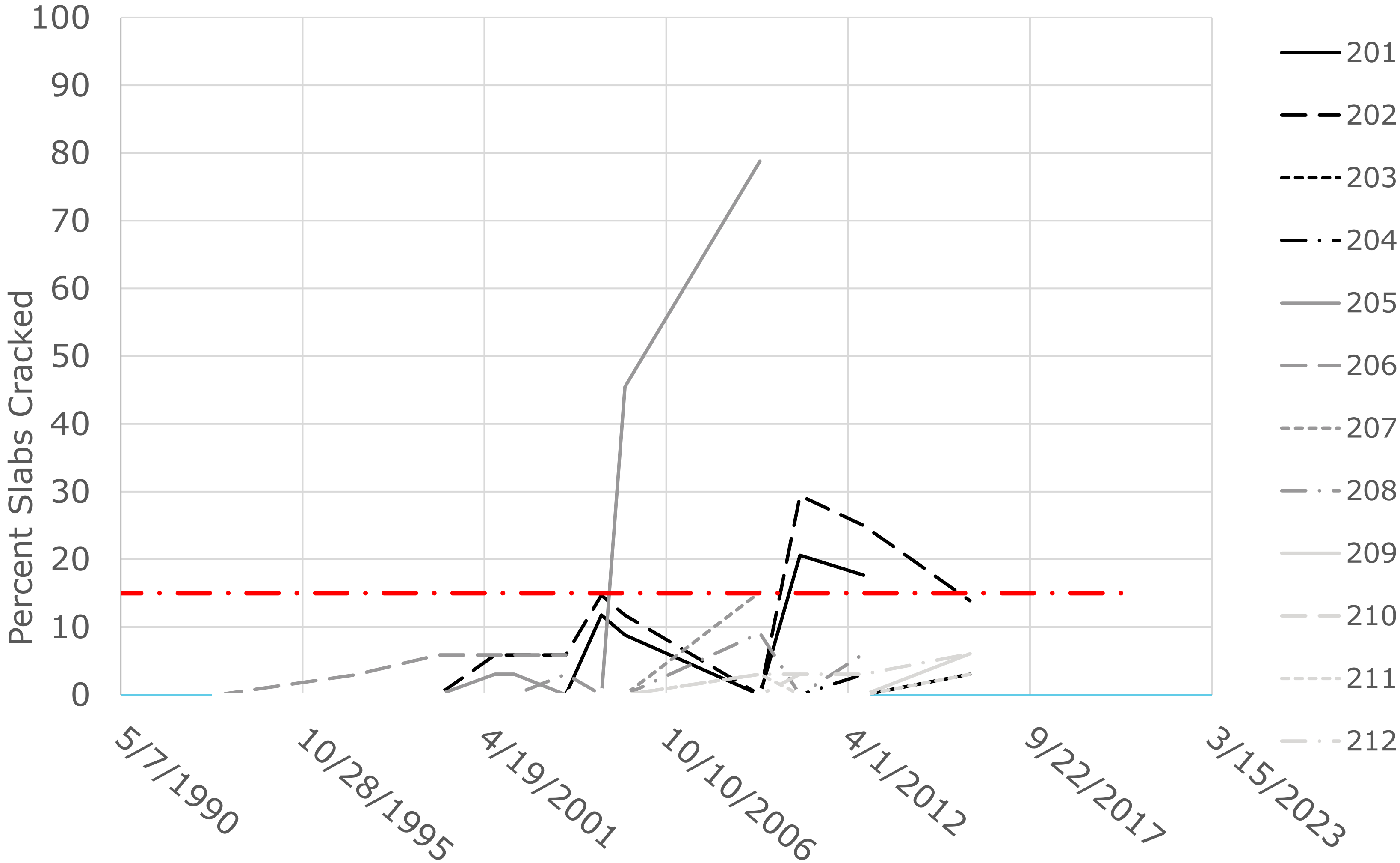

Figure 21. Average Percent Slabs Cracked of Kansas SPS-2 Test Sections

Both test section 200201 and 200205 exhibited poor performance with respect to roughness while most other test sections exhibited fair performance. Test sections 200201 and 200202 exhibited much higher levels of wheel-path faulting, well into the poor performance threshold, and much higher than all other test sections, which had relatively low wheel-path faulting. Test sections 200201, 200202, and 200205 all exhibited poor performance with respect to slab cracking and test section 200205 exhibited the highest level of slab cracking of all test sections. A summary of the performance trends of the Kansas SPS-2 test sections are given in Table 25 below.

Table 25. Performance Trends Across Kansas SPS-2 Test Sections

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
200201	POOR	POOR	POOR
200202	FAIR	POOR	POOR
200203	FAIR	GOOD	GOOD
200204	FAIR	GOOD	GOOD
200205	POOR	POOR	GOOD
200206	POOR	FAIR	GOOD
200207	FAIR	POOR	GOOD
200208	FAIR	FAIR	GOOD
200209	GOOD	FAIR	GOOD
220210	FAIR	GOOD	GOOD
200211	GOOD	GOOD	GOOD
200212	FAIR	FAIR	GOOD
200259	FAIR	GOOD	GOOD

The performance of these test sections is moderate with several test sections obtaining "poor" performance ratings across all three performance metrics. The specific test sections which received metrics "poor" performance are given in Table 26 below.

Table 26. Kansas SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
200201	2018-2019	2010-2012	2002
200202		2010-2012	2019
200205	2014-2019	2005-2009	
200206	2019		
200207		2009	

Generally, most poor performance was due to cracking with some corresponding roughness, which would be expected with a high level of cracking.

4.7.5 FAILURE SUMMARY

Few construction and materials related deviations were explicitly mentioned in the construction report for the Kansas SPS-2 test sections. However, a summary of construction and material factors that may contribute to the observed poor performance of several test sections is given in Table 27 below. Test sections with observed poor performance based on the performance metrics are written bold font.

Table 27. Summary of Construction Factors for Kansas SPS-2 Test Sections

Construction Station	SHRP ID	Base Type and Thickness	Lane Width	PCC thickness		14-day modulus of rupture, psi	
				Design	Built	Design	Built
264+28 to 269+28	200259	6″ stabilized base 6″ Mod flyash	12′	12″	12.2″	600	647
270+28 to 275+78	200209	4″ PATB 4″DGAB	12′	8″	8.5″	550	600
277+23 to 282+23	200210		14′	8″	8.3″	900	882
302+58 to 307+58	200211		14′	11″	10″	550	625
329+43 to 334+43	200212		12′	11″	9.1″	900	928
335+73 to 340+73	200208	6″ LCB	12′	11″	11.1″	900	945
342+18 to **347+18**	**200207**		**14′**	**11″**	**10.1″**	**550**	**617**
348+63 to 353+63	**200205**		**12′**	**8″**	**8.1″**	**550**	**704**
355+08 to 360+08	**200206**		**14′**	**8″**	**7.8″**	**900**	**879**
361+53 to 366+53	**200202**	6″DGAB	**14′**	**8″**	**8.2″**	**900**	**857**
367+98 to **372+98**	**200201**		**12′**	**8″**	**7.8″**	**550**	**600**
393+18 to 398+18	200204		12′	11″	11.4″	900	817
399+63 to 404+63	200203		14′	11″	11.2″	550	626

Based on project stationing, it appears that the five test sections with poor performance all occur together and continuously in the middle of the project, which could indicate an issue with sublayers. In general, these test sections were the thinner test sections that were constructed on either LCB or DGAB with the exception of test section 200207 which was constructed an inch thinner than the design requirement. This could imply that there could be a drainage or subgrade issue affecting this group of test sections that contributed to the faulting, cracking and increased IRI.

4.8 Michigan (26)

In 1993, 13 experimental sections for the SPS-2 experiment were constructed in Michigan, a wet-freeze climatic region. These 13 original test sections were taken out of study: one section (260218) was taken out of study in 1998, two more sections (260217 and 260213) were taken out of study in 1999, section 260215 was taken out of study in 2000, test section 260214 was taken out of study in 2007 and finally, test sections 260219, 260220, 26022, 260216, 260223, 260224, and 260259 were all taken out of study together in 2013.

4.8.1 Traffic and climate deviations

At construction, the intended level of traffic of this section was 1330 KESALs while the measured KESALs per year, as of 2021, was 1870, indicating the actual traffic was more than the expected. The construction report noted that the traffic flow all over the test sections was not uniform and a road intersected these test sections, which potentially alters traffic values. The freezing index in this area was measured to be 370 freezing days per year and the average annual precipitation was 34.5 inches, well within the designation for a wet-freeze climatic region.

4.8.2 Construction related deviations

The construction report indicated several construction related deviations. During the subgrade preparation, the moisture content of the compacted subgrade fell below the required range of 85% to 120% of the optimum moisture content on test sections 260213, 260214, 260215, 260216, 260218, 260219, and 260220.

There were several construction related deviations specifically relating to the PATB layer. For all test sections with a PATB layer, the geotextile filter fabric for underdrains did not extend a minimum of 1 ft under the pavement. Additionally, all sections with a PATB base experienced rutting of the PATB layer, though there was not a clear reason for this.

There were also several construction related deviations for test sections with an LCB layer. Test sections 260217 and 260220 exhibited longitudinal cracking across the LCB layer and the LCB material from test sections 260218, 260219, and 260220 all had a slump lower than the lower limit of 1 inch and the LCB layer in test section 260218 specifically did not meet the thickness requirements. Full as-constructed thickness results for this experiment are presented in Table 28 below.

Table 28. Measured Layer Thicknesses for Michigan SPS-2 Test Sections

	As-constructed layer thicknesses, inches		
SHRP ID	PCC	LCB	PATB
260213	8.5		
260214	8.9		
260215	11.2		
260216	11.6		
260217	8.5	6.1	
260218	7.1	6.9	
260219	10.8	6.3	
260220	11.0	5.8	
260221	8.1		
260222	8.5		4.0
260223	11.0		4.0
260224	11.1		

Significant deviations from the target thicknesses occurred in test section 260218, which had an LCB layer with an additional inch of thickness and a resulting PCC surface layer of only 7 inches rather than the targeted 8 inches. Other sections did not experience as extreme a deviation as this test section; however, thickness tolerances for the PCC layer were not met for sections 260213, 260214, 260217, 260218, and 260222.

There were construction issues with the DGAB layer in some cases as well. The DGAB segregated in section 260221, and, during construction, the DGAB was not kept uniformly moist in some test section areas.

Additionally, the bituminous shoulders were not placed for several weeks following placement. The initial joint sawcutting was performed soon after placement; however, it was observed that many of the joints did not fully activate before placement of the asphalt shoulders. On average, it appeared that only approximately every fourth sawcut joint activated prior to the placement of the shoulders.

4.8.3 MATERIALS RELATED DEVIATIONS

There were several materials related deviations that occurred during the construction of the Michigan SPS-2 test sections, and specifically in the PCC layer. First, measured strength values varied significantly from target values as can be seen from the measured modulus of rupture values given in Table 29 below.

Table 29. Measured Modulus of Rupture for Specific Michigan SPS-2 Test Sections

	Measured modulus of rupture, psi (target 14 day modulus of rupture, psi)		
SHRP ID	14-day	28-day	365-day
260213	645 (550)	760	915
260214	975 (900)	980	1000
260215	585 (550)	900	915
260219	620 (550)	1040	835
260220	970 (900)	1015	965
260224	840 (900)	940	875
260259	690	790	970

This testing data shows that while the high strength (900 psi) mixture aligned closely with its target value, the low strength (550 psi) mixture well exceeded the target.

Finally, the subgrade encountered in some areas was much harder than expected and contained a much higher content of gravel and cobblestones. This required the use of split spoon samplers rather than Shelby tube samplers to obtain subgrade samples. However, there were other areas of subgrade that were excessively soft and failed proof rolling prior to paving. This area of excessively soft subgrade required undercutting and replacement with a more stable embankment material for test sections 260216, 260222 and 260223. These undercuts were approximately 36 feet wide and 1 foot deep and were backfilled with compacted embankment borrow clay.

Though this was not a materials-related deviation, a possible materials related issue that could have contributed to some of the early failure observed in this section was the low-strength mixture proportions. The low strength mixture (targeted 550 psi modulus of rupture mix) had a low total cementitious materials content per cubic yard of 376 lbs per cubic yard and a high w/cm of 0.56. The concrete mixtures used for the low strength (550 psi), high strength (900 psi) and state supplementary sections (650 psi) are given in Table 30 below.

Table 30. Concrete Mixture Designs for Michigan SPS-2 Test Sections

SHRP ID	CA[1], lbs/CY	FA[1], lbs/CY	Cement, lbs/CY	Fly ash, lbs/CY	Water, lbs	w/cm	AE[1]	WRA[1]
550 psi	1827	1485	376		211	0.56	1	3
900 psi	1605	1307	750		285	0.38	1.7	3
600 psi (state mix)	1915	1278	451	113	290	0.51	3	3

[1] CA (coarse aggregate), FA (fine aggregate), AE (air entrainer), WRA (water reducing admixture). AE and WRA doses are given in oz/100 lbs cementitious material

The measured air content of test sections 260214, 260219 and 260220 all fell below the limit of 5% and the concrete used on test sections 260215 and 260219 both did not meet the lower limit the slump test of 1 inch.

4.8.4 TEST SECTION PERFORMANCE

Most test sections generally exhibited fair performance across performance metrics, with the exception being surface roughness, which had several test sections exhibiting poor performance. Individualized plots of these performance metrics by year are given in Figure 22, Figure 23, and Figure 24.

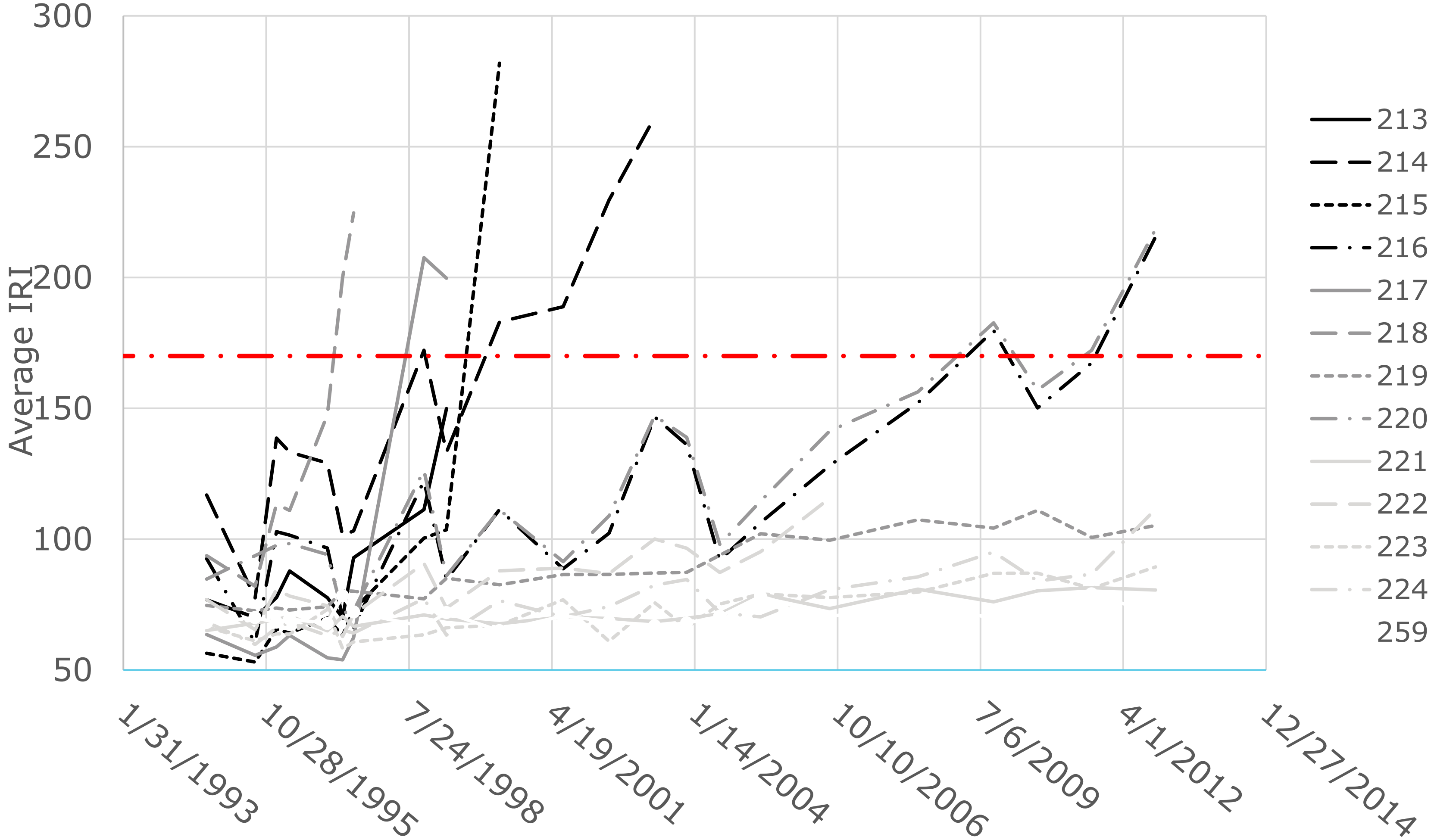

Figure 22. Average Roughness (in IRI) of Michigan SPS-2 Test Sections

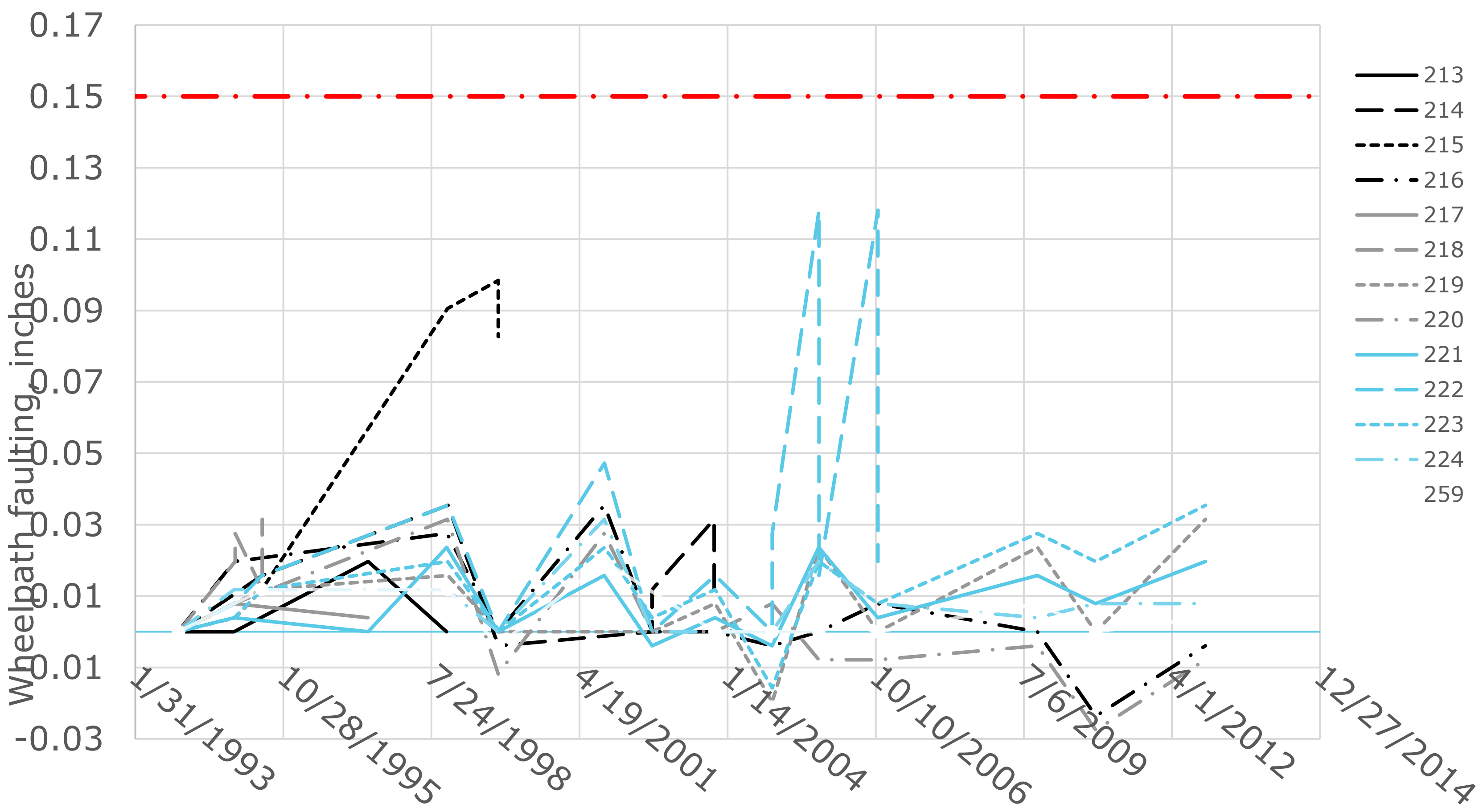

Figure 23. Average Wheel-Path faulting (in inches) for Michigan SPS-2 Test Sections

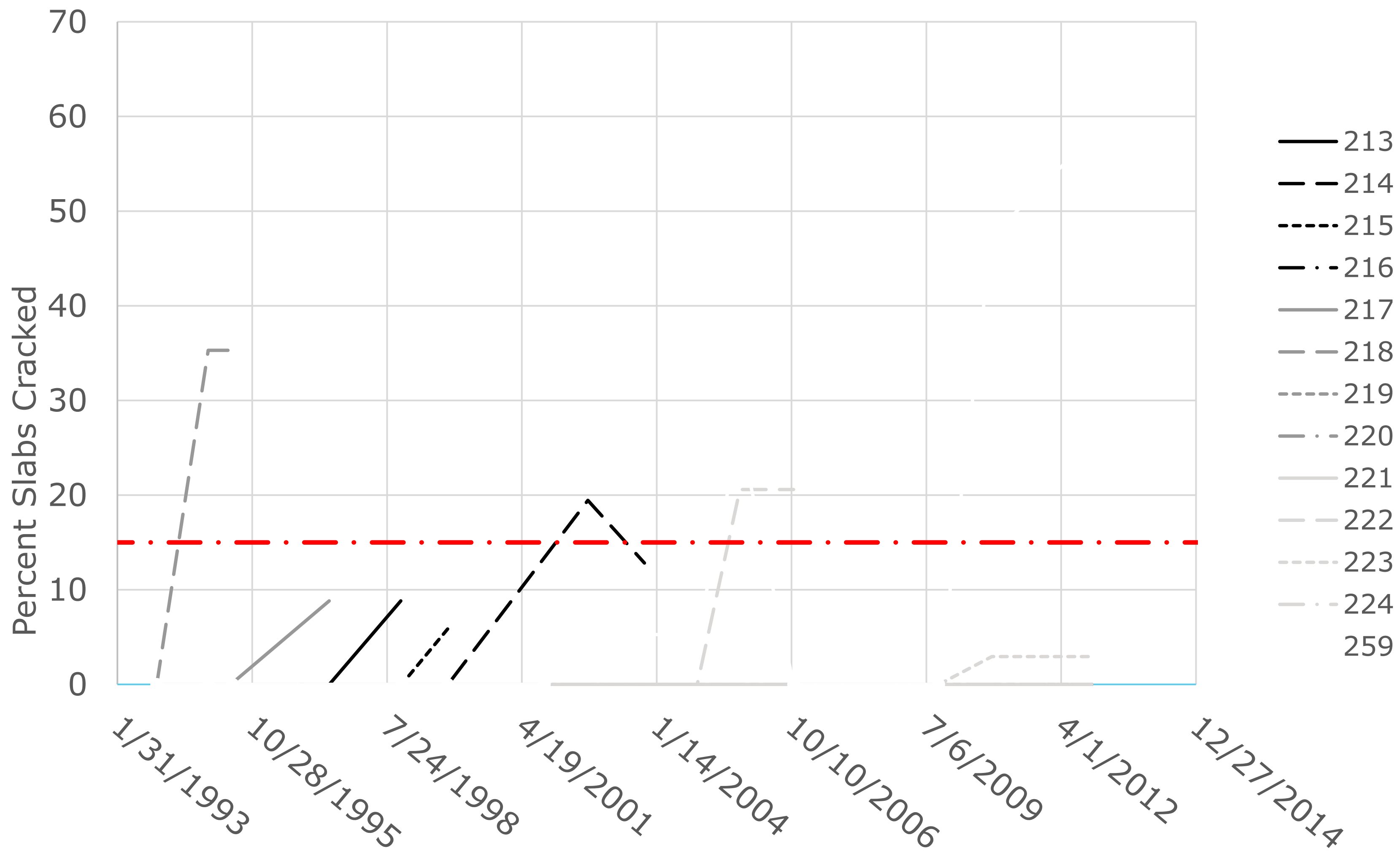

Figure 24. Average Percent Slabs Cracked for Michigan SPS-2 Test Sections

Test section 260214, 260215, 260216, 260217, 260218, and 260220 all exhibited poor performance with respect to roughness. It can also be seen that all test sections were well below the poor threshold for wheel-path faulting with test sections 260215 and 260222 exhibited the highest recorded level among the test sections. Test sections 260214, 260218, 260222 and 260259 exhibited poor performance with respect to slab cracking. Summarized performance trends of the Michigan SPS-2 test sections are given in Table 31 below.

Table 31. Performance Trends Across Michigan SPS-2 Test Sections

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
260213	FAIR	FAIR	GOOD
260214	POOR	POOR	GOOD
260215	POOR	FAIR	FAIR
260216	POOR	GOOD	GOOD
260217	POOR	FAIR	GOOD
260218	POOR	POOR	GOOD
260219	FAIR	GOOD	GOOD
260220	POOR	GOOD	GOOD
260221	GOOD	GOOD	GOOD
260222	FAIR	POOR	FAIR
260223	GOOD	GOOD	GOOD
260224	FAIR	GOOD	GOOD
260259	GOOD	POOR	GOOD

In general, the test sections performed fair, with most poor performance regarding smoothness (measured as IRI). The specific test sections that received "poor" performance are given in Table 32.

Table 32. Michigan SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
260214	1998-2003	2002	
260215	2000		
260216	2009-2012		
260217	1998-1999		
260218	1997	1994-1995	
260220	2009-2012		
260222		2005-2006	
260259		2005	

4.8.5 FAILURE SUMMARY

An early manual distress survey, outside of the LTPP distress surveying, was conducted of the Michigan SPS-2 project to observe some of the early distresses. The entire length of the core test section had extensive longitudinal joint seal damage along the lane/shoulder joint. No joint sealant damage was observed in 260259. The joint damage consisted of raveling and cracking near the shoulder interface. By early December 1994, it was observed that pumping of pavement fines were observed in test sections 260213, 260214, 260215, 260217, 260218, 260219 and 260220. Notably absent from this list were the PATB test sections, which did not experience any longitudinal joint pumping. By far, the most severe pumping was observed on test section 260218.

By December 1994, all transverse joints in test section 260214 exhibited loss of sealant. Most joint seal damage was categorized as low to moderate severity. Also, during this distress survey, test section 260218 was observed to have mid panel longitudinal and transverse cracking. Pumping and faulting was observed at these cracks. Additionally, reflective cracks correlating to the transverse joint dowel bar placement was observed at transverse joints in this section as well. Test section 260218 was the thinnest constructed section (constructed PCC thickness of 7 inches instead of the 8 inch design).

A follow-up distress survey in June 1995 found all longitudinal joint seals exhibited damage at the lane/shoulder joint except for test section 260259. All test sections with an LCB layer and most sections with a DGAB layer exhibited pumping at the longitudinal joint along the outside shoulder. No pumping was observed on test sections 260216 and on test sections 260221-260224, which were the test sections with the PATB layer. By this 1995 distress survey, the amount and severity of pumping at the site had increased. In general, the drained base sections performed better than the undrained sections. Thinner test sections with LCB were observed to have the most pumping. It was also observed that pumping was more severe on test sections 260218 and 260219, which were located on superelevated sections that allowed for water to drain toward the outside shoulder. Further investigation into the distress mechanism of test section 260218 revealed multiple contributing factors including the 7-inch constructed thickness (below the design thickness of 8 inches) and cracking and corner breaks, which could be a result of curl or warp of the concrete slabs.

Additionally, the sections that failed before 2007 did not pass their thickness tolerance requirement. A relatively weak, thin concrete layer would be more susceptible to damage due to poor support that would result from fee moisture in the sublayers. This issue would be exacerbated with the higher than planned traffic levels that these test sections experienced.

The SPS-2 test sections in Michigan that did not exhibit "poor" performance included 260213, 260219, 260221, 260223 and 260224. Most of these test sections were paved on the PATB base layer.

4.9 Nevada (32)

In 1993, 13 experimental sections for the SPS-2 experiment were constructed in Nevada, a dry-freeze climatic region. Of the original 13 experimental sections, 2 test sections (320202 and 320206) were taken out of study in 1997 while the remaining 11 sections were taken out of study in 2004.

4.9.1 4.9.1 TRAFFIC AND CLIMATE DEVIATIONS

At construction, the intended level of traffic of this section was 800 KESALs while the measured KESALs per year, as of 2021, was 730, indicating the actual traffic was slightly less than expected. A second traffic deviation from original design indicated that the test sections experienced two-way traffic during the first three months following construction. Additionally, the freezing index of this area was measured to be 190 freezing days per year and the average annual precipitation was 9.7 inches, well within the designation for a dry-freeze climatic region.

4.9.2 4.9.2. CONSTRUCTION RELATED DEVIATIONS

There were several construction related deviations noted during the construction of the Nevada SPS-2 test sections. The removal of the existing pavement layers (AC surface layer, cement treated base layer, and dense graded aggregate base layer) revealed an inadequate subgrade layer. This existing subgrade material was determined to be unsuitable based on NDOT subgrade specifications and to move forward with the construction, this subgrade was first stabilized with lime and topped with additional embankment material. The underlying soil was stabilized with hydrated lime mixed at 3 percent by volume of soil and 1 ft deep into the unsuitable subgrade material.

FWD testing was then conducted on the outer wheel-path and midlane for the stabilized subgrade and embankment prior to the placement of the pavement layers. The results from this FWD testing are reproduced in Figure 25 and Figure 26. These figures show that despite the stabilization, there were still substantial deflections detected in test sections 320205, 320201, and 320209.

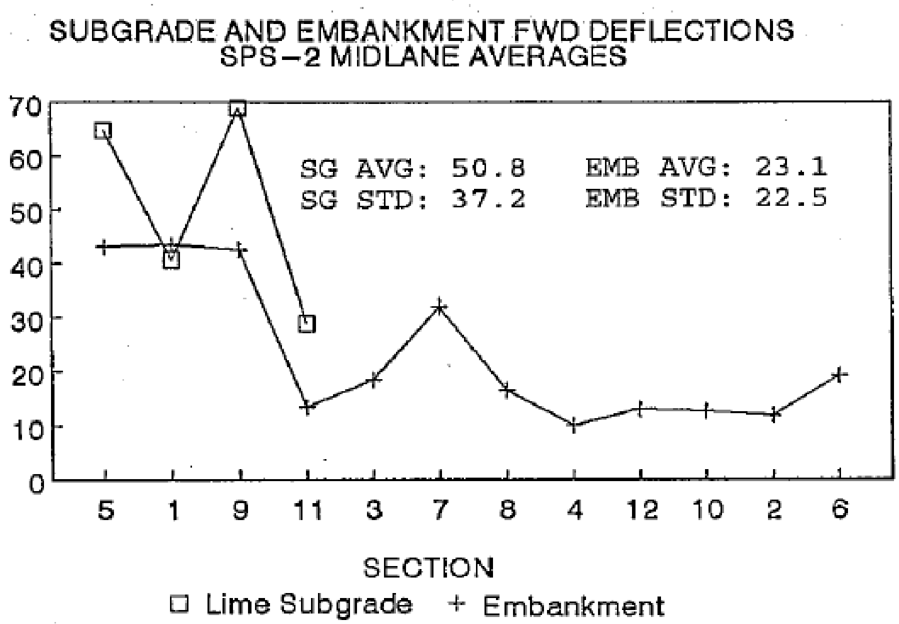

Figure 25. Subgrade and Embankment Midlane FWD Results Prior to Construction for Nevada SPS-2 Test Sections

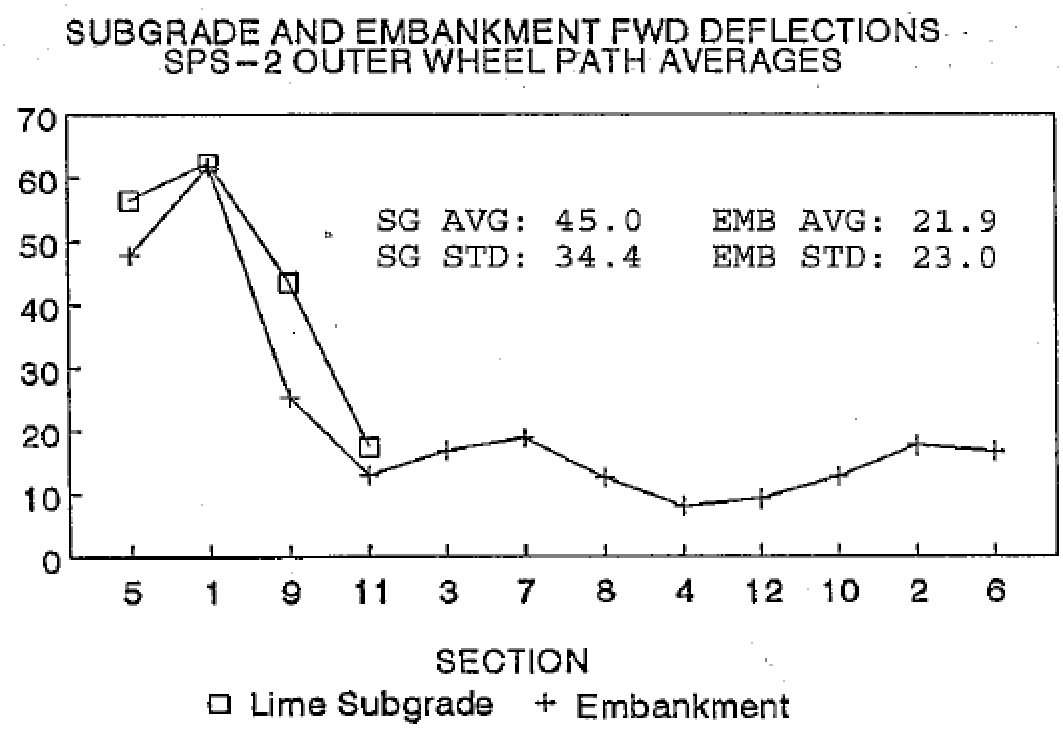

Figure 26. Subgrade and Embankment Outer Wheel Path FWD Results Prior to Construction for Nevada SPS-2 Test Sections

The on-site moisture content and average dry density of the subgrade layers were taken and are given in Table 33.

Table 33. Measured Dry Density and Moisture Content of Subgrade

SHRP ID	Average test dry density (pcf)	Percent moisture
320201	105.5	10.6
320204	98.8	17.3
320205	102.8	16.6
320206	98	19.2
320207	105.2	16
320210	108.8	16.5
320211	103.4	20.7
320259	107.6	14.7
320259	106	15.6
320259	109.1	15.1
320259	107.4	14.9

This table shows substantial variation of the in-situ conditions of the subgrade. For subgrade compaction, a target dry density and moisture content are prescribed, but the variation presented here indicates a high level of inconsistency through the site, possibly indicating these sections required more preparation (between possible dewatering or increased compaction) before this subgrade material reached optimal targets. The moisture content varies by 10% across test sections and the dry density varies by almost 10 pcf between test sections, which is likely outside of the acceptable range of embankment acceptance, though this direct target information was not given in the original construction report.

Additionally, a small slope was observed on sections 320202 and 320206, which resulted in a positive grade in these two sections.

There were some construction issues with the LCB layer resulting in premature cracking of this surface. It was observed that the LCB layer in section 320205 showed extensive shrinkage cracking prior to PCC paving while the LCB layer in sections 320307 and 320208 showed random block cracking prior to PCC paving. There were also construction related issues during the PCC paving. During the paving of section 320203, the concrete behind the paver was watered frequently. Additionally, there was some amount of constructed thickness deviation from the planned thicknesses, as can be seen in Table 34.

Table 34. Constructed Layer Thicknesses for the Nevada SPS-2 Test Sections

	Average layer thickness, inches (standard deviation, inches)			
SHRP ID	DGAB	PATB[1]	LCB	PCC
320201	5.9 (0.6)			9.2 (1.1)
320202	5.8 (0.4)			8.2 (0.3)
320203	5.7 (0.4)			11.6 (0.4)
320204	6.2 (0.2)			11.2 (0.3)

	Average layer thickness, inches (standard deviation, inches)			
SHRP ID	DGAB	PATB[1]	LCB	PCC
320205			7.2 (0.67)	8.3 (0.3)
320206			6.6 (0.23)	8.0 (0.1)
320207			6.9 (0.10)	10.3 (0.2)
320208			7.5 (0.61)	11.1 (0.2)
320209	4.2 (0.3)	4.1 (0.3)		8.0 (0.4)
320210	4.2 (0.2)	4.0 (0.1)		8.3 (0.2)
320211	4.0 (0.3)	4.1 (0.6)		10.8 (0.7)
320212	4.2 (0.2)	4.2 (0.4)		10.7 (0.7)
320259				12.7 (0.4)

[1]PATB thicknesses are given as loose lift (rather than compacted) thickness

The PCC layer thickness varied substantially for test sections 320201, 320203, 320207, and 320212, with at least 0.4 inches variation from design thickness. Also notable was the deviation of the PATB thickness, which was planned to be 4 inches compacted and was approximately 4 inches loose. This layer thickness varied and low sections throughout the PATB section paving were reported to have a thickness of as low as 2.9 inches.

