DEPARTMENT OF TRANSPORTATION

# Impact of Low Asphalt Binder for Coarse HMA Mixes


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Research Project
Final Report 2017-27

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Asphalt mixtures are commonly specified using volumetric controls in combination with aggregate gradation limits, like most transportation agencies, MnDOT also uses this approach. Since 2010 onward, several asphalt paving projects for MnDOT have been constructed using coarser asphalt mixtures that are manufactured with lower total asphalt binder contents. Due to the severe cold climate conditions in Minnesota, there are concerns of premature cracking and inferior durability in asphalt mixtures with lower asphalt binder contents. This research project evaluated 13 low asphalt binder content mixes from 10 actual field projects to determine whether there is potential for poor cracking performance and high permeability. Assessment of field performance indicated an average of 7.75 years of life until 100% transverse cracking level is reached. The pavement structure played a significant factor in controlling the cracking rates. Thin overlays showed almost ten times inferior transverse cracking performance as compared to asphalt wearing courses on full-depth reclamation. Asphalt mixture volumetric factors did not show a statistically significant effect on cracking rates; however, the asphalt binder grade did show a strong effect. Eight out of the 13 coarse asphalt mixtures evaluated in this study have higher permeability than the typical dense graded asphalt mixtures. Performance evaluations using lab measured properties predicted poor thermal cracking performances. No discernable trends were observed between measured or predicted cracking performance and mix volumetric measures. Use of performance tests based on specifications for design and acceptance purposes is reinforced through this study.

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# Impact of Low Asphalt Binder for Coarse HMA Mixes

## FINAL REPORT

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# EXECUTIVE SUMMARY

Asphalt mixtures are commonly specified using volumetric controls in combination with aggregate gradation limits. Asphalt mixture specifications for the Minnesota Department of Transportation (Section 2360) follow a similar process with volumetric controls in the form of adjusted Asphalt Film Thickness (AFT). Since 2010 onward, several asphalt paving projects for MnDOT have been constructed using mixtures that are substantially coarser in gradation and manufactured with lower total asphalt binder contents (typically at or under 4.50% by weight of mix). These mixtures meet the current volumetric and aggregate gradation specification limits. Due to the severe cold climate conditions in Minnesota there is high propensity for premature cracking and durability concerns in asphalt mixtures with lower asphalt binder contents. This case-study oriented research project was designed to determine whether there is potential for poor cracking performance and high permeability for low asphalt content coarser mixtures. The increased permeability of the mix goes against the traditional pavement design assumption that dense graded surface layers drain water over the surface and away from the underlying granular layers. Thus, pavements with permeable asphalt mix will be more susceptible to moisture damage as well as other distresses due to the reduction of unbound layer modulus values.

This research study evaluated 13 low asphalt binder content mixes from 10 actual field projects. The majority of sections were constructed between 2010 and 2013.  For comparison purposes, two sections from 2005 construction were also included. Field performance was assessed through the use of pavement management data and site visits. Overall, the sections indicated an average of 7.75 years of life until 100% transverse cracking was observed. The pavement structure played a significant factor in controlling the cracking rates.  Thin overlays on milled pavements showed almost ten times inferior transverse cracking performance compared to sections constructed as overlays with full-depth reclamation. From a mixture perspective, the volumetric factors did not show a statistically significant effect on cracking rates; however, the asphalt binder grade did show a strong effect. Mixtures manufactured with -34 performance graded low-temperature binders showed substantially better cracking performance compared to mixtures made using -28 low-temperature graded binders.

The field samples were obtained from all sections through coring. Cored specimens were evaluated to determine in-place asphalt volumetric measures, aggregate gradation, permeability, and mechanical performance properties in the form of dynamic modulus and disk-shaped compact tension fracture energy. Eight out of the 13 coarse asphalt mixtures evaluated in this study have higher permeability than the typical dense graded asphalt mixtures. Performance evaluations using lab measured properties predicted very inferior thermal cracking performances. Remaining service lives to reach 100% cracking were predicted to be between less than 1 year to 5 years. No discernable trends were seen between measured or predicted cracking performance and mix volumetric measures. Use of performance tests based on specifications for design and acceptance purposes is reinforced through this study. Lower asphalt content coarse asphalt mixtures studied herein were found to be inferior in terms of thermal

cracking performance and a majority of them were also found to have higher permeability as opposed to typical asphalt mixtures.