4.9.3 4.9.3. MATERIALS RELATED DEVIATIONS

A significant materials related deviation noted in the deviation report indicated that the 550 psi and 900 psi design strengths were changed to 975 psi and 750 psi design strengths due to materials constraints. However, average modulus of rupture testing results given in Table 35 and specific modulus of rupture testing results given in Table 36 indicate that the tested modulus of rupture values failed to meet the original target strength values for each mix.

Table 35. Average Measured Modulus of Rupture Across All Nevada SPS-2 Test Sections

	Target 14-day strength	Average 14-day strength	Average 28-day strength	Average 365-day strength
Low strength sections (odd numbered sections)	550 psi	522 psi	561 psi	631 psi
High strength sections (even numbered sections)	900 psi	785 psi	838 psi	872 psi

Table 36. Measured Modulus of Rupture for Specific Nevada SPS-2 Test Sections

	Measured modulus of rupture, psi (target 28 day modulus of rupture, psi)		
SHRP ID	14-day	28-day	365-day
320201	520 (550)	575	605
320204	885 (900)	890	920
320206	730 (900)	840	845
320207	490 (550)	525	575
320210	740 (900)	785	850
320211	555 (550)	585	715

The high strength concrete mix, which had a target strength of 900 psi, only reached an average strength of 785 psi at 14 days, over 100 psi below the target. While the low strength mix was generally closer, it still fell below the target strength of 550 psi. It was a noted that from section 320211 to the end of the site that the ¾" aggregate was lowered 2% and the fine aggregate was raised 2% from the prior PCC paving. The mix designs used for the experimental sections are given in Table 37 below.

Table 37. Concrete Mix Designs Used in the Nevada SPS-2 Test Sections

Mix Type	CA[1], lbs/CY	FA[1], lbs/CY	Cement lbs/CY	w/cm	SL[1], inches	Air content (%)	WRA[1]
475 psi mix	2024	1198	423	0.49	1.3	5.2	2
750 psi mix	1640	1055	846	0.32	1.5	4	3
4000 psi mix	1850	1097	611	0.41	1.5	4.4	2

[1] CA (coarse aggregate), FA (fine aggregate), SL (slump), WRA (water reducing admixture). AE and WRA doses are given in oz/100 lbs cementitious material

4.9.4 TEST SECTION PERFORMANCE

Most test sections exhibited fair performance across performance metrics, with the exception of slab cracking, with most test sections exhibiting poor performance shortly after construction. Individualized plots of these performance metrics by year are given in Figure 27, Figure 28, and Figure 29 below.

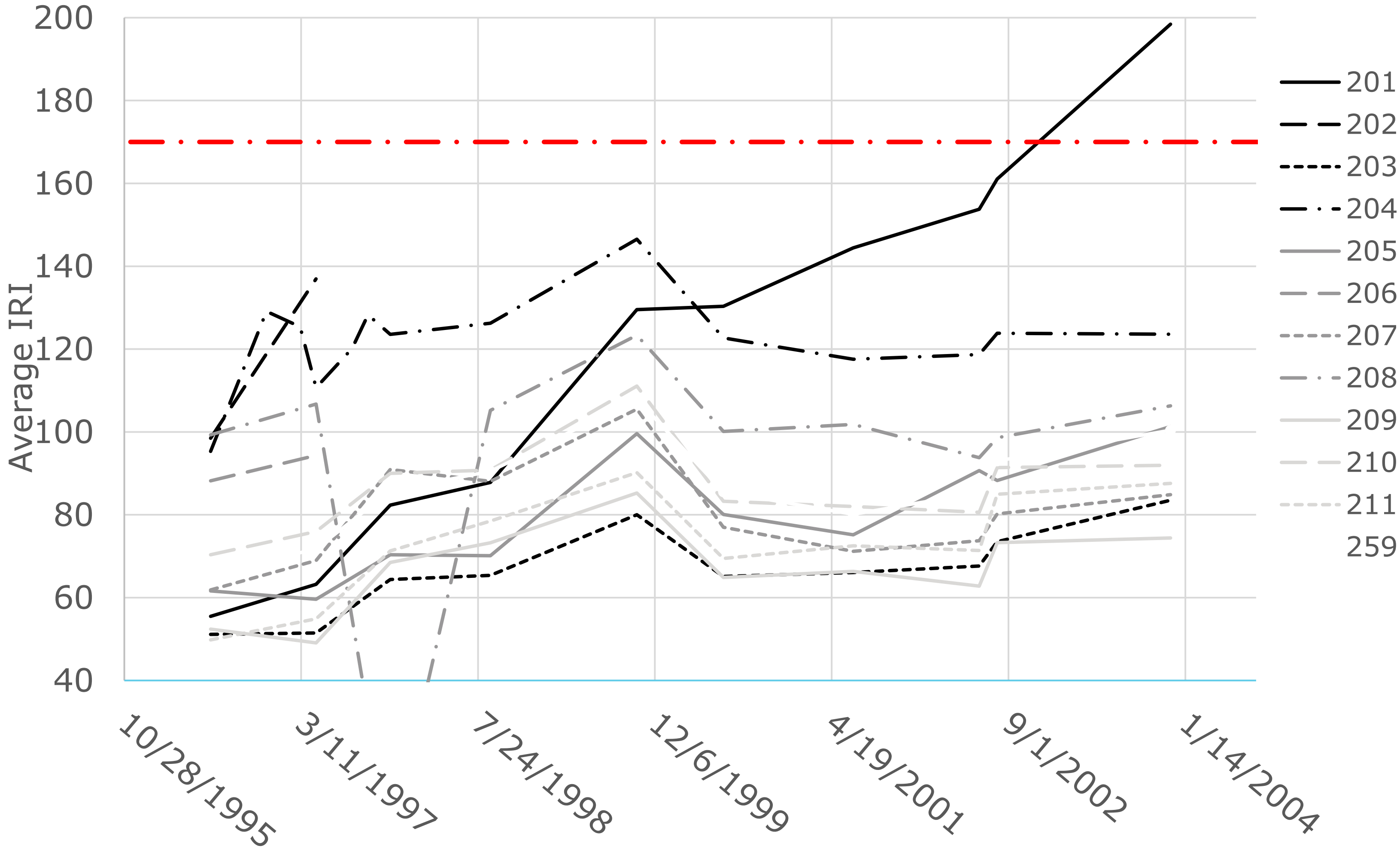

Figure 27. Average Roughness (in IRI) for Nevada SPS-2 Test Sections

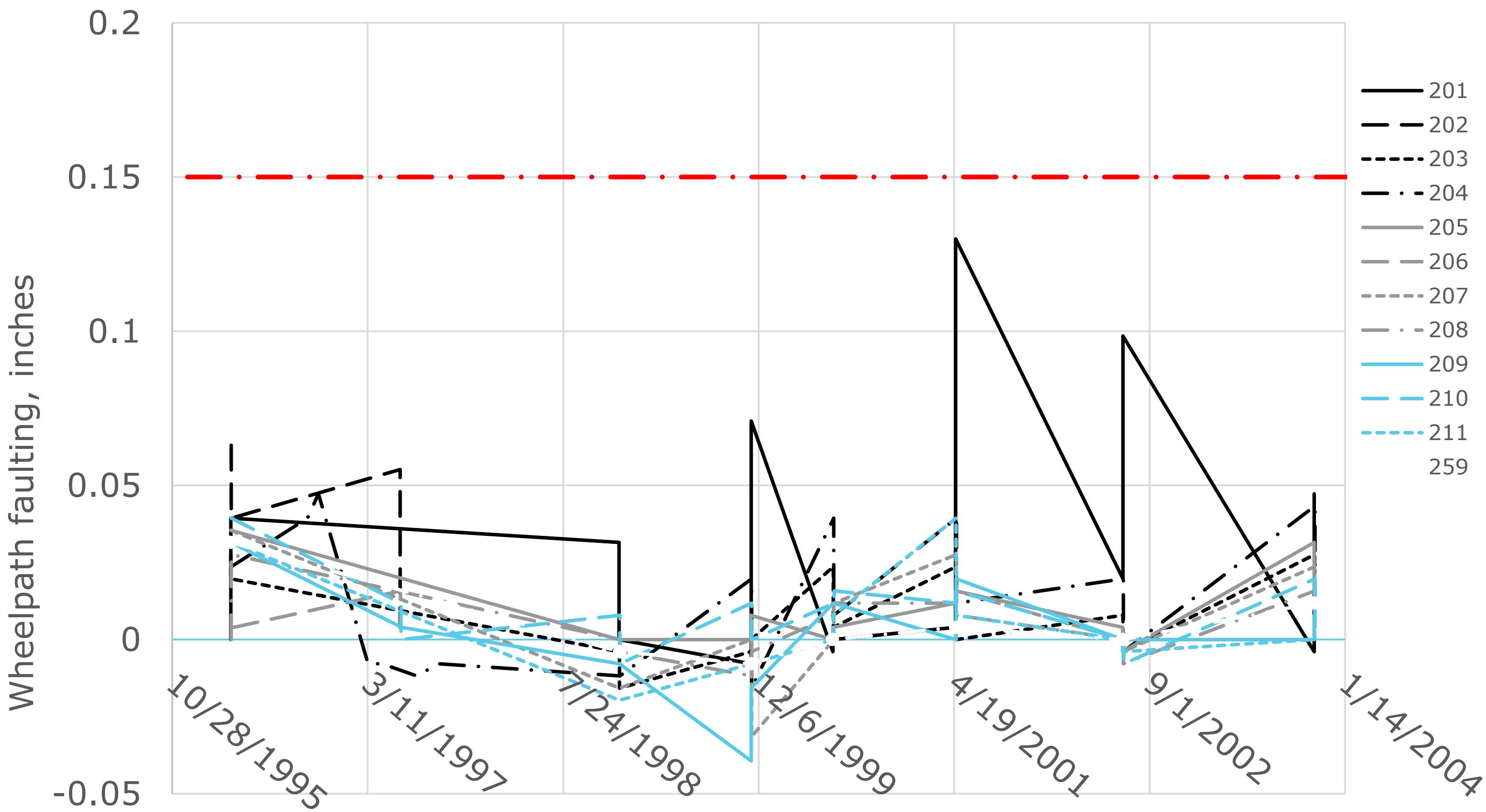

Figure 28. Average Wheel-Path faulting (in inches) for Nevada SPS-2 Test Sections

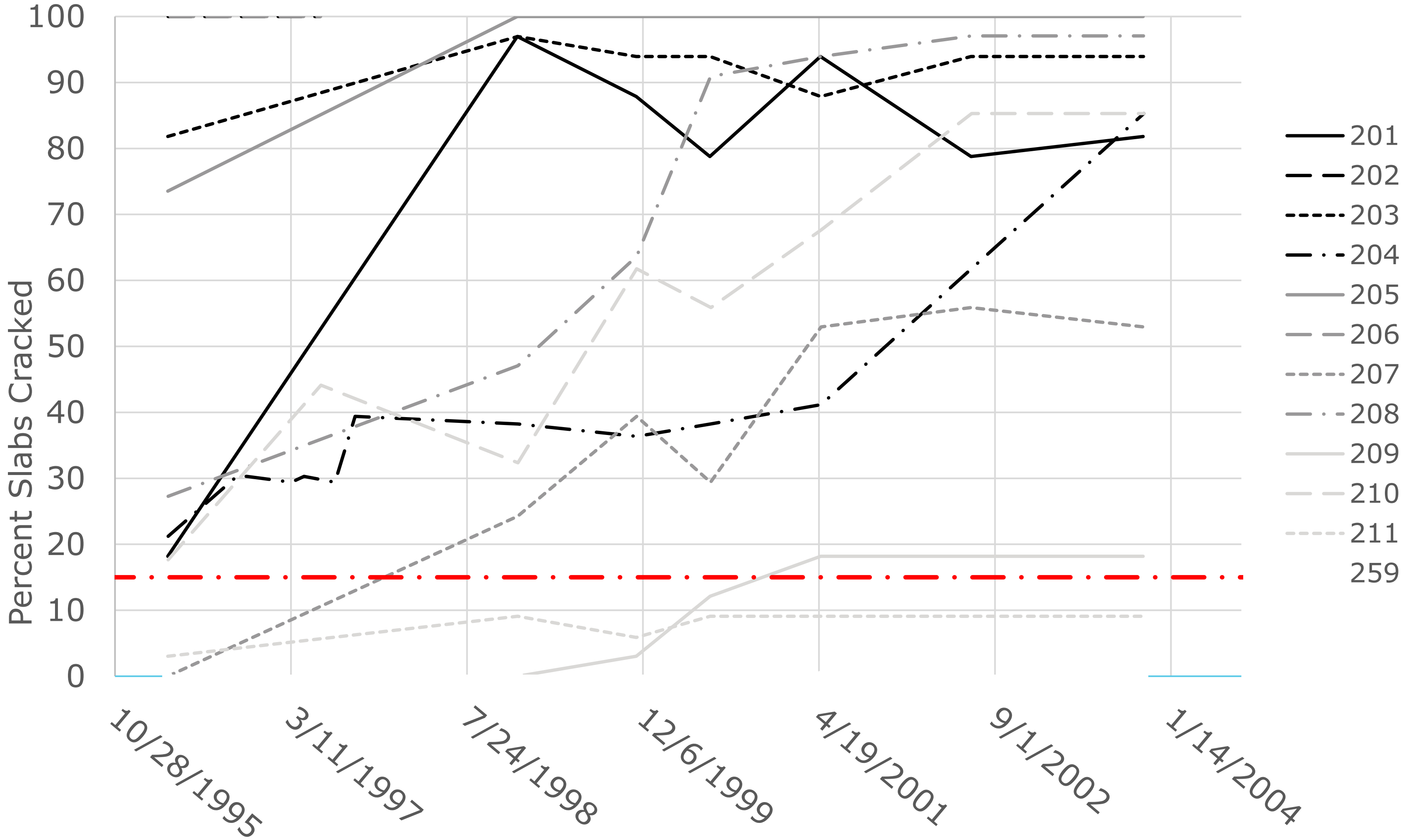

Figure 29. Average Percent Slabs Cracked for Nevada SPS-2 Test Sections

Only test section 320201 exhibited poor performance with respect to surface roughness while no sections exhibited poor performance with respect to wheel-path faulting. However, most test sections exhibited poor performance with respect to slab cracking with all test sections but 320259 and 320211 exhibiting poor performance with respect to slab cracking within ten years of initial construction. The summarized performance trends of the Nevada SPS-2 test sections, while still in study, are given in Table 38.

Table 38. Performance Trends of Nevada SPS-2 Test Sections

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
320201	POOR	POOR	FAIR
320202	FAIR	POOR	GOOD
320203	GOOD	POOR	GOOD
320204	FAIR	POOR	GOOD
320205	FAIR	POOR	GOOD
320206	FAIR	POOR	GOOD
320207	FAIR	POOR	GOOD
320208	FAIR	POOR	GOOD
320209	GOOD	POOR	GOOD
320210	FAIR	POOR	GOOD
320211	GOOD	FAIR	GOOD
320212	GOOD		GOOD
320259	FAIR	GOOD	GOOD

Many of the test sections performed poorly based on slab cracking. The specific test sections which earned a "poor" performance rating during distress surveys are given in Table 39 below.

Table 39. Nevada SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
320201	2003	1996-2003	
320202		1996-1997	
320203		1996-2001	
320204		1996-2003	
320205		1996-2003	
320206		1996-1997	
320207		1996-2003	
320208		1996-2003	
320209		2001-2003	
320210		1996-2003	

4.9.5 FAILURE SUMMARY

There were many construction and material deviations which could have contributed to the poor performance of these Nevada SPS-2 test sections. These test sections failed early, and performance data indicated the test sections had excessively high cracking for most sections.

The slightly higher traffic levels, the unstable subgrade (with excessive deflections even following lime stabilization), and low modulus of rupture values could have contributed to early failures. Additionally, the concrete contained relatively low air content and no air entraining admixture, resulting in air contents as low as 4%, which is needed for countering freeze-thaw issues. This is unusual and appears to be the only set of test sections constructed without an air entraining admixture added. While air entrainer is often added for increased resistance to freeze-thaw damage, the addition of entrained air contributes significantly to improved workability and general uniformity and homogeneity of the final mix.

Despite being located in a dry-freeze area and not receiving substantial precipitation, higher moisture contents in some of the subgrade indicate the presence of moisture. This could also be a contributing factor to early failures. Finally, there was some substantial variation of the constructed layer thickness.

4.10 North Carolina (37)

In 1992, 14 experimental sections for the SPS-2 experiment were constructed in North Carolina, a wet-no-freeze climatic region. Of these 14 original test sections, 6 sections (370201, 370202, 370205, 370206, 370209, and 370210) were taken out of study in 2003. In general, these test sections are generally receiving good performance ratings.

4.10.1 TRAFFIC AND CLIMATE DEVIATIONS

At construction, the intended level of traffic of this section was 540 KESALs while the measured KESALs per year, as of 2021, was 760 KESALs, indicating the actual traffic was more than expected. Additionally, the freezing index of this area was measured to be 32 freezing days per year and the average annual precipitation was 43.8 inches, well within the designation for a wet-no-freeze climatic region.

4.10.2 CONSTRUCTION RELATED DEVIATIONS

Several construction related deviations were noted for the North Carolina test sites. This test site contained a separate construction section, an "add-on lane" for some test sections while other test sections were constructed in the "main line." The add-on lane contained test sections 370201, 370202, 370205, 370206, 370209 and 370210. The construction of the sections in the add-on lane included a different construction method with the concrete being side-dumped and spread with an arm attached to the front end of the loader. Construction of the test sections on the main line began on October 24th while the construction of the test sections in the add-on lane began November 21st.

Several construction related difficulties were encountered during the paving of test section 370208. This included some difficulty placing the LCB layer in this section which required adding water to the LCB layer to allow for finishing, which was difficult for this mix. The LCB layer in test section 370205 had contraction cracks, which likely contributed to reflective cracking that was observed on the PCC surface. There was also noted difficulty in placing the PCC layer with the spreader and finisher having poor traction and slipping due to the stiff PCC mix requiring water to be added to overcome the spinning. The paver was stopped several times during finishing due to the slow concrete supply with haul trucks only carrying 2/3 of their ordinary capacity.

4.10.3 MATERIALS RELATED DEVIATIONS

Several materials-related deviations were noted in the construction report. All test sections constructed in the add-on lane (test sections 370201, 370202, 370205, 370206, 370209, and 370210) were constructed with 1” diameter dowels rather than the prescribed 1.25” diameter dowel bars. No explanation was provided for this deviation. Additionally, test section 370202 had an inadequate lime slurry and water was added to this section to help finishing. Measured average modulus of rupture results are given in Table 40 and modulus of rupture values for specific test sections are given in Table 41.

Table 40. Average Measured Modulus of Rupture Across All North Carolina SPS-2 Test Sections

	Target 14-day strength	Average 14-day strength	Average 28-day strength
Low strength sections (odd numbered sections)	550 psi	693	650
High strength sections (even numbered sections)	900 psi	850	1007
State supplementary section 370259		578	616
State supplementary section 370260		663	642

Table 41. Measured Modulus of Rupture for Specific North Carolina SPS-2 Test Sections

	Measured modulus of rupture, psi (target 14 day modulus of rupture, psi)	
SHRP ID	14-day	28-day
370201	736 (550)	564
370202		1020
370206		994
370207	650 (550)	736
370212	850 (900)	
370259	578	616
370260	663	642

Unfortunately, the strength data for these sections was limited. It can be seen from the modulus of rupture data that the low strength mix generally exceeded the target strength requirement of 550 psi and the high strength mix was relatively close and only 50 psi less than the target strength of 900 psi. The mixture proportions for all mixture designs are given in Table 42.

Table 42. Concrete Mix Designs Used in the North Carolina SPS-2 Test Sections

Mix Type	CA[1], lbs/CY	FA[1], lbs/CY	Cement lbs/CY	Fly ash, lbs/CY	Water, gal	w/cm	AE	Re	WRA[1]
550 psi	1924	1155	493	148	30.5	0.40	5 lbs		27.35
SHRP 550 psi - REV	1924	1241	421	126	30.5	0.46		5.24	27.35
900 psi	1900	743	772	232	35	0.29		5.0	60.2

[1] CA (coarse aggregate), FA (fine aggregate), WRA (water reducing admixture), Re (retarding admixture) Re and WRA doses are given in oz/100 lbs cementitious material

The revised low strength mix (the mix that was actually used on the test sections) had an increased *w/cm* from the other mixture designs. Additionally, none of the test section mixtures contained an air entrainer; however, the test sections required a retarding admixture. All mixtures utilized fly ash as a supplementary cementitious material.

4.10.4 TEST SECTION PERFORMANCE

Most test sections generally exhibited good performance across performance metrics. Individualized plots of these performance metrics by year are given in Figure 30, Figure 31, and Figure 32.

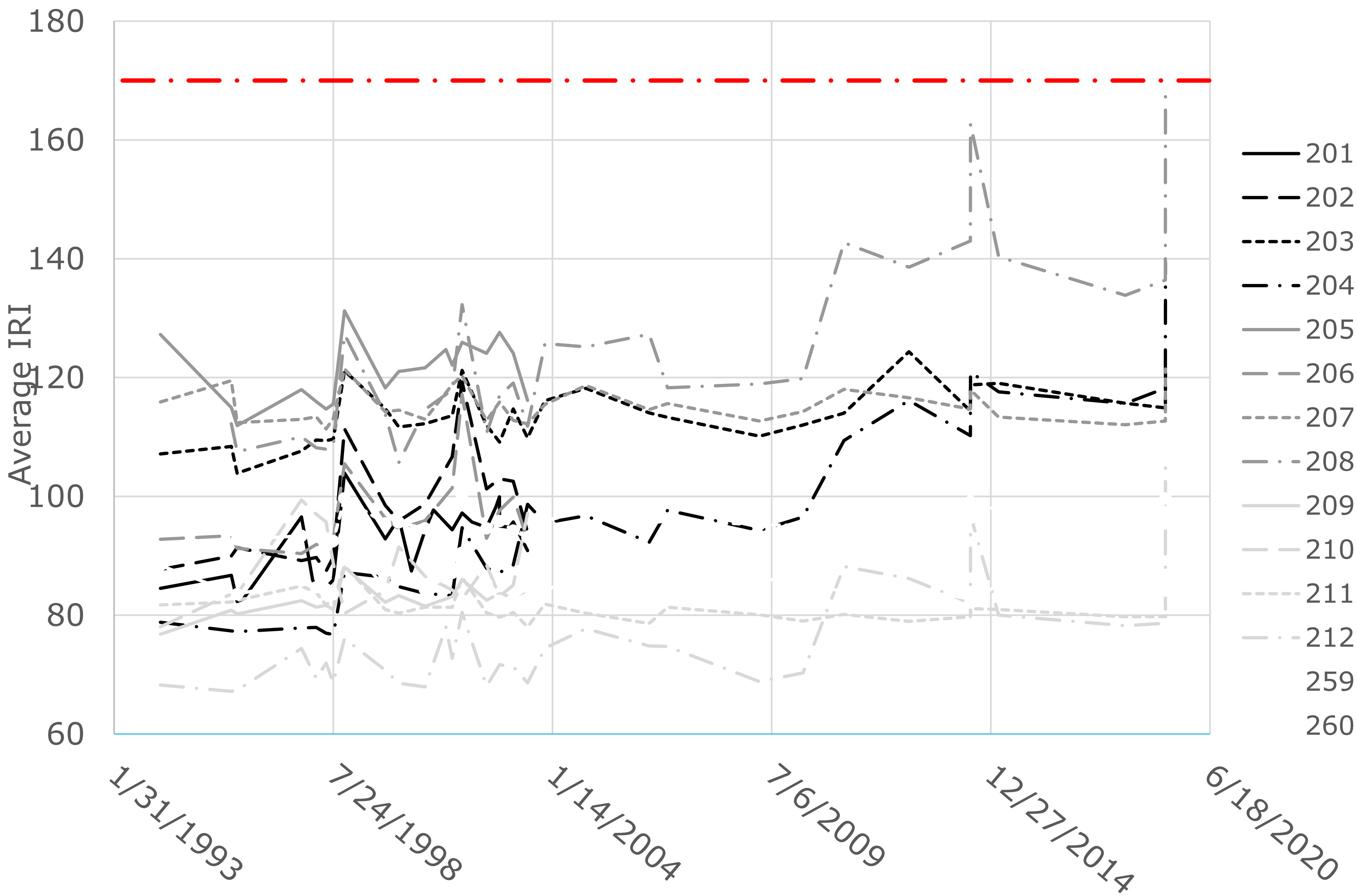

Figure 30. Average Roughness (in IRI) for North Carolina SPS-2 Test Sections

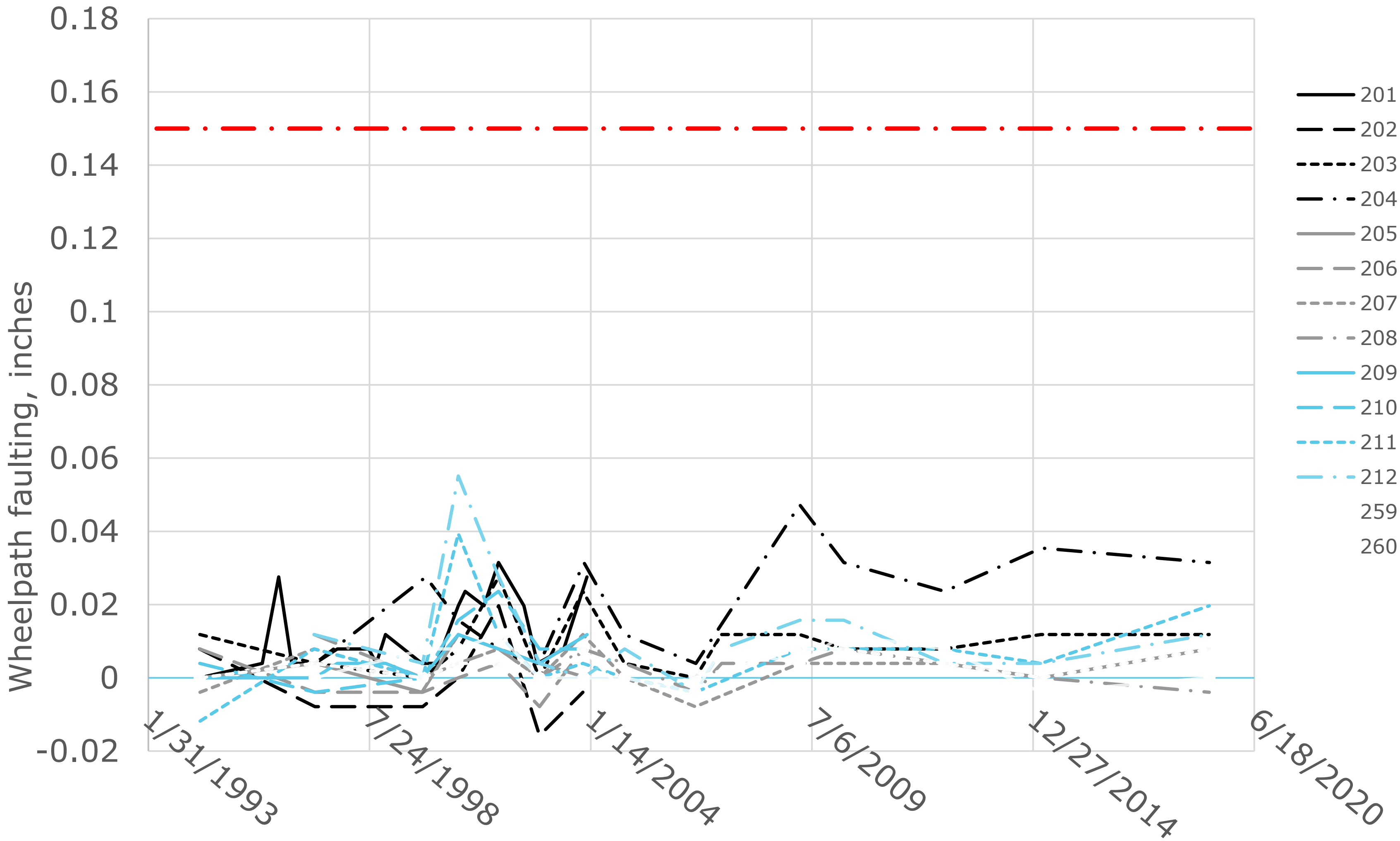

Figure 31. Average Wheel-Path faulting (in inches) for North Carolina SPS-2 Test Sections

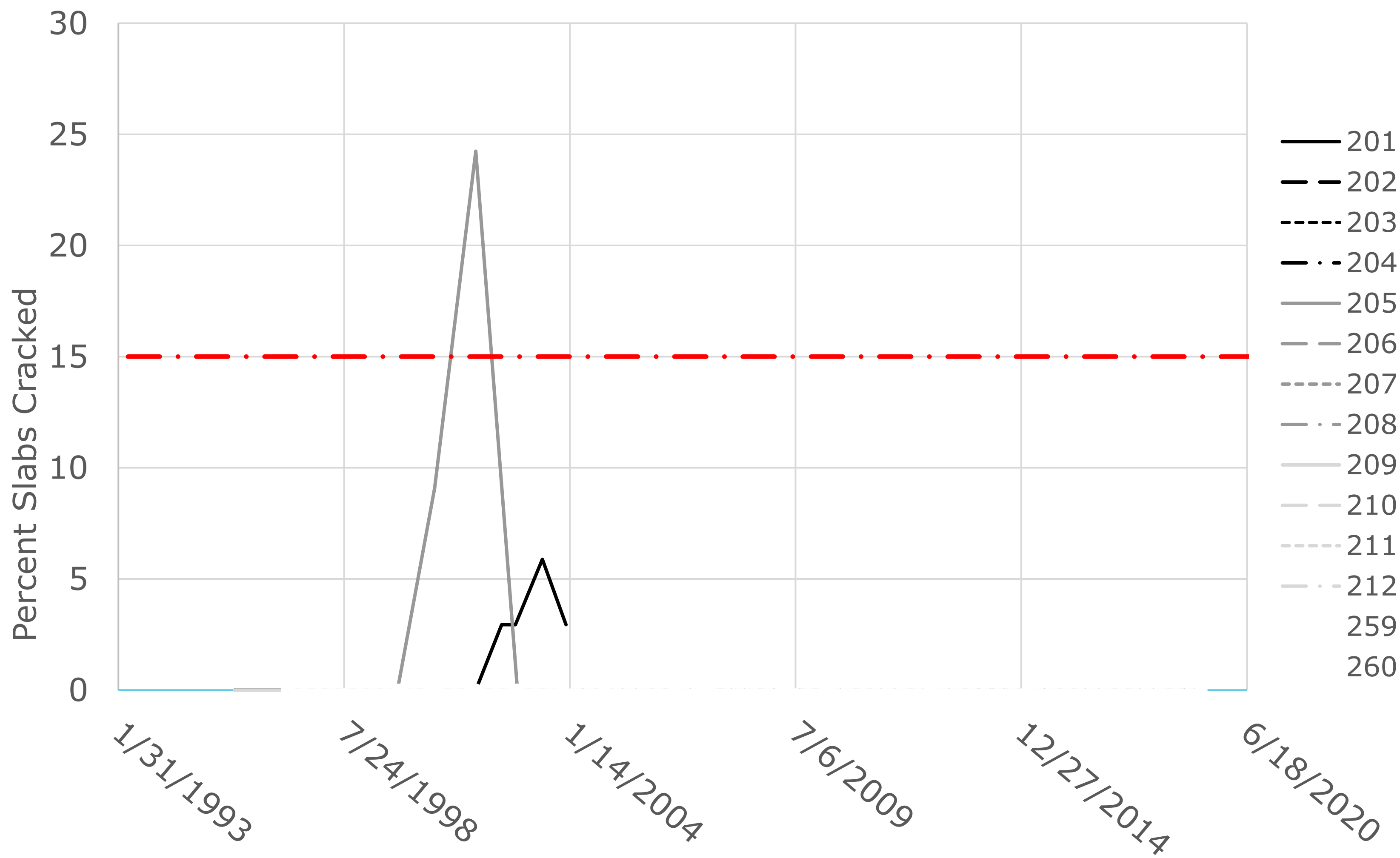

Figure 32. Average Percent Slabs Cracked for North Carolina SPS-2 Test Sections

The test sections are generally performing well. Only test section 370208 exhibited poor performance with respect to surface roughness. No test sections exhibited poor performance with respect to wheel-path faulting, with all rated as having good performance. Only test section 370205 exhibited poor performance with respect to slab cracking, whereas all other test sections exhibited good ratings. A table of summarized performance trends of the test sections is given in Table 43.

Table 43. Performance Trends of North Carolina SPS-2 Test Sections

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
370201	FAIR	FAIR	GOOD
370202	FAIR	GOOD	GOOD
370203	FAIR	GOOD	GOOD
370204	FAIR	GOOD	GOOD
370205	FAIR	POOR	GOOD
370206	FAIR	GOOD	GOOD
370207	FAIR	GOOD	GOOD
370208	POOR	GOOD	GOOD
370209	GOOD	GOOD	GOOD
370210	FAIR	GOOD	GOOD
370211	GOOD	GOOD	GOOD
370212	FAIR	GOOD	GOOD
370259	GOOD	GOOD	GOOD
370260	FAIR	GOOD	GOOD

While generally performing well, there are several sections that have earned a "poor" performance rating across one of the three distress metrics. This was as a result of high roughness measured as IRI in 2 sections, 1 of which also had a poor rating due to cracking as shown in Table 35.

Table 44. North Carolina SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
370205			2001
370208	2019	2019	

4.10.5 FAILURE SUMMARY

While there were multiple construction and material related deviations for the North Carolina SPS-2 experiment, there are several that may be significant relating to the performance of these sections. Test section 370205, which experienced "poor" performance ratings, was constructed in the add-on lane was noted to have contraction cracking in the LCB layer, which reflected to the PCC surface. This was observed relatively soon after construction and is the most likely cause of the cracking failures. Test section 370208 experienced several issues in placing the PCC layer including difficulty in finishing and frequent loss of traction requiring water being added to the concrete.

4.11 North Dakota (38)

In 1995, 18 experimental sections for the SPS-2 experiment were constructed in North Dakota, a wet-freeze climatic region. These test sections are performing relatively well.

4.11.1 TRAFFIC AND CLIMATE DEVIATIONS

At construction, the intended level of traffic of this section was 2150 KESALs per year while the measured KESALs per year, as of 2021, was 480, indicating the actual traffic load was significantly lower than expected. The freezing index of this area was measured to be 1283 F days per year and the average annual precipitation was 25.2 inches, indicating the climate was well within the expected boundaries for this climatic region.

4.11.2 CONSTRUCTION RELATED DEVIATIONS

There were several construction related deviations that occurred in the North Dakota SPS-2 project that could contribute to the performance of these sections.

The major difficulty was in placing the lean concrete base layer. The mixture had to be constructed stronger than the design mixture to ensure the sides were sufficiently stiff for placement. The mixture was adjusted during construction to account for this issue. It was observed that the LCB developed transverse cracks across the surface prior to placement of the PCC layer. Test section 380217 exhibited transverse cracks in the PCC layer within 5 days of placing due to reflective cracking from the LCB layer. These cracks were sealed following this observation.

There was also difficulty in placing the PATB which was found to be very difficult to roll due to its high fluidity. It was theorized this construction difficulty was due to the short sections of placement.

4.11.3 MATERIALS RELATED DEVIATIONS

No specific materials-related deviations were noted in the construction report. Modulus of rupture values from the PCC layer of the test sections is given in Table 45.

Table 45. Measured Modulus of Rupture for Specific North Dakota SPS-2 Test Sections

SHRP ID	Measured modulus of rupture, psi (target 14 day modulus of rupture, psi)
380213	710 (550)
380216	980 (900)
380217	665 (550)
380220	910 (900)
380221	630 (550)
380262	640
380264	820

These modulus of rupture test results show that the measured strength values exceeded the target values across the sections tested. The low strength mix was well above its target of 550 psi 14-day modulus of rupture across sections and the high strength mix tested slightly above its 900 psi target.

4.11.4 TEST SECTION PERFORMANCE

Most test sections generally exhibited good performance across performance metrics. Individualized plots of these performance metrics by year are given in Figure 33, Figure 34, and Figure 35.

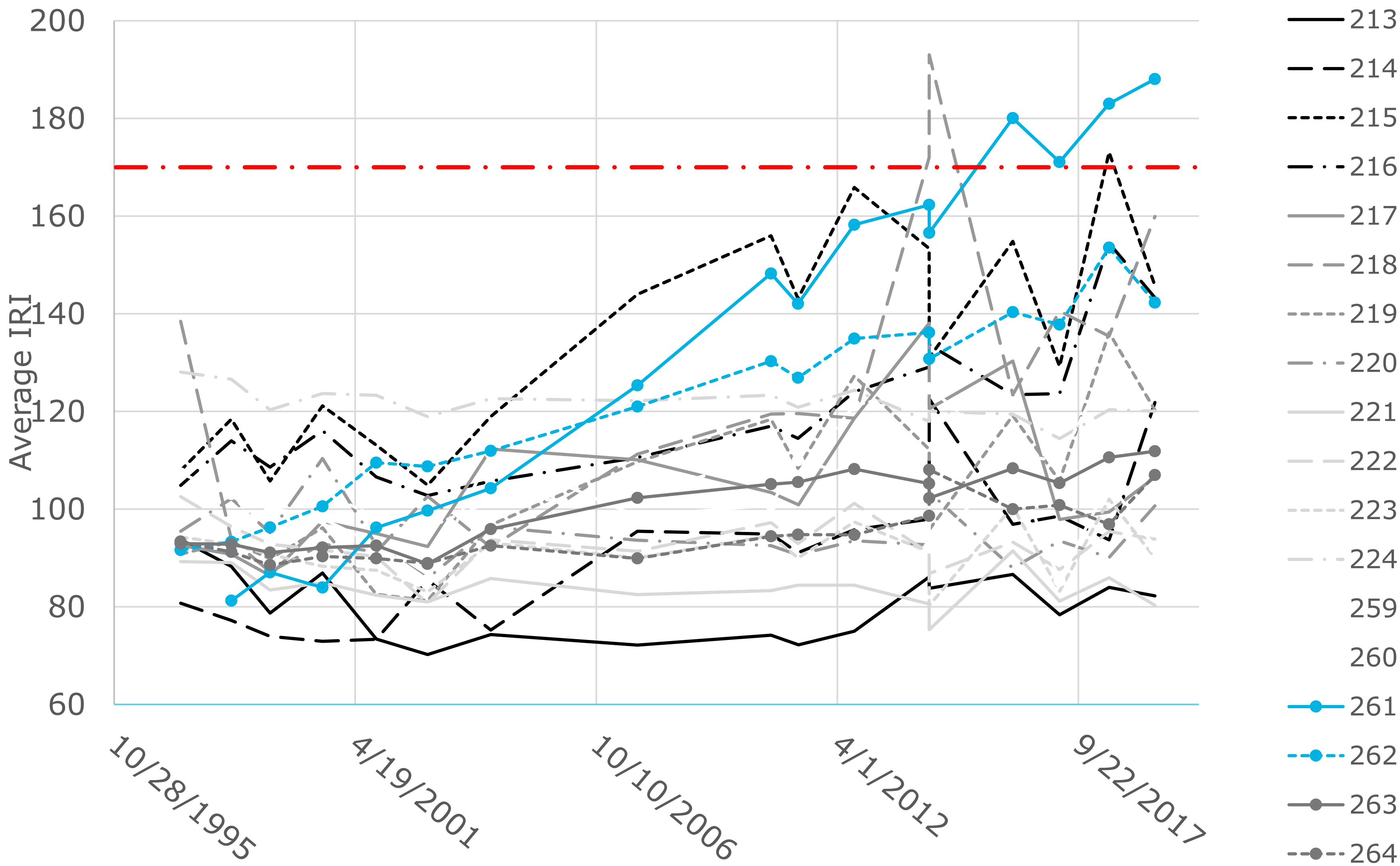

Figure 33. Average Roughness (in IRI) for North Dakota SPS-2 Test Sections

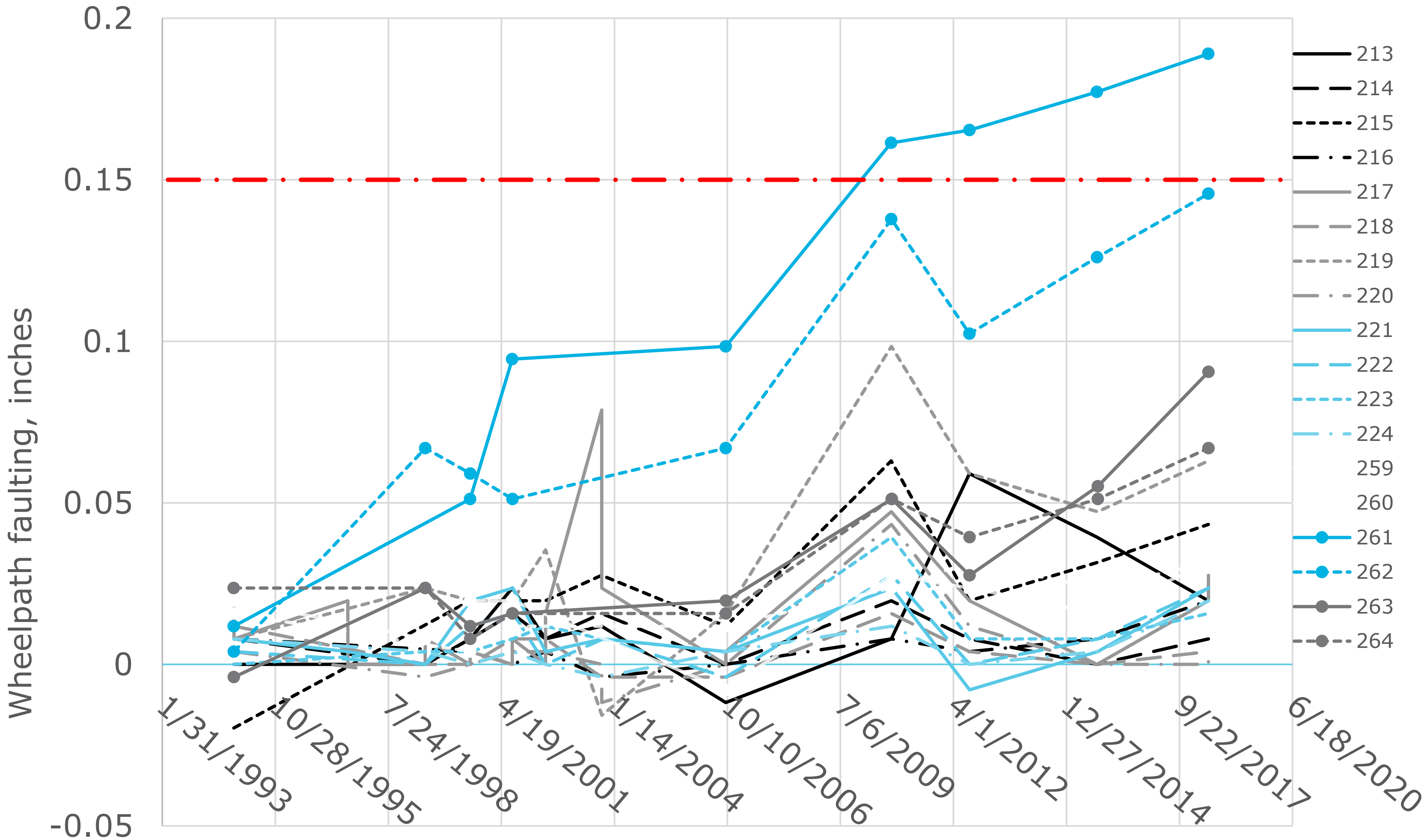

Figure 34. Average Wheel-Path faulting (in inches) for North Dakota SPS-2 Test Sections

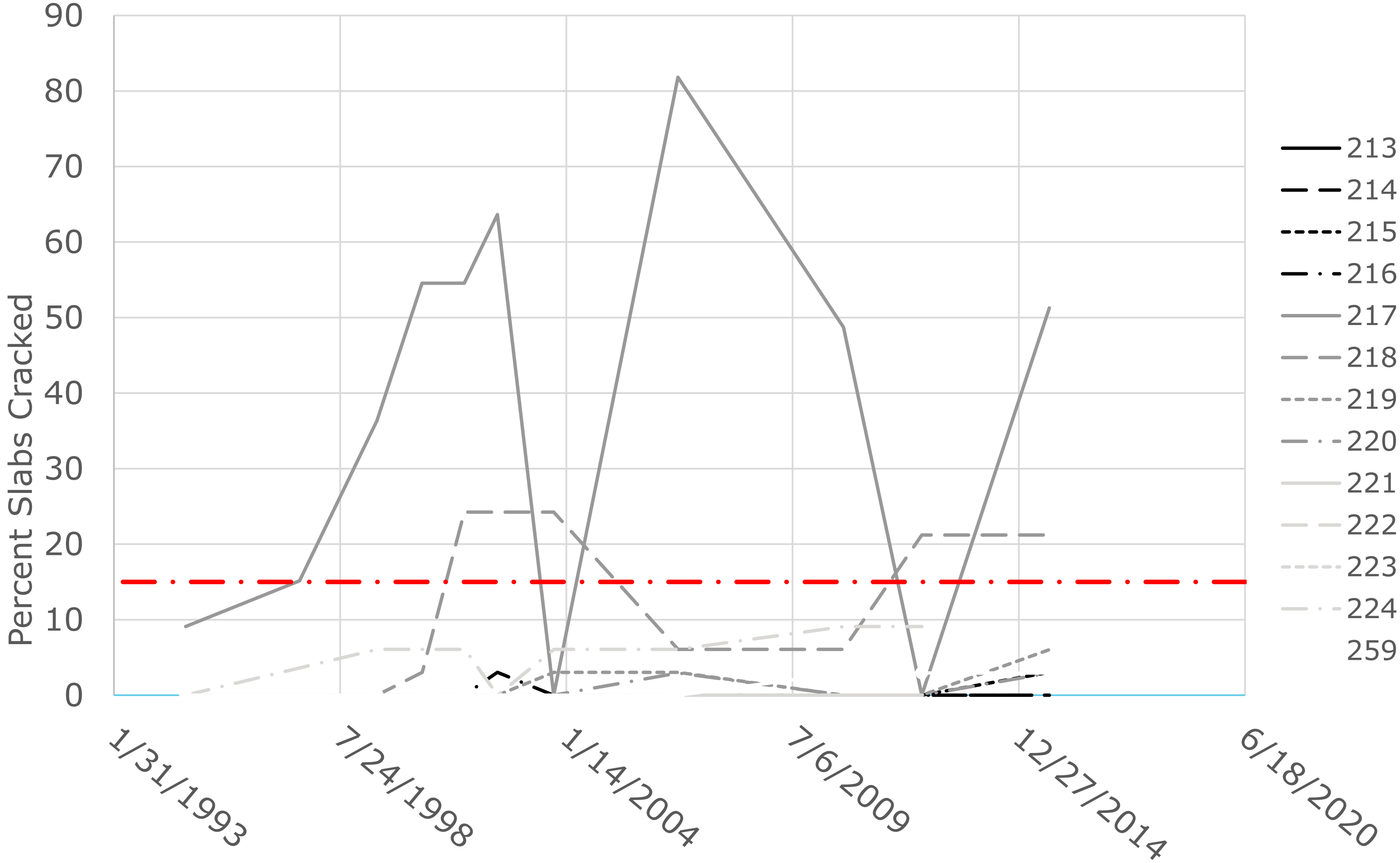

Figure 35. Average Percent Slabs Cracked for North Dakota SPS-2 Test Sections

Most test sections experienced heightened surface roughness with three test sections, 380215, 380218, and 380261 exhibiting poor levels of performance with respect to surface roughness. Test section 380262 experienced poor performance with respect to wheel-path faulting and test section 380261 was very near to the threshold. Most other test sections experienced very low levels of wheel-path faulting. Test sections 380217 and 380218 were the only test sections that exhibited poor performance with respect to cracking while most other test sections exhibited good performance with respect to slab cracking. Test section 380217 exhibited by far the highest level of slab cracking of all test sections. A summarized table of test section performance is given in Table 36.

Table 46. Performance Trends of SPS-2 Test Sections in North Dakota

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
380213	GOOD	GOOD	GOOD
380214	FAIR	GOOD	GOOD
380215	POOR	GOOD	GOOD
380216	FAIR	GOOD	GOOD
380217	FAIR	POOR	GOOD
380218	POOR	POOR	GOOD
380219	FAIR	FAIR	GOOD
380220	FAIR	GOOD	GOOD
380221	GOOD	GOOD	GOOD
380222	FAIR	GOOD	GOOD
380223	FAIR	GOOD	GOOD
380224	FAIR	FAIR	GOOD
380259	FAIR	GOOD	GOOD
380260	FAIR	GOOD	GOOD
380261	POOR	GOOD	POOR
380262	FAIR	GOOD	FAIR
380263	FAIR	GOOD	GOOD
380264	FAIR	GOOD	GOOD

Only 4 sections earned a performance rating of “poor” in any of the three performance as given in Table 47.

Table 47. North Dakota SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
380215	2018		
380217		1997-2015	
380218	2014-2019	2001-2015	
380261	2016-2019		2010-2018

Extreme distresses were limited to core test sections 380215, 380217, and 380218 with some distress in state supplemental section 380261.

4.11.5 FAILURE SUMMARY

Despite several construction and materials deviations present in the North Dakota SPS-2 test sections, there were ultimately only four test sections that exhibited poor performance. The specific design features of these four test sections are summarized in Table 48.

Table 48. Summary of Design Parameters for North Dakota SPS-2 Test Sections

SHRP ID	Base Type and Thickness	Lane Width	PCC thickness		14-day modulus of rupture, psi	
			Design	Built	Design	Built
380215	DGAB, 6″	12 ft	11″	10.9″		
380217	LCB, 6″	14 ft	8″	7.9″	550	665
380218	LCB, 6″	12 ft	11″			
380261	DGAB, 6″	12 ft	11″	11″		

Given the well-documented difficulty in placing the LCB layer, it is unsurprising to see 2 of the 5 test sections with the LCB layer included in this list. The most likely explanation for the poor performance of test sections 380217 and 380218 is their location in the test sections. These two test sections were the first two sections paved with the LCB. Despite having constructability issues with this layer, ultimately, the contractor was able to achieve some level of smoothness and continue to successfully construct the rest of the LCB.

The relatively poor performance of test section 380261 is discussed relative to the structural performance of the other supplementary test sections. Differentiating structural and material details between the supplemental test sections are given in Table 49.

Table 49. North Dakota SPS-2 Supplemental Section Details

Test Section	PCC Thickness, in	14 day Flexural Strength, psi	Base type	Joint orientation	Transverse joint spacing, ft	Load transfer device
380259	10		8" Salve	Skewed	15	Dowels
380260	11		Class 5 Agg	Skewed	15	Dowels
380261	11	550	Class 5 Agg	Skewed	Variable	None
380262	11	550	LCB	Skewed	Variable	None
380263	11	550	PASB	Skewed	Variable	None
380264	11		PASB	Skewed	15	None

Test section 380261 did not contain dowels, had variable transverse joint spacing, and was constructed on an unbound base. It was the only supplemental test section to be constructed under those conditions. Given the lack of information regarding distinct construction or material deviations, it is possible that the relatively poor performance of this section could be due to these structural parameters.

4.12 Ohio (39)

In 1994, 19 experimental sections for the SPS-2 experiment were constructed in Ohio, a wet-freeze climatic region. Of these original 19 test sections, 7 test sections (390201, 390202, 390204, 390205, 390206, 390210 and 390259) were taken out of study in 2007. Three more sections (390209, 390208 and 390264) were taken out of study in 2012 and 2 more sections (390218 and 390212) were taken out of study in 2020.

4.12.1 TRAFFIC AND CLIMATE DEVIATIONS

At construction, the intended level of traffic of this section was 910 KESALs per year while the measured KESALs per year, as of 2021, was 630, indicating the actual traffic was less than the expected. The freezing index of this area was measured to be 327 freezing days per year and the average annual precipitation was 41.2 inches, well within the designation for a wet-freeze climatic region.

4.12.2 CONSTRUCTION RELATED DEVIATIONS

Minimal construction related deviations were mentioned in the construction report. Test section 390204 exhibited some cracking on the surface aggregate due to compaction. The unbound aggregate base layers required cutting to grade using a CMI trimming machine across all test sections.

4.12.3 MATERIALS RELATED DEVIATIONS

Minimal material related deviations were reported in the construction report; however, there were several significant differences that may affect performance. First, the construction report indicated test sections 390204 and 390212 required a retarding admixture (Daratard) that was not used in any other test section, but no explanation for this deviation was given.

Next, the modulus of rupture data for all Ohio SPS-2 sites is given in Table 50 while modulus of rupture data for each SPS-2 test section is given in Table 51.

Table 50. Average Measured Modulus of Rupture Across All Ohio SPS-2 Test Sections

	Target 14-day strength	Average 14-day strength	Average 28-day strength	Average 365-day strength
Low strength sections (odd numbered sections)	550 psi	684 psi	804 psi	904 psi
High strength sections (even numbered sections)	900 psi	614 psi	834 psi	944 psi
Supplementary sections (390259)		568 psi	489 psi	1075 psi
Supplementary sections (390260)		730 psi	790 psi	1040 psi
Supplementary sections (390262)		565 psi	705 psi	850 psi

Table 51. Measured Modulus of Rupture for Specific Ohio SPS-2 Test Sections

	Measured modulus of rupture, psi (target 14 day modulus of rupture, psi)		
SHRP ID	14-day	28-day	365-day
390201	659 (550)	831	850
390202	713 (900)	890	946
390203	645 (550)	702	918
390208	690 (900)	784	955
390211	749 (550)	880	945
390212	438 (900)	828	930
390259	568	489	1075
390260	730	790	1040
390262	565	705	850

The target strength requirements are exceeded by over 130 psi for the low strength concrete mixture. However, the high strength sections had an average strength of 614 psi and fell far below their target strength of 900 psi. In fact, the average 14-day strength values between the high and low strength mixtures are relatively close and differ only by 70 psi. Based on target strength, this difference should be much closer to 350 psi, indicating an extreme deviation of this mixture. The complete mixture designs used in the Ohio SPS-2 test sections are given in Table 52.

Table 52. Concrete Mix Designs Used in the Ohio SPS-2 Test Sections

SHRP ID	CA[1], lbs/CY	FA[1], lbs/CY	Cement, lbs/CY	Fly ash lbs/CY	Water, lbs	w/cm	AE[1]	WRA[1]
550 psi	1680	1260	510	90	240	0.4	7.2-9.6	18
900 psi	1850	950	750	113	270	0.31	8.0-12.7	26.3-36.8

[1] CA (coarse aggregate), FA (fine aggregate), AE (air entrainer), WRA (water reducing admixture), AE and WRA doses are given in oz/100 lbs cementitious material

Both mixtures utilized the same components but the high strength mixture had a substantially lower *w/cm*.

4.12.4 TEST SECTION PERFORMANCE

Most test sections generally exhibited good performance based on roughness (IRI) and wheel-path faulting, but most experienced excessive slab cracking. Individualized plots of these performance metrics by year are given in Figure 36, Figure 37, and Figure 38.

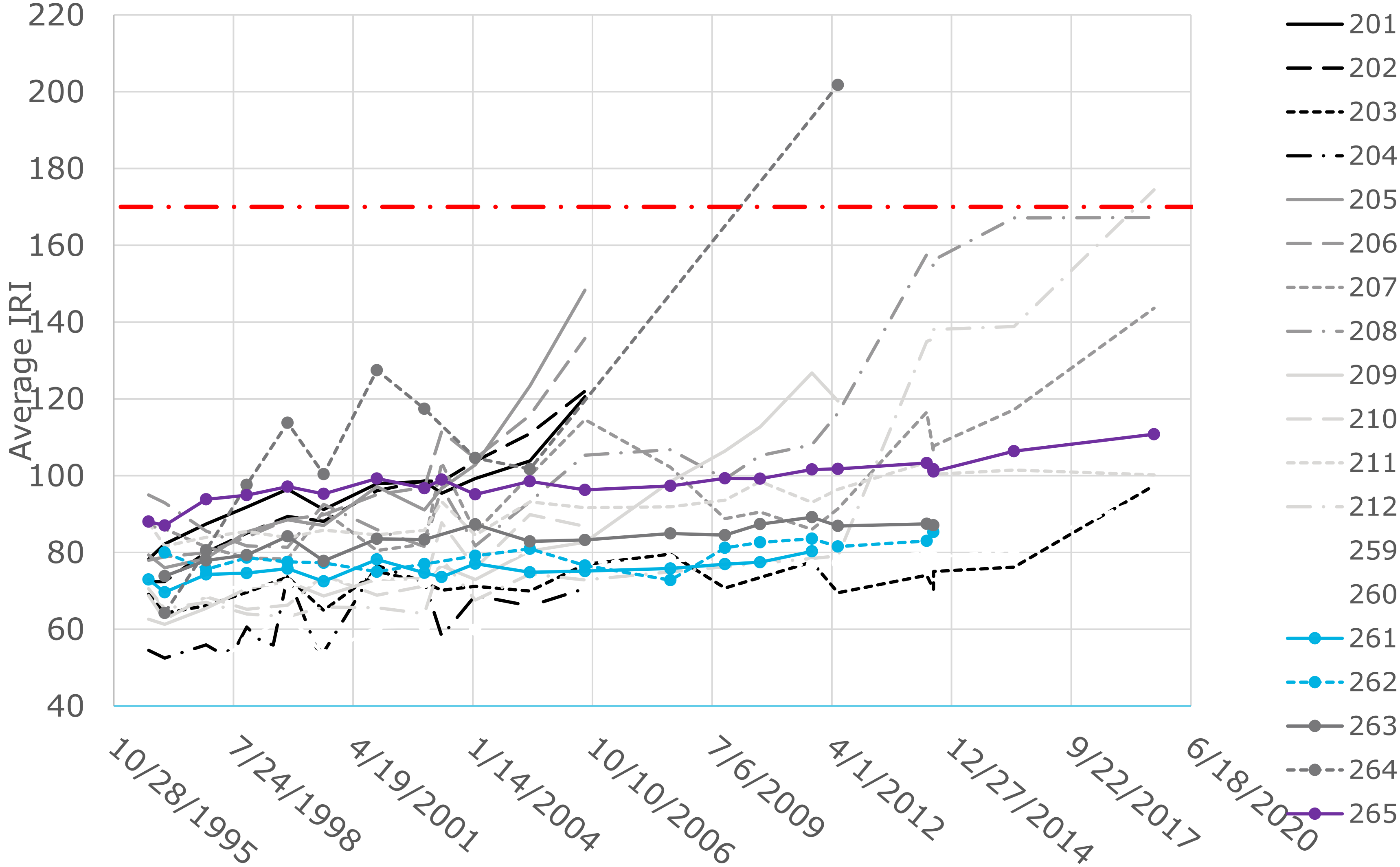

Figure 36. Average Roughness (in IRI) for Ohio SPS-2 Test Sections

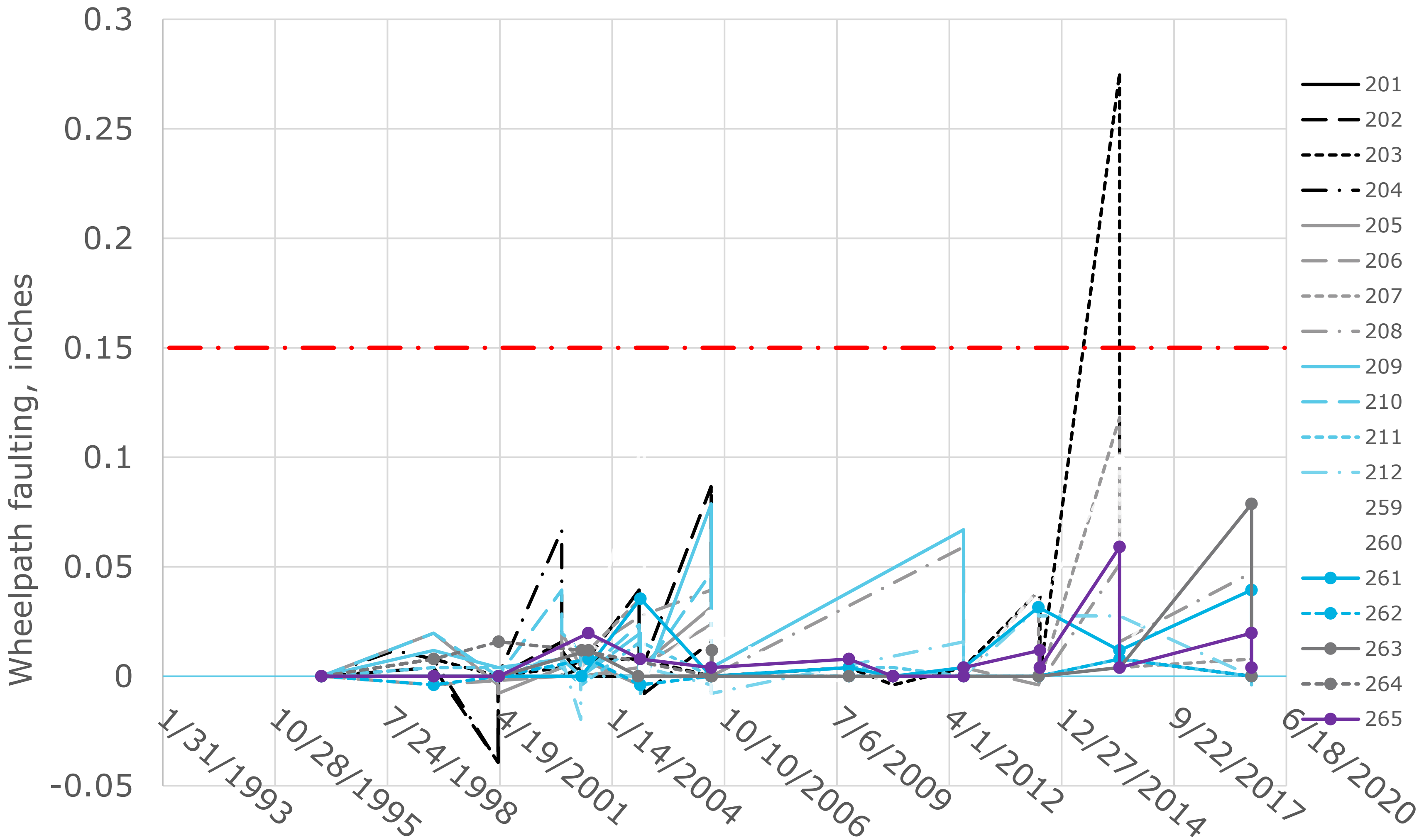

Figure 37. Average Wheel-Path faulting (in inches) for Ohio SPS-2 Test Sections

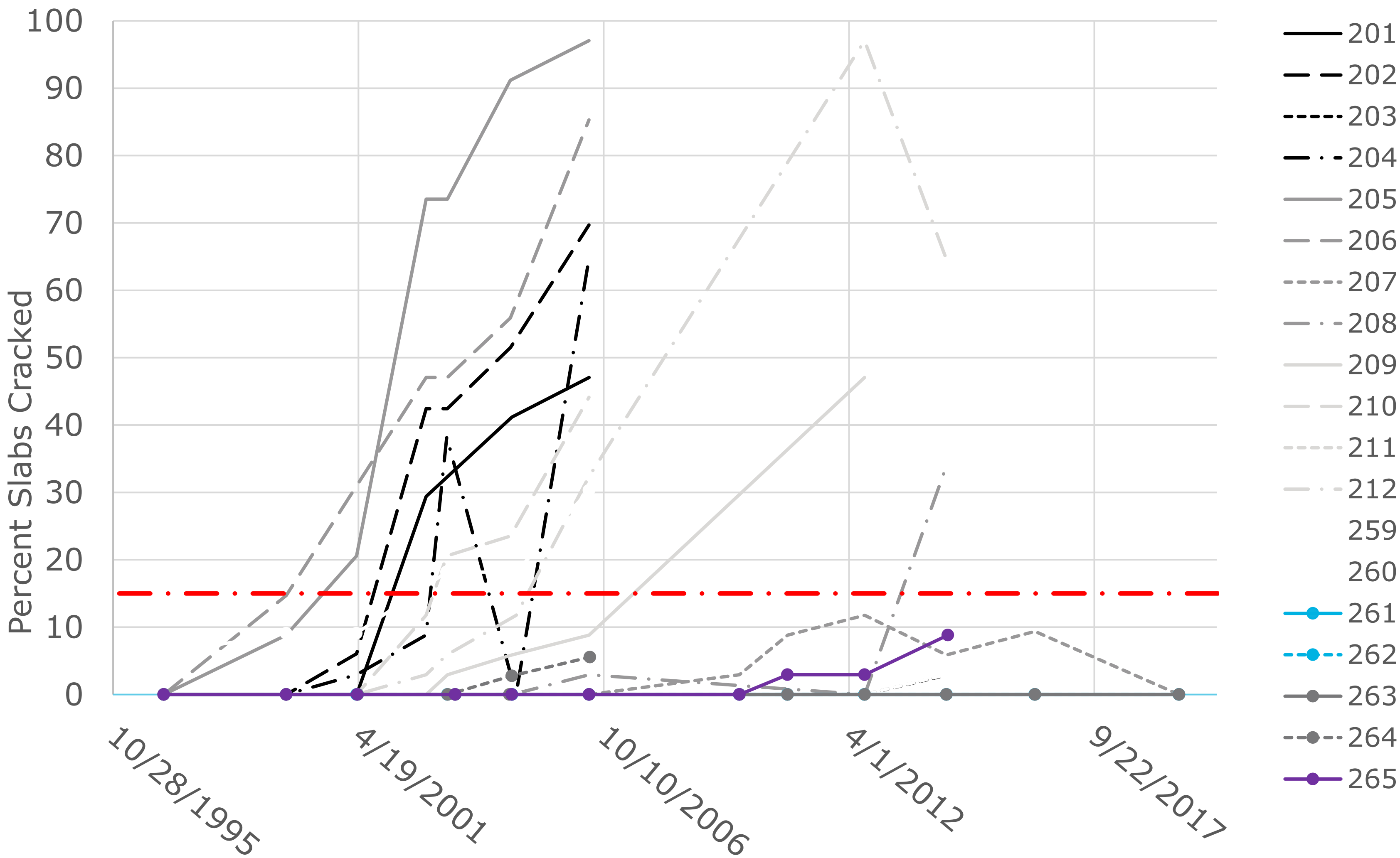

Figure 38. Average Percent Slabs Cracked for Ohio SPS-2 Test Sections

Test sections 390212 and 390264 exhibited poor levels of surface roughness while test section 390208 was just immediately below the threshold. Only test section 390203 exhibited poor performance with respect to wheel-path faulting. Most test sections exhibited poor performance with respect to slab cracking and most test sections exhibited excessive slab cracking within nine years of construction. Test sections 390201, 390202, 390204, 390205, 390206, 390208, 390209, 390210, 390212, and 390259 all exhibited poor performance with respect to slab cracking. A summarized overview of these performance trends is given in Table 53.

Table 53. Performance Trends of Ohio SPS-2 Test Sections

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
390201	FAIR	POOR	GOOD
390202	FAIR	POOR	GOOD
390203	FAIR	GOOD	POOR
390204	GOOD	POOR	GOOD
390205	FAIR	POOR	GOOD
390206	FAIR	POOR	GOOD
390207	FAIR	FAIR	FAIR
390208	FAIR	POOR	GOOD
390209	FAIR	POOR	GOOD
390210		POOR	GOOD
390211	FAIR	GOOD	GOOD
390212	POOR	POOR	GOOD
390259	GOOD	POOR	FAIR
390260	FAIR	GOOD	GOOD
390261	GOOD	GOOD	GOOD
390262	GOOD	GOOD	GOOD
390263	FAIR	GOOD	FAIR
390264	POOR	FAIR	GOOD
390265	FAIR	FAIR	GOOD

Most sections were not performing well and many test sections received a “poor” rating in the percent slabs cracked performance metric. Test sections that have received a rating in the “poor” range of performance across any year is given in Table 54.

Table 54. Ohio SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
390201		2002-2006	
390202		2002-2006	
390203			2016
390204		2003	
390205		2001-2006	
390206		2002-2006	
390208		2014	
390209		2012	
390210		2003-2006	
390212	2019	2006-2014	
390259		2003-2006	
390264	2012		

Of the 19 constructed test sections, 10 exhibited substantial cracking.

4.12.5 FAILURE SUMMARY

Of the originally constructed 19 SPS-2 experimental sections in Ohio, 12 experienced significant distress and were considered to have poor performance during the pavement life. Without significant construction or materials related distress information from the construction and deviation reports, similarities were sought between the low-distress sections to provide insight into the poor performances.

The low distress sections in Ohio were test sections 390207, 390211 and the four supplemental sections 390260, 390261, 390262, and 390263. All of these sections had 11" thick concrete pavements and most of the sections had 14 ft lanes. Significant construction related and materials related parameters are given in Table 55. Sections with low distress ratings are indicated with bold type font.

Table 55. Summary of Design Parameters for Ohio SPS-2 Test Sections

SHRP ID	Base Type and Thickness	Lane Width	PCC thickness		14-day modulus of rupture, psi		28-day modulus of rupture, psi
			Design	Built	Design	Built	
390201	6″ DGAB	12	8	7.9	550	659	831
390202	6″ DGAB	14	8	8.3	900	713	890
390203	6″ DGAB	14	11	11.2	550	645	702
390204	6″ DGAB	14	11	11.1	900		
390205	6″ LCB	12	8	8	550		
390206	6″ LCB	14	8	7.9	900		
390207	**6″ LCB**	**14**	**11**	**11.2**	**550**		
390208	6″ LCB	12	11	11.1	900	690	784
390209	4″ PATB 4″ DGAB	12	8	8.3	550		
390210	4″ PATB 4″ DGAB	14	8	8	900		
390211	**4″ PATB 4″ DGAB**	**14**	**11**	**11.3**	**550**	**749**	**880**
390212	4″ PATB 4″ DGAB	12	11	10.8	900	438	848
390259	4″ DGAB	12	11	10.9		568	489
390260	**4″ PATB 4″ DGAB**	**12**	**11**	**11.6**		**730**	**790**
390261	**4″CTFDB 4″DGAB**	**14**	**11**	**11.1**			
390262	**4″CTFDB 4″DGAB**	**12**	**11**	**11.5**		**565**	**705**
390263	**6″DGAB**	**14**	**11**	**11.1**			
390264	4″CTFDB 4″DGAB	12		11.5			
390265	**4″ PATB 4″ DGAB**	**12**		**11.2**			

Interestingly, the low distress core sections represent test sections utilizing the 550 psi mix design with 11″ concrete pavement. This observation could indicate an issue with the 900 psi concrete mixture, which may be corroborated by the discrepancy in the tested modulus of rupture values. However, this is difficult to definitively determine based on the available information.

4.13 Washington (53)

In 1995, 13 experimental sections for the SPS-2 experiment were constructed in Washington, a dry-freeze climatic region. The sections are generally performing well.

4.13.1 TRAFFIC AND CLIMATE DEVIATIONS

Some construction variations were noted in the construction report. Following initial clearing and grubbing, there was a significant rainfall that required the excavation of the saturated subgrade material in some areas. A layer of shotrock was placed as a drainage layer and embankment material was placed on top of this shotrock layer. This created some inconsistencies as not every section was placed on top of this shotrock layer.

Additionally, it was observed that compaction densities for the subgrade material were generally high (an average of 100% of the maximum dry density) at a moisture content 5.8% lower than the optimum moisture content. This indicated that increased construction traffic on the bare embankment likely provided additional compaction.

There was difficulty in constructed the LCB layer. Section 530206 exhibited variation in workability, and there was some variation in the *w/cm* during construction. It was measured that all mixtures had a lower *w/cm* than intended. During the paving of the LCB for test section 530207, the first 7 loads of LCB material were rejected due to high air contents. The mix was observed to be very difficult to work with noticeable rough patches on one side of the lane and very wet mix on the other side of the lane. During this time, the concrete curing machine was broken and water was hand-applied as an interim cure for several hours until the machine was running again. This mix required significant hand-finishing. It was observed in the construction reports that despite having sufficient water for the mix, the mix appeared to be very dry and required significant hand finishing. Ultimately, it was concluded in the report that there may have been insufficient mixing time at the batch plant. The LCB for test section 530208 appeared to run much more smoothly; however, there was rain during the paving of this section.

Due to this initial difficulty paving the LCB layer, an initial distress survey of just the LCB layer was completed prior to PCC paving. This distress survey revealed a single crack in the LCB layer of test section 530205 and cracking in test sections 530206, 530207, and 530208, with the most severe cracking in the LCB layer for test section 530208. Additionally, despite average thicknesses aligning closely with the planned constructed thickness of 6 inches, all LCB layers varied between 5 inches and 7 inches across the test sections following construction.

During the construction of the PCC layer, the low strength mix was much coarser than expected and the edges required substantial finishing. Even following aggressive finishing measures, the surface maintained a rough surface following construction. The water content was adjusted throughout the construction of all test sections during construction.

4.13.2 MATERIALS RELATED DEVIATIONS

There were several material-related deviations during the construction of the Washington SPS-2 test sections. During the paving of the PCC layer, several adjustments were made to the PCC mixtures. This resulted in the water content varying slightly across the test sections. The modulus of rupture data for these test sections is given in Table 56 below.

Table 56. Measured Modulus of Rupture for Specific Washington SPS-2 Test Sections

	Measured modulus of rupture, psi (target 14-day modulus of rupture, psi)		
SHRP ID	14-day	28-day	365-day
530202	823 (900)	1041	807
530203	413 (550)	622	667
530204	870 (900)	915	880
530205	487 (550)	524	597
530206	801 (900)	880	738
530207	546 (550)	611	772
530211	494 (900)	703	667
530259	625 (650)	690	792

None of the low-strength or high-strength mixtures met the targeted 14-day modulus of rupture value of 550 psi or 900 psi .

4.13.3 TEST SECTION PERFORMANCE

Most test sections generally exhibited good performance across performance metrics. Individualized plots of these performance metrics by year are given in Figure 39, Figure 40, and Figure 41.