# CHAPTER 1: INTRODUCTION

## 1.1 BACKGROUND

Historically asphalt mixes in Minnesota have been produced to be fine graded in nature. In recent years there have been a large number of relatively coarse graded mixes being produced and used in highway construction. These coarse graded mixes typically have lower total-asphalt binder content as compared to the fine graded ones. The performance of the coarser low-asphalt content mixes was unknown. Some preliminary testing had shown that these mixes might be prone to premature cracking. Furthermore, the use of coarser mixes with lower-asphalt content increases the permeability of the mix, making them more prone to moisture-induced damage. The increased permeability of mix is counter to pavement design assumption that a dense graded surface layer drains water over the surface away from underlying granular layers. Thus, pavements with permeable asphalt mix will be more susceptible to moisture damage as well as other distresses due to the reduction of unbound layer modulus values.

This case-study oriented research project focused on quantifying the performance effects and pavement service life of lower-asphalt binder coarse mixes. It is very important to evaluate the asphalt mixes that are locally produced and placed in Minnesota and produced according to MnDOT 2360 specifications. The main objective of the study was to quantitatively and qualitatively determine whether the low-asphalt binder coarse mixes are prone to performance issues and make recommendations regarding potential solutions to alleviate any identified problems. This project evaluated 13 low-asphalt binder content mixes from 10 actual field projects. The field samples were evaluated using a battery of tests to determine the pavement performance using parameters, such as fracture energy, dynamic modulus and permeability. The lab results were analyzed to predict the distress severity and life expectancies of the pavements. Analyses were also conducted to identify and quantify the effects of total asphalt binder content on pavement performance.

## 1.2 ORGANIZATION OF THE REPORT

This research study was organized into six tasks:

- Task-1: Mix Design Record Data Collection and Selection of Field Sections for Evaluation (Chapter 2);
- Task-2: Sampling Plans (Task-2);
- Task-3A: Laboratory Testing Part-1 (Task-3A);
- Task-3B: Laboratory Testing Part-1 (Task-3A);
- Task-4A: Data Analysis (Chapter 6);
- Task-4B: Pavement Performance (Chapter 7).

This final report is organized in a manner similar to that of the project. Chapters 2 through 7 present activities and findings of each of the study tasks. The final chapter (Chapter 8) provides overall summary, conclusions, and recommendations.

# CHAPTER 2: MIX DESIGN RECORD DATA COLLECTION AND SELECTION OF FIELD SECTIONS FOR EVALUATION (TASK-1)

## 2.1 INTRODUCTION

### 2.1.1 Overview of Task-1

Task 1 presents the selection of field sections that were studied for determination of the impact of lower asphalt content coarse hot-mix asphalt mixes under research contract number 99008 work order number 100. The selection of the field sections was made in two steps. The researchers as well as staff at MnDOT Office of Materials and Road Research (OM&RR) evaluated the mix design records (MDR) from past several years and identified potential candidate mixes. Next a meeting was held between the researchers and the technical advisory panel (TAP) for the project. The aforementioned lists were discussed during this meeting and a final list of nine (9) field sections was selected. The details of section sis presented in the subsequent section.

## 2.2 FIELD SECTIONS

The field sections that were studied through this research project are listed in Table 2.1: Field Sections. In several instances each field section has more than one pavement profile, for example, part of the section is construction as overlay on milled pavement and other part is over reclaimed base. The mix designs for each of the mixes/sections studied herein were extracted from the MDR database that is available to the researchers through another study (Contract 99008, work order 40). Mix designs for each site are presented in

Table 2.2: Mix Designs.

**Table 2.1: Field Sections**

| | Highway | SP Number | MDR | Date Visited |
|---|---|---|---|---|
| **PRIMARY SITES** | MN Trunk Highway 6 (TH 6) | 1103-25 | 3A-2010-128 | --- |
| | MN Trunk Highway 9 (TH 9) | 6010-26 | 02-2011-063 | 01/02/2014 |
| | Itasca County Rd 10 | 031-610-016 | 01-2012-128 | --- |
| | MN Trunk Highway 10 (TH 10) | 5606-42 | 04-2013-033 | --- |
| | MN Trunk Highway 11 (TH 11) | 3604-72 | 02-2012-055 | --- |
| | MN Trunk Highway 25 (TH 25) | 7104-19 | 3A-2011-109 | 01/08/2014 |
| | MN Trunk Highway 28 (TH 28) | 6104-11 | 04-2012-026 | --- |
| | MN Trunk Highway 210 (TH 210) | 1805-72 | 3A-2010-073 | 01/08/2014 |
| | MN Trunk Highway 220 (TH 220) | 6016-37 | 02-2012-045 | --- |
| **ALTERNATIVE SITES** | MN Trunk Highway 27 (TH 27) | 4803-19 | 3A-2010-045 | --- |
| | MN Trunk Highway 95 (TH 95) / County Road 30 | 1306-44 | 0-2012-170 | --- |
| | MN Trunk Highway 361 (TH 361) | 13-601-10 | 0-2012-093 | --- |