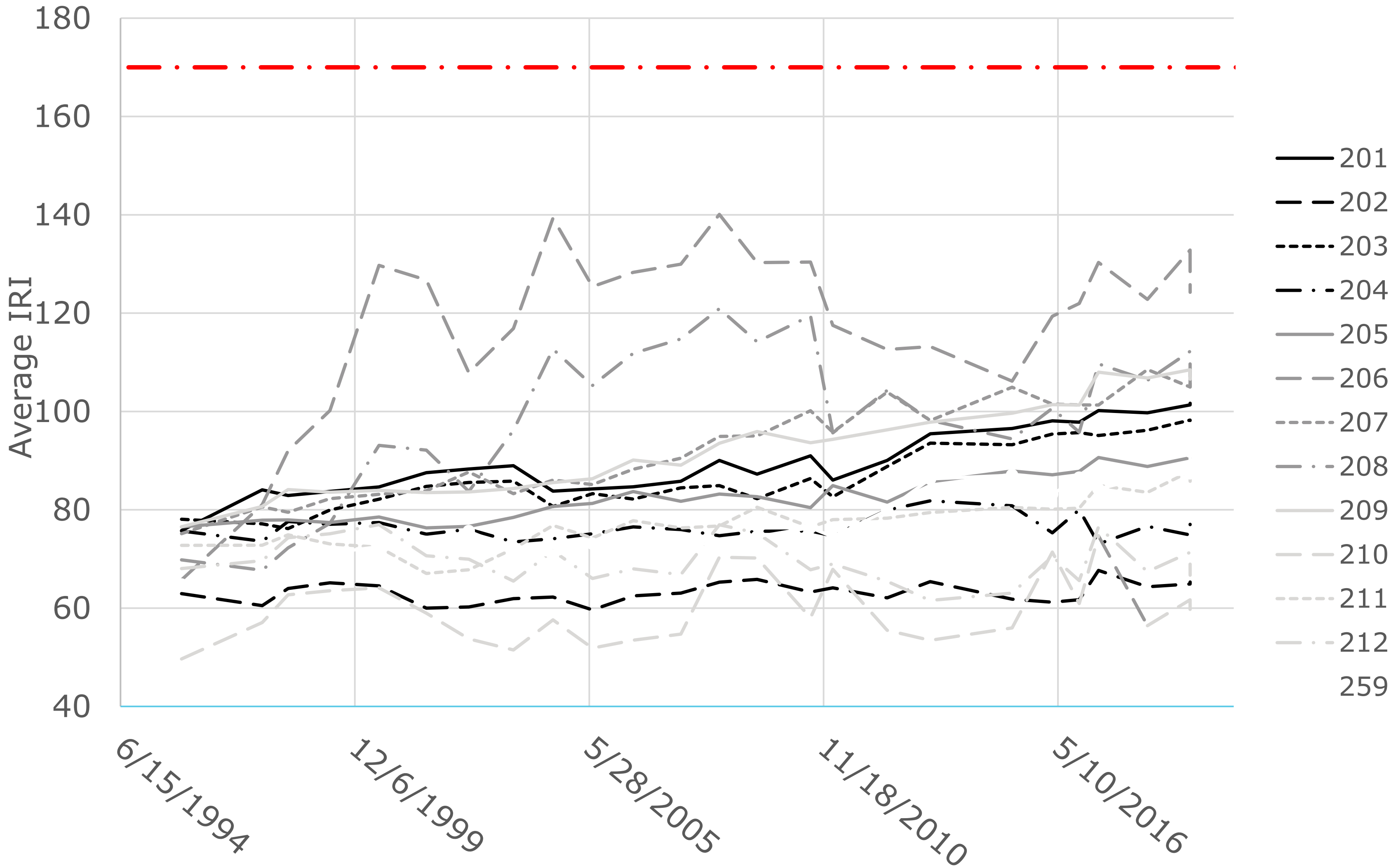

Figure 39. Average Roughness (in IRI) for Washington SPS-2 Test Sections

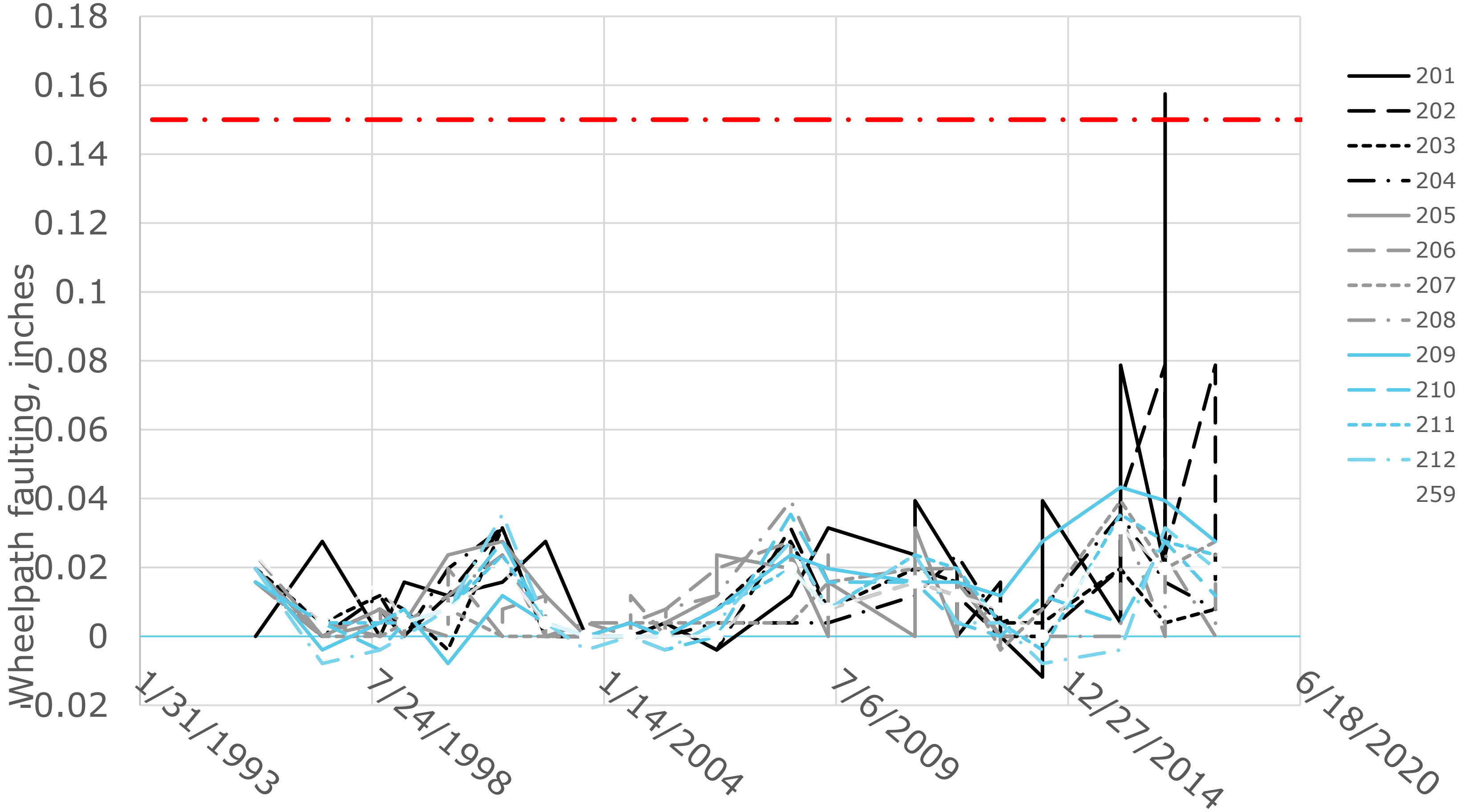

Figure 40. Average Wheel-Path Faulting (in inches) for Washington SPS-2 Test Sections

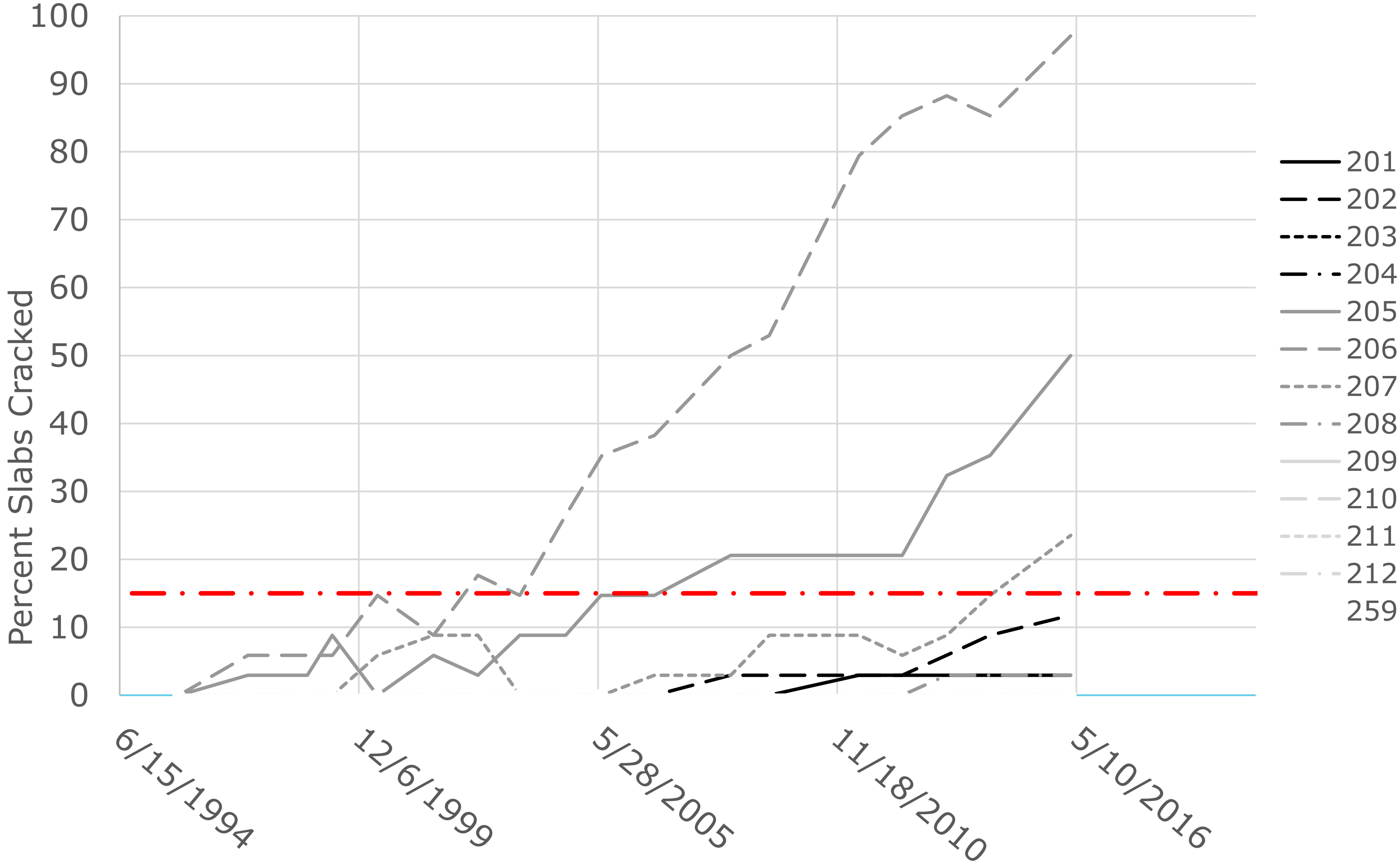

Figure 41. Average Percent Slabs Cracked for Washington SPS-2 Test Sections

None of the Washington test sections exhibited poor performance with respect to surface roughness and only 1 test section (530201) experienced poor levels of wheel-path faulting while all other test sections had relatively low levels of wheel-path faulting. Test sections 530205, 530206, and 530207 all exhibited poor performance with respect to slab cracking with test section 530207 exhibiting poor slab cracking performance within 8 years of initial construction. Summarized performance trends of the Washington test sections are given in Table 57.

Table 57. Washington SPS-2 Sections with Current Performance Trends

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
530201	FAIR	GOOD	GOOD
530202	GOOD	FAIR	FAIR
530203	FAIR	GOOD	GOOD
530204	GOOD	GOOD	GOOD
530205	GOOD	POOR	GOOD
530206	FAIR	POOR	GOOD
530207	FAIR	POOR	GOOD
530208	FAIR	GOOD	GOOD
530209	FAIR	GOOD	GOOD
530210	GOOD	GOOD	GOOD
530211	GOOD	GOOD	GOOD
530212	GOOD	GOOD	GOOD
530259	GOOD	GOOD	GOOD

Most sections are performing well and generally, the test sections have very little faulting. There are 3 sections that have a poor rating with respect to slab cracking. Approximately half of the test sections have measured smoothness ratings (IRI) that correspond to "fair" performance. Test sections that have received a "poor" rating in any year are given in Table 58.

Table 58. Washington SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
530201			2017
530205		2008-2014	
530206		2004-2016	
530207		2016	

Test sections that have exhibited poor performance include test sections 530201, 530205, 530206, and 530207. Cracking appears to be the most significant distress across these sections with test sections 530205 and 530206 experiencing more cracking than other test sections.

4.13.4 FAILURE SUMMARY

The three test sections that were experiencing higher rates of cracking (530205, 530206, and 530207) were all constructed on the lean concrete base. Despite the many other possible contributing variations, including variations across subgrade and PCC mixture designs, the difficulty in constructing the LCB layer and the behavior of slabs cast on stiff support are the most likely cause of the difference in performance of these sections compared to other test sections. The stiff and inconsistent lean concrete mix that was paved across all test sections exhibited early cracking even prior to PCC placement and it is very likely that this is contributing to the higher cracking in these test sections.

4.14 Wisconsin (55)

In 1999, 20 experimental sections for the SPS-2 experiment were constructed in Wisconsin, a wet-freeze climatic region. These sections remain in study and are generally performing well.

4.14.1 TRAFFIC AND CLIMATE DEVIATIONS

At construction, the intended level of traffic of this section was 752 KESALs per year while the measured KESALs per year, as of 2021, was 280 KESALs per year. Additionally, the freezing index of this area was measured to be 913 F days per year and the average annual precipitation was 33.5 inches, indicating the climate was well within the expected boundaries for this climatic region.

4.14.2 CONSTRUCTION RELATED DEVIATIONS

Very few construction related deviations were noted in the construction report. The most significant deviation was remnants of old PCC pavement were found in the subgrade when sampling with Shelby tubes. This required these pieces of older PCC pavement be completely removed and the subgrade brought to the correct required elevation prior to the planned construction of the SPS-2 test sections.

4.14.3 MATERIALS RELATED DEVIATIONS

Similar to construction related deviations, very few materials-related deviations were noted in the construction report for the Wisconsin SPS-2 test sections. Results from modulus of rupture testing conducted on specimens from the test sections is given in Table 59. Test section 550265 was not included in this testing.

Table 59. Measured Modulus of Rupture for Specific Wisconsin SPS-2 Test Sections

	Measured modulus of rupture, psi (target 14 day modulus of rupture, psi)	
SHRP ID	14-day	28-day
550213	610 (550)	665
550214	865 (900)	945
550215	625 (550)	645
550218	960 (900)	1115
550220	840 (900)	970
550223	665 (550)	700
550224	870 (900)	920
550260	595 (550)	640
550263	665 (550)	695
550264	605 (550)	635

The modulus of rupture results shows that generally the concrete mixtures were within reasonable range of the target values. The 550 psi mix was generally slightly above the target value and the 900 psi mix was generally slightly lower than the target value.

4.14.4 Test section performance

Most test sections exhibited good performance across performance metrics. Individualized plots of these performance metrics by year are given in Figure 42, Figure 43, and Figure 44.

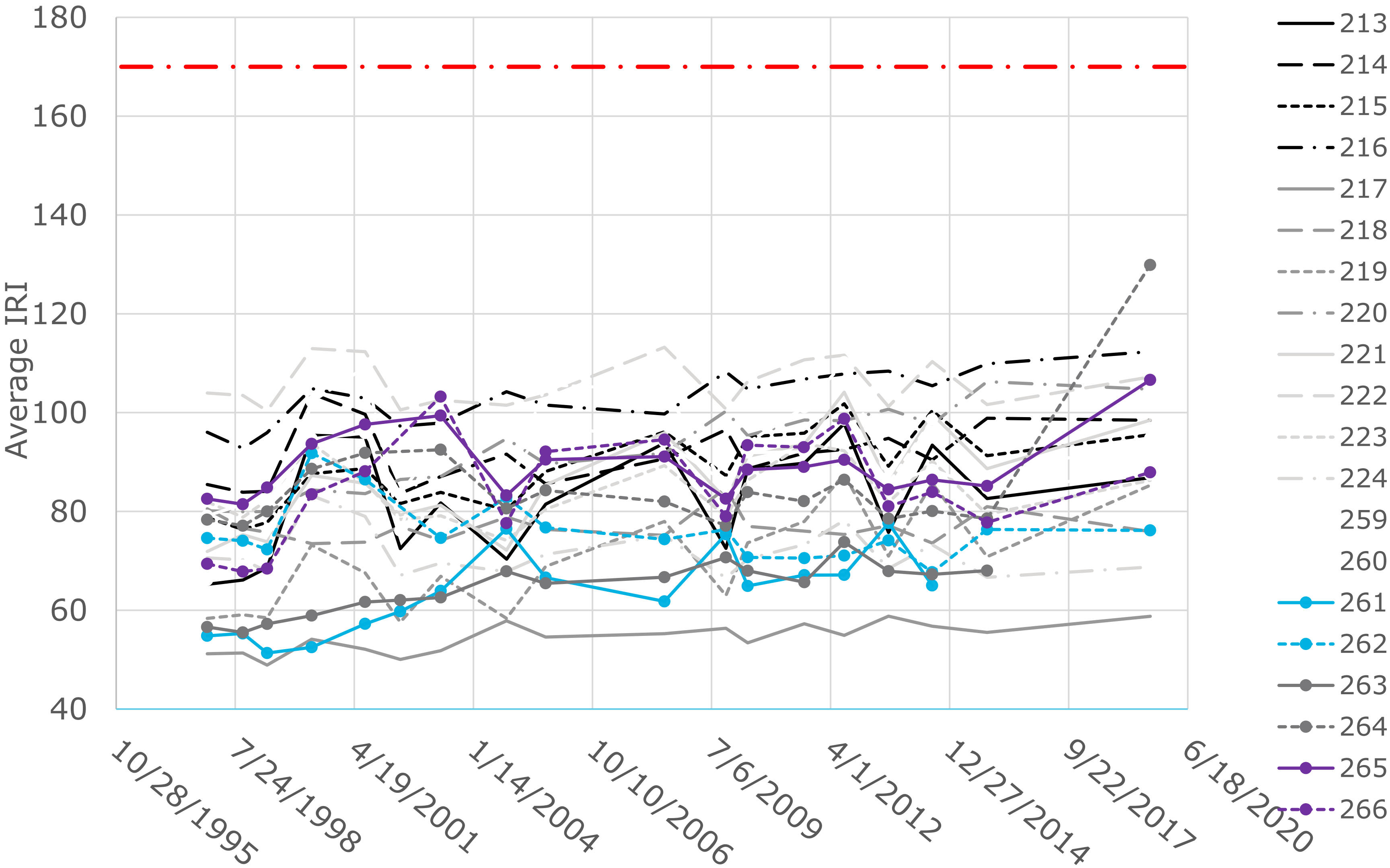

Figure 42. Average Roughness (IRI) for Wisconsin SPS-2 Test Sections

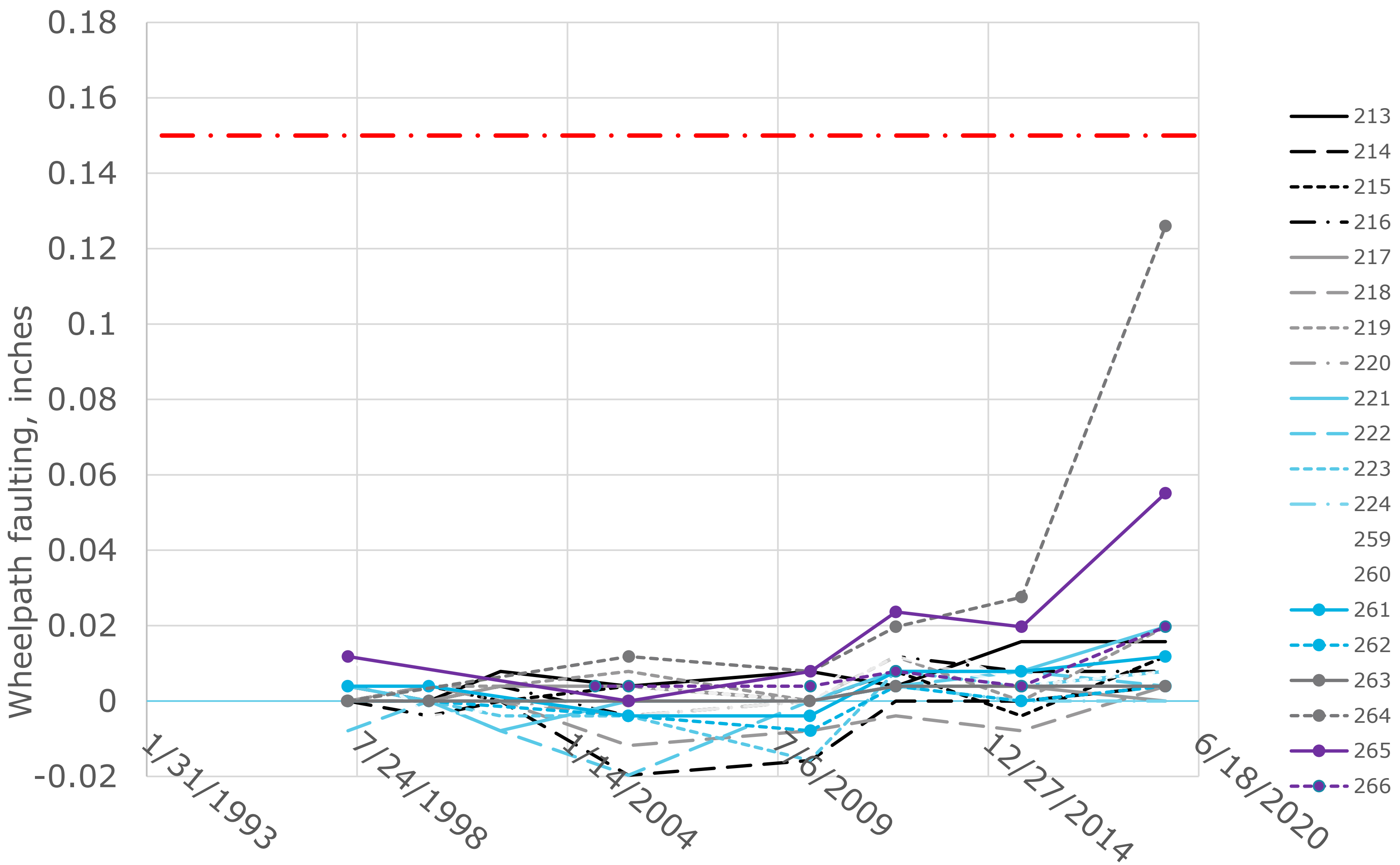

Figure 43. Average Wheel-Path Faulting (in inches) for Wisconsin SPS-2 Test Sections

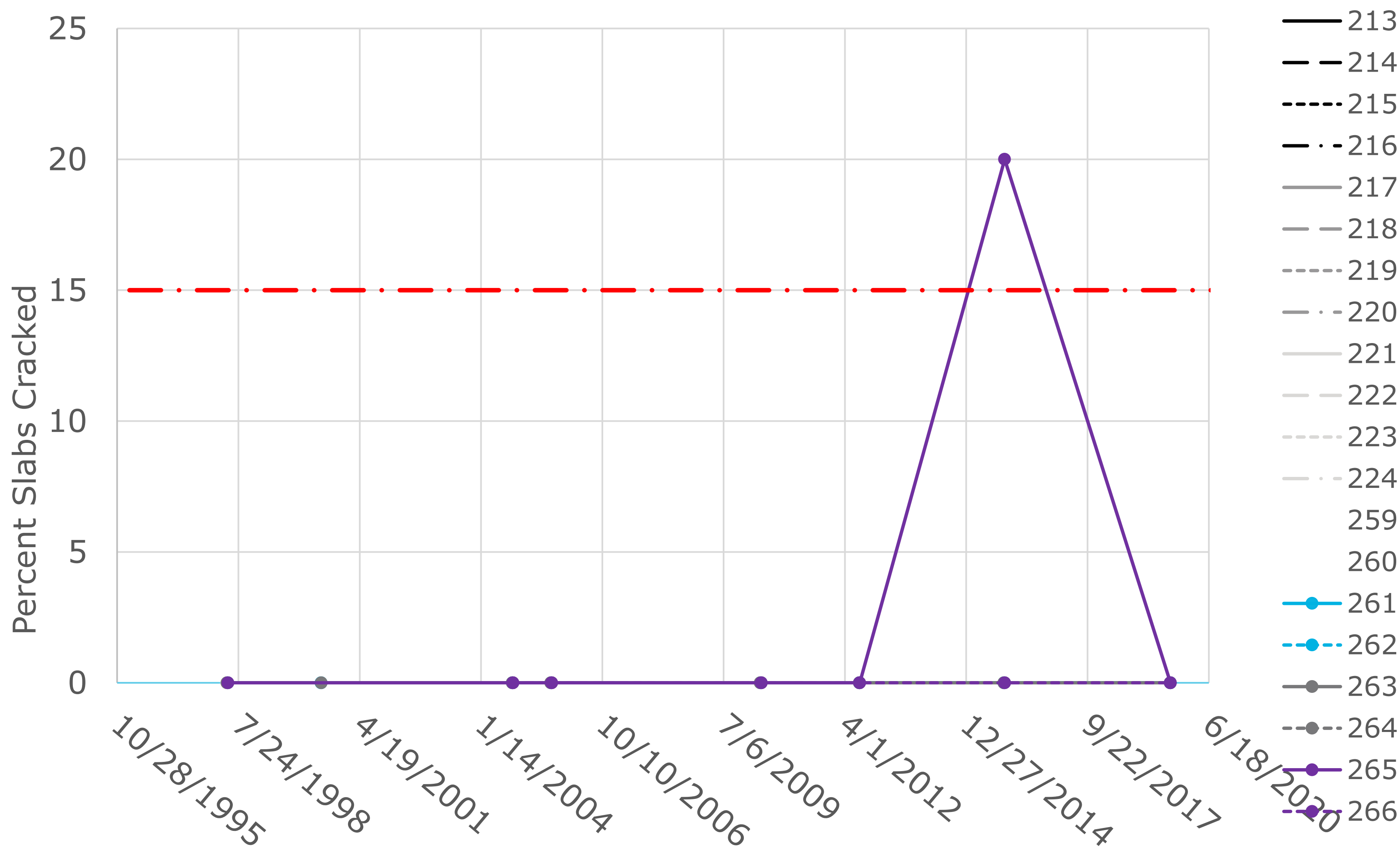

Figure 44. Average Percent Slabs Cracked for Wisconsin SPS-2 Test Sections

No test section exhibited poor performance with respect to surface roughness. Additionally, most test sections had very low measurements for wheel-path faulting except for test sections 550264 and 550265. While neither of these test sections exhibited poor performance with respect to wheel-path faulting, both were trending upward and experienced significantly more wheel-path faulting than other test sections. Test section 550265 exhibited poor performance with respect to slab cracking while other test sections exhibited no slab cracking. A table of summarized performance trends for Wisconsin test sections is given in Table 60 below.

Table 60. Wisconsin SPS-2 Sections with Current Performance Trends

SHRP ID	Lowest rating received during any distress survey across pavement performance life		
	IRI	% Cracking	Faulting
550213	FAIR	GOOD	GOOD
550214	FAIR	GOOD	GOOD
550215	FAIR	GOOD	GOOD
550216	FAIR	GOOD	GOOD
550217	GOOD	GOOD	GOOD
550218	GOOD	GOOD	GOOD
550219	GOOD	GOOD	GOOD
550220	FAIR	GOOD	GOOD
550221	FAIR	GOOD	GOOD
550222	FAIR	GOOD	GOOD
550223	FAIR	GOOD	GOOD
550224	GOOD	GOOD	GOOD
550259	FAIR	GOOD	GOOD
550260	FAIR	GOOD	GOOD
550261	GOOD	GOOD	GOOD
550262	GOOD	GOOD	GOOD
550263	GOOD	GOOD	GOOD
550264	FAIR	GOOD	GOOD
550265	FAIR	POOR	FAIR
550266	FAIR	GOOD	GOOD

Most sections are performing well across the three primary distress metrics of IRI, slab cracking and faulting. Only test section 550265 exhibited lower metrics for cracking and faulting. The test sections exhibiting “poor” performance for any of the three distress metrics are given in Table 61.

Table 61. Wisconsin SPS-2 Sections Exhibiting "Poor" Performance Classification

SHRP ID	Years that the test section obtained a "poor" performance measurement		
	IRI	% Cracking	Faulting
550265		2015	

Only test section 550265, a state supplemental section, exhibited poor performance amongst the Wisconsin SPS-2 test sections.

4.14.5 FAILURE SUMMARY

Most test sections in the Wisconsin SPS-2 test sections appear to be performing well and the construction report and selected materials data gave little indication that there were significant deviations during the construction of these test sections. However, test section 550265 did experience excessive cracking compared to other test sections. This section was a state supplemental section with a structural and mixture design developed by the Wisconsin DOT. Details for the supplemental sections used in this project are given in Table 62.

Table 62. Wisconsin SPS-2 Supplemental Section Details

Test Section	PCC Thickness, in	Target 14 day Flexural Strength, psi	Base type	Base thickness, in
550259	11	550	DGAB	6
550260	11	550	DGAB	6
550261	8	550	DGAB and CSOGB	4 / 4
550262	8	900	DGAB	6
550263	10	550	DGAB	6
550264	11	550	DGAB	6
550265	11	550	DGAB **and OGBC**	6 / 4

The primary difference between test section 550265 and the other supplemental sections was the use of a cement treated open graded base course in addition to the dense graded aggregate base. Only test section 550265 utilized the open graded base course. Test section 550261 utilized a cement stabilized open graded base course, which was also intended for use on test section 550265 yet ultimately was not used. Despite being planned, it appears that the open graded base course was not included and the constructed section consists of 6" DGAB only. Unlike surrounding sections, which were built on top of 24 inches of embankment fill, test section 550265 was constructed on 10 inches of existing subbase. Due to the section geometry, test sections 550214, 550222, 550223, 550262, 550218, 550219, and 550215 were also constructed on existing 10 inches of subbase rather than 24 inches of embankment.

It seems likely that test section 550265 was under designed, without the intended additional 4 inches of open graded base course, this could contribute to the disproportionate cracking, especially in a wet-freeze zone, where additional drainage under base layers is beneficial.

4.15 Task 1 Summary

The purpose of Task 1 was to investigate possible causality between noted construction and material deviations of the SPS-2 test sections and performance trends: specifically observing test sections exhibiting poor performance with noted deviations. While most test sections in the SPS-2 experiment remain in study and continue to perform moderate to well, some sections did exhibit poor performance as rated through roughness, slab cracking, and wheel-path faulting.

After analyzing each test sections construction report, deviation reports, possible traffic or climatic deviations, and available strength and other testing data, many causes of the poor performance of test sections could be identified. In many cases, construction or material related deviations could be identified that could possibly contribute to the poor performance exhibited by these test sections. In these cases, issues with all concrete mixture designs, subgrade irregularities and issues (moisture content or strength issues) and increased traffic conditions could have been more likely indicators of poor performance than specific construction or material issues that may pertain to only one test section. There were several consistent deviations observed across some test sections exhibiting poor performance:

- ***Lean concrete base (LCB) layer deviations***. Many agencies explicitly noted difficulties in constructing this layer which frequently led to surface cracking observed on the LCB surface itself. In many cases, this was not repaired and many of the test sections with an LCB layer exhibited early failure
- ***PCC mix design variations***. Several agencies which exhibited consistent early failure across multiple test sections (including Michigan, Nevada, and Ohio) all had either a very low cementitious materials content per CY for the low strength mix designs (below 400 lbs/CY) or a very high cementitious materials content per CY for high strength mixtures (above 700 lbs/CY). Both of these extreme mix design values can contribute to the early failure of PCC pavements. A very low cementitious content lacks sufficient hydration sites for a substantially durable and dense concrete matrix and a very high cementitious content can exhibit increased early age drying shrinkage cracking.
- ***Subgrade moisture variations.*** Several agencies reported deviations in subgrade moisture content or density, both of which can adversely affect the performance of concrete pavements. Thinner PCC test sections are more susceptible to damage due to variations across the subgrade layer.

In addition to these consistencies and possible poor performance, there was still a significant number of test sections exhibiting poor performance without a direct cause as identified from initial construction or material deviations.

5.0 TASK 2 – IMPACT OF CONSTRUCTION AND MATERIALS ISSUES

Following a review of the material and construction deviations that may have impacted the performance of the SPS-2 test sections, as outlined previously in Chapter 4.0, similarities between common materials and construction issues between the test sections are now discussed. SPS-2 test sections are considered by deviation and compared across all other test sections to evaluate the potential impact of specific construction and materials related distresses discussed previously.

First, construction related issues are discussed individually, such as issues with base or PCC layer construction, site issues, joint sawing, and dowel bar insertion. Next, materials related issues are discussed individually, such as deviations in PCC strength across test sections. Finally, both construction and material related deviations specifically relating to the lean concrete base (LCB) layer are discussed. The previous review of deviations and performance completed in Chapter 4.0 revealed significant difficulty and deviation across most agencies in the construction and performance of the LCB layer specifically. Due to both the extent of this issue and the significant impact on performance, these issues are discussed separately.

5.1 Construction Related Issues

First, test sections are grouped and investigated issues specifically relating to construction and site deviations. This discussion is limited to common deviations found across multiple test sections discussed previously in Section 4.0. This includes traffic and climate deviations, site location deviations, PATB layer construction deviations, and PCC layer construction deviations, which includes finishing, joint sawing, and dowel bar insertion. Performance trends between test sections exhibiting the same deviations are analyzed and discussed.

5.1.1 TRAFFIC AND CLIMATE DEVIATIONS

No test sections exhibited substantial deviation from the intended climatic zone. However, there was some variation across the intended traffic levels and the actual traffic experienced by each site. A full comparison of traffic levels is given in Table 63 below. Note the traffic for the Arizona sections was given as AADT instead of KESALS per year and was not included in this traffic level comparison.

Table 63. Variation of expected and measured traffic levels across SPS-2 sites

	KESALs per year	
State	Expected	Measured
Arizona (04)		1610
Arkansas (05)	1700	3560
California (06)	2405	1870
Colorado (08)	780	390
Delaware (10)	203	250
Iowa (19)	329	570
Kansas (20)	1300	720
Michigan (26)	1330	1870
Nevada (32)	800	730
North Carolina (37)	540	760
North Dakota (38)	900	480
Ohio (39)	910	630
Washington (53)	875	420
Wisconsin (55)	752	280

It can be seen that despite some variation between states, Arkansas was the only state with nearly double the traffic level anticipated. From the previous discussion of performance, many test sections in Arkansas exhibited poor performance, described in more detail in Section 4.2.4; however, there were other factors that may have contributed to the measured poor performance. Given the behavior of all test sections, it is difficult to conclude whether the noted poor performance of the Arkansas SPS-2 test section could have resulted from receiving the highest traffic loading across all test sections.

5.1.2 SITE DEVIATIONS

There were several significant site deviations described in the construction reports. Multiple test sections had documented site deviations which either changed the layout of the test sections or resulted from previously unknown materials being found below the test sections during construction. In Kansas, four test sections (test sections 200204, 200208, 200209, and 200211) were constructed on top of existing embedded box culverts, which were discovered during construction of the test sections. Similarly, Colorado test section 080215 was constructed on top of a 24-inch diameter pipe. Also in Colorado, test section 080221 was found to have a 4-inch pipe protruding at the surface, which was sawed off, capped, and paved over. Additionally, several test sections in North Carolina, test sections 370201, 370202, 370205, 370206, 370209 and 370210 were all constructed as an "add on lane" rather than the "main line" test sections. This altered the test sections significantly (including using a different sized dowel bar).

While these deviations were all substantial, none appeared to have a significant effect on the test section performance for these test sections.

5.1.3 PATB CONSTRUCTION ISSUES

Several test sections had issues with the construction of the PATB layer, including the correct installation of the filter fabric. Specifically, the Arizona PATB test sections exhibited difficulty in wrapping the filter fabric around the edge of the PATB layer material itself. Kansas exhibited a similar difficulty in wrapping the filter fabric and laying edge drains. Kansas also experienced difficulty in achieving the correct PATB layer thickness and the layer required trimming and was noted to be extremely difficult to core. Similarly, test sections in California were noted to have difficulty in achieving consistent thickness of the PATB layer which resulted in a variable thickness was measured in these test sections. To compare the performance of test sections with PATB layers to investigate the impact of this specific construction issue, all current performance ratings of all test sections with PATB layers is provided in Table 64 below. Test sections that experienced early failure, as defined in Chapter 6.0 are indicated with an asterisk (*) while test sections with noted deviations are given in bold type font.