Between mid-December 2013 and early-January 2014 the researchers (Eshan Dave, Ben Helmer and Jay Dailey) and Mr. Luke Johanneck from MnDOT OM&RR visited three field sites (The visit dates are indicated in Table 2.1: Field Sections). During the field visits 1000 ft. long field sections were identified. Crack counts and distress surveys were conducted for these sites. The coring locations were also identified and GPS coordinates were obtained for the coring locations.

The construction plans for the field projects were made available by the MnDOT OM&RR. The construction plans are attached with this report as Appendix A.

**Table 2.2: Mix Designs**

| | Highway | Mix Design | PG | Asphalt Content (%) | Percent Passing | | RAP (%) |
|---|---|---|---|---|---|---|---|
| | | | | | #4 | #8 | |
| PRIMARY SITES | MN Trunk Highway 6 (TH 6) | SPWEB340B | 58-28 | 4.4 | 53 | 45 | 30 |
| | MN Trunk Highway 9 (TH 9) | SPWEB340C | 58-34 | 3.9 | 52 | 44 | --- |
| | Itasca County Rd 10 | SPWEB240B | 58-28 | 4.3 | 50 | 42 | 20 |
| | MN Trunk Highway 10 (TH 10) | SPWEB440B | --- | 4.3 | 59 | 44 | 22 |
| | MN Trunk Highway 11 (TH 11) | SPWEB340C | 58-34 | 4.1 | 46 | 39 | 20 |
| | MN Trunk Highway 25 (TH 25) | SPWEB440F | 64-34 | 4.6 | 46 | 33 | 12 |
| | MN Trunk Highway 28 (TH 28) | SPWEB340C | --- | 4.2 | 52 | 41 | 20 |
| | MN Trunk Highway 210 (TH 210) | SPWEB440B | 58-28 | 4.4 | 54 | 40 | 30 |
| | MN Trunk Highway 220 (TH 220) | SPWEB340B | 58-28 | 4.2 | 50 | 36 | 20 |
| ALTERNATIVE SITES | MN Trunk Highway 27 (TH 27) | SPWEB340B | 58-28 | 4.3 | 48 | 38 | 30 |
| | MN Trunk Highway 95 (TH 95) / County Road 30 | SPWEB440E | --- | 4.4 | 44 | 32 | 17 |
| | MN Trunk Highway 361 (TH 361) | SPWEB440 | 58-34 | 4.4 | 44 | 32 | 20 |

# CHAPTER 3: SAMPLING PLANS (TASK-2)

## 3.1 INTRODUCTION

### 3.1.1 Overview of Task 2

Task 2 presents the sampling plans for obtaining field cores for volumetric and performance testing to determine the impacts of lower-asphalt content, coarse hot-mix asphalt mixes under research contract number 99008 work order number 100. The selection of the field sections was completed as Task-1 of this project and is described in Chapter 2.

## 3.2 FIELD SECTIONS

The field sections that are being studied through this research project are listed in Table 3.1: Field Sections. In several instances each field section has more than one pavement profile, for example, part of the section is construction as overlay on milled pavement and other part is over reclaimed base. In such instances or in cases where the project yielded significantly different performance over its length, two pavement sections were selected. All of these sites have been visited and on basis of the site visits, 1000 ft. long pavement sections were identified. Field sampling plans have been developed for each of those sections. In addition to development of field sampling plans, the visual distress surveys and crack counts were also performed.

**Table 3.1: Field Sections**

| Highway | SP Number | MDR | Date Visited |
|---|---|---|---|
| MN Trunk Highway 6 (TH 6) | 1103-25 | 3A-2010-128 | 07/30/2014 |
| MN Trunk Highway 9 (TH 9) | 6010-26 | 02-2011-063 | 01/02/2014 |
| Itasca County Rd 10 | 031-610-016 | 01-2012-128 | 07/30/2014 |
| MN Trunk Highway 10 (TH 10) | 5606-42 | 04-2013-033 | 07/29/2014 |
| MN Trunk Highway 25 (TH 25) | 7104-19 | 3A-2011-109 | 01/08/2014 |

| | | | |
|---|---|---|---|
| MN Trunk Highway 28 (TH 28) | 6104-11 | 04-2012-026 | 04/10/2014 |
| MN Trunk Highway 210 (TH 210) | 1805-72 | 3A-2010-073 | 01/08/2014 |
| MN Trunk Highway 220 (TH 220) | 6016-37 | 02-2012-045 | 07/29/2014 |
| MN Trunk Highway 27 (TH 27) | 4803-19 | 3A-2010-045 | 04/10/2014 |
| MN Trunk Highway 95 (TH 95) / County Road 30 | 1306-44 | 0-2012-170 | 07/28/2014 |

# CHAPTER 4: LABORATORY TESTING PART-1 (TASK-3A)

## 4.1 INTRODUCTION

### 4.1.1 Overview of Task-3A

Task-3A of the "Impact of Lower Asphalt Binder for Coarse Hot Mix Asphalt Mixtures" project involved a series of laboratory tests that were conducted on the field procured samples. This report presents the laboratory testing results which will provide the information required to evaluate the impacts of lower-asphalt content coarse hot-mix asphalt mixes under research contract number 99008 work order number 100. Please note that the laboratory testing effort has been divided into two parts (Chapters 4 and 5), this deliverable is for the first of two and discusses laboratory test results from: mix volumetric, lab permeability, disk-shaped compact tension and asphalt content and gradation testing. The pavement cracking performance as well as comparisons between laboratory measured parameters discussed herein with the field cracking performance are presented in Chapter 6.

The selection of the field sections and collection of mix design records (MDR) was completed as Task-1 of this project. The field sampling plans and sample procurement were conducted as Task-2 of this project. Both of these tasks are further described in the corresponding Chapter 2 and Chapter 3.

## 4.2 FIELD SECTIONS

The field sections that are being studied through this research project are listed in Table 4.1: Field Section Highway and Project Information. In several instances each field section has more than one pavement profile, for example, part of the section is construction as overlay on milled pavement and other part is over reclaimed base. In such instances or in cases where the project yielded significantly different performance over its length, two pavement sections were selected. All of these sites have been visited and on basis of the site visits, 1000 ft. long pavement sections were identified. Typically, the sections were identified to be beginning at a mile post (RP) so that they could be easily identified for purposes of sampling and also to ensure that performance data from pavement management system (PMS) is easily accessible. Field sampling plans have been developed for each of those sections. In addition to development of field sampling plans, the visual distress surveys and crack counts were also performed.

The information about the highway where pavement sections are located is presented in Table 4.1: Field Section Highway and Project Information. The table describes the highway location, project number, mix design record information as well as the date of crack count and visual distress survey. The specific information regarding the location of pavement section on the highways indicated in Table 4.1: Field Section Highway and Project Information is shown in Table 4.2: Summary of Pavement Sections. This table also shows the information regarding the lane where sections are located, the year of construction, qualitative performance on basis of visual observations during site visits and the type of pavement construction. From these two tables it can be seen that this study captures a breadth of asphalt pavements in terms of their location, pavement types and years in service.

**Table 4.1: Field Section Highway and Project Information**

| Highway | SP Number | MDR | MnDOT District | Date Visited |
|---|---|---|---|---|
| MN Trunk Highway 6 (TH 6) | 1103-25 | 3A-2010-128 | 3 | 07/30/2014 |
| MN Trunk Highway 9 (TH 9) | 6010-26 | 02-2011-063 | 2 | 01/02/2014 |
| Itasca County Rd 10 (CSAH 10) | 031-610-016 | 01-2012-128 | 1 | 07/30/2014 |
| MN Trunk Highway 10 (TH 10) | 5606-42 | 04-2013-033 | 4 | 07/29/2014 |
| MN Trunk Highway 25 (TH 25) | 7104-19 | 3A-2011-109 | 3 | 01/08/2014 |
| MN Trunk Highway 28 (TH 28) | 6104-11 | 04-2012-026 | 4 | 04/10/2014 |
| MN Trunk Highway 210 (TH 210) | 1805-72 | 3A-2010-073 | 3 | 01/08/2014 |
| MN Trunk Highway 220 (TH 220) | 6016-37 | 02-2012-045 | 2 | 07/29/2014 |
| MN Trunk Highway 27 (TH 27) | 4803-19 | 3A-2010-045 | 3 | 04/10/2014 |
| MN Trunk Highway 95 (TH 95) / County Road 30 (CSAH 30) | 1306-44 | 0-2012-170 | Metro | 07/28/2014 |