Table 64. Performance Behavior of PATB Test Sections

	Lowest rating received during any distress survey across pavement performance life			Noted PATB construction or materials issues
SHRP ID	IRI	% Cracking	Faulting	
040221	**FAIR**	**POOR**	**GOOD**	Difficulty wrapping filter fabric around the edge of the PATB layer material itself
040222	**GOOD**	**POOR**	**GOOD**	
040223	**FAIR**	**GOOD**	**GOOD**	
040224*	**FAIR**	**POOR**	**GOOD**	
050221	FAIR	FAIR	GOOD	
050222	FAIR	GOOD	GOOD	
050223	FAIR	GOOD	GOOD	
050224	FAIR	GOOD	GOOD	
060209	**FAIR**	**FAIR**	**GOOD**	Difficulty achieving consistent thickness of PATB layers during construction
060210	**FAIR**	**GOOD**	**GOOD**	
060211	**FAIR**	**GOOD**	**GOOD**	
060212	**FAIR**	**GOOD**	**GOOD**	
080221	FAIR	FAIR	GOOD	
080222	FAIR	FAIR	GOOD	
080223	FAIR	POOR	GOOD	
080224	FAIR	GOOD	GOOD	
100209	GOOD	GOOD	GOOD	
100210	GOOD	FAIR	GOOD	
100211	GOOD	GOOD	GOOD	
100212	FAIR	GOOD	GOOD	
190221	FAIR	GOOD	GOOD	
190222	FAIR	FAIR	GOOD	
190223	FAIR	GOOD	GOOD	
190224	FAIR	FAIR	GOOD	

	Lowest rating received during any distress survey across pavement performance life			Noted PATB construction or materials issues
SHRP ID	IRI	% Cracking	Faulting	
200209	**GOOD**	**FAIR**	**GOOD**	Difficulty in correctly wrapping filter fabric around edge drains and difficulty during construction achieving consistent layer thickness
220210	**FAIR**	**GOOD**	**GOOD**	
200211	**GOOD**	**GOOD**	**GOOD**	
200212	**FAIR**	**FAIR**	**GOOD**	
260221	GOOD	GOOD	GOOD	
260222*	FAIR	POOR	FAIR	
260223	GOOD	GOOD	GOOD	
260224	FAIR	GOOD	GOOD	
320209	GOOD	POOR	GOOD	
320210	FAIR	POOR	GOOD	
320211	GOOD	FAIR	GOOD	
320212	GOOD		GOOD	
370209*	GOOD	GOOD	GOOD	
370210*	FAIR	GOOD	GOOD	
370211	GOOD	GOOD	GOOD	
370212	FAIR	GOOD	GOOD	
380221	GOOD	GOOD	GOOD	
380222	FAIR	GOOD	GOOD	
380223	FAIR	GOOD	GOOD	
380224	FAIR	FAIR	GOOD	
390209	FAIR	POOR	GOOD	
390210*		POOR	GOOD	
390211	FAIR	GOOD	GOOD	
390212*	POOR	POOR	GOOD	
530209	FAIR	GOOD	GOOD	
530210	GOOD	GOOD	GOOD	
530211	GOOD	GOOD	GOOD	
530212	GOOD	GOOD	GOOD	
550221	FAIR	GOOD	GOOD	
550222	FAIR	GOOD	GOOD	
550223	FAIR	GOOD	GOOD	
550224	GOOD	GOOD	GOOD	

Several trends were observed across the 56 test sections constructed with a PATB layer:

- 10 (18%) had a “poor” rating across any one of the three performance metrics
    - 3 of these 10 (30%) had a noted PCC-related construction issue listed in the table above.
- 1 (2%) had a “poor” rating with respect to roughness
    - None of these had a noted PCC related construction issue
- 10 (18%) had a “poor” rating with respect to cracking
    - 3 of these 10 (30%) had a noted PCC related construction issue

- 0 (0%) had a "poor" rating with respect to wheel-path faulting
  - None of these had a noted PCC related construction issue
- 6 (11%) overall experienced early failure (exhibiting "poor" performance within ten years of construction)
  - 1 of these 6 (17%) had a noted PCC related construction issue

It can be seen there was not strong correlation between sections with poor performance and PATB layer construction issues. Most significantly, of the twelve test sections with noted PATB layer issues, only one test section, 040221, exhibited early failure as defined and discussed in Chapter 6.0. This likely indicates the construction issues observed for the PATB layers did not appear to significantly impact the performance of these test sections.

5.1.4 PCC LAYER CONSTRUCTION DEVIATIONS

There were several types of deviations that occurred during the construction of the PCC layer. These included difficulties with the construction of the PCC layer itself, such as finishing or stoppages during paving. There were also noted issues with the insertion of dowel bars prior to and during paving, and there were construction issues with joint sawing and sealing of the joints. The effects of these deviations on test section performance are examined individually and then as a composite of potential PCC construction deviations. A summary of these trends is given in Table 65. Test sections that experienced early failure, as defined in Chapter 6.0, are indicated with an asterisk (*) while test sections with noted deviations are given in bold type font.

Table 65. Performance Summary of Sections with PCC Construction Deviations

	Lowest rating received during any distress survey across pavement performance life			Noted PCC layer construction deviations
SHRP ID	IRI	% Cracking	Faulting	
040213*	**POOR**	**POOR**	**GOOD**	Dowel bar inserter broken and required installation by hand
040214	FAIR	GOOD	POOR	
040215	**FAIR**	**GOOD**	**GOOD**	Paver stopping during construction
040216	FAIR	GOOD	GOOD	
040217*	FAIR	POOR	GOOD	
040218*	**GOOD**	**POOR**	**GOOD**	Paver stopping during construction
040219	**FAIR**	**POOR**	**GOOD**	Paver stopping during construction
040220	GOOD	POOR	GOOD	
040221	FAIR	POOR	GOOD	
040222	GOOD	POOR	GOOD	
040223	FAIR	GOOD	GOOD	
040224*	FAIR	POOR	GOOD	
040259	GOOD	GOOD	GOOD	
040260	FAIR	GOOD	GOOD	

	Lowest rating received during any distress survey across pavement performance life			Noted PCC layer construction deviations
SHRP ID	IRI	% Cracking	Faulting	
040261	FAIR	GOOD	GOOD	
040262*	POOR	POOR	POOR	
040263	FAIR	POOR	GOOD	
040264	FAIR	GOOD	GOOD	
040265*	POOR	GOOD	POOR	
040266	**FAIR**	**GOOD**	**GOOD**	Joints cut too wide
040267	**FAIR**	**GOOD**	**GOOD**	Joint sawing possibly damaged dowel bars
040268	FAIR	GOOD	GOOD	
050213*	**POOR**	**POOR**	**GOOD**	No joint sealing
050214	**POOR**	**GOOD**	**GOOD**	
050215	**FAIR**	**GOOD**	**FAIR**	
050216	**FAIR**	**GOOD**	**GOOD**	
050217*	**POOR**	**POOR**	**GOOD**	
050218*	**FAIR**	**POOR**	**GOOD**	
050219	**FAIR**	**GOOD**	**GOOD**	
050220	**FAIR**	**GOOD**	**GOOD**	
050221	**FAIR**	**FAIR**	**GOOD**	
050222	**FAIR**	**GOOD**	**GOOD**	
050223	**FAIR**	**GOOD**	**GOOD**	
050224	**FAIR**	**GOOD**	**GOOD**	
060201*	**POOR**	**POOR**	**FAIR**	Temporary stoppage of paving to repair tie bar inserter throughout project. Left depressions that were repaired
060202*	**FAIR**	**POOR**	**GOOD**	
060203	**FAIR**	**FAIR**	**GOOD**	
060204	**FAIR**	**GOOD**	**GOOD**	
060205*	**FAIR**	**POOR**	**GOOD**	
060206*	**FAIR**	**POOR**	**GOOD**	
060207	**FAIR**	**POOR**	**GOOD**	
060208*	**FAIR**	**POOR**	**GOOD**	
060209	**FAIR**	**FAIR**	**GOOD**	
060210	**FAIR**	**GOOD**	**GOOD**	
060211	**FAIR**	**GOOD**	**GOOD**	
060212	**FAIR**	**GOOD**	**GOOD**	
080213	GOOD	FAIR	GOOD	
080214	FAIR	POOR	FAIR	
080215	FAIR	GOOD	GOOD	
080216*	FAIR	POOR	GOOD	
080217*	**POOR**	**POOR**	**GOOD**	Heavy rain during construction and the paver sank into outside lane during construction
080218	POOR	POOR	POOR	

	Lowest rating received during any distress survey across pavement performance life			Noted PCC layer construction deviations
SHRP ID	IRI	% Cracking	Faulting	
080219	FAIR	GOOD	GOOD	
080220	FAIR	GOOD	GOOD	
080221	**FAIR**	**FAIR**	**GOOD**	Dowel basket was pulled out and not replaced during construction
080222	FAIR	FAIR	GOOD	
080223	FAIR	POOR	GOOD	
080224	FAIR	GOOD	GOOD	
080259	GOOD	GOOD	GOOD	
100201	FAIR	GOOD	GOOD	
100202	GOOD	GOOD	GOOD	
100203	FAIR	FAIR	GOOD	
100204	FAIR	GOOD	GOOD	
100205*	FAIR	POOR	FAIR	
100206	GOOD	GOOD	GOOD	
100207*	FAIR	POOR	GOOD	
100208	POOR	GOOD	GOOD	
100209	GOOD	GOOD	GOOD	
100210	GOOD	FAIR	GOOD	
100211	GOOD	GOOD	GOOD	
100212	FAIR	GOOD	GOOD	
100259	FAIR	GOOD	GOOD	
100260	FAIR	GOOD	GOOD	
190214	POOR	FAIR	POOR	
190215	FAIR	GOOD	GOOD	
190216	FAIR	FAIR	POOR	
190217*	FAIR	POOR	FAIR	
190218	POOR	GOOD	POOR	
190219	FAIR	GOOD	GOOD	
190220	FAIR	GOOD	GOOD	
190221	FAIR	GOOD	GOOD	
190222	**FAIR**	**FAIR**	**GOOD**	Issue with dowel bar insertion
190223	FAIR	GOOD	GOOD	
190224	FAIR	FAIR	GOOD	
190259	GOOD	GOOD	GOOD	
200201*	POOR	POOR	POOR	
200202*	FAIR	POOR	POOR	
200203	FAIR	GOOD	GOOD	
200204	FAIR	GOOD	GOOD	
200205*	POOR	POOR	GOOD	

	Lowest rating received during any distress survey across pavement performance life			Noted PCC layer construction deviations
SHRP ID	IRI	% Cracking	Faulting	
200206	POOR	FAIR	GOOD	
200207	FAIR	POOR	GOOD	
200208	FAIR	FAIR	GOOD	
200209	GOOD	FAIR	GOOD	
200210	FAIR	GOOD	GOOD	
200211	GOOD	GOOD	GOOD	
200212	FAIR	FAIR	GOOD	
200259	FAIR	GOOD	GOOD	
260213	**FAIR**	**FAIR**	**GOOD**	Late joint sawing without joint activation
260214*	**POOR**	**POOR**	**GOOD**	
260215*	**POOR**	**FAIR**	**FAIR**	
260216	**POOR**	**GOOD**	**GOOD**	
260217*	**POOR**	**FAIR**	**GOOD**	
260218*	**POOR**	**POOR**	**GOOD**	
260219	**FAIR**	**GOOD**	**GOOD**	
260220	**POOR**	**GOOD**	**GOOD**	
260221	**GOOD**	**GOOD**	**GOOD**	
260222*	**FAIR**	**POOR**	**FAIR**	
260223	**GOOD**	**GOOD**	**GOOD**	
260224	**FAIR**	**GOOD**	**GOOD**	
260259*	**GOOD**	**POOR**	**GOOD**	
320201*	POOR	POOR	FAIR	
320202	FAIR	POOR	GOOD	
320203*	**GOOD**	**POOR**	**GOOD**	Issues with surface finishing
320204*	FAIR	POOR	GOOD	
320205*	FAIR	POOR	GOOD	
320206*	FAIR	POOR	GOOD	
320207*	FAIR	POOR	GOOD	
320208*	FAIR	POOR	GOOD	
320209*	GOOD	POOR	GOOD	
320210*	FAIR	POOR	GOOD	
320211	GOOD	FAIR	GOOD	
320212	GOOD		GOOD	
320259	FAIR	GOOD	GOOD	
370201	**FAIR**	**FAIR**	**GOOD**	Constructed with 1” diameter dowels instead of 1.25” diameter
370202	**FAIR**	**GOOD**	**GOOD**	Inadequate lime slurry and water was added for finishing. Constructed with 1” diameter dowels instead of 1.25” diameter

	Lowest rating received during any distress survey across pavement performance life			Noted PCC layer construction deviations
SHRP ID	IRI	% Cracking	Faulting	
370203	FAIR	GOOD	GOOD	
370204	FAIR	GOOD	GOOD	
370205*	**FAIR**	**POOR**	**GOOD**	Constructed with 1” diameter dowels instead of 1.25” diameter
370206	**FAIR**	**GOOD**	**GOOD**	Constructed with 1” diameter dowels instead of 1.25” diameter
370207	FAIR	GOOD	GOOD	
370208	POOR	GOOD	GOOD	
370209	**GOOD**	**GOOD**	**GOOD**	Constructed with 1” diameter dowels instead of 1.25” diameter
370210	**FAIR**	**GOOD**	**GOOD**	Constructed with 1” diameter dowels instead of 1.25” diameter
370211	GOOD	GOOD	GOOD	
370212	FAIR	GOOD	GOOD	
370259	GOOD	GOOD	GOOD	
370260	FAIR	GOOD	GOOD	
380213	GOOD	GOOD	GOOD	
380214	FAIR	GOOD	GOOD	
380215	POOR	GOOD	GOOD	
380216	FAIR	GOOD	GOOD	
380217*	FAIR	POOR	GOOD	
380218*	POOR	POOR	GOOD	
380219	FAIR	FAIR	GOOD	
380220	FAIR	GOOD	GOOD	
380221	GOOD	GOOD	GOOD	
380222	FAIR	GOOD	GOOD	
380223	FAIR	GOOD	GOOD	
380224	FAIR	FAIR	GOOD	
380259	FAIR	GOOD	GOOD	
380260	FAIR	GOOD	GOOD	
380261*	POOR	GOOD	POOR	
380262	FAIR	GOOD	FAIR	
380263	FAIR	GOOD	GOOD	
380264	FAIR	GOOD	GOOD	
390201*	FAIR	POOR	GOOD	
390202*	FAIR	POOR	GOOD	
390203	FAIR	GOOD	POOR	
390204*	GOOD	POOR	GOOD	
390205*	FAIR	POOR	GOOD	

	Lowest rating received during any distress survey across pavement performance life			Noted PCC layer construction deviations
SHRP ID	IRI	% Cracking	Faulting	
390206*	FAIR	POOR	GOOD	
390207	FAIR	FAIR	FAIR	
390208	FAIR	POOR	GOOD	
390209	FAIR	POOR	GOOD	
390210*		POOR	GOOD	
390211	FAIR	GOOD	GOOD	
390212*	POOR	POOR	GOOD	
390259*	GOOD	POOR	FAIR	
390260	FAIR	GOOD	GOOD	
390261	GOOD	GOOD	GOOD	
390262	GOOD	GOOD	GOOD	
390263	FAIR	GOOD	FAIR	
390264*	POOR	FAIR	GOOD	
390265	FAIR	FAIR	GOOD	
530201	**FAIR**	**GOOD**	**GOOD**	550 psi mix coarser than expected and required adjusting water content for finishing
530202	GOOD	FAIR	FAIR	
530203	**FAIR**	**GOOD**	**GOOD**	550 psi mix coarser than expected and required adjusting water content for finishing
530204	GOOD	GOOD	GOOD	
530205*	**GOOD**	**POOR**	**GOOD**	550 psi mix coarser than expected and required adjusting water content for finishing
530206*	FAIR	POOR	GOOD	
530207	**FAIR**	**POOR**	**GOOD**	550 psi mix coarser than expected and required adjusting water content for finishing
530208	FAIR	GOOD	GOOD	
530209	**FAIR**	**GOOD**	**GOOD**	550 psi mix coarser than expected and required adjusting water content for finishing
530210	GOOD	GOOD	GOOD	
530211	**GOOD**	**GOOD**	**GOOD**	550 psi mix coarser than expected and required adjusting water content for finishing
530212	GOOD	GOOD	GOOD	
530259	GOOD	GOOD	GOOD	
550213	FAIR	GOOD	GOOD	
550214	FAIR	GOOD	GOOD	
550215	FAIR	GOOD	GOOD	
550216	FAIR	GOOD	GOOD	
550217	GOOD	GOOD	GOOD	
550218	GOOD	GOOD	GOOD	
550219	GOOD	GOOD	GOOD	

	Lowest rating received during any distress survey across pavement performance life			Noted PCC layer construction deviations
SHRP ID	IRI	% Cracking	Faulting	
550220	FAIR	GOOD	GOOD	
550221	FAIR	GOOD	GOOD	
550222	FAIR	GOOD	GOOD	
550223	FAIR	GOOD	GOOD	
550224	GOOD	GOOD	GOOD	
550259	FAIR	GOOD	GOOD	
550260	FAIR	GOOD	GOOD	
550261	GOOD	GOOD	GOOD	
550262	GOOD	GOOD	GOOD	
550263	GOOD	GOOD	GOOD	
550264	FAIR	GOOD	GOOD	
550265	FAIR	POOR	FAIR	
550266	FAIR	GOOD	GOOD	
550263	GOOD	GOOD	GOOD	
550264	FAIR	GOOD	GOOD	
550265	FAIR	POOR	FAIR	
550266	FAIR	GOOD	GOOD	

Several trends were observed across the 208 test sections constructed:

- 79 (38%) had a "poor" rating across any one of the three performance metrics
  - 31 of these 79 (39%) had a noted PCC-related construction issue listed in the table above.
- 28 (13%) had a "poor" rating with respect to roughness
  - 15 of these 28 (53%) had a noted PCC related construction issue
- 62 (29%) had a "poor" rating with respect to cracking
  - 55 of these 62 (88%) had a noted PCC related construction issue
- 11 (5%) had a "poor" rating with respect to wheel-path faulting
  - 0 of these had a noted PCC related construction issue
- 52 (25%) overall experienced early failure (exhibiting "poor" performance within ten years of construction)
  - 20 of these 52 (38%) had a noted PCC related construction issue

Therefore, there are some consistencies between these issues, but overall, it would be difficult to conclude that the specific PCC-layer construction related issues had a significant impact on the poor performance or early failures noted by the SPS-2 experimental test sections.

5.2 Materials Related Issues

Next, test sections are grouped and investigated issues specifically relating to materials related issues. This discussion is limited to common deviations found across multiple test sections discussed previously in Section 4.0. This includes subgrade deviations, strength deviations, and other PCC materials related deviations (slump, air content, etc.). Performance trends between test sections exhibiting the same deviations are analyzed and discussed.

5.2.1 SUBGRADE DEVIATIONS

Several test sections experienced some variation across the subgrade material itself, including a soft or otherwise unstable subgrade. Specifically, these agencies included Nevada, Michigan, California, and Colorado. Nevada noted having an unstable subgrade, which was confirmed by FWD measurements conducted prior to construction. Michigan also observed having an unstable subgrade with moisture contents that were outside of the specification. California test sections were a blend of both stable and unstable subgrades across certain test sections. Finally, Colorado test sections were a mix of cut and fill with some test sections receiving additional compaction. A summary of the performance of relevant test sections with possible subgrade issues is given in Table 66 below. The performance ratings in the table are based off the ranges supplied by Visintine et al (2018) and represent the lowest score across any year achieved by a test section. Test sections that experienced early failure, as defined in Chapter 6.0 are indicated with an asterisk (*) while test sections with noted deviations are given in bold type font.

Table 66. Comparison of Subgrade Variations and Test Section Performance

	Lowest rating received during any distress survey across pavement performance life			Noted subgrade materials issues
SHRP ID	IRI	% Cracking	Faulting	
060201*	**POOR**	**POOR**	**FAIR**	Unstable subgrade (deflections exceeded allowable)
060202*	**FAIR**	**POOR**	**GOOD**	
060203	FAIR	FAIR	GOOD	
060204	**FAIR**	**GOOD**	**GOOD**	Unstable subgrade (deflections exceeded allowable)
060205*	**FAIR**	**POOR**	**GOOD**	
060206*	FAIR	POOR	GOOD	
060207	FAIR	POOR	GOOD	
060208*	FAIR	POOR	GOOD	
060209	**FAIR**	**FAIR**	**GOOD**	Unstable subgrade (deflections exceeded allowable)
060210	**FAIR**	**GOOD**	**GOOD**	
060211	**FAIR**	**GOOD**	**GOOD**	
060212	**FAIR**	**GOOD**	**GOOD**	
080213	GOOD	FAIR	GOOD	
080214	FAIR	POOR	FAIR	
080215	**FAIR**	**GOOD**	**GOOD**	Inconsistent subgrade comprised of old highway fill
080216*	FAIR	POOR	GOOD	
080217*	**POOR**	**POOR**	**GOOD**	Subgrade was in a “wetland area” with an

	Lowest rating received during any distress survey across pavement performance life			Noted subgrade materials issues
SHRP ID	IRI	% Cracking	Faulting	
				exceptionally high water table
080218	POOR	POOR	POOR	
080219	FAIR	GOOD	GOOD	
080220	FAIR	GOOD	GOOD	
080221	**FAIR**	**FAIR**	**GOOD**	Subgrade received more compaction than other layers
080222	FAIR	FAIR	GOOD	
080223	FAIR	POOR	GOOD	
080224	FAIR	GOOD	GOOD	
080259	GOOD	GOOD	GOOD	
260213	**FAIR**	**FAIR**	**GOOD**	Subgrade moisture content outside of range
260214*	**POOR**	**POOR**	**GOOD**	Subgrade moisture content outside of range
260215*	**POOR**	**FAIR**	**FAIR**	Subgrade moisture content outside of range
260216	**POOR**	**GOOD**	**GOOD**	Subgrade moisture content outside of range Excessively soft subgrade required undercutting due to unstable soils
260217*	POOR	FAIR	GOOD	
260218*	**POOR**	**POOR**	**GOOD**	Subgrade moisture content outside of range
260219	**FAIR**	**GOOD**	**GOOD**	Subgrade moisture content outside of range
260220	**POOR**	**GOOD**	**GOOD**	Subgrade moisture content outside of range
260221	GOOD	GOOD	GOOD	
260222*	**FAIR**	**POOR**	**FAIR**	Excessively soft subgrade required undercutting due to unstable soils
260223	**GOOD**	**GOOD**	**GOOD**	
260224	FAIR	GOOD	GOOD	
260259*	GOOD	POOR	GOOD	
320201*	**POOR**	**POOR**	**FAIR**	Substantial subgrade deflections after stabilization Excessively soft subgrade required lime stabilization
320202	**FAIR**	**POOR**	**GOOD**	Excessively soft subgrade required lime stabilization
320203*	**GOOD**	**POOR**	**GOOD**	
320204*	**FAIR**	**POOR**	**GOOD**	
320205*	**FAIR**	**POOR**	**GOOD**	Substantial subgrade deflections after stabilization
320206*	**FAIR**	**POOR**	**GOOD**	Excessively soft subgrade required lime stabilization
320207*	**FAIR**	**POOR**	**GOOD**	
320208*	**FAIR**	**POOR**	**GOOD**	
320209*	**GOOD**	**POOR**	**GOOD**	Substantial subgrade deflections after stabilization

	Lowest rating received during any distress survey across pavement performance life			Noted subgrade materials issues
SHRP ID	IRI	% Cracking	Faulting	
320210*	**FAIR**	**POOR**	**GOOD**	Excessively soft subgrade required lime stabilization
320211	**GOOD**	**FAIR**	**GOOD**	
320212	**GOOD**		**GOOD**	
320259	**FAIR**	**GOOD**	**GOOD**	

Several trends were observed across the 51 test sections considered here:

- 29 (57%) had a "poor" rating across any one of the three performance metrics
  - 20 of these 29 (69%) had a noted subgrade material issue listed in the table above.
- 10 (20%) had a "poor" rating with respect to roughness
  - 8 of these 10 (80%) had a noted subgrade material issue listed in the table above.
- 25 (50%) had a "poor" rating with respect to cracking
  - 17 of these 25 (68%) had a noted subgrade material issue listed in the table above.
- 1 (2%) had a "poor" rating with respect to wheel-path faulting
  - This section did not have a noted subgrade material issue listed in the table above.
- 22 (43%) overall experienced early failure (exhibiting "poor" performance within ten years of construction)
  - 17 of these 22 (77%) had a noted subgrade material issue listed in the table above.

Therefore, there are consistent, significant trends between test sections with noted subgrade materials issues and lowered performance, measured both by poor performance over the entire lifetime as well as by early failures.

5.2.2 PCC STRENGTH DEVIATIONS

There was substantial variation across many agencies in the measured strength of the PCC surface layers. While there may be mixing or construction factors that contribute to this distress, this section specifically discusses variations in the final 14-day modulus of rupture only. A summary of all test sections with measurements from the PCC layer for the 14-day modulus of rupture with their performance across three metrics and the specific variance between the target and measured 14-day modulus of rupture is given in *Table 67* below. An asterisk (*) included by the SHRP ID indicates test sections that exhibited early failures, described later in Chapter 6.0. These were defined as any test section receiving a "poor" rating across any of the three performance metrics within ten years of construction. The performance ratings in the table are based off the ranges supplied by Visintine et al (2018) and represent the lowest score across any year achieved by a test section.

Table 67. Comparison of PCC Strength Variations and Test Section Performance

	14-day modulus of rupture values			Lowest rating received during any distress survey across pavement performance life		
SHRP ID	Target	Measured	Difference (measured - target)	IRI	% Cracking	Faulting
040213*	560	550	10	POOR	POOR	GOOD
040214	810	900	-90	FAIR	GOOD	POOR
040215	580	550	30	FAIR	GOOD	GOOD
040216	790	900	-110	FAIR	GOOD	GOOD
040218*	860	900	-40	GOOD	POOR	GOOD
040219	575	550	25	FAIR	POOR	GOOD
040220	810	900	-90	GOOD	POOR	GOOD
040222	945	900	45	GOOD	POOR	GOOD
040224*	805	900	-95	FAIR	POOR	GOOD
040262	580	550	30	POOR	POOR	POOR
040265	515	550	-35	POOR	GOOD	POOR
040267	570	550	20	FAIR	GOOD	GOOD
040268	520	550	-30	FAIR	GOOD	GOOD
050213*	568	550	18	POOR	POOR	GOOD
050217*	564	550	14	POOR	POOR	GOOD
050218*	825	900	-75	FAIR	POOR	GOOD
050219	506	550	-44	FAIR	GOOD	GOOD
050221	521	550	-29	FAIR	FAIR	GOOD
050223	568	550	18	FAIR	GOOD	GOOD
050224	506	900	-394	FAIR	GOOD	GOOD
080213	520	550	-30	GOOD	FAIR	GOOD
080214	930	900	30	FAIR	POOR	FAIR
080215	510	550	-40	FAIR	GOOD	GOOD
080216*	900	900	0	FAIR	POOR	GOOD
080217*	508	550	-42	POOR	POOR	GOOD
080218	810	900	-90	POOR	POOR	POOR
080219	515	550	-35	FAIR	GOOD	GOOD
080220	925	900	25	FAIR	GOOD	GOOD
080221	475	550	-75	FAIR	FAIR	GOOD
080222	950	900	50	FAIR	FAIR	GOOD
080223	595	550	45	FAIR	POOR	GOOD
080224	815	900	-85	FAIR	GOOD	GOOD
190213	500	550	-50	GOOD	GOOD	GOOD
190214	700	900	-200	POOR	FAIR	POOR
190219	440	550	-110	FAIR	GOOD	GOOD
190220	770	900	-130	FAIR	GOOD	GOOD
190223	460	550	-90	FAIR	GOOD	GOOD

	14-day modulus of rupture values			Lowest rating received during any distress survey across pavement performance life		
SHRP ID	Target	Measured	Difference (measured - target)	IRI	% Cracking	Faulting
190224	790	900	-110	FAIR	FAIR	GOOD
200201*	606	550	56	POOR	POOR	POOR
200202*	803	900	-97	FAIR	POOR	POOR
200203	595	550	45	FAIR	GOOD	GOOD
200204	784	900	-116	FAIR	GOOD	GOOD
200205*	702	550	152	POOR	POOR	GOOD
200206	829	900	-71	POOR	FAIR	GOOD
200207	560	550	10	FAIR	POOR	GOOD
200208	855	900	-45	FAIR	FAIR	GOOD
200209	624	550	74	GOOD	FAIR	GOOD
200210	924	900	24	FAIR	GOOD	GOOD
200211	576	550	26	GOOD	GOOD	GOOD
200212	865	900	-35	FAIR	FAIR	GOOD
200259	618	650	-32	FAIR	GOOD	GOOD
260213	645	550	95	FAIR	FAIR	GOOD
260214*	975	900	75	POOR	POOR	GOOD
260215*	585	550	35	POOR	FAIR	FAIR
260219	620	550	70	FAIR	GOOD	GOOD
260220	970	900	70	POOR	GOOD	GOOD
260224	840	900	-60	FAIR	GOOD	GOOD
260259*	690	650	40	GOOD	POOR	GOOD
320201*	520	550	-30	POOR	POOR	FAIR
320204*	885	900	-15	FAIR	POOR	GOOD
320206*	730	900	-170	FAIR	POOR	GOOD
320207*	490	550	-60	FAIR	POOR	GOOD
320210*	740	900	-160	FAIR	POOR	GOOD
320211	555	550	5	GOOD	FAIR	GOOD
370201	736	550	186	FAIR	FAIR	GOOD
370207	650	550	100	FAIR	GOOD	GOOD
370212	850	900	-50	FAIR	GOOD	GOOD
370259	578	550	28	GOOD	GOOD	GOOD
370260	663	550	113	FAIR	GOOD	GOOD
380213	710	550	160	GOOD	GOOD	GOOD
380216	980	900	80	FAIR	GOOD	GOOD
380217*	665	550	115	FAIR	POOR	GOOD
380220	910	900	10	FAIR	GOOD	GOOD
380221	630	550	80	GOOD	GOOD	GOOD
380262	640	No target strength values given		FAIR	GOOD	FAIR

	14-day modulus of rupture values			Lowest rating received during any distress survey across pavement performance life		
SHRP ID	Target	Measured	Difference (measured - target)	IRI	% Cracking	Faulting
380264	820			FAIR	GOOD	GOOD
390201*	659	550	109	FAIR	POOR	GOOD
390202*	713	900	-187	FAIR	POOR	GOOD
390203	645	550	95	FAIR	GOOD	POOR
390208	690	900	-210	FAIR	POOR	GOOD
390211	749	550	199	FAIR	GOOD	GOOD
390212*	438	900	-462	POOR	POOR	GOOD
390259*	568	550	18	GOOD	POOR	FAIR
390260	730	900	-170	FAIR	GOOD	GOOD
390262	565	550	15	GOOD	GOOD	GOOD
530202	823	900	-77	GOOD	FAIR	FAIR
530203	413	550	-137	FAIR	GOOD	GOOD
530204	870	900	-30	GOOD	GOOD	GOOD
530205*	487	550	-63	GOOD	POOR	GOOD
530206*	801	900	-99	FAIR	POOR	GOOD
530207	546	550	-4	FAIR	POOR	GOOD
530211	494	900	-406	GOOD	GOOD	GOOD
530259	625	650	-25	GOOD	GOOD	GOOD
550213	610	550	60	FAIR	GOOD	GOOD
550214	865	900	-35	FAIR	GOOD	GOOD
550215	625	550	75	FAIR	GOOD	GOOD
550218	960	900	60	GOOD	GOOD	GOOD
550220	840	900	-60	FAIR	GOOD	GOOD
550223	665	550	115	FAIR	GOOD	GOOD
550224	870	900	-30	GOOD	GOOD	GOOD
550260	595	550	45	FAIR	GOOD	GOOD
550263	665	550	115	GOOD	GOOD	GOOD
550264	605	550	55	FAIR	GOOD	GOOD

Several trends were observed across the 103 test sections considered here:

- 42 (57%) had a “poor” rating across any one of the three performance metrics
  - Average difference between target and measured modulus of rupture was -21 psi
- 16 (20%) had a “poor” rating with respect to roughness
  - Average difference between target and measured modulus of rupture was -30 psi
- 35 (50%) had a “poor” rating with respect to cracking
  - Average difference between target and measured modulus of rupture was -34 psi
- 8 (2%) had a “poor” rating with respect to wheel-path faulting
  - Average difference between target and measured modulus of rupture was -41 psi

- 26 (25%) overall experienced early failure (exhibiting "poor" performance within ten years of construction)
  - Average difference between target and measured modulus of rupture was -31 psi

Therefore, while there are some trends between the poor performance exhibited by test section and variation in the modulus of rupture of the PCC layer, it does not appear to be a significant contributing factor to either poor performance or early failure.

5.2.3 OTHER PCC MATERIAL DEVIATIONS

In addition to the deviations in strength described in the previous section, there was substantial variation across many agencies in the composition of the PCC surface layer. Specifically, agencies were given target requirements for construction (14-day modulus of rupture values, slump, air content) but the composition of the mixture itself was very flexible to obtain these metrics. However, this allowed for substantial variation between agencies. A summary of the composition of the core mixture designs (low strength and high strength mixtures) is given based on available information from the construction reports in Table 68 below. The performance ratings in the table are based off the ranges supplied by Visintine et al (2018) and represent the lowest score across any year achieved by a test section. The total number of test sections with any given concrete mixture is given for each mixture type as well as the specific metric receiving "poor" performance is also given.

Table 68. Concrete Mixture Designs with Corresponding Performance

State	Mix ID	CA[1], lbs/CY	FA[1], lbs/CY	Cement, lbs/CY	Fly ash, lbs/CY	Water, lbs	w/cm	Total number of test sections	Number of test sections receiving a "poor" rating with the following distresses			Total number of test sections receiving a poor rating
									IRI	% Cracking	Faulting	
04 (Arizona)	550 psi	1939	1285	400	100	232	0.47	6	1	2	0	4
	900 psi	1826	1207	811	0	292	0.36	6	0	4	1	5
06 (California)	550 psi	1254	732	206	69	140	0.51	6	1	3	0	3
	900 psi	1042	572	467	0	204	0.44	6	0	3	0	3
08 (Colorado)	550 psi	1720	1430	399	100	236	0.47	6	1	2	0	2
	900 psi	1865	935	749	150	257	0.29	6	0	3	0	3
10 (Delaware)	100205, 100201, 100209, 100259	1812	1257	367	197	254	0.45	4	0	1	0	1
	100211, 100203, 100207, 100260	1899	1281	564		254	0.45	4	0	1	0	1
	100210	1838	1239	397	214	254	0.42	1	0	0	0	0
	100206, 100202	1945	1114	487	257	267	0.36	2	0	0	0	0
	100212, 100208, 100204	1945	1114	735		267	0.36	3	1	0	0	1
19 (Iowa)	550 psi	1481	1752	347	61	218	0.53	6	0	1	0	1
	900 psi	1717	1132	639	112	263	0.35	6	2	0	3	3
20 (Kansas)	550 psi	891	2071	532	0	266	0.5	6	2	3	0	3
	900 psi	1349	1347	862	0	301	0.35	6	1	1	1	2
26 (Michigan)	550 psi	1827	1485	376	0	211	0.56	6	2	0	0	2
	900 psi	1605	1307	750	0	285	0.38	6	4	3	0	5

Table 68 (continued). Concrete Mixture Designs with Corresponding Performance

State	Mix ID	CA[1], lbs/CY	FA[1], lbs/CY	Cement, lbs/CY	Fly ash, lbs/CY	Water, lbs	w/cm	Total number of test sections	Number of test sections receiving a "poor" rating with the following distresses			Total number of test sections receiving a poor rating across any metric
									IRI	% Cracking	Faulting	
32 (Nevada)	475 psi	2024	1198	423	0	207	0.49	6	1	5	0	5
	750 psi	1640	1055	846	0	271	0.32	6	0	5	0	5
37 (North Carolina)	550 psi - REV	1924	1241	421	126	254	0.46	6	0	1	0	1
	900 psi	1900	743	772	232	292	0.29	6	1	0	0	1
38 (North Dakota)	550 psi	2007	1399	320	56	169	0.45	6	1	1	0	2
	900 psi	2000	960	660	116	250	0.32	6	1	1	0	1
39 (Ohio)	550 psi	1680	1260	510	90	240	0.4	6	0	3	1	4
	900 psi	1850	950	750	113	270	0.31	6	1	6	0	6
53 (Washington)	550 psi	1919	1385	423	47	230	0.49	6	0	2	0	2
	900 psi	1833	948	925	0	285	0.29	6	0	1	0	1

Several trends can be observed from the data presented. Several states can be identified as having more than half of their test sections with a "poor" performance rating for each high or low concrete mixes. These include Arizona (high and low strength), Michigan (high strength), Nevada (high and low strength) and Ohio (high and low strength mixes). Interestingly, there were not specific trends between the states that had more test sections experiencing poor performance and specific mix design metrics. Some state concrete mixtures with very low (less than 400 lbs/CY) cementitious materials content did not appear to have an increased level of poor performance. However, there was a slightly increased tendency for pavement to experience poor performance for test sections with higher cementitious materials content (greater than 800 lbs/CY). Of the six high strength mixtures with a cementitious materials content greater than 800 lbs/CY, four of these mixtures had 50% or greater of test sections paved with these mixtures experience "poor" performance across one of the three primary performance metrics.

Therefore, despite this small trend, there is not a significant correlation between the type of mix design or variation across concrete mix design components into the section performance.

5.3 Lean Concrete Base (LCB) Deviations

There was substantial difficulty across many agencies in constructing, mixing, or placing the lean concrete base (LCB) layer in the SPS-2 experimental sections. Because this was a consistent issue observed across most agencies, the LCB layer specifically is discussed separately from material and construction issues. A summary of all test sections with an LCB layer with their performance across three metrics and any noted LCB specific construction or materials issues is given in Table 69 below. An asterisk (*) included by the SHRP ID indicates test sections that exhibited early failures, described later in Chapter 6.0. These were defined as any test section receiving a "poor" rating across any of the three performance metrics within ten years of construction. Additionally, any test section with a noted LCB deviation is indicated with bold type font. The performance ratings in the table are based off the ranges supplied by Visintine et al (2018) and represent the lowest score across any year achieved by a test section.