**Table 4.2: Summary of Pavement Sections**

| Section | RP / Landmark | Specimen Letter | Construction Year | Performance | Lane | Construction Type |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| TH 220 | RP 12 | K | 2012 | Good/Fair | D | 3” M/O |
| CSAH 10 | Jct 445B | L | 2012 | Poor | D | 1.5" O/L on old AC |
| TH 27 | RP 171 | M | 2010 | Poor | D | 3" M/O |
| TH 27 | RP 174 | N | 2010 | Good | D | 3" M/O |
| TH 9 | RP 208 | O | 2011 | Poor | D | 3" O/L on reclaimed AC |
| TH 9 | RP 214 | P | 2011 | Good | D | 3" O/L on reclaimed AC |
| TH 28 | RP 81 | Q | 2012 | Poor | D | 4.5" M/O |
| TH 28 | RP 88 | R | 2012 | Good | D | 4.5" M/O |
| TH 6 | RP 53 | S | 2010 | Poor | D | 1.5" M/O |
| TH 10 | RP 75 | T | 2013 | Poor | D/P | 3.5" M/O |
| CSAH 30 | Jct TH 95 | U | 2012 | Good/Fair | D | 6” M/O |
| TH 10 | RP 159 | V | 2005 | Poor | D/P | 4" M/O (sealed cracks) |
| TH 10 | RP 161 | W | 2005 | Good | D/P | 4" M/O (cracks not sealed) |
| M/O = Mill and Overlay; O/L = Overlay ; BAB = Bituminous on Aggregate Base<br>*Where the term “Jct” is referenced as a landmark, a signpost for the specific roadway is being specified. | | | | | | |

## 4.3 LABORATORY TESTS, RESULTS, AND DISCUSSION

This section discusses the laboratory tests and corresponding results for the field procured samples. For each of the pavement sections the MnDOT Office of Materials and Road Research (OM&RR) obtained the cored samples. The coring was conducted by a consultant hired by MnDOT OM&RR and coring was done as per the plans submitted by researchers as part of Task-2 of this project.

### 4.3.1 Volumetric Properties

The asphalt mix properties of the wear course mixtures of the various pavement sections under study are presented in Table 4.3: Section Mix Design Properties. The table shows the pertinent parameters that are typically used for the purpose of characterizing asphalt mixtures. The asphalt binder grade used for the virgin binder component of the mixture is shown along with the amount of binder contribution to the mixes form recycled sources. Currently, the three most commonly used volumetric parameters for characterization and specification of asphalt mixtures in practice are adjusted asphalt film thickness (Adj. AFT), voids in mineral aggregates (VMA) and voids filled with asphalt (VFA). Currently, the MnDOT 2360 specification for plant produced asphalt mixtures utilizes Adj. AFT as a control parameter. The field core samples were tested as per the AASHTO T166 specifications to measure the bulk specific gravities of the asphalt mixtures. These are also reported in Table 4.3: Section Mix Design Properties.

**Table 4.3: Section Mix Design Properties**

| Section | Specimen Letter | PG Grade | PG Spread | Asphalt Content | Recycled Asphalt Content | Adj. AFT | Voids in Mineral Aggregate (VMA) | Voids Filled with Asphalt (VFA) | Average Bulk Specific Gravity($G_{mb}$) |
|---|---|---|---|---|---|---|---|---|---|
| TH 220 | K | 58-28 | 86 | 4.2% | 23.80% | 9.5 | 13.50% | 70.3% | 2.307 |
| CSAH 10 | L | 58-28 | 86 | 4.3% | 23.30% | 9.1 | 13.50% | 70.4% | 2.382 |
| TH 27 | M | 58-28 | 86 | 4.3% | 37.20% | 8.8 | 13.60% | 70.6% | 2.399 |
| TH 27 | N | 58-28 | 86 | 4.3% | 37.20% | 8.8 | 13.60% | 70.6% | 2.401 |
| TH 9 | O | 58-34 | 92 | 4.2% | 26.20% | 8.9 | 13.10% | 69.6% | 2.370 |
| TH 9 | P | 58-34 | 92 | 4.2% | 26.20% | 8.9 | 13.10% | 69.6% | 2.379 |
| TH 28 | Q | 58-34 | 92 | 4.2% | 23.80% | 9.4 | 12.50% | 68.1% | 2.343 |
| TH 28 | R | 58-34 | 92 | 4.2% | 23.80% | 9.4 | 12.50% | 68.1% | 2.340 |
| TH 6 | S | 58-28 | 86 | 4.4% | 36.40% | 9.2 | 13.90% | 71.2% | 2.365 |
| TH 10 | T | 58-28 | 86 | 4.3% | 23.30% | 8.9 | 13.70% | 70.8% | 2.356 |
| CSAH 30 | U | 64-34 | 98 | 4.4% | 11.40% | 9.0 | 13.40% | 70.2% | 2.512 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| TH 10 | V | 64-28 | 92 | 5.3% | 45.30% | 7.8 | 14.40% | 72.3% | 2.339 |
| TH 10 | W | 64-28 | 92 | 5.3% | 45.30% | 7.8 | 14.40% | 72.3% | 2.536 |

### 4.3.2 Laboratory Permeability Testing

The permeability of asphalt mixtures has been hypothesized to have significant effect on the durability and performance. The cause of high permeability is primarily presence of interconnected voids. The use of permeability over air void level has been recommended by researchers in past as a better measure of asphalt mixture durability, for example the work by Cooley et al. (2002). The typical permeability of asphalt permeability has been presented by Cooley et al. (2002), this information is presented in Figure 4.1: Comparison of in-place air voids and permeability of asphalt mixtures (reproduced from Cooley et al., 2002). In this study, the permeability was measured using the Karol-Warner Permeameter, also commonly referred to as the Florida DOT (FLDOT) lab permeability measurement device. An image of the permeameter as well as the schematic is provided in Figure 4.2: Karol-Warner Permeameter. The procedure described in the Florida DOT test specification FM 5-565 were followed in the current study. These procedures utilize Darcy's law for measurement of the asphalt mixture's hydraulic conductivity or permeability.

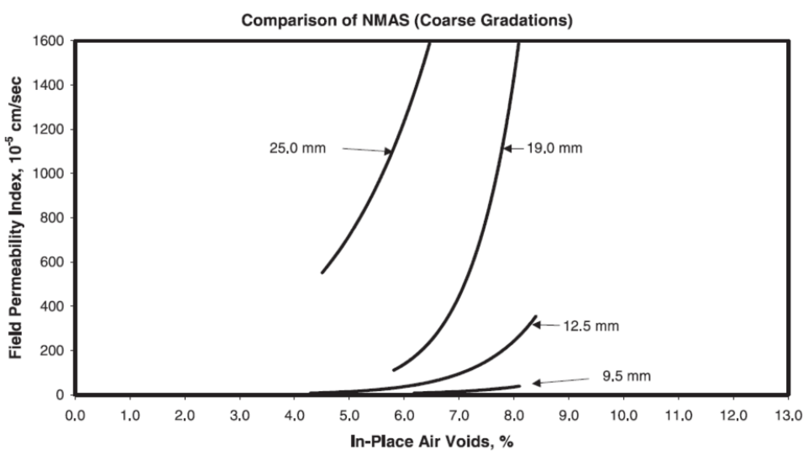



**Figure 4.1: Comparison of in-place air voids and permeability of asphalt mixtures (reproduced from Cooley et al., 2002)**

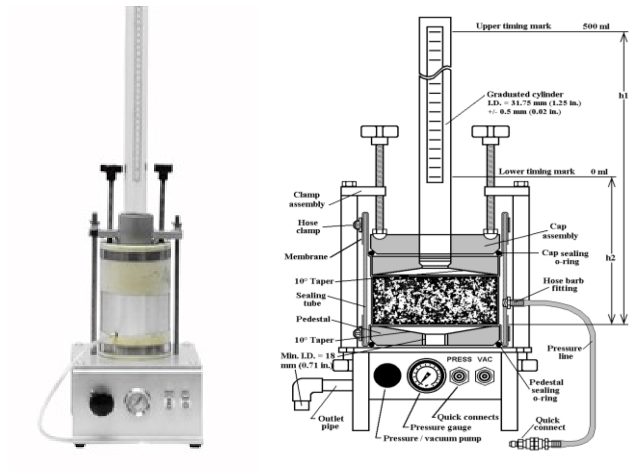



**Figure 4.2: Karol-Warner Permeameter**

The lab measure permeability for the cored specimens is presented in Table 4.4: Permeability of various asphalt mixtures.. Please note that prior to permeability measurement the cored specimens were processed by cutting the wear course lifts from the rest of the core. The wear course was tested using the Karol-Warner permeameter. As it can be seen from the results the permeability varied quite significantly for the asphalt mixtures. The typical permeability range for these mixtures (all of them are ¾ inch sized mixtures as per the MnDOT 2360 designation) would be between 1E-05 to 1E-06 cm/s range. The mixtures that have permeability greater than this typical range are indicated. It can be seen that more than half of the mixtures have permeability that is significantly higher than the typical range. These mixtures are thus prone to inferior durability. The comparison of measure permeability with the field cracking performance is conducted and discussed in Chapter 6.