Table 69. LCB Test Sections and Corresponding Construction or Materials Issues

	Lowest rating received during any distress survey across pavement performance life			Noted LCB construction or materials issues
SHRP ID	IRI	% Cracking	Faulting	
040217*	**FAIR**	**POOR**	**GOOD**	LCB mixture was too dry and required additional curing
040218*	**GOOD**	**POOR**	**GOOD**	LCB mixture was too dry
040219	**FAIR**	**POOR**	**GOOD**	
040220	**GOOD**	**POOR**	**GOOD**	
050217*	POOR	POOR	GOOD	
050218*	FAIR	POOR	GOOD	
050219	FAIR	GOOD	GOOD	
050220	FAIR	GOOD	GOOD	

	Lowest rating received during any distress survey across pavement performance life			Noted LCB construction or materials issues
SHRP ID	IRI	% Cracking	Faulting	
060205*	**FAIR**	**POOR**	**GOOD**	LCB mixture was cured inadequately and was noted to have cracks prior to PCC placement
060206*	**FAIR**	**POOR**	**GOOD**	
060207	**FAIR**	**POOR**	**GOOD**	
060208*	**FAIR**	**POOR**	**GOOD**	
080217*	POOR	POOR	GOOD	Pumping was observed during construction of LCB layer for test sections 080217 and 080220. Subgrade was compacted additionally before the placement of the LCB layer. Transverse cracking, segregations, and depressions were noted in the LCB layer prior to PCC placement
080218	POOR	POOR	POOR	
080219	FAIR	GOOD	GOOD	
080220	FAIR	GOOD	GOOD	
100205*	**FAIR**	**POOR**	**FAIR**	Difficulty with construction of the LCB layer – paver stopping multiple times throughout paving
100206	**GOOD**	**GOOD**	**GOOD**	
100207*	**FAIR**	**POOR**	**GOOD**	
100208	**POOR**	**GOOD**	**GOOD**	
190217*	FAIR	POOR	FAIR	
190218	POOR	GOOD	POOR	
190219	FAIR	GOOD	GOOD	
190220	FAIR	GOOD	GOOD	
200205*	POOR	POOR	GOOD	
200206	POOR	FAIR	GOOD	
200207	FAIR	POOR	GOOD	
200208	FAIR	FAIR	GOOD	
260217*	**POOR**	**FAIR**	**GOOD**	LCB layer was noted to be generally too thin (outside of spec) and the slump was extremely low (indicating a dry mixture)
260218*	**POOR**	**POOR**	**GOOD**	
260219	**FAIR**	**GOOD**	**GOOD**	
260220	**POOR**	**GOOD**	**GOOD**	
320205*	**FAIR**	**POOR**	**GOOD**	No direct construction difficulties noted; however, LCB layer had notable premature cracking prior to placement of the PCC layer
320206*	**FAIR**	**POOR**	**GOOD**	
320207*	**FAIR**	**POOR**	**GOOD**	
320208*	**FAIR**	**POOR**	**GOOD**	
370205*	**FAIR**	**POOR**	**GOOD**	LCB layer was dry which caused noticeably poor finishing. Extra water was added during finishing
370206	**FAIR**	**GOOD**	**GOOD**	
370207	**FAIR**	**GOOD**	**GOOD**	
370208	**POOR**	**GOOD**	**GOOD**	
380217*	**FAIR**	**POOR**	**GOOD**	Noted difficulty of placing the LCB layer during construction. The mixture was noted as being very stiff and developed transverse cracks prior to PCC placement.
380218*	**POOR**	**POOR**	**GOOD**	
380219	**FAIR**	**FAIR**	**GOOD**	

	Lowest rating received during any distress survey across pavement performance life			Noted LCB construction or materials issues
SHRP ID	IRI	% Cracking	Faulting	
380220	**FAIR**	**GOOD**	**GOOD**	
390205*	FAIR	POOR	GOOD	
390206*	FAIR	POOR	GOOD	
390207	FAIR	FAIR	FAIR	
390208	FAIR	POOR	GOOD	
530205*	**GOOD**	**POOR**	**GOOD**	Noted difficulty of placing LCB layer due to variations in workability and achieving specification. Thickness varied between a minimum of 5 and a maximum of 7 for the target thickness of 6 inches
530206*	**FAIR**	**POOR**	**GOOD**	
530207	**FAIR**	**POOR**	**GOOD**	
530208	**FAIR**	**GOOD**	**GOOD**	
550217	GOOD	GOOD	GOOD	
550218	GOOD	GOOD	GOOD	
550219	GOOD	GOOD	GOOD	
550220	FAIR	GOOD	GOOD	

Several trends could be observed across the 56 total test sections with an LCB layer considered:

- 37 (66%) had a "poor" rating across any one of the three performance metrics
  - 27 of these 37 (73%) had a noted material or construction issue with the LCB layer listed in the table above
- 12 (21%) had a "poor" rating with respect to roughness
  - 8 of these 12 (67%) had a noted material or construction issue with the LCB layer listed in the table above
- 31 (55%) had a "poor" rating with respect to cracking
  - 23 of these 31 (74%) had a noted material or construction issue with the LCB layer listed in the table above
- 2 (4%) had a "poor" rating with respect to wheel-path faulting
  - 1 of these 2 (50%) had a noted material or construction issue with the LCB layer listed in the table above
- 25 (45%) overall experienced early failure (exhibiting "poor" performance within ten years of construction)
  - 19 of these 25 (76%) had a noted material or construction issue with the LCB layer listed in the table above

Therefore, there are consistent, significant trends between test sections with noted LCB layer materials or construction issues and lowered performance, measured both in terms of poor performance over the entire lifetime as well as early failures.

5.4 Task 2 Summary

The purpose of Task 2 was to investigate trends between SPS-2 test sections that experienced similar materials or construction issues, as identified previously in Task 1, and outlined in Section 4.0. Specifically, the similarities in performance, as measured by three performance metrics, across test sections experiencing similar materials or construction issues, was compared relative to both poor performance exhibited by these test sections as well as early failures, as discussed in more detail in Section 6.0. While most test sections in the SPS-2 experiment remain in study and continue to perform moderate to well, some sections did exhibit poor performance as rated through roughness, slab cracking, and wheel-path faulting.

After analyzing information for each test section including project construction reports, deviation reports, possible traffic or climatic deviations, and available strength and other testing data, many clusters of similar material and construction distresses could be identified. These included external deviations such as traffic and climate, and construction-related deviations such as site, PATB construction issues and PCC layer construction issues as well as materials related issues such as subgrade, PCC strength deviations and other PCC materials related deviations. Finally, it was observed that the deviations in constructing the LCB layer were both common and significant, and this was discussed separately. In some cases, trends could be observed between test sections that exhibited similar performance and those with similar deviations. There were several consistent trends between specific material and construction deviation and test section performance:

- ***Lean concrete base (LCB) layer deviations***. Construction deviations of the LCB layer were significant with 76% of LCB test sections experiencing early failure having noted issues with the construction of the LCB layer. Frequently, this resulted in premature cracking of the LCB surface, often resulting in cracking of the PCC surface.
- ***Permeable Asphalt Treated Base (PATB) layer deviations***. Unlike the test sections containing an LCB layer, while there were noted cases of difficulties constructing the PATB layer across test sections, there was not a significant relationship between PATB issues and resulting performance.
- ***Subgrade material variations***. Several agencies reported subgrade material variations, including incorrect or highly varying moisture contents or unstable subgrades which exceeded the allowable deflections of the experiment. Test sections with subgrade material variations also tended to exhibit poor performance, and many test sections exhibiting early failure had documented variations of the subgrade material.
- ***PCC layer variations***. While there was variation of the PCC material layer itself and deviations across construction practices of the PCC layer, there was not a significant relationship between test section performance and deviations of the PCC material itself.

6.0 TASK 3 – REVIEW OF SPS-2 EARLY FAILURES

Each state with SPS-2 experimental sections that exhibited early failure are now presented. Reviewed data and information for each failure are given as outlined in the methodology discussion. This includes construction and materials related possible causes of early failures as discussed in the construction reports, deviation reports, material testing results and information, section construction data, and performance trend data. Early failure was defined as any SPS-2 test section that experienced a 'poor' level of performance across any of the three outlined performance criteria (roughness, wheel-path faulting, and cracking) using the criteria defined by Visintine et al (2018) and reproduced in Table 1 within ten years of initial construction. In order to control against potential variations across climate and traffic, early failures are discussed by state.

Once test sections are identified by state that have experienced early failure, these sections are cross-referenced against the previously listed construction and materials related distresses to identify possible causes of early failure trends.

6.1 Arizona (04)

In 1993, 21 experimental sections for the SPS-2 experiment were constructed in Arizona, a dry-no-freeze climatic region. Of these 21 original test sections, 2 were removed from study in 2018; however, these two sections represented state supplemental sections that were surfaced in asphalt cement. Outside of the 19 original test sections that were surfaced in PCC, six test sections experienced early failure as defined above. The timeline of the progression of each of these failures can be seen previously in *Figure 1*, *Figure 2*, and *Figure 3*. A summary of the structural characteristics of these six test sections is given in *Table 70* below.

Table 70. Arizona Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
040213	550	8	14	DGAB	Percent slabs cracked
040217	550	8	14	LCB	Percent slabs cracked
040218	900	8	12	LCB	Percent slabs cracked
040224	900	11	14	PATB	Percent slabs cracked
040262	550	8	14	DGAB	Roughness
040265	550	11	12	DGAB	Roughness Wheel-path faulting

It can be seen from the information above that there is not a clear consistency between structural characteristics and early failures and the sections exhibiting failure were distributed across different PCC thicknesses, strengths, lane widths and base types. However, the most common distress resulting in early failure was slab cracking.

There were several possible contributing construction and material deviations that could have contributed to these early failures. As discussed previously, there was significant difficulty constructing the LCB sections: the concrete mixture was too dry and was cured inadequately (late and with spotty application). Test section 040217 required a follow-up curing as the original curing was completed during a light rain. During the construction of the PATB layer, there was difficulty wrapping the filter fabric around the layer's edge to prevent soil infiltration in the drain, so this was not completed. There was also a dust storm and hard rain during the construction of the PATB sections.

During the PCC paving of the test sections, several construction difficulties were noted. During the paving of test section 040213, all dowel bars had to be inserted by hand following the breaking of the dowel bar inserter. Paver stoppages also occurred during the paving of sections 040218 and 040219 due to issues with the paver itself. The paver leaked oil onto test section 040218 and experienced frequent stoppages during the paving of test section 040219.

During the construction of the PATB layer of test section 040224, it was noted that the paver's auger broke down after 1 pass of PCC paving. This caused a stoppage of 3 hours before restarting, which was then shut down after an additional hour due to lack of materials. It was noted that both hard rain and a dust storm occurred during the construction of the PATB layer of this test section.

During the construction of the supplemental sections, it was noted that the saw blade cut joints that were far too wide in test section 040266, which did require epoxy patching. Additionally, the saw blade sparked while sawing joints in test section 040267, which could possibly have compromised the dowels.

There were several materials related deviations noted in the construction report, most commonly during the construction of the state supplemental sections. The DGAB layer used for test sections 040263, 040264, and 040265 was out of specification due to excess material on the 3/8" sieve.

For the supplied concrete of the supplemental sections, it was found test section 040262 had almost a 3 inch slump, well beyond the specifications, and was noted to "appear wet", and the material in test section 040264 was found to have a slump of 4 inches and an air content of 12-13%. Both of these metrics far exceed the target values for this mixture.

Therefore, several conclusions can be drawn between the early failures and possible deviations of the test sections. The early failure of test section 040213 could possibly be attributed to the hand insertion of the dowel bars during construction; however, this seems an unlikely cause of slab cracking as dowel bar insertion issues would be more likely to cause issues with surface roughness between joints. Additionally, it was noted that the dowels were inserted manually, which is a deviation, but no issues were noted with this method of insertion. While possible, it would be unlikely that this would cause early failure as slab cracking as seen.

The difficulties listed in constructing the LCB layer could have easily contributed to the early failures experienced by test sections 040217 and 040218, which were the test sections with a thinner PCC layer. For potential early cracking in the LCB layer, it would be expected that this would more significantly affect the test sections with a thinner PCC layer, especially if this cracking were reflected or compromised the structure of the entire section. Thicker PCC test sections would be less susceptible to cracking due to a cracked or weaker base layer.

The early failure exhibited in test section 040224 is less likely to be related to the listed construction deviation of the difficulty in correctly placing the filter fabric as this was noted to affect all PATB test sections and failure was only observed on test section 040224, the test section with the highest strength and thickest PCC layer. However, the listed construction difficulty during construction of the PATB layer, including a 3 hour stoppage followed by more stoppages due to lack of materials followed by severe weather, could have contributed to the early failure of this test section. The other PATB test sections had already been constructed at the point of this level of construction difficulty and did not experience the severe weather or stoppages exhibited by the test section.

The materials related deviations of test section 040262 may have been sufficiently significant to contribute to the early failure of this test section. As previously noted, this mixture was delivered on site and appeared to be very wet with a high slump of 3”. This indicates that this mixture was very likely too wet; however, the water was reduced in the mixture to counter this increased slump. This mixture deviation may have contributed to the early failure observed by this test section.

During the construction of test section 040265, some depressions were noted in the PCC surface layer caused by the automatic tie bar insertion. These depressions were patched by hand. It was noted in the construction report that the tie bar inserter, “impacts caused concrete to liquefy and drop slightly.” This test section was also noted to have the lowest measured strength of all Arizona test sections, as seen previously in Table 2. The target strength of this test section was 550 psi and the measured strength was 515 psi, the lowest measured strength of all Arizona test sections. However, this possible increase of surface liquid requiring hand patching could have contributed to the lower strength and increased surface cracking and failure observed on this test section.

6.2 Arkansas (05)

In 1993, 12 experimental sections for the SPS-2 experiment were constructed in Arkansas, a wet-no-freeze climatic region. Of these 12 original test sections, 1 section (050213) was removed from study in 2008 while the remaining 11 experimental sections were removed from study in 2013. Despite the removal from study, only three of these test sections are considered to have experienced early failure as defined previously. The timeline of the progression of each of these failures can be seen previously in Figure 4, Figure 5, and Figure 6. A summary of the structural characteristics of these three test sections is given in *Table 71* below.

Table 71. Arkansas Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
050213	550	8	14	DGAB	Roughness Cracking
050217	550	8	14	LCB	Cracking
050218	900	8	12	LCB	Cracking

It can be seen that of the three test sections experiencing early failure were all thinner (8 inch) PCC surfaces. There were some significant project deviations that could have contributed to the early failures of these test sections.

First, the Arkansas test sections experienced much different traffic loading than originally anticipated. At construction, the intended level of traffic of this section was 1700 KESALs while the measured KESALs per year, as of 2021, was 3560, indicating the actual traffic load was double the expected traffic load for this experiment.

While there were several construction related deviations listed in the construction report, there were not any significant construction related deviations related to these three test sections specifically. In general, there was a consistently low modulus of rupture across all test sections. Despite target values of 550 psi and 900 psi for the low and high strength mixtures, the Arkansas SPS-2 test sections failed to meet these strength targets, with some heightened deviations in specific test sections. Specific strength data from these test sections is given in *Table 72* below.

Table 72. Specific Modulus of Rupture Values for Arkansas SPS-2 Test Sections

SHRP ID	14-day modulus of rupture, psi	28-day modulus of rupture, psi	Difference between 14 day target and 28 day measured strength	365-day modulus of rupture, psi
050213	568 (550)	414	-136	585
050217	564 (550)	491	-59	630
050218	825 (900)	557	-343	
050219	506 (550)	439	-111	
050221	521 (550)	555	+5	625
050223	568 (550)	493	-57	
050224	506 (900)	752	-148	814

It can be seen that the test sections exhibiting early failure had exceptionally low measured 28-day modulus of rupture values. The column outlining the difference between the 14 day target strength and the 28 day measured strength indicates that the three test sections exhibiting early failure had some of the largest differences between the intended and measured modulus of rupture values. This strength discrepancy, coupled with the increased traffic and increased subgrade moisture contents, could have easily contributed to the early failure exhibited across Arkansas SPS-2 test sections.

6.3 California (06)

In 1999, 12 experimental sections for the SPS-2 experiment were constructed in California, a dry-no-freeze climatic region. Of these 12 original test sections, 2 sections (060201 and 060204) were removed from study in 2017. Additionally, five test sections are considered to have experienced early failure as defined previously. The timeline of the progression of each of these failures can be seen previously in Figure 7, Figure 8, and Figure 9. A summary of the structural characteristics of these three test sections is given in *Table 73* below.

Table 73. California Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
060201	550	8	12	DGAB	Cracking
060202	900	8	14	DGAB	Cracking
060205	550	8	12	LCB	Cracking
060206	900	8	14	LCB	Cracking
060208	900	11	12	LCB	Cracking

It can be seen that there are some similarities between the sections that exhibited early failures. Most sections that exhibited early failure had a thinner PCC surface (8 inches) and three of the four test sections with LCB bases exhibited early failure. There were several construction and material related deviations that could have contributed to the occurrence of these early failures.

First, the subgrade was noted to be too soft and failed the LTPP requirements: four of the sections did ultimately have subgrade deemed 'stable' but 8 test sections were constructed on 'unstable' subgrade. The test sections that did have appropriate 'stable' subgrade deflection measurements were 060203, 060206, 060207, and 060208. All other test sections had subgrade deflection measurements that exceeded the allowable deflection for this experiment. This includes test sections 060201, 060202, and 060205 of the sections that exhibited early failure. It is possible that this soft subgrade contributed to the failure observed in test sections 060201, 060202, and 060205. It should be noted that the test sections exhibiting early failure were thinner PCC test sections which would be more susceptible to cracking failure if placed on a soft subgrade with a dense graded base. Test sections with bound base layers and test sections with thicker PCC sections would be less prone to early failure due to this softer subgrade layer.

The LCB base layer, utilized in test sections 060205, 060206, 060207 and 060208, was found to have some issues during construction, likely due to mix discrepancies in the LCB material itself. Two plants were used to supply LCB to the project: an on-site concrete plant and an off-site concrete plant; however, there were noticeable differences in quality between these two mixtures. The LCB layer from the on-site plant was found to develop cracks after placement and appeared to have a larger fraction of coarse aggregate than the mix from the off-site plant. Therefore, more aggregate segregation of the LCB layer was observed in the mix produced from the on-site plant. Additionally, during construction of the LCB layers, curing compound was applied inadequately and cracking was observed on the surface of the LCB layer prior to placement of the PCC.

Therefore, the early failure exhibited by test sections 060205, 060206 and 060208 could be directly due to the segregated, dry LCB test layer. As mentioned previously, the base layer had noted surface cracking prior to placement of the PCC layer.

6.4 Colorado (08)

In 1993, 13 experimental sections for the SPS-2 experiment were constructed in Colorado, a dry-freeze climatic region. Of these 13 original test sections, 1 section (080217) was removed from study in 2014 and 2 additional sections (080215 and 080221) were removed from study in 2017. Two test sections were considered to have experienced early failure as defined previously. The timeline of the progression of each of these failures can be seen previously in Figure 10, Figure 11, and Figure 12. A summary of the structural characteristic of these two test sections is given in *Table 74* below.

Table 74. Colorado Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
080216	900	11	14	DGAB	Cracking
080217	550	8	14	LCB	Cracking

It can be seen that there were not distinct similarities between the two test sections exhibiting early failure. However, there were several construction and materials related deviations that may have contributed to these early failures.

First, prior to construction, it was observed that test section 080217 was constructed in a 'wetland-like' area containing a high water table. Two soft spots from the subgrade were removed and the area was replaced with fine sand fill and compacted.

During the construction of the LCB layer for test section 080217, pumping was noted in this section across the travel lane, possibly due to issues with the high water table as previously discussed. To remedy this observed distress, CDOT inspectors on site required the subgrade be compacted with a steel wheel roller immediately in front of the LCB dump trucks. Paving of

the LCB layer did continue, though the construction report notes that this additional steel-wheel compaction did not sufficiently repair the observed poor subgrade in this section and no additional repairs were completed. Transverse cracking, segregation, and depressions were observed on the LCB layer of this test section within one week of placing the LCB layer.
During the PCC paving of section 080217, the spreader sank on the outside edge of the lane due to heavy rain during the construction of this section. According to the construction report, test section 080217 was constructed on a subgrade with a high moisture content and some pumping was evident as a result of this higher moisture content.

Many of these listed construction and materials related distresses could have potentially contributed to the early failure observed in test section 080217. However, there were no distinct construction or materials related deviation that likely contributed to the early failure observed in test section 080216. As seen previously, the measured 14-day modulus of rupture for this test section was on target and no significant deviations were noted for this test section; therefore, it is difficult to conclude whether any deviations contributed to the early failure of this test section.

6.5 Delaware (10)

In 1992, 14 experimental sections for the SPS-2 experiment were constructed in Delaware, a wet-freeze climatic region. Of these 14 original test sections, all 14 of these test sections were removed from study in 2016. Two test sections were considered to have experienced early failure as defined previously. The timeline of the progression of each of these failures can be seen previously in Figure 13, Figure 14, and Figure **15**. A summary of the structural characteristic of these two test sections is given in *Table 75* below.

Table 75. Delaware Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
100205	550	8	12	LCB	Cracking
100207	550	11	14	LCB	Cracking

It can be seen that both sections that failed early contained low strength PCC mixtures constructed on a lean concrete base (LCB), though the PCC thickness and lane width varied between the test sections. However, there were several additional construction and material deviations that also could have contributed to the early failures.

First, it was observed that the low strength sections (550 psi strength) of 100205, 100201 and 100209 experienced excessive shrinkage cracking. These were originally placed in June 1995 and were replaced in October 1995.

Additionally, across all test sections, the bases did not extend the full width of the shoulders and the edge drains were not placed at the required minimum of 3 ft from the edge of the pavement or shoulder.

Finally, there was significant noted difficulty in constructing the test sections with LCB (100205, 100206, 100207, and 100208). The LCB paver stopped several times and caused slight depressions. Shrinkage cracking was noticed and developed in all of these observed depressions. High spots were milled before the paving of the overlaying PCC layer. The exact locations of these depressions were not noted; however, this was documented as occurring across the LCB layer.

While there were well-documented issues with the PCC mixture across all sections, the combination of the low-strength mixture with the noted difficulties in constructing the LCB could likely have contributed to the early failure observed of these two test sections. Again, since the exact location of these depressions was not noted, it could be assumed that the increased distresses observed on test sections 100205 and 100207 could be as a result of increased distresses on the LCB layer in these locations.

6.6 Iowa (19)

In 1995, 13 experimental sections for the SPS-2 experiment were constructed in Iowa, a wet freeze climatic region. All of these test sections remain in study and seem to have an overall moderate performance. Only one test section exhibited early failure, as defined previously. The timeline of the progression of this failure can be seen previously in Figure 16, Figure 17, and Figure 18. A summary of the structural characteristics of this test section is given in *Table 76*.

Table 76. Iowa Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
190217	550	8	14	LCB	Cracking

There was a significant materials related deviation for the Iowa SPS-2 test sections. The high strength mixture was unable to meet its required flexural strength and the average 14 day modulus of rupture testing revealed this mix was 150 psi below the target strength (750 psi instead of 900 psi).

However, the test section exhibiting early failure, test section 190217, was not a high strength section, nor a section listed previously in Iowa having any construction deviations. There does not appear to be a construction related or materials related deviation that could have contributed to this early failure.

6.7 Kansas (20)

In 1992, 13 experimental sections for the SPS-2 experiment were constructed in Kansas, a wet-freeze climatic region. All of these test sections remain in study and seem to have an overall moderate performance. Three test sections exhibited early failure, as defined previously. The timeline of the progression of this failure can be seen previously in Figure 19, Figure 20, and Figure 21. A summary of the structural characteristics of these test sections is given in *Table 77* below.

Table 77. Kansas Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
200201	550	8	12	DGAB	Wheel-path faulting Cracking
200202	900	8	14	DGAB	Cracking
200205	550	8	12	LCB	Cracking

It can be seen that there are several similarities between the test sections experiencing early failure: all three test sections exhibiting early failure were thinner (8 inch) PCC sections, two were low-strength sections, and two were placed on the DGAB layer.

Despite the noted construction issues with the PATB layer, including being placed too thick during initial construction, none of the test sections experiencing early failure were placed on the PATB layer. However, construction of all test sections was initially delayed due to an exceptionally rainy season and there were delays throughout construction due to continually rainy weather during construction. Type C fly ash was used to dry subgrade soil prior to construction of the stabilized aggregate subbase.

An interesting materials deviation was noted previously in Table 24; the modulus of rupture of the two concrete mixtures did fluctuate from the intended mix strength. The test sections experiencing early failure did have some deviation from the intended strength. Test section 200201 had a 14-day target strength of 550 psi and a tested 14-day strength of 606 psi. Test section 200202 had a 14-day target strength of 900 psi and a tested 14 day strength of 803 psi. Test section 200205 had a 14-day target strength of 550 psi and a tested 14 day modulus of rupture of 702 psi. Test section 200205 did have one of the largest deviations from the intended target strength, despite being markedly above-target, this strength did deviate almost 200 psi from the intended 14 day strength. However, this deviation indicates a strength higher than anticipated for the low strength mixture which would be an unlikely contributor to early failure.

Therefore, it’s difficult to conclude whether or not any of these factors maybe have contributed to the early failures exhibited by these sections. The discrepancy in strength between the expected performance of test section 200205 could indicate an inconsistency with the concrete mixture itself. However, it is more likely that these construction and material related deviations did not directly impact the early failure of these test sections.

6.8 Michigan (26)

In 1993, 13 experimental sections for the SPS-2 experiment were constructed in Michigan, a wet-freeze climatic region. All of these 13 original test sections were taken out of study: one section (260218) was taken out of study in 1998, two more sections (260217 and 260213) were taken out of study in 1999, section 260215 was taken out of study in 2000, test section 260214 was taken out of study in 2007 and finally, test sections 260219, 260220, 26022, 260216, 260223, 260224, and 260259 were all taken out of study together in 2013. Six test sections exhibited early failure, as defined previously. The timeline of the progression of this failure can be seen previously in Figure 22, Figure 23, and Figure 24. A summary of the structural characteristics of this test section is given in *Table 78* below.

Table 78. Michigan Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
260214	900	8	14	DGAB	Roughness Cracking
260215	550	11	12	DGAB	Roughness
260217	550	8	14	LCB	Roughness
260218	900	8	12	LCB	Roughness Cracking
260222	900	8	12	PATB	Cracking
260259	650	10.5	12	Open graded aggregate base / DGAB	Cracking

It can be seen that most test sections exhibiting early failure across the Michigan SPS-2 test sections were constructed with thinner PCC sections. There was not a distinct trend across the base type with test sections across all three base types exhibiting early failure. However, it can be seen there are two primary modes of poor performance across these test sections: roughness and cracking. The test sections which exhibited early failure due to cracking were exclusively thinner PCC sections. Additionally, only the high strength (900 psi) test sections exhibiting cracking failures while the low strength test sections exhibited failure due to roughness.

The two test sections exhibiting both roughness and cracking, test sections 260214 and 260218, were observed to have a subgrade moisture content outside of the acceptable range of 85% to 120% of the optimum moisture content. The moisture content of the compacted subgrade fell below the required range of 85% to 120% of the optimum moisture content on test sections 260213, 260214, 260215, 260216, 260218, 260219, and 260220.

There were several construction related deviations specifically relating to the PATB layer. For all test sections with a PATB layer, the geotextile filter fabric for underdrains did not extend a minimum of 1 ft under the pavement. Additionally, all sections with a PATB base experienced rutting of the PATB layer, though there was not a clear reason for this.

There were also several construction related deviations for test sections with an LCB layer. Test sections 260217, which exhibited early failure, and 260220 exhibited longitudinal cracking across the LCB layer and the LCB material from test sections 260218, 260219, and 260220 all had a slump lower than the lower limit of 1 inch and the LCB layer in test section 260218 specifically did not meet the thickness requirement outlined by this experiment. These as-constructed thickness results were given previously in Table 28.

These results indicated that there were significant deviations from the target thicknesses occurred in test section 260218 which had an LCB layer with an additional inch of thickness and a resulting PCC surface layer of only 7 inches rather than the required 8 inches. Other sections did not experience as extreme a deviation as this test section; however, thickness tolerances for the PCC layer were not met for sections 260213, 260214, 260217, 260218, and 260222. Interestingly, only test section 260213 did not experience early failure out of these five test sections with a PCC test layer outside of the tolerances given for the project.

Finally, some areas of the encountered subgrade material were much harder than expected and contained a much higher content of gravel and cobblestones. This required the use of split spoon samplers rather than Shelby tube samplers to obtain subgrade samples. However, there were other areas of subgrade that were excessively soft and failed proofrolling prior to paving. This area of excessively soft subgrade required undercutting of a more stable embankment material and test sections 260216, 260222 and 260223 all required undercutting due to unstable soils. These undercuts were approximately 36 feet wide and 1 foot deep and were backfilled with compacted embankment borrow clay.

Though this was not a materials-related deviation, a possible materials related issue that could have contributed to some of the early failure observed in this section was the low-strength mixture design. The low strength mixture design (550 psi modulus of rupture mix) had a very low cement content per cubic yard of 376 lbs per cubic yard. Contrasting this with the Arizona state DOT 550 psi concrete mixture, which contained a total cementitious materials content of 500 lbs per cubic yard (comprised of 400 lbs cement and 100 lbs of fly ash), this is an extremely low cementitious content for a concrete mixture. The concrete mixtures used for the low strength (550 psi), high strength (900 psi) and state supplementary sections (650 psi) were given previously in Table 30. Additionally, on-site testing indicated that the measured air content of test sections 260214, 260219 and 260220 all fell below the low limit of 5% and the concrete used on test sections 260215 and 260219 both did not meet the lower limit the slump test of 1 inch.

As previously observed, the test sections exhibiting early failure overwhelmingly utilized the high strength (900 psi) mixture. As indicated by the mixture design, the high strength mixture contained 750 lbs of cementitious material per cubic yard of concrete, a very high amount of cementitious material that could increase the drying shrinkage cracking potential of the mixture. This high cementitious materials content per cubic yard could have contributed to the early failure of the mixtures.

While a specific, independent cause of failure for these sections is difficult to determine given the deviation information for this project, several key deviations could contribute to the early failures observed on this project. First, the very low cementitious materials content of the mixture designs could contribute to the early failures the low strength mixtures. While a low cementitious material concrete mixture would not contribute directly to the mechanism of pumping, it could lead to deterioration of the joints, which could exacerbate the pumping mechanism observed on site. Similarly, the exceptionally high cementitious materials content used in the high strength mixtures could have also contributed to early age drying shrinkage cracking.

Additionally, the observation that all sections that failed before 2007 did not pass their thickness tolerance requirement could be significant. Despite some mention of possible subgrade issues, a relatively thin concrete layer would be more susceptible to damage due to weak sublayers. This issue would be exacerbated with the higher than planned traffic levels that these test sections experienced.

6.9 Nevada (32)

In 1993, 13 experimental sections for the SPS-2 experiment were constructed in Nevada, a dry-freeze climatic region. Of the original 13 experimental sections, two test sections (320202 and 320206) were taken out of study in 1997 while the remaining 11 sections were taken out of study in 2004. Nine test sections exhibited early failure, as defined previously. The timeline of the progression of this failure can be seen previously in Figure 27, Figure 28, and Figure 29. A summary of the structural characteristics of this test section is given in *Table 79* below.

Table 79. Nevada Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
320201	550	8	12	DGAB	Cracking
320203	550	11	14	DGAB	Cracking
320204	900	11	12	DGAB	Cracking
320205	550	8	12	LCB	Cracking
320206	900	8	14	LCB	Cracking
320207	550	11	14	LCB	Cracking
320208	900	11	12	LCB	Cracking
320209	550	8	12	PATB	Cracking
320210	900	8	14	PATB	Cracking

It can be seen that almost all test sections, except test sections 320202 and 320211, experienced early failure in Nevada, indicating a problem across the construction of all test sections. As mentioned previously, there were many deviations during the construction of these test sections.

There were several noted deviations with the existing subgrade material. First, the original existing subgrade material was determined to be unsuitable based on NDOT subgrade specifications and in order to move forward with the construction of experimental sections, this subgrade was first stabilized with lime and topped with additional embankment material. The underlying soil was stabilized with hydrated lime mixed at three percent by volume of soil and 1 ft deep into the unsuitable subgrade material. The results of FWD testing of the outer wheelpath and midlane for the stabilized subgrade and embankment, shown in Figure 25 and Figure 26, indicate that test sections 320201, 320205, and 320209 all continued to have substantial deflections following stabilization. There was also high variability in the moisture content of the subgrade, the tested results of which were given in Table 33.

It can be seen from this table there was some substantial variation of the in-situ conditions of the subgrade. For subgrade compaction, a target dry density and moisture content are prescribed, but the variation presented here indicates a high level of inconsistency through the site, possibly indicating these sections required more preparation (between possible dewatering or increased compaction) before this subgrade material reached these optimal targets. The moisture content varies by 10% across test sections and the dry density varies by almost 10 pcf between test sections, which is likely outside of the acceptable range of embankment acceptance, though this direct target information was not given in the original construction report.

Additionally, a small slope was observed on sections 320202 and 320206, which resulted in a positive grade in these two sections.

There were some construction issues with the LCB layer resulting in premature cracking of this surface. It was observed that the LCB layer in section 320205 showed extensive shrinkage cracking prior to PCC paving while the LCB layer in sections 320307 and 320208 showed random block cracking prior to PCC paving. There were also some construction related issues during the PCC paving. During the paving of section 320203, the concrete behind the paver was watered frequently. Additionally, there was some amount of constructed thickness deviation from the planned thicknesses, given previously in Table 34. The PCC layer thickness varied substantially for test sections 320201, 320203, 320207, and 320212 of at least 0.4 inches variation from design thickness. Also notable was the deviation of the PATB thickness, which was planned to be 4 inches compacted and was approximately 4 inches loose. This layer thickness varied and low sections throughout the PATB section paving were reported to have a thickness of as low as 2.9 inches.

A significant materials related deviation noted in the deviation report indicated that the 550 psi and 900 psi design strengths were changed to 975 psi and 750 psi design strengths due to materials constraints. However, average modulus of rupture testing results given in Table 35 and specific modulus of rupture testing results given in Table 36 indicated that the tested modulus of rupture values failed to meet the original target strength values for each mix.

It can be seen here that the mix designs, and particularly the high strength concrete mix, which had a target strength of 900 psi, only reached an average strength of 785 psi, over 100 psi below this target. While the low strength mix was generally closer, it still fell below the target strength of 550 psi as well. It was also noted that from section 320211 to the end, the ¾″ aggregate was lowered 2% and the fine aggregate was raised 2% from the prior PCC paving. The mix designs used for the experimental sections were given previously in Table 37, which indicated significant variation of the mixtures. It should be noted that the low strength mixture had an exceptionally low cementitious materials content of 423 lbs/CY and the high strength mixture had an exceptionally high cementitious materials content of 846 lbs/CY. As observed previously in the Michigan SPS-2 test sections, a low cementitious materials content can contribute to low strength and early failure while a high cementitious materials content can also contribute to early failure through increased drying shrinkage and early age cracking.

There were many construction and material deviations that may have contributed to the early failure of these Nevada SPS-2 test sections. Performance data indicated the test sections had excessively high IRI, cracking, and faulting throughout all measured sections.

The slightly higher traffic levels, coupled with the unstable subgrade (with excessive deflections even following lime stabilization) could have contributed to early failures. The low modulus of rupture values across all mixtures may also have contributed to these problems, as would excessive shrinkage as evidenced in the early-age cracking. Additionally, these mixtures were not air entrained and contained relatively low air content as low as 4%, which may not be sufficient to counter freeze-thaw damage. This is unusual and appears to be the only set of test sections constructed without an air entraining admixture added.

Despite being located in a dry-freeze area and not receiving substantial precipitation, higher moisture contents in some of the subgrade sections were observed. This could also be a contributing factor to early failures. Finally, there was significant variation of the constructed layer thickness. These combined factors likely resulted in the early failure of these test sections.

6.10 North Carolina (37)

In 1992, 14 experimental sections for the SPS-2 experiment were constructed in North Carolina, a wet-no-freeze climatic region. All of these 14 original test sections, six sections (370201, 370202, 370205, 370206, 370209, and 370210) were taken out of study in 2003. In general, these test sections are performing relatively well. Only one test section exhibited early failure, as defined previously. The timeline of the progression of this failure can be seen previously in Figure 30, Figure 31, and Figure 32. A summary of the structural characteristics of this test section is given in *Table 80*.

Table 80. North Carolina Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
370205	550	8	12	LCB	Cracking

A critical observation during the construction of test section 370205 were contraction cracks, which likely contributed to reflective cracking that was observed on the PCC surface.

Several materials-related deviations were noted in the construction report. All test sections constructed in the add-on lane (test sections 370201, 370202, 370205, 370206, 370209, and 370210) were constructed with 1” diameter dowels rather than the prescribed 1.25” diameter dowel bars. No explanation was provided for this deviation. Measured 14-day modulus of rupture testing, seen in Table 40 indicated the only mixture-related deviation was that the low strength mixture had approximately 140 psi higher tested strength than the target strength. Similarly, Table 42 did not indicate any deviations from the concrete mixture itself.

Therefore, while the site deviation of constructing test sections in an add-on lane was significant, it is much more likely that the early failure observed in test section 370205 was more likely due to the reflective cracking observed on the LCB layer due to the difficulties in constructing the LCB layer.

6.11 North Dakota (38)

In 1995, 18 experimental sections for the SPS-2 experiment were constructed in North Dakota, a wet-freeze climatic region. In general, these test sections are performing relatively well. Three test sections exhibited early failure, as defined previously. The timeline of the progression of this failure can be seen previously in Figure 33, Figure 34, and Figure 35. A summary of the structural characteristics of this test section is given in *Table 81* below.