**Table 4.4: Permeability of various asphalt mixtures.**

| Section | RP / Landmark | Specimen Letter | Permeability (cm/s) | Comparison to Typical Range<br><br>(1E-05 – 1E-06 cm/s) |
|---|---|---|---|---|
| TH 220 | RP 12 | K | 6.28E-04 | Very High |
| CSAH 10 | Jct 445B | L | 4.81E-05 | High |
| TH 27 | RP 171 | M | 1.48E-05 | Borderline High |
| TH 27 | RP 174 | N | 2.33E-07 | |
| TH 9 | RP 208 | O | 8.18E-06 | |
| TH 9 | RP 214 | P | 9.69E-05 | High |

| | | | | |
|---|---|---|---|---|
| TH 28 | RP 81 | Q | 7.86E-06 | |
| TH 28 | RP 88 | R | --- | |
| TH 6 | RP 53 | S | 1.26E-05 | Borderline High |
| TH 10 | RP 75 | T | 5.39E-05 | High |
| CSAH 30 | Jct TH 95 | U | 5.65E-07 | |
| TH 10 | RP 159 | V | 5.23E-05 | High |
| TH 10 | RP 161 | W | 5.53E-05 | High |

### 4.3.3 Disk Shaped Compact Tension Test

The DCT test is standardized by ASTM D7313-13. The primary function of the test is to quantify the resistance an asphalt mixture will have to low temperature cracking. This is done by the measurement of the fracture energy of the asphalt mixtures. All of the sections in this study, along with the majority of the State of Minnesota, undergo extensive low temperature climatic conditions. This study uses the DCT test on field cored samples to determine if any trends are found for use in comparison to various mixture parameters and transverse cracking performance in Chapter 6.

For this study, specimens were loaded into the testing chamber at a temperature 10°C greater than the 98% reliability environmental low temperature using Superpave specifications. For example, instead of testing a PG XX-34 at -24°C, temperature data shows (with 98% reliability) that this roadway will only experience -31°C. Therefore, DCT test conditioning for the corresponding specimens will target -21°C. This eliminates the unnecessary "penalization" for a binder in this scenario, as it will likely never see the extreme temperature recommended by the ASTM standard. Alternatively, a PG XX-28 binder tested at -18°C will not provide accurate DCT results for an environment experiencing temperatures colder than -28°C. Location is a primary function of this study. This required the research team to provide site-specific temperature conditioning data. In order to achieve this, historical temperature data was required to accurately predict this 98% reliability. LTPPBind software was utilized to determine these values based on the specific location of each section.

The results from each highway project and the individual study sections that were established can be found Table 4.5: DCT fracture energy results (all replicates). Please note that typically the coefficient of variation for the DCT facture energy for asphalt samples is in range of 10 – 15%. As seen in **Error! Reference source not found.**, several set of samples showed significantly higher variability than this typical range.  However, the typical range (10-15%) is primarily applicable to lab produced specimens and/or cores taken in close grouping from the pavement section and roadways that have been in service for short duration. In the present study, the field cores are separated by distance of 200 ft. along the roadway. Furthermore, most pavements have been in service for several years and finally most lifts are of thickness lower than preferred specimen thickness of 50 mm. Thus, the higher variability is not entirely surprising. As this was anticipated by researchers, they requested a significantly larger number of specimens as opposed to what is needed for typical DCT testing (typically 3 replicates). Wherever high variability was noted, several additional DCT tests were conducted and the data was trimmed to eliminate the outliers on the basis of statistical testing. For example, in the case of TH27 RP 174, the test replicates were measured to be 281.78, 266.60, 268.66, 429.42 J/m$^2$. It can be seen that first three replicates have a relatively close grouping compared to the fourth replicate. The results after trimming of apparent outliers data points is presented in Table 4.6: DCT fracture energy results (trimmed data). It can be seen that after trimming the COV are within acceptable ranges. Only two set of specimens show COV that outside of typical range.

The previous and currently on-going research efforts of using the DCT fracture energy as a performance indicator of the transverse cracking performance have shown that a value of 400 J/m$^2$ typically ensures good performance from asphalt mixture. As seen here, only two mixtures exceed this threshold. The threshold of 400 J/m$^2$ is recommended for lab or plant produced mixtures with short term aging, thus a direct comparison is not possible, however the majority of mixtures have fracture energies that are substantially lower than the recommended threshold. On basis of this data it can be inferred that a large number of mixtures, especially ones with fracture energies that are near or below 250 J/m$^2$ are anticipated to have significantly inferior thermal cracking performance.