Table 81. Arizona Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
380217	550	8	14	LCB	Cracking
380218	900	8	12	LCB	Cracking
380261	550	11		Class 5 Agg	Wheel-path faulting

The primary similarity between the two prematurely failed core sections is that both test sections contained thin concrete surfaces (8 inches of PCC) constructed on the LCB layer.

There were several construction related deviations that occurred in the North Dakota SPS-2 project that could be contributing to the poor performance of these sections. First, it was noted in the construction report that test sections 380260 and 380261 were constructed on slight super elevations.

Critically, there was noted difficulty in placing the lean concrete base (LCB) layer. The mixture had to be constructed with a higher strength than the design mixture to ensure the sides were sufficiently stiff for placement. The mixture was adjusted during construction to account for this issue. It was observed that the LCB developed transverse cracks across the surface prior to placement of the PCC layer. It was observed that test section 380217 exhibited transverse cracks in the PCC layer within 5 days of placing due to reflective cracking from the LCB layer. These cracks were sealed following this observation.

There was also difficulty in placing the permeable asphalt treated base which was found very difficult to roll due to its high fluidity. It was theorized this construction difficulty was due to the short sections of placement. However, none of the test sections exhibiting early failure were placed on this PATB layer.

The construction report did not indicate any potential construction or materials related deviation that could have contributed to the early failure of test section 380261. It should be noted this was the only test section designed without dowels and on an unbound base.

There were no specific materials-related deviations listed in the report and tested modulus of rupture values do not indicate materials deviations with the strength of the concrete mixture itself. Therefore, the difficulty in placing the LCB layer and transverse cracking could have contributed to the early failure observed of test sections 380217 and 380218.

6.12 Ohio (39)

In 1994, 19 experimental sections for the SPS-2 experiment were constructed in Ohio, a wet-freeze climatic region. Of these original 19 test sections, seven test sections (390201, 390202, 390204, 390205, 390206, 390210 and 390259 were taken out of study in 2007. Three more sections (390209, 390208 and 390264) were taken out of study in 2012 and two more sections (390218 and 390212) were taken out of study in 2020. Nine test sections exhibited early failure, as defined previously. The timeline of the progression of this failure can be seen previously in Figure 36, Figure 37, and Figure 38. A summary of the structural characteristics of this test section is given in *Table 82* below.

Table 82. Ohio Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
390201	550	8	12	DGAB	Cracking
390202	900	8	14	DGAB	Cracking
390204	900	11	12	DGAB	Cracking
390205	550	8	12	LCB	Cracking
390206	900	8	14	LCB	Cracking
390210	900	8	14	PATB	Cracking
390212	900	11	12	PATB	Cracking
390259	550	11		DGAB	Cracking

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
390264		11		DGAB	Roughness

There are some similarities between the sections exhibiting early failure. First, most test sections experiencing early failure were constructed with the high strength (900 psi at 14-day) concrete mixture. Most failed test sections also contained thinner PCC surface layers; however, test sections otherwise varied across land width and base type variables.

Minimal construction related deviations were mentioned in the construction report. Test section 390204 exhibited some cracking on the surface aggregate due to compaction. The unbound aggregate base layers required cutting to grade using a CMI trimming machine across all test sections.

Minimal material related deviations were reported in the construction report; however, there were several significant differences that may affect performance. First, the construction report indicated test sections 390204 and 390212 required a retarding admixture (Daratard) that was not used in any other test section, but no explanation for this deviation was given. These two test sections both exhibited early failure from excessive cracking.

Most significantly, it can be seen previously from Table 51 that the target strength requirements for the PCC layer were met, and exceeded by over 130 psi, for the low strength concrete mixture. However, the high strength sections had an average strength of 614 psi and fell far below their target strength of 900 psi. These discrepancies could indicate an extreme deviation from the intended concrete mixture. The material constituents of the concrete mixture were given previously in Table 52 which indicate that the high strength mixture contained an extremely low w/cm ratio.

The extremely low w/cm ratio and very low strength of the high strength (900 psi at 14-day) indicate that there was an issue with this concrete mixture. The mixture design also indicates a very high volume of cementitious materials per square yard, which can easily contribute to premature shrinkage cracking of concrete mixtures. The mixture design for the high strength mixtures indicates 863 lbs/CY of cementitious material for the mixture which can increase the early age drying shrinkage cracking of concrete mixtures. Therefore, despite the other potential deviations of the test sections, there was most likely an issue with the 900 psi concrete mix itself that contributed to the premature failures predominantly observed in the high strength test sections.

6.13 Washington (53)

In 1995, 13 experimental sections for the SPS-2 experiment were constructed in Washington, a dry-freeze climatic region. The sections are generally performing well. Two test sections exhibited early failure, as defined previously. The timeline of the progression of this failure can be seen previously in Figure 39, Figure 40, and Figure 41. A summary of the structural characteristics of this test section is given in *Table 83* below.

Table 83. Washington Test Sections Experiencing Early Failure

Test section	PCC Strength	PCC thickness	Lane width	Base	Failure performance criteria
530205	550	8	12	LCB	Cracking
530206	900	8	14	LCB	Cracking

It should be noted that the primary two similarities of the test sections experiencing early failure are that these are two thin (8 inch) test sections construction on the LCB base. The construction report outlined specific difficulties in constructing the LCB layer. Specifically, the LCB used below test section 530206 exhibited significant variation in workability and it was observed that there was variation in the water/cement ratio during construction. All LCB mixtures had a lower w/cm ratio than designed.

During the paving of the LCB for test section 530207, the first 7 loads of LCB material were rejected due to high air contents. The mix was observed to be very difficult with noticeable rough patches on one side of the lane and very wet mix on the other side of the lane. During this time, the concrete curing machine was broken and water was hand-applied as an interim cure for several hours until the machine was running again. This mix required significant hand-finishing. It was observed in the construction reports that despite having sufficient water for the mix, the mix did appear to be very dry and required significant hand finishing. Ultimately, it was concluded in the report that there may have been insufficient mixing time at the batch plant. The LCB for test section 530208 appeared to run much more smoothly; however, there was rain during the paving of this section.

Due to this initial difficulty paving the LCB layer, an initial distress survey of just the LCB layer was completed prior to PCC paving. This distress survey revealed a single crack in the LCB layer of test section 530205 and cracking in test sections 530206, 530207, and 530208, with the most severe cracking in the LCB layer for test section 530208. Additionally, despite average thicknesses aligning closely with the planned constructed thickness of 6 inches, all LCB layers varied between 5 inches and 7 inches across the test sections following construction.

There was also some discrepancy between the measured and target 14 day modulus of rupture values, predominantly affecting the low-strength mix. These values can be seen in Table 56. However, despite this strength discrepancy, it is much more likely that the prematurely cracked LCB layer affected the early cracking observed in Test sections 530205 and 530206.

The prematurely cracked LCB layer could affect the performance of the test section through two primary methods. First, the cracks from the LCB layer could reflectively crack through the surface PCC layer. Thinner PCC layers would be more susceptible to reflective cracking from the LCB layer. Additionally, the cracked LCB layer would also be providing decreased structural stability. This decrease in base layer strength would require likely require a thicker PCC layer for better performance, resulting in cracks in thinner sections only. Therefore, the early failures seen in test sections 530205 and 530206 are likely due to the construction issues from the LCB layer itself.

6.14 Wisconsin (55)

In 1999, 20 experimental sections for the SPS-2 experiment were constructed in Wisconsin, a wet-freeze climatic region. All of these sections remain in study and are generally performing well. No SPS-2 test sections in Wisconsin exhibited early failure, as defined previously. The timeline of the performance of these test sections can be seen previously in Figure 42, Figure 43, and Figure 44.

The most significant construction deviation noted was that remnants of old PCC pavement were found in the subgrade when sampling with Shelby tubes which required that these unexpected older PCC pavement slabs be completely removed and the subgrade was then brought to the correct required elevation. Modulus of rupture testing results, seen in Table 59, indicated that the 14-day target values aligned closely with the tested values. Generally, the concrete mixtures were within reasonable range to target values. The 550 psi mix was generally slightly above the target value and the 900 psi mix was generally slightly lower than the target value. However, none of these deviations appeared to have affected performance as none of the Wisconsin SPS-2 test sections experienced early failure.

6.15 Task 3 Summary

The purpose of Task 3 was to provide insight into the SPS-2 test sections which exhibited early failure. While most test sections in the SPS-2 experiment remain in study and continue to perform well, some sections were removed from study early.

After analyzing each project's construction report, deviation report, possible traffic or climatic deviations, and available strength and other testing data, many potential causes of the early failures of test sections were identified. For some states, selected test sections were removed from study and specific deviations, such as location and constructed thickness, could be directly responsible for this early failure.

There were several consistent deviations observed across some test sections exhibiting early failure:

- ***Lean concrete base (LCB) layer deviations***. Many agencies explicitly noted difficulties in constructing this layer which frequently led to surface cracking observed on the LCB surface itself. In many cases, this was not repaired and many of the test sections with an LCB layer exhibited early failure
- ***PCC mix design variations***. Several agencies which exhibited consistent early failure across multiple test sections (including Michigan, Nevada, and Ohio) all had either a very low cementitious materials content per CY for the low strength mix designs (below 400 lbs/CY) or a very high cementitious materials content per CY for high strength mixtures (above 700 lbs/CY). Both of these extreme mix design values can contribute to the early failure of PCC pavements. A very low cementitious content

lacks sufficient hydration sites for a substantially durable and dense concrete matrix and a very high cementitious content can exhibit increased early age drying shrinkage cracking.

- ***Subgrade moisture variations.*** Several agencies reported deviations in subgrade moisture content or density, both of which can adversely affect the performance of concrete pavements. Thinner PCC test sections are more susceptible to damage due to variations across the subgrade layer.

In addition to these consistencies and possible early failure causes, there were several test sections exhibiting early failure without a direct cause as identified from initial construction or material deviations.

7.0 TASK 4 – LESSONS LEARNED FROM STATE SUPPLEMENTAL SECTIONS

The original SPS-2 experiment consisted of states constructing a set of 12 core test sections adhering to a specific layout and structure. The participating agencies also had the opportunity to add supplemental test sections to the experiment, if desired. Because these test sections were selected and constructed at the state level, the analysis of the state supplemental sections are presented by state to ensure other possibly complicating factors (weather, traffic, etc.) are mitigated.

Test sections were analyzed differently if the test section contained only one supplemental test section or if the state agency had chosen to conduct a more thorough supplemental test section experiment. For states with only a single supplemental test section, consistently numbered -0259, this test section was constructed with the concrete mixture design and structure typical for each participating agency. For these states, the performance of this supplemental test section was compared to the performance of all of the core test sections within the same state and observations were drawn regarding the performance of the standard agency concrete section and the core experimental sections of the SPS-2 project.

For states choosing to conduct an entirely separate supplemental experiment, the performance of these test sections was evaluated against each other within the state and against the standard performance of the other core experimental sections in the SPS-2 project.

Additionally, the predicted and measured performance for all of the SPS-2 supplemental experiment sections were compared for this task. The measured performance metrics used for comparison included roughness (IRI), percent slabs cracked, and measured wheel-path faulting. The predicted performance data also included these metrics and calculated by running performance predictions utilizing the AASHTOWARE PavementME software. Predictions were made across the service life of each pavement section and then linear regressions were fit to each predicted and measured set of data. The slope and intercept for each linear trendline is given for each section and compared between the three measured and predicted performance metrics.

Finally, these multiple sources of data were analyzed together to provide insight into possible conclusions that may be drawn from the analysis of data collected regarding the SPS-2 supplemental test sections.

7.1 Arizona (04)

In 1993, 21 experimental sections for the SPS-2 experiment were constructed in Arizona, a dry-no-freeze climatic region. Of these 21 original test sections, nine test sections were state supplemental test sections, designed and constructed outside of the core experiment. These supplemental test section varied design factors including surface material, base type, lane width, and the use of dowels. A summary of design factors for the Arizona SPS-2 supplemental test sections is given in *Table 84* below.

Table 84. Experimental Design Factors for Arizona Supplemental Test Sections

Test Section	Surface	Base	Strength	Lane	Dowels
040260	8.5″ AC	4″ DGAB			
040261	8.5″ AC	4″ DGAB			
040262	8″ PCC	6″ DGAB	550 psi	14 ft	No
040263	8″ PCC	4″ PBTB/ 4″DGAB	550 psi	14 ft	No
040264	11″ PCC	4″ PBTB/ 4″DGAB	550 psi	12 ft	No
040265	11″ PCC	6″ DGAB	550 psi	12 ft	No
040266	12.5″ PCC	4″ BTB	550 psi	14 ft	Yes
040267	11″ PCC	4″ BTB	550 psi	14 ft	Yes
040268	8″ PCC	4″ BTB	550 psi	14 ft	Yes

It can be seen from Table 84, above, that supplemental test sections 040260 and 040261 were surfaced in asphalt cement, instead of Portland cement concrete. Therefore, these test sections are not included in the analysis of supplemental test section performance. Otherwise, it can be seen that the primary variations of these test sections included base type and thickness, lane width, and presence of dowels. The concrete strength was not varied across the supplemental test sections and is the same low-strength concrete mix utilized for the low-strength test sections in the core experiment.

7.1.1. Section performance

During construction of the supplemental sections, it was noted the saw blade cut joints that were far too wide in test section 040266, which did require epoxy patching. Additionally, the saw blade sparked while sawing joints in test section 040267, which could possibly have compromised the dowels.

There were several materials related deviations noted in the construction report, most commonly during the construction of the state supplemental sections. The DGAB layer used for test sections 040263, 040264, and 040265 was out of specification due to excess material on the 3/8″ sieve.

For the supplied concrete of the supplemental sections, it was found test section 040262 had almost a 3 inch slump, well beyond the specifications, and was noted to “appear wet”, and the material in test section 040264 was found to have a slump of 4 inches and an air content of 12-13%. Both of these metrics far exceed the target values for this mixture. The measured modulus of rupture values for these test sections is given in *Table 85* below.

Table 85. Measured Modulus of Rupture for Specific Arizona SPS-2 Test Sections

	Measured modulus of rupture, psi (target 14 day modulus of rupture, psi)		
SHRP ID	14-day	28-day	365-day
040262	580 (550)	670	845
040265	515 (550)	545	890
040267	570 (550)	580	815
040268	520 (550)	625	770

It can be seen that the measured modulus of rupture values was close to the target of 550 psi. Test section 040265 had the lowest measured strength across the supplemental test sections. It should be noted that specific compressive strength cores from test section 040264, the test section most out of specification based on fresh concrete properties, were not taken.

The performance of the Arizona SPS-2 test sections relative to the measured performance metrics of roughness (IRI), percent of slabs cracked, and measured wheel-path faulting were given previously in Table 3. It can be seen that the pavement performance for the sections is generally moderate with cracking the most common cause of poor ratings across test sections. In general, faulting is not a problem and roughness is a moderate problem across sections. It can be seen that state supplemental section 040262 appears to have the worst performance across all sections, with "Poor" performance across all three performance metrics. Interestingly, test section 040259, the Arizona DOT state supplemental section, had the best performance across all test sections, achieving "Good" performance across all three performance parameters. Individualized plots of these performance metrics by year were given previously in Figure 1, Figure 2, and Figure 3.

It can be seen from the plots that supplemental test section 040262 consistently had poor IRI performance when compared to other experimental sections. Supplemental test sections 040265 and 040264 also performed poorly, relative to IRI. It can be seen from the wheel-path faulting plot, that supplemental test sections 040262 and 040265 performed poorly with respect wheel-path faulting. Interestingly, no state supplemental sections exhibited any measure of slab cracking, as evidenced from the slab cracking plot.

There are several interesting trends that can be inferred from this data. First, supplemental test section 040262 had exceptionally poor performance; however, the construction report did indicate this mix appeared to be the wettest by a substantial margin, with a 3" slump measurement that was significantly out of specification. Additionally, other poorly performing test sections, 040264 and 040265, did have an out of spec DGAB layer. However, test sections 040266 and 040267 also had constructability issues with joint sawing but they did not exhibit extremely poor performance. Among the supplemental test sections, the doweled test sections far outperformed the undoweled supplemental test sections.

7.1.1 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for each supplemental experiment section, as previously, is given in *Table 86* below.

Table 86. Arizona SPS-2 Supplemental Sections Performance Predictions

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
040262	Faulting	-0.001	0.001014	0.034	0.009375
	Cracked slabs	-0.5020	0.1430	-0.8430	0.1120
	Roughness (IRI)	69.98	0.742	88.35	7.017
040263	Faulting	0.000	0.000197	0.021	-0.000183
	Cracked slabs	-0.7530	0.2150	-2.024	0.3460
	Roughness (IRI)	71.09	0.334	75.11	0.519
040264	Faulting	0.000	0.000215	0.028	-0.000491
	Cracked slabs	-0.0040	0.0010	-0.670	0.0830
	Roughness (IRI)	109.85	0.147	110.19	1.322
040265	Faulting	-0.001	0.000507	0.06	0.003826
	Cracked slabs	-3.1010	1.2220	0.000	0.0000
	Roughness (IRI)	85.14	1.345	92.00	3.329
040266	Faulting	0.000	0.000262	0.018	-0.000287
	Cracked slabs	0.0290	0.0110	0.000	0.0000
	Roughness (IRI)	86.54	0.166	86.84	1.413
040267	Faulting	0.000	0.000243	0.014	-0.000223
	Cracked slabs	-0.4520	0.1540	0.000	0.0000
	Roughness (IRI)	90.03	0.288	97.81	-0.733
040268	Faulting	-0.002	0.000867	0.018	0.000125
	Cracked slabs	-8.050	3.1110	0.000	0.0000
	Roughness (IRI)	85.43	3.053	90.50	0.270

Several observations can be drawn from the information presented in Table 86. First, the intensity of the slope can indicate the severity of the degradation with respect to time. Second, the difference between the measured and predicted values can indicate whether or not the behavior of these test sections can be modeled effectively using PavementME. Consistently, it can be seen that the roughness (measured as IRI) varied the most between measured and predicted slope values, which indicate the rate of deterioration. Generally, the measured rate of deterioration was higher than predicted, although test sections 040267 and 040268 were observed exceptions to this trend. The primary difference between test sections 040266, 040267, and 040268 was the use of a bituminous treated base material, which may have contributed to the difficulty in correctly modeling the behavior of this layer.

.

7.2 Colorado (08)

In 1993, 13 experimental sections for the SPS-2 experiment were constructed in Colorado, a dry-freeze climatic region. Of these 13 original test sections, one state supplemental test section was constructed. The state supplemental section contained 11″ of PCC with 650 psi flexural strength and 12 foot lanes. The supplemental section was placed directly on the subgrade with no base and was paved with the standard Colorado DOT 650 psi concrete mix. Relevant design factor details for this supplemental test section are given in *Table 87* below.

Table 87. Design Factors for Colorado SPS-2 State Supplemental Test Sections

Test Section	Surface	Base	Strength	Lane
040259	11″ PCC	None	650 psi	12 ft

Despite a number of construction and material deviations affecting other core experimental test sections on the Colorado SPS-2 site, the state supplemental test section 080259 did not experience significant construction or materials related deviations during construction.

7.2.1 SECTION PERFORMANCE

To compare the performance of the state supplemental test section against the other experimental sections, the performance of all test sections was given previously in Table 12. It can be seen from the table that most sections are generally performing well, with the most consistent poor performance is due to slab cracking. However, the state supplemental test section, 080259, is the only test section across the entire experiment with consistently good metrics across all three primary performance measures. In the Colorado SPS-2 experiment, surface roughness (measured as IRI) was the most consistent issue that resulted in a lower performance reading and only test sections 080259 and 080213 consistently measured a "Good" IRI value. Individualized plots of these performance metrics by year were given previously in Figure 10, Figure 11, and Figure 12. It can be seen from the performance plots that the supplemental test section 040259 consistently performed very well across all three performance measured compared with the experimental test sections.

7.2.2 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for each supplemental experiment section, as previously, is given in *Table 88*.

Table 88. Colorado SPS-2 Supplemental Sections Measured and Predicted Performance

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
080259	Faulting	-0.00100	0.000373	0.0140	-0.00107
	Cracked slabs	0.00000	0.00000	0.0000	0.0000
	Roughness (IRI)	72.784	0.7120	72.898	-0.0150

Several conclusions can be drawn from this information. First, it can be seen that while slab cracking was predicted correctly, the faulting and roughness of the supplemental test section was overestimated for this section and the state supplemental test section performed much better than expected. It can be seen that PavementME most significantly varied with the prediction of roughness, measured as IRI. This could potentially be a result of the difficulty of the software to effectively model a concrete pavement that does not have a base layer. This could also indicate increased performance of the test section, since this test section utilized the standard DOT concrete mixture and structure with no noted issues or errors. This lack of difficulty or issue in mix design or construction may have contributed to the increased performance observed for this test section.

7.3 Delaware (10)

In 1994, 14 experimental sections for the SPS-2 experiment were constructed in Delaware, a wet-freeze climatic region. Of these 14 original test sections, two state supplemental test sections were constructed.

Design factors for the two state supplemental sections were held consistent, with only the type of dowel bar material used varying between the test sections. The concrete mix, base material, and surface thickness all replicated standard Delaware DOT concrete paving practice. The design factors of the Delaware state supplemental sections are given in *Table 89* below.

Table 89. Design Factors for Delaware SPS-2 State Supplemental Test Sections

Test Section	Surface	Base	Strength	Lane	Dowels
100259	10″ PCC	8″ DGAB	650 psi	12 ft	Steel dowels
100260	10″ PCC	8″ DGAB	650 psi	12 ft	Plastic dowels

7.3.1 SECTION PERFORMANCE

There were several relevant construction and materials related deviations during the construction of the Delaware SPS-2 test sections. The test sections 100205, 100201, and 100209 were cast together and finishing of these sections was noted to be very difficult. Shrinkage cracking was already evident after finishing these sections. The Delaware DOT believed the shrinkage cracking to be caused by the very low cement content of the concrete mix. A different concrete mixture, the Delaware DOT Type B mixture (with a flexural strength of 650 psi) was used for test sections 100201, 100203, and 100207. It should be noted that the concrete mixtures used in test section 100259 is the same concrete mixture design used in test sections 100201, 100205, and 100209, while the concrete mixture used in test section 100260 is the same concrete mixture used in test sections 100203, 100207, and 10211. The mixture designs used for the test sections were given previously in Table 14. It can be seen the original low-strength mixture had an extremely high w/cm of 0.63. These sections were removed and replaced due to excessive shrinkage cracking.

Unsurprisingly, these mixtures did not fulfill the target requirements, especially for the low strength mix, which as seen above, was replaced by the standard Delaware DOT 650 psi strength mix and the average strength results for the test sections were given previously in Table 16. It can also be seen that the concrete mixtures for the Delaware DOT mixtures in the supplemental sections most closely aligned with their target strength values. This possibly indicates the familiarity the contractor has with consistently constructing the Delaware DOT standard concrete paving mix.

To compare the performance of the state supplemental test section against the other experimental sections, the performance of all test sections was given previously in Table 17. It can be seen from the table that the state supplemental test sections generally performed very well across the three measured performance metrics and received a performance rating of "Fair" only regarding roughness. The only core experimental test sections that performed better than the two supplemental test sections were 100202, 100206 and 100209, while test sections 100201, 100204 and 100210 performed comparably. Individualized plots of these performance metrics by year were given previously in Figure 13, Figure 14, and Figure 15.

It can be seen from the performance plots that test section 100260 did exhibit high levels of roughness compared to all other test sections, while the supplemental section 100259 experienced a moderate amount of roughness. It was also observed that the supplemental test section 100260 experienced higher values of wheel-path faulting while test section 100259 experienced low levels of wheel-path faulting relative to the other test sections. Additionally, it can be seen from the plots that neither supplemental test section experienced any cracking.

Since there was very little construction variation between the supplementary test sections, it can be reasonably inferred that the dowel bar material did significantly contribute to the differences observed between the roughness and wheel-path faulting between these two test sections. This would indicate that the steel dowels used in test section 100259 were much more effective at load transfer, as observed through roughness and joint faulting, than the plastic dowels used in test section 100260.

7.3.2 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for each supplemental experiment section, as outlined previously, is given in Table 90 below.

Table 90. Delaware SPS-2 Supplemental Sections Measured and Predicted Performance

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
100259	Faulting	-0.0010	0.000531	0.00200	0.000183
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	74.4690	0.4540	73.795	0.2460
100260	Faulting	-0.00300	0.001379	0.00200	0.001757
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	74.138	0.8980	64.343	2.803

It can be seen that the AASHTOWARE PavementME accurately predicted the cracking behavior of the supplemental Delaware SPS-2 test sections. Interestingly, the faulting model appeared to predict slightly more accurately for the plastic doweled test section, 100260, than the steel doweled test section, 100259, despite the software being unable to model the specific dowel bar material (and modeling with a default dowel bar material of steel). However, the roughness prediction for the plastic doweled supplemental section, 100260, was highly inaccurate, while the roughness prediction for the steel doweled supplemental section, 100259, was much closer to the measured value. The AASHTOWARE PavementME software severely overestimated the smoothness performance of the plastic dowels, which is expected as this material could not effectively be modeled.

7.4 Iowa (19)

In 1995, 13 experimental sections for the SPS-2 experiment were constructed in Iowa, a wet-freeze climatic region. Of these 13 original test sections, one state supplemental test section was constructed. The state supplemental section had an intended layer thickness of 11 inches and a 14 ft lane. This section was constructed with the standard Iowa DOT concrete paving mix, though no strength information was given for this test section. The relevant design factors for this supplemental section are given in Table 91 below.

Table 91. Summary of Design Factors for Iowa Supplemental Test Sections

Test Section	Surface	Base	Strength	Lane	Dowels
190259	11″ PCC	6″ DGAB		14 ft	Yes

7.4.1 SECTION PERFORMANCE

At construction, the intended level of traffic of this section was 329 KESALs while the measured KESALs per year, as of 2021, was 570, indicating the actual traffic load was significantly higher than the expected load. Additionally, the freezing index of this area was measured to be 548 F days and the average annual precipitation was 35.6 inches, indicating the climate was well within the expected boundaries for this climatic region.

Additionally, though no mention of the deviation of the supplemental test section was made in the construction report, data indicates the actual constructed thickness of the PCC surface layer is 8.5," which is significantly below the design thickness of 11 inches. Unfortunately, no target strength or mix design data was supplied for the Iowa DOT concrete paving mixture used in the supplemental test section, so deviation from this mixture cannot be established.

To compare the performance of the state supplemental test section against the other experimental sections, the performance of all test sections was given previously in Table 21.

It can be seen that in general, the performance of these test sections is moderate and the supplemental test section performed relatively well. Only test section 190213 performed similarly, with all three performance parameters rated as 'good' across all metrics. While it is known that this pavement was constructed on a comparable base to other DGAB sections and was constructed with wide lanes (14 ft), the actual and target strength for the concrete mixture provided for this section is still unknown and therefore, drawing conclusions regarding the performance of this mixture is difficult. Individualized plots of these performance metrics by year were given previously in Figure 16, Figure 17, and Figure 18.

It can be seen that the supplemental test section performed extremely well compared to the other test sections across all three performance metrics. Test section 190259 experienced no measured slab cracking, very little wheel-path faulting, and maintained a very low roughness.

7.4.2 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for the supplemental experiment section, as previously outlined, is given in Table 92 below.

Table 92. Iowa SPS-2 Supplemental Sections Measured and Predicted Performance

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
190259	Faulting	-0.00800	0.005686	0.00000	0.000173
	Cracked slabs	-0.0420	0.0100	0.00000	0.00000
	Roughness (IRI)	71.102	3.656	75.271	0.2970

It can be seen that there was some significant variation between the predicted and measured performance of the supplemental test section, specifically with respect to section roughness. The predicted deterioration rate for section roughness was significantly higher than anticipated; however, the cracking slabs and faulting metrics were predicted relatively well.

7.5 Kansas (20)

In 1992, 13 experimental sections for the SPS-2 experiment were constructed in Kansas, a dry-freeze climatic region. Of these 13 original test sections, one state supplemental test section was constructed. The constructed state supplemental test section in Kansas replicated the standard PCC mix design and section utilized by the Kansas DOT. The design factors of this test section are given in Table 93 below.

Table 93. Experimental Design Factors for Kansas Supplemental Test Sections

Test Section	Surface	Base	Strength	Lane	Dowels
200259	12″ PCC	6″ stabilized base 6″ modified flyash	600 psi	12 ft	Yes

It can be immediately seen that the supplemental test section in Kansas was substantially thicker than all other test sections with a 12 inch PCC surface and contained a subgrade layer modified with flyash that was unique to this supplemental test section.

7.5.1 SECTION PERFORMANCE

Despite some impactful construction related deviations affecting the construction of the core test sections, including construction during rain and difficulty with the PATB layer, there were no specific construction related deviations outlined in the construction report for the state supplemental section. A summary of the measured modulus of rupture values for the test sections is given in Table 94 below.

Table 94. Performance Trends Across Kansas SPS-2 Test Sections

Mix Type	Compressive strength, psi		Flexural strength, psi	
	14-day	28-day	14-day	28-day
550 psi mix	4269	5039	608	649
900 psi mix	6918	7904	843	925
200259 mix (KDOT mix)	4094	4768	618	677

It can be seen that the KDOT mixture aligned much more closely with the target values than the other concrete mixtures. This could imply the familiarity of the contractor with the KDOT paving mix. To compare the performance of the state supplemental test section against the other experimental sections, the performance of all test sections was given previously in Table 25.

It can be seen from the performance data that the supplemental test section performed very well across the three performance metrics. Most test sections performed well against the performance metric of faulting. Test section 200211 exhibited the best performance across these test metrics across all test sections; however, test sections 200203, 200204, 200209, 200210 and 200259 all performed comparably well. Against slab cracking specifically, the supplemental test section performed as well as test sections 220210, 200212, 200203 and 200204. Individualized plots of these performance metrics by year were given previously in Figure 19, Figure 20, and Figure 21.

7.5.2 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for each supplemental experiment section, using previously described methodology, is given in Table 95 below.

Table 95. Kansas SPS-2 Supplemental Sections Measured and Predicted Performance

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
200259	Faulting	-0.0010	0.001042	0.00400	0.000119
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	98.322	0.9960	80.831	0.6400

It can be seen that the prediction model for the roughness and faulting of the supplemental section appears to be slightly incorrect, while the cracking prediction for test section 200259 is correct. However, roughness was significantly overpredicted, especially with respect to the overpredicted intercept, indicating that the overall observed amount of roughness should be much higher than observed. The faulting model slightly overpredicted the faulting performance as well.

This could be as a result of the difficulty of accurately predicting the performance of the test section, especially since this test section utilized 6 inches of flyash stabilization of the subgrade layer, which may be difficult to accurately model with the AASHTOWARE PavementME software.

7.6 Michigan (26)

In 1993, 13 experimental sections for the SPS-2 experiment were constructed in Michigan, a wet-freeze climatic region. Of these 13 original test sections, one state supplemental test section was constructed. The state supplemental test section consisted of 10.5″ of PCC paving over a 4″ open graded base and 3″ aggregate base. The concrete mixture and section structure were standard to the Michigan DOT concrete paving. The test section also had tied concrete shoulders, neoprene transverse joint seals and hot-poured rubberized asphalt longitudinal joints. The design factors of this test section are given in Table 96 below.

Table 96. Experimental Design Factors for Michigan Supplemental Test Sections

Test Section	Surface	Base	Strength	Lane	Dowels
260259	10.5″ PCC	4″ Open graded base; 3″ aggregate base	650 psi	12 ft	Yes

Three mixture designs were used for all Michigan SPS-2 test sections, and were given previously in Table 30. This included low strength and high strength mixtures used for all core test sections and a control section mix used for test section 260259. It can be seen that only the concrete mixture used for test section 260259 contained flyash and had a comparably high amount of coarse aggregate and relatively low fine aggregate composition, implying a coarser aggregate blend than the mixtures used for the core experimental sections.

7.6.1 SECTION PERFORMANCE

It was also noted in the construction report that the traffic flow all over the test sections was not uniform and a road intersected these test sections, which potentially alters traffic values.

Additionally, the bituminous shoulders were not placed for several weeks following paving of the test sections. The initial joint sawcutting was performed soon after placement; however, it was observed that many of the joints did not fully activate before placement of the asphalt shoulders. On average, it appeared that only approximately every fourth sawcut joint activated prior to the placement of the shoulders.

Despite several deviations of the core test sections from the intended construction, including difficulty with subgrade moisture content and construction of the PATB and LCB base layers, in addition to issues maintaining moisture of the DGAB base layer, there were no specific listed construction-related deviations of the supplemental test section.

Modulus of rupture testing data from the project was given previously in Table 29. It can be seen from the strength testing data that most tested 14 day strengths were within reasonable range of the target strength.

There was significant early failure observed in the Michigan SPS-2 test sections, resulting in the completion of an early manual distress survey, outside of the LTPP distress surveying. The entire length of each core test section along the lane/shoulder joint for the entire project had extensive longitudinal joint seal damage. No joint sealant damage was observed in 260259. The joint damage consisted of raveling and cracking near the shoulder interface. By early December 1994, it was observed that pumping of pavement fines were observed in test sections 260213, 260214, 260215, 260217, 260218, 260219 and 260220. Notably absent from this list were the PATB test sections, which did not experience any longitudinal joint pumping at that time. The most severe pumping was observed on test section 260218.

To compare the performance of the state supplemental test section against the other experimental sections, the performance of all test sections was given previously in Table 31. Again, it can be seen that the most common distress corresponding to "poor" performance was increased roughness across the test sections. While the performance of test section 260259 was rated as 'Good' across faulting and smoothness, it was rated as poor in cracking. However, test section 260259 did perform better than most experimental sections. Individualized plots of these performance metrics by year were given previously in Figure 22, Figure 23, and Figure 24.

It can be seen that the supplemental test section 260259 exhibited very low roughness and wheelpath cracking; however, this test section exhibited poor performance measured from percent slabs cracked approximately beginning 12 years after construction. Cracking dropped due to maintenance treatments, but then the test section exhibited almost 50% slabs cracked at 17 years after construction.

7.6.2 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for each supplemental experiment section, as outlined previously, is given in Table 97 below.

Table 97. Michigan SPS-2 Supplemental Sections Measured and Predicted Performance

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
260259	Faulting	0.02300	0.00992	0.0060	-0.000126
	Cracked slabs	0.0000	0.0000	-11.038	2.874
	Roughness (IRI)	75.313	3.4660	68.224	0.3270

It can be seen that AASTHOWARE PavementME significantly underpredicted slab cracking and significantly overpredicted surface roughness. It can also be seen that the actual slab cracking was much higher than predicted; however, due to the difficulties exhibited during construction, including trouble achieving the mixture design, the cracking may be due to construction and materials issues rather than the inability of AASHTOWARE PavementME to adequately predict distresses. Factors affecting the early failure exhibited by these sections were discussed previously in Section 6.8.

7.7 Nevada (32)

In 1993, 13 experimental sections for the SPS-2 experiment were constructed in Nevada, a dry-freeze climatic region. Of these 13 original test sections, one state supplemental test section was constructed. The state supplemental test section consisted of 10.5" of PCC paving over a 1.5" leveling course. The concrete mixture and section structure were standard to Nevada DOT concrete paving. The design factors of this test section are given in Table 98 below.

Table 98. Experimental Design Factors for Nevada Supplemental Test Sections

Test Section	Surface	Base	Strength
320259	10.5" PCC	1.5" leveling course	4000 psi compressive strength

7.7.1 SECTION PERFORMANCE

There were several construction related deviations noted during the construction of the Nevada SPS-2 test sections. The removal of the existing pavement layers (AC surface layer, cement treated base layer, and dense graded aggregate base layer) revealed an inadequate subgrade layer. This existing subgrade material was determined to be unsuitable based on

NDOT subgrade specifications and in order to move forward with the construction of experimental sections, this subgrade was first stabilized with lime and topped with additional embankment material. The underlying soil was stabilized with hydrated lime mixed at three percent by volume of soil and 1 ft deep into the unsuitable subgrade material. Additionally, the on-site moisture content and average dry density of the subgrade layers were taken and all were given previously in Table 33.

It could be seen from this table that there was substantial variation of the in-situ conditions of the subgrade; however, the supplemental test section measured relatively high density and a lower moisture content compared to the other test sections, which was consistent across the four measurements taken from the subgrade below the supplemental test section. Additionally, there was some amount of constructed thickness deviation from the planned thicknesses, as given previously in Table 34. It can be seen that the supplemental test section was constructed at 12.7”, substantially thicker than the design.

Many of the test sections on this project performed poorly, especially across the metric of slab cracking. However, the state supplemental section, 320259, consistently performed well across performance metrics. Individualized plots of these performance metrics by year were given previously in Figure 27, Figure 28, and Figure 29.

It can be seen that the performance of the state supplemental test section was generally very strong across all three performance metrics compared to other test section performance. During construction, there was much noted difficulty in working with both high strength and low strength mixtures, with resulting early cracking, among other construction difficulties. The lack of construction difficulty and deviation of the supplemental test section could likely be due to the contractor’s familiarity mixing and constructing the standard Nevada DOT concrete paving mix. As previously discussed in Section 6.9, both the high strength and low strength mixtures had design cement contents that were either very high (over 800 lbs/CY) or very low (below 450 lbs/CY), which could contribute to early failure. The mix design used for the supplemental test section, however, incorporated approximately 600 lbs/CY of cement, typically an optimal amount of cement content for consistent performance with limited cracking.

7.7.2 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for each supplemental experiment section, as outlined previously, is given in Table 99 below.

Table 99. Nevada SPS-2 Supplemental Sections Measured and Predicted Performance

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
320259	Faulting	0.001705	-0.0060	0.0000	0.0000
	Cracked slabs	0.0000	0.0000	0.01600	-0.00217
	Roughness (IRI)	61.452	1.9470	73.9910	2.7980

It can be seen that the AASHTOWARE PavementME incorrectly predicted the extent of the observed roughness deterioration; however, it did predict the trajectory of the IRI and closely estimated the faulting and slab cracking for this test section. AASHTOWARE PavementME appeared to underestimate the roughness of the section. The primary difference between this test section and the core test sections was the mix design itself and the base layer structure, which included 1.5 inches of a base leveling course, rather than the aggregate or bound bases utilized by the other test sections. Depending on the ability of the AASHTOWARE PavementME to effectively model this leveling course, this could be a contributing factor to the underprediction of roughness for this test section.

7.8 North Carolina (37)

In 1992, 14 experimental sections for the SPS-2 experiment were constructed in North Carolina, a wet-no-freeze climatic region. Of these 14 original test sections, two state supplemental test sections were constructed. The two supplemental test sections compared standard paving practices of the North Carolina DOT, which included using 1” of an AC leveling course, a permeable base layer and lime-stabilizing the subgrade. A comparison of the design factors of these two sections is given in Table 100 below.

Table 100. North Carolina SPS-2 Supplemental Sections Design Factors

Section	Surface	Base	Strength	Lane	Dowels
370259	10” PCC	4 inches PATB on 1 inch AC on 8 inches lime-stabilized subgrade	550 psi	12 ft with 10 ft untied econocrete shoulder	Yes
370260	11” PCC	1 inch AC on 5 inches BTB on 8 inches cement treated subgrade	550 psi	14 ft with 8 ft untied econocrete shoulder	Yes

While no specific materials related deviations were listed in the construction report, measured average modulus of rupture results were given previously in Table 40. It can be seen from the limited modulus of rupture data that the low strength mix generally exceeded the target strength requirement of 550 psi and the high strength mix was only 50 psi less than the target strength of 900 psi. Importantly, it can be seen that while the supplemental test section 370259 was quite close to the target 550 psi strength, supplemental test section 370260 far exceeded this target by over 100 psi.

7.8.1 SECTION PERFORMANCE

To compare the performance of the state supplemental test sections against the other experimental sections, the performance of all test sections was previously given in Table 43. It can be seen that while generally performing well, there are several sections that have earned a "poor" performance rating across one of the three distress metrics. Most commonly, this was as a result of high roughness measured as IRI. Generally, both of the supplemental test sections performed well, receiving "Good" ratings across all test metrics with only the roughness of test section 370260 receiving a "Fair" rating. Individualized plots of these performance metrics by year are given in Figure 30, Figure 31, and Figure 32.

It can be seen from the plots that, generally, the supplemental sections performed very well with minimal exhibited distresses. The only test sections with lower roughness measurements than the supplemental sections were those with a PATB base layer, which included drainage. This could imply the benefit of drainage for road roughness as all test sections with more drainage did have consistently lower roughness measurements. It also could simply be a matter of the PATB being the best of the three base types, regardless of drainage.

7.8.2 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for each supplemental experiment section, as outlined previously, is given in Table 101 below.

Table 101. North Carolina SPS-2 Supplemental Sections Measured and Predicted Performance

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
370259	Faulting	-0.0030	0.000952	0.0050	-0.000088
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	88.464	0.6400	86.656	-0.1570
370260	Faulting	0.0000	0.00016	0.0010	0.000132
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	98.054	0.2140	94.372	0.1280

It can be seen that, in general, the measured and predicted performances aligned well. The cracking model was predicted well; however, there was some variation with the faulting and roughness predictions. The primary difference between these test sections and the core sections was the structure of the base and base material, which included bituminous treated base and stabilized subgrade layers (utilizing both lime and cement). However, as previously mentioned, test section 370260 did have 100 psi higher 14-day modulus of rupture strength than planned, which should be reflected in the prediction. However, this construction deviation did not appear to affect the variation between the measured and predicted behavior of this test section.

7.9 North Dakota (38)

In 1995, 18 experimental sections for the SPS-2 experiment were constructed in North Dakota, a dry-freeze climatic region. Of these 18 original test sections, six state supplemental test section were constructed.

The North Dakota state supplemental experimental project included one test section, 380259, that utilized the standard paving concrete mix design and structure utilized by North Dakota DOT. The other test sections were constructed with a consistent base surface thickness with varying base types, lane width, use of dowels, and skew of joints. A summary of the design factors used in the state supplemental sections is given in Table 102 below.

Table 102. Design Factors for North Dakota SPS-2 Supplemental Experiment Test Sections

Test Section	Surface	Base	Strength	Lane	Dowels
380259	10” PCC	Salve		12 ft	Yes; skewed joints
380260	11” PCC	DGAB		14 ft	Yes; skewed joints
380261	11” PCC	DGAB	550 psi	12 ft	No; skewed joints
380262	11” PCC	PATB		14 ft	No; with skewed joints of various lengths
380263	11” PCC	PATB		12 ft	No; with random skewed joints
380264	11” PCC	PATB		14 ft	No; with skewed joints

It can be seen that North Dakota conducted a varied supplemental section experiment, including investigating the variation between joints, dowels, lane width and base type while most PCC surfaces were kept consistent.

7.9.1 SECTION PERFORMANCE

In order to compare the performance of the state supplemental test section against the other experimental sections, the performance of all test sections was previously given in Table 36 and individualized plots of these performance metrics by year were given previously in Figure 33, Figure 34, and Figure 35.

It can be seen that most sections are performing acceptably, with some sections earning a performance rating of “poor” in any of the three performance metrics. The relatively poor performance of test section 380261 should be discussed relative to the structural performance of the other supplementary test sections. Test section 380261 was the only supplemental test section of the North Dakota SPS-2 experiment to achieve poor performance. Differentiating structural and material details between the supplemental test sections are given in Table 103 below.

Table 103. North Dakota SPS-2 Supplemental Section Details

Test Section	PCC Thickness, in	14 day Flexural Strength, psi	Base type	Joint orientation	Transverse joint spacing, ft	Load transfer device
380259	10		8" Salve	Skewed	15	Dowels
380260	11		Class 5 Agg	Skewed	15	Dowels
380261	11	550	Class 5 Agg	Skewed	Variable	None
380262	11	550	LCB	Skewed	Variable	None
380263	11	550	PASB	Skewed	Variable	None
380264	11		PASB	Skewed	15	None

The unique design features of test section 380261 include that it did not contain dowels, had variable transverse joint spacing, and was constructed on an unbound base. It was the only supplemental test section to be constructed under those conditions. Given the lack of information regarding distinct construction or material deviations, it is possible that the relatively poor performance of this section could be due to its structural parameters.

Most significantly, it can be seen that test sections 380261 and 380262 had the highest levels of wheel-path faulting. These supplemental test sections were undoweled, so this is an expected trend. However, supplemental test sections 380263 and 380264 were also undoweled, but these test sections were constructed on a PASB base layer and experienced much lower levels of wheel-path faulting.

7.9.2 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for each supplemental experiment section, as outlined previously, is given in Table 104 below.

Table 104. North Dakota SPS-2 Supplemental Sections Measured and Predicted Performance

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
380259	Faulting	0.0000	0.000852	0.0140	0.000159
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	108.10	2.3370	98.586	0.2680
380260	Faulting	0.0000	0.000069	0.0070	0.000881
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	105.138	1.9540	89.638	1.4970
380261	Faulting	0.0000	0.000263	0.0160	0.008167
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	82.158	2.2490	57.398	5.380
380262	Faulting	0.0000	0.000091	0.0200	0.005389
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	92.649	2.0490	86.837	2.5190

380263	Faulting	0.0000	0.000117	0.0000	0.002337
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	94.060	2.0510	87.320	0.9580
380264	Faulting	0.0000	0.000117	0.0100	0.001725
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	94.5830	1.9780	86.885	0.6010

It can be seen that no supplemental test sections exhibited any slab cracking, which was reflected in the prediction models. However, there is significant variation between the predicted and measured values for the failure metrics of wheel-path faulting and surface roughness. The only previously noted construction and materials related distress for these supplemental test sections is the presence of a superelevation on test sections 380260 and 380261, with some noted construction difficulty in the LCB and PATB base layers.

The predicted roughness most closely aligned with measured roughness for test sections 380260 and 380262. However, the predicted roughness aligned very poorly with the measured roughness behavior for test sections 380259, 380261, 380263, and 380264. Test sections 380261, 380262, 380263, and 380264 did not have dowels while only test section 380262 was constructed on LCB. Test sections 380261, 380262 and 380263 all had variable joint spacing, and AAHSTOWARE PavementME cannot appropriately model this. It is possible there is difficulty in AASHTOWARE PavementME in predicting the roughness behavior of undoweled sections with skewed joints.

The predicted faulting most closely aligned with the measured faulting for test sections 380259 and 380260 with larger variations in predictions for test sections 380261, 380262, 380263, and 380264. The most significant variation between these test sections was that test sections 380259 and 380260 contained dowels while the other test sections did not. Similar to the roughness model, it is possible the faulting model does not adequately predict the load transfer performance of undoweled pavement sections.

7.10 Ohio (39)

In 1994, 19 experimental sections for the SPS-2 experiment were constructed in Ohio, a wet-freeze climatic region. Of these 19 original test sections, seven state supplemental test sections were constructed.

The Ohio state supplemental experimental project included one test section, 390259, that utilized the standard paving concrete mix design and structure utilized by Ohio DOT. The other test sections were constructed with a consistent PCC surface thickness with varying base types, lane width, use of dowels, and skew of joints. A summary of the design factors used in the state supplemental sections is given in Table 105 below.

Table 105. Design Factors for Ohio SPS-2 State Supplemental Test Sections

Test Section	Surface	Base	Strength	Lane
390259	11″ PCC	6″ DGAB	550 psi	12 ft
390260	11″ PCC	4″ PATB / 4″ DGAB	550 psi	12 ft
390261	11″ PCC	4″ CTPB / 4″ DGAB	550 psi	14 ft
390262	11″ PCC	4″ CTPB / 4″ DGAB	550 psi	12 ft
390263	11″ PCC	6″ DGAB	550 psi	14 ft
390264	11″ PCC	6″ DGAB	550 psi	12 ft
390265	11″ PCC	4″ PATB / 4″ DGAB	550 psi	12 ft

It can be seen that the most test sections exhibited substantial cracking, while there was limited faulting and roughness. However, of the 19 constructed test sections, 10 exhibited substantial cracking.

7.10.1 SECTION PERFORMANCE

To compare the performance of the state supplemental test section against the other experimental sections, the performance of all test sections was given previously in Table 53. It can be seen that most sections were not performing well and many test sections received a "poor" rating in the percent slabs cracked performance metric. Individualized plots of these performance metrics by year are given in Figure 36, Figure 37, and Figure 38. These plots show that test section 390264 had a significantly higher measured level of roughness across the test sections. Supplemental test sections 390263 and 390259 exhibited higher levels of cracking than most other test sections. Interestingly, these three test sections were the only supplemental test sections constructed on unbound granular base layers. All other supplemental test sections were constructed on bound bases, included cement treated permeable bases and permeable asphalt treated bases.

7.10.2 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for each supplemental experiment section, as discussed previously, is given in *Table 106* below.

Table 106. Ohio SPS-2 Supplemental Sections Measured and Predicted Performance

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
390259	Faulting	0.0050	0.006497	0.00300	-0.000851
	Cracked slabs	-6.1660	3.0070	2.319	2.3750
	Roughness (IRI)	46.459	6.622	50.852	1.510

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
390260	Faulting	-0.0020	0.001963	-0.0010	0.000712
	Cracked slabs	0.0000	0.0000	-1.17	0.1920
	Roughness (IRI)	70.464	1.626	71.174	0.460
390261	Faulting	-0.002	0.00160	0.0000	0.000746
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	71.630	1.476	73.520	0.2080
390262	Faulting	-0.001	0.001013	-0.00100	0.000209
	Cracked slabs	0.0000	0.0000	0.00000	0.000
	Roughness (IRI)	78.95	1.143	75.597	0.4270
390263	Faulting	-0.003	0.004723	0.00200	-0.00001
	Cracked slabs	0.0000	0.0000	0.0000	0.0000
	Roughness (IRI)	73.901	3.111	78.551	0.5350
390264	Faulting	-0.0010	0.002540	0.00400	0.001163
	Cracked slabs	0.0000	0.0000	-1.4590	0.5280
	Roughness (IRI)	64.43	1.875	71.941	7.236
390265	Faulting	-0.0020	0.002139	0.00400	0.000055
	Cracked slabs	0.0000	0.0000	-2.3880	0.4390
	Roughness (IRI)	88.075	1.755	91.988	0.6030

It can be seen that the roughness for each test section was generally overestimated, with the exception of test section 390264. Cracking was severely overestimated for test section 390259 but was otherwise accurate across test sections with the exception of minor cracking in test sections 390260 and 390264, which were predicted to exhibit no cracking but did exhibit some slab cracking. Finally, faulting was overpredicted across all test sections. There were marked difficulties in the construction of the Ohio SPS-2 test sections which did lead to a significant number of test sections exhibiting early failure, as discussed previously in Section 6.12. Some of this early failure behavior could be attributed to the inconsistencies and structure of the selected concrete mixtures, which were also used for the supplemental experiment sections. This could be a contributing factor in the discrepancy between measured and predicted performance.

7.11 Washington (53)

In 1995, 13 experimental sections for the SPS-2 experiment were constructed in Washington, a dry-freeze climatic region. Of these 13 original test sections, one state supplemental test section was constructed. The state supplemental section contained 10” of PCC with 650 psi flexural strength on base layer consisting of 3 inches of ATB over 2 inches of CSBC. A summary of the design factors in this experiment is given in Table 107 below.

Table 107. Washington SPS-2 Supplemental Test Section Design Factors

Section	Surface	Base	Strength	Lane	Dowels
530259	10” PCC	3” ATB/2” Base CSBC	650 psi	14	Yes

On this project, there were significant noted difficulties in constructing the LCB layer and some issues with the subgrade consistency. There were also significant construction deviations of the low-strength mix; however, none of these construction or materials related issues affected the supplemental test section, which was not constructed with an LCB layer nor with the low strength PCC mixture.

7.11.1 SECTION PERFORMANCE

To compare the performance of the state supplemental test section against the other experimental sections, the performance of all test sections was given previously in Table 57. Individualized plots of these performance metrics by year are given in Figure 39, Figure 40, and Figure 41. It can be seen that most sections are performing well and generally, the test sections have very little faulting. There are a number of sections that have received a percent cracking rating corresponding to “poor” performance and approximately half of the test sections have measured smoothness ratings (IRI) that correspond to “fair” performance.

The supplemental test section exhibited no cracking, while other test sections, specifically those with an LCB layer, exhibited very high percentages of slabs cracking. The supplemental test section exhibited moderate faulting performance and moderate performance with respect to IRI as well, comparable to most other test sections on this project.

7.11.2 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for each supplemental experiment section, as outlined previously, is given in *Table 108* below.

Table 108. Washington SPS-2 Supplemental Sections Measured and Predicted Performance

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
530259	Faulting	0.00000	0.00520	0.00800	0.000174
	Cracked slabs	-0.00100	0.00000	0.0000	0.0000
	Roughness (IRI)	65.093	0.6150	64.943	0.9420

It can be seen there was some variation between the predicted and measured performance metrics. While cracking was predicted accurately, the roughness prediction was very close to the measured deterioration slope. However, the faulting performance metric prediction varied from the measured deterioration slope. The predicted faulting model indicated more severe faulting than measured.

7.12 Wisconsin (55)

In 1999, 20 experimental sections for the SPS-2 experiment were constructed in Wisconsin, a wet-freeze climatic region. Of these 20 original test sections, eight state supplemental test sections were constructed.

The Wisconsin supplemental experiment test sections contained one test section, 550259, that utilized the concrete mixture and standard structure of the typical concrete paving sections constructed by the Wisconsin DOT. Other design factors included in this experimental test section included varying PCC strength, PCC layer thickness, lane width, base type and thickness and dowel use and placement. The full summary of all design factors considered in the supplemental experiment is given in Table 109 below.

Table 109. Wisconsin SPS-2 Sections with Current Performance Trends

Test Section	Surface	Base	Strength	Lane	Dowels
550259	11″ PCC	6″ DGAB	550 psi	14 ft	
550260	11″ PCC	6″ DGAB	550 psi	14 ft	Alternate dowel bar placement
550261	8″ PCC	4″ CSOGB / 4″ DGAB	550 psi	12 ft	
550262	8″ PCC	6″ DGAB	900 psi	12 ft	Tied concrete shoulder
550263	10″ PCC	6″ DGAB	550 psi	14 ft	
550264	11″ PCC	6″ DGAB	550 psi	14 ft	Composite dowels
550265	11″ PCC	4″ CSOGB / 6″ DGAB	550 psi	14 ft	Stainless steel dowels
550266				14 ft	

Very few construction related deviations were noted in the construction report. The most significant deviation occurred when construction began and remnants of old PCC pavement were found in the subgrade when sampling with Shelby tubes. This required these unexpected older PCC pavement slabs be completely removed and the subgrade was then brought to the correct required elevation prior to the planned construction of the SPS-2 test sections.

Similar to construction related deviations, very few materials-related deviations were noted in the construction report for the Wisconsin SPS-2 test sections. Results from modulus of rupture testing conducted on specimens from the test sections were given previously in Table 59.

7.12.1. Section performance

To compare the performance of the state supplemental test sections against the other experimental sections, the performance of all test sections was previously given in Table 57 and individualized plots of these performance metrics by year were given previously in Figure 42, Figure 43, and Figure 44.

It can be seen that currently, most sections are performing well across the three primary distress metrics of roughness, slab cracking and faulting. It can also be seen that only test section 550265 exhibited lower metrics for cracking and faulting while many sections exhibited fair roughness readings (measured as IRI). State supplemental sections 550261, 550262, and 550263 performed well across all performance metrics. However, only test section 550265, also a state supplemental section, exhibited poor performance across all metrics.

The primary difference between test section 550265 and the other supplemental sections was the use of the open graded base course in addition to the dense graded aggregate base. Only test section 550265 utilized the open graded base course. It can be seen that test section 550261 utilized a cement stabilized open graded base course. Despite being the planned layer structure for this section, it does not appear the open graded base course was included on this section. In fact, the constructed section consists of 6” DGAB only. Unlike surrounding sections, which were built on top of 24 inches of embankment fill, test section 550265 was constructed on 10 inches of existing subbase. Due to the section geometry, test sections 550214, 550222, 550223, 550262, 550218, 550219, and 550215 were also constructed on existing subbase, rather than embankment.

It seems likely that if this section were under designed, without the intended additional four inches of open graded base course, this could contribute to the disproportionate cracking, especially in a wet-freeze zone, where additional drainage under base layers is beneficial.

7.12.1 COMPARING MEASURED AND PREDICTED PERFORMANCE

The measured and predicted slope and intercept for each least squares linear regression line for each supplemental experiment section, as discussed previously, is given in *Table 110* below.

Table 110. Wisconsin SPS-2 Supplemental Sections Measured and Predicted Performance

SHRP ID	Distress Type	Predicted		Measured	
		Intercept	Slope	Intercept	Slope
550259	Faulting	-0.00100	0.001273	0.00200	0.000176
	Cracked slabs	-0.0250	0.00800	0.0000	0.0000
	Roughness (IRI)	79.752	1.8070	87.5120	0.1240
550260	Faulting	-0.00100	0.001567	0.00300	0.000277
	Cracked slabs	-0.10800	0.03300	0.0000	0.0000
	Roughness (IRI)	66.192	1.971	83.5990	0.6910
550261	Faulting	0.00000	0.000560	0.00100	0.000178
	Cracked slabs	0.00000	0.00000	0.0000	0.0000
	Roughness (IRI)	55.736	1.569	54.3490	1.1910

550262	Faulting	0.00000	0.000353	-0.0010	0.00001
	Cracked slabs	0.00000	0.00000	0.0000	0.0000
	Roughness (IRI)	75.629	1.378	80.1880	-0.4550
550263	Faulting	-0.00400	0.002272	-0.0010	0.00023
	Cracked slabs	-0.01500	0.00400	0.0000	0.0000
	Roughness (IRI)	54.995	2.242	58.0010	0.70500
550264	Faulting	-0.00100	0.001715	-0.0020	0.00140
	Cracked slabs	-0.12300	0.03700	0.0000	0.0000
	Roughness (IRI)	77.593	2.047	84.3610	-0.2380
550265	Faulting	-0.00100	0.002488	0.0050	0.00071
	Cracked slabs	-0.03400	0.01000	-0.8020	0.1330
	Roughness (IRI)	82.400	2.330	89.1770	-0.1630
550266	Faulting	-0.00100	0.000999	0.0040	0.000105
	Cracked slabs	-0.00300	0.00100	0.0000	0.0000
	Roughness (IRI)	69.371	1.7440	78.9740	0.4940

Several observations can be drawn from the information presented in Table 110. First, it can be seen that the rate of deterioration with respect to cracking was overpredicted for test sections 550259, 550260, 550263 and 550264 while the rate of cracking was underpredicted for test sections 550265. Faulting was overpredicted for all test sections except 550264 and roughness was severely overpredicted for all test sections except for test section 550261.

It should be noted that AASHTOWARE PavementME does not consider different dowel materials or alternate dowel bar placements, which would have affected the accuracy of the predictions for test sections 550260, 550264, and 550265. This inability for AASHTOWARE PavementME to predict this behavior is likely due to these variations in the dowel placement and material.

7.13 Task 4 Summary

The purpose of Task 4 was to provide insight into the SPS-2 supplemental test sections, designed and constructed outside of the core SPS-2 experiment. This component of the SPS-2 experiment was optional and generally consisted of a state constructing a single test section using their own state standard concrete paving mixture and structure, or conducting a full separate experiment comprised of multiple supplemental test sections. Altogether, twelve states elected to construct supplemental test sections, with six states constructing only a single test section of their own concrete paving mixture and structure and six states electing to construct more than one supplemental test section to investigate more design variables.

After analyzing each project’s construction report, deviation report, possible traffic or climatic deviations, and available strength and other testing data, trends of the behavior of the supplemental test sections could be observed. Additionally, a comparison of the expected performance, as predicted by AASTHOWARE PavementME against the measured performance, revealed some discrepancies in performance and predictive behavior.

While drawing broad conclusions regarding supplemental test sections was largely not feasible, there were two interesting trends observed between these supplemental experiments:

- ***Performance of the -0259 test sections***. As noted previously, the state supplemental test sections numbered -0259 were constructed using the state's standard paving mix and structure. It was observed in many cases that these state supplemental test sections exhibited strong performance relative to other test sections. Additionally, it was observed that the progression of these distresses was sometimes overestimated by AASHTOWARE PavementME, despite having relatively simple and straightforward pavement structures that should be easily and accurately measured by the software. However, some of the explanation of this increased performance of these test sections could be due to the familiarity of the contractor and agency with the concrete mixture and structure constructed. In many agencies, difficulties were experienced with working with the very low or very high strength mixtures, but very few construction-related deviations were reported for these supplemental test sections. This could possibly be due to the decreased variation seen in these mixtures and structure, as well as familiarity on the part of the contractors in working with standard agency mixes and structural sections.
- ***Limitations of AASHTOWARE PavementME modeling***. The core test sections of the SPS-2 experiment were utilized in the calibration of the AASHTOWARE PavementME software. The supplemental test sections frequently contained components that were outside of the inference space of the AASHTOWARE PavementME, including dowel bars of different materials and utilizing different spacing, skewing joints, or using varied joint spacing, or certain base layers and soil stabilization methods. The differences shown between the predicted and measured behavior of these test sections could be attributed to the limitations of modeling in the AASHTOWARE PavementME software.

8.0 CONCLUSION

Task 1 revealed some significant state-by-state deviations that likely contributed to the final performance of certain test sections. Most significantly, states with some consistent project-wide inconsistencies were addressed. These included Arkansas, Michigan, Ohio, and Nevada. Arkansas test sections had inconsistent subgrade moisture and constructed sites were likely built on a spring, and these test sections experienced almost double the expected traffic loading, all of which could have contributed to the performance of this section. Michigan, Ohio, and Nevada had consistent issues with the PCC mix designs across the state. While this was specifically discussed later in materials related issues, these were consistent enough across the state to indicate a potential issue with the mixture itself that affected the project, rather than smaller-scale materials issues that may have affected the test sites individually. Some significant observations following the completion of Task 1 include:

- ***Lean concrete base (LCB) layer deviations***. Many agencies explicitly noted difficulties in constructing this layer which frequently led to surface cracking observed on the LCB surface itself. In many cases, this was not repaired and many of the test sections with an LCB layer exhibited early failure
- ***PCC mix design variations***. Several agencies which exhibited consistent early failure across multiple test sections (including Michigan, Nevada, and Ohio) all had either a very low cementitious materials content per CY for the low strength mix designs (below 400 lbs/CY) or a very high cementitious materials content per CY for high strength mixtures (above 700 lbs/CY). Both of these extreme mix design values can contribute to the early failure of PCC pavements. A very low cementitious content lacks sufficient hydration sites for a substantially durable and dense concrete matrix and a very high cementitious content can exhibit increased early age drying shrinkage cracking.
- ***Subgrade moisture variations.*** Several agencies reported deviations in subgrade moisture content or density, both of which can adversely affect the performance of concrete pavements. Thinner PCC test sections are more susceptible to damage due to variations across the subgrade layer.

Task 2 revealed trends across some of the most consistent materials and construction related issues uncovered in Task 1 between test sections across states. Specifically, materials and construction issues relating specifically to the subgrade, the PCC layer (strength), the PCC layer (other materials issues), the PATB layer and the LCB layer were primarily discussed. Smaller deviations among traffic and climate were also included in that section. *Table 111* below provides the summary of the performance of test sections with and without noted construction failures. This data is also synthesized with information from Task 3, which sought to establish relationships between early failures, defined as any test section receiving "poor" performance within the first ten years of construction, and any of the previously discussed construction or materials deviations. These are also incorporated into *Table 111*.

Table 111. Summary of Construction and Material Issues and Poor Performance Ratings

	Total number of applicable test sections	Number (percent) of test sections exhibiting early failure	Number (percentage of applicable test sections) with a "poor" rating across any performance metric			
			Overall	Due to roughness	Due to cracking	Due to wheel-path faulting
Applicable test sections to subgrade construction issues	51	22 (43%)	29 (57%)	10 (20%)	25 (50%)	1 (2%)
Applicable test sections **with a poor rating** with noted subgrade related construction issues		17 (77%)	20 (69%)	8 (80%)	17 (68%)	0 (0%)
Applicable test sections with an LCB layer	56	25 (45%)	37 (66%)	12 (21%)	31 (55%)	2 (4%)
Applicable test sections **with a poor rating** with noted LCB related construction issues		19 (76%)	27 (73%)	8 (67%)	23 (74%)	1 (50%)
Applicable test sections with a PATB layer	56	6 (11%)	10 (18%)	1 (2%)	10 (18%)	0 (0%)
Applicable test sections **with a poor rating** with noted PATB related construction issues		1 (17%)	3 (30%)	0 (0%)	3 (30%)	0 (0%)
Applicable test sections to PCC-related construction issues	208	52 (25%)	79 (38%)	28 (13%)	62 (29%)	11 (5%)

	Total number of applicable test sections	Number (percent) of test sections exhibiting early failure	Number (percentage of applicable test sections) with a "poor" rating across any performance metric			
			Overall	Due to roughness	Due to cracking	Due to wheel-path faulting
Applicable test sections **with a poor rating** with noted PCC-related construction issue		20 (38%)	31 (39%)	15 (28%)	55 (88%)	0 (0%)
Applicable test sections to PCC-related strength issues	103	26 (25%)	42 (57%)	16 (20%)	35 (50%)	8 (2%)
Average difference between target and measured modulus of rupture for test sections **with a poor rating**		-31 psi	-21 psi	-30 psi	-34 psi	-41 psi

It can be seen from the table that issues with the LCB layer had a very clear trend between test sections with an LCB layer and noted construction difficulties and LCB test sections with poor performance. This indicates there was a significant likelihood that observed early failures in the test sections with an LCB layer could be due to noted construction and material difficulties of the material as outlined in Tasks 2 and 3.

Conversely, there was not a significant correlation between the performance of the test sections with a PATB layer which were performing poorly that had initial construction issues, indicating that the test sections failing early or performing poorly with a PATB layer were likely due to issues outside of the construction or material deviations.

Significant trends observed following the completion of Task 2 include:

- ***Lean concrete base (LCB) layer deviations***. Construction deviations of the LCB layer were significant with 76% of LCB test sections experiencing early failure having noted issues with the construction of the LCB layer. Frequently, this resulted in premature cracking of the LCB surface often resulting in cracking of the PCC surface.
- ***Permeable Asphalt Treated Base (PATB) layer deviations***. Unlike the test sections containing an LCB layer, while there were noted cases of difficulties constructing the PATB layer across test sections, there was not a significant relationship between PATB issues and resulting performance.
- ***Subgrade material variations***. Several agencies reported subgrade material variations, including incorrect or highly varying moisture contents or unstable subgrades which exceeded the allowable deflections of the experiment. Test sections with subgrade material variations also tended to exhibit poor performance and many test sections exhibiting early failure had documented variations of the subgrade material.
- ***PCC layer variations***. While there was variation of the PCC material layer itself and deviations across construction practices of the PCC layer, there was not a significant relationship between test section performance and deviations of the PCC material itself.

Task 3 synthesized content established from Tasks 1 and 2 to better identify the correlation between test sections that exhibited early failure, defined as test sections with a performance rating across any of the three primary performance metrics (roughness, cracking or wheel-path faulting) and potential construction or materials related deviations. Some of this information is included in *Table 111*, above, where it can be seen that issues with the LCB layer most greatly affected the prevalence of early failures of the consistent materials and construction related deviations identified previously in Task 2.

Key conclusions from Task 3 include finding were several consistent deviations observed across some test sections exhibiting early failure:

- ***Lean concrete base (LCB) layer deviations***. Many agencies explicitly noted difficulties in constructing this layer which frequently led to surface cracking observed on the LCB surface itself. In many cases, this was not repaired and many of the test sections with an LCB layer exhibited early failure

- ***PCC mix design variations***. Several agencies which exhibited consistent early failure across multiple test sections (including Michigan, Nevada, and Ohio) all had either a very low cementitious materials content per CY for the low strength mix designs (below 400 lbs/CY) or a very high cementitious materials content per CY for high strength mixtures (above 700 lbs/CY). Both of these extreme mix design values can contribute to the early failure of PCC pavements. A very low cementitious content lacks sufficient hydration sites for a substantially durable and dense concrete matrix and a very high cementitious content can exhibit increased early age drying shrinkage cracking.
- ***Subgrade moisture variations.*** Several agencies reported deviations in subgrade moisture content or density, both of which can adversely affect the performance of concrete pavements. Thinner PCC test sections are more susceptible to damage due to variations across the subgrade layer.

Finally, Task 4 sought to analyze the supplemental test sections more deeply, whose experimental design varied widely across different state agencies. Performance of these test sections was correlated with previously introduced data regarding potentially complicating initial construction or material deviations. Many test sections had only a state supplemental test section, which sometimes performed generally better than the SPS-2 core data sections. This could be explained by easier constructability and general familiarity with the concrete mixtures and pavement structures. Finally, the performance of these test sections was compared to the predicted performance of these test sections as calculated through the AASHTOWARE PavementME software.

However, there were several interesting trends observed between these supplemental experiments:

- ***Performance of the -0259 test sections***. As noted previously, the state supplemental test sections numbered -0259 were constructed using the state's standard paving mix and structure. It was observed in many cases that these state supplemental test sections exhibited strong performance relative to other test sections. Additionally, it was observed that the progression of these distresses was sometimes overestimated by AASHTOWARE PavementME, despite having relatively simple and straightforward pavement structures that should be easily and accurately measured by the software. However, some of the explanation of this increased performance of these test sections could be due to the familiarity of the contractor and agency with the concrete mixture and structure constructed. In many agencies, difficulties were experienced with working with the very low or very high strength mixtures, but very few construction-related deviations were reported for these supplemental test sections. This could possibly be due to the decreased variation seen in these mixtures and structure, as well as familiarity on the part of the contractors in working with standard agency mixes and structural sections.
- ***Limitations of AASHTOWARE PavementME modeling***. The core test sections of the SPS-2 experiment were utilized in the calibration of the AASHTOWARE PavementME software. The supplemental test sections frequently contained components that were

outside of the inference space of the AASHTOWARE PavementME, including dowel bars of different materials and utilizing different spacing, skewing joints, or using varied joint spacing, or certain base layers and soil stabilization methods. The differences shown between the predicted and measured behavior of these test sections could be attributed to the limitations of modeling in the AASHTOWARE PavementME software.

The findings from this report should be used to assist future researchers in most completely analyzing failure and performance data from the SPS-2 experiments. While significant information can be found based on trends in the performance and project information, there are significant outliers presented in this report which should be carefully considered before drawing conclusions and analyzing the complete SPS-2 dataset. This report specifically outlined issues found in construction and deviation reports and other supplementary early information to establish potential correlations between early failure or poor performance with noted construction or materials deviations. Test sections with significant deviations that ultimately affected the performance data should be analyzed cautiously and potentially removed from some analyses. Finally, it should be noted that there is an inherent limitation to this entire analysis, such that there was significant variability in the details included in the construction and deviation reports for each state. While noted issues are discussed with relation to performance, there is a possibility that there were unaccounted for construction or materials deviations.

Finally, in addition to these consistencies and possible poor performance, it should be noted that there were still a significant number of test sections exhibiting poor performance without a direct cause as identified from initial construction or material deviations.

9.0 REFERENCES

Federal Highway Administration (FHWA). 2016. *Bases and Subbases for Concrete Pavements*. Federal Highway Administration TechBrief FHWA-HIF-16-005. Washington, DC.

Gardner, Mark. 1997. *SPS-2 Project 0502: Strategic Study of Structural Factors for Rigid Pavements I-30 Westbound Hot Springs County, Arkansas.* Prepared by Brent Rauhut Engineering Inc. for Federal Highway Administration. Washington, DC.

Johnson, Ann. 1993. *SPS-2 Construction Report I-70 Near Abilene, Kansas Sections 200201 to 200212.* Prepared by Braun Intertec Corporation for Federal Highway Administration. Washington, DC.

Keller, Cary and Gemayel, Chuck. 1995. *Construction Report on SPS-2 US 23 Northbound, Monroe County, Michigan.* Prepared by Braun Intertec Corporation for Federal Highway Administration. Washington, DC.

Nichols Consulting Engineers. 1998. *SPS-2 Construction Report SHRP 080200.* Prepared by Nichols Consulting Engineers. for Federal Highway Administration. Washington, DC.

Nichols Consulting Engineers. 1997. *Construction Report on Site 530200 Strategic Study of Structural Factors for Rigid Pavements SR 395 – Adams County, Washington.* Prepared by Nichols Consulting Engineers for Federal Highway Administration. Washington, DC.

Mehnert, Brenda. 1999. *SPS-2 Construction Report STH 29, Westbound Marathon Count, Wisconsin 3.5 Miles east of Hatley, Wisconsin.* Prepared by Nichols Consulting Engineers for Federal Highway Administration. Report No. DTFH61-96-C-00013. Washington, DC.

Pozsgay, Mike. 1998. *SPS-2 Construction Report U.S. Highway 23, Northbound Delaware County, Ohio 30 Miles North of Columbus, Ohio.* Prepared by ERES Consultants, Inc. for Federal Highway Administration. Report No. DTFH61-96-C-00013. Washington, DC.

Rutka, Alex. 1996. *Construction Report on SHRP 100200, SPS-2 Project Ellendale, Delaware.* Prepared by ITX Stanley Ltd for Federal Highway Administration. Report No. FHWA-TS-96-10-04. Washington, DC.

Rutka, Alex. 1994. *Construction Report on SPS-2, Project 3702000. US Route 52 SB, Lexington By-Pass, North Carolina.* Prepared by Pavement Management Systems Ltd for Federal Highway Administration. Report No. FHWA-RD-94-3701. Washington, DC.

Senn, Kevin. 1998. *Construction Report Strategic Highway Research Program SPS-2 Experimental Projects Interstate Highway No. I-80 Humboldt and Lander Counties, Nevada.* Prepared by ERES Consultants, Inc. for Federal Highway Administration. Washington, DC.

Senn, Kevin. 2001. *California SPS-2 Strategic Study of Structural Factors for Rigid Pavements.* Prepared by Nichols Consulting Engineers. for Federal Highway Administration. Washington, DC.

Szrot, Robert. 1994. *Specific Pavement Studies Construction Report for Experiment SPS-2 Strategic Study of Structural Factors for Rigid Pavement Ehrenberg-Phoenix Highway, Maricopa County, Arizona.* Prepared by Nichols Consulting Engineers for Federal Highway Administration. Washington, DC.

Urbach, Ronald and Worel, Benjamin. 1996. *SPS-2 Construction Report US-65 Northbound Polk County Northeast of Des Moines, Iowa Sections 190213 to 190224.* Prepared by Braun Intertec Corporation for Federal Highway Administration. Report No. DBNX-92-700. Washington, DC.

Urbach, Ronald and Worel, Benjamin. 1996. *SPS-2 Construction Report I-94 Eastbound West of Fargo, North Dakota, Sections 380213-380224.* Prepared by Braun Intertec Corporation for Federal Highway Administration. Report No. DBNX-92-700. Washington, DC.

Visintine, B., Rada, G.R., Simpson, A.L. 2018. *Guidelines for Informing Decisionmaking to Affect Pavement Performance Measures: Final Report*. Federal Highway Administration Report No. FHWA-HRT-17-090. Washington, DC.