**Table 4.5: DCT fracture energy results (all replicates)**

| Section | RP / Landmark | Specimen Letter | Fracture Energy (J/m$^2$) | | | | COV | Sample Size |
|---|---|---|---|---|---|---|---|---|
| | | | Standard Deviation | Maximum | Minimum | Mean | | |
| TH 220 | RP 12 | K | 60.93 | 305.83 | 152.31 | 220.64 | 27.62% | 6 |
| CSAH 10 | Jct 445B | L | 96.53 | 468.55 | 250.78 | 379.81 | 25.42% | 4 |
| TH 27 | RP 171 | M | 137.35 | 589.98 | 265.50 | 385.72 | 35.61% | 5 |
| TH 27 | RP 174 | N | 68.69 | 429.42 | 266.60 | 315.02 | 21.81% | 5 |
| TH 9 | RP 208 | O | 36.63 | 386.15 | 309.00 | 351.99 | 10.41% | 4 |
| TH 9 | RP 214 | P | 11.39 | 281.77 | 257.12 | 270.99 | 4.20% | 4 |
| TH 28 | RP 81 | Q | 46.21 | 366.50 | 253.32 | 310.23 | 14.90% | 4 |
| TH 28 | RP 88 | R | 26.24 | 245.67 | 208.56 | 227.12 | 11.55% | 2 |
| TH 6 | RP 53 | S | 93.08 | 333.46 | 89.43 | 226.03 | 41.18% | 5 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| TH 10 | RP 75 | T | 50.30 | 302.25 | 171.16 | 229.96 | 21.87% | 5 |
| CSAH 30 | Jct TH 95 | U | 245.37 | 660.32 | 113.68 | 453.46 | 54.11% | 4 |
| TH 10 | RP 159 | V | 25.35 | 307.22 | 231.80 | 269.98 | 9.39% | 6 |
| TH 10 | RP 161 | W | 76.00 | 364.99 | 181.70 | 252.35 | 30.12% | 5 |

Table 4.6: DCT fracture energy results (trimmed data)

| Section | RP / Landmark | Specimen Letter | Fracture Energy (J/m$^2$) | COV | Sample Size |
|---|---|---|---|---|---|
| TH 220 | RP 12 | K | 182.86 | 11.1% | 4 |
| CSAH 10 | Jct 445B | L | 422.81 | 10.4% | 3 |
| TH 27 | RP 171 | M | 334.65 | 22.8% | 4 |
| TH 27 | RP 174 | N | 272.34 | 2.5% | 3 |
| TH 9 | RP 208 | O | 351.99 | 10.4% | 4 |
| TH 9 | RP 214 | P | 270.99 | 4.2% | 4 |
| TH 28 | RP 81 | Q | 291.47 | 9.3% | 3 |
| TH 28 | RP 88 | R | 227.12 | 11.6% | 2 |
| TH 6 | RP 53 | S | 260.18 | 20.5% | 4 |
| TH 10 | RP 75 | T | 211.89 | 14.1% | 4 |
| CSAH 30 | Jct TH 95 | U | 566.72 | 16.6% | 3 |
| TH 10 | RP 159 | V | 270.21 | 3.6% | 4 |
| TH 10 | RP 161 | W | 238.35 | 16.8% | 3 |

### 4.3.4 Asphalt Content and Gradation Results

The asphalt mixture specimens that were used for DCT testing were also tested using the ignition oven. The testing followed the AASHTO T308 test procedure. The test resulted in the measurement of the approximate asphalt content in the mixture. The residue from this testing was used to conduct washed aggregate gradation following the AASHTO T27 test procedure. Approximately half of the DCT specimens post-testing were tested. It should be noted that the measured asphalt contents using the ignition oven test requires calibration of the ignition oven through the use of a chemical extraction process. This was not within the scope of current study, hence the ignition oven measured asphalt contents should be treated as approximate asphalt contents.

The results from ignition oven testing is shown in Table 4.7: Asphalt content results.. The comparison between design asphalt contents and measured asphalt contents are shown in Figure 4.3: Comparison of Design and Measured Asphalt Content. As discussed before, further investigation is presently underway to determine the discrepancy between design and measured asphalt contents.

**Table 4.7: Asphalt content results.**

| Section | RP / Landmark | Specimen Letter | Design Asphalt Content (%) |
|---|---|---|---|
| TH 220 | RP 12 | K | 4.2 |
| CSAH 10 | Jct 445B | L | 4.3 |
| TH 27 | RP 171 | M | 4.3 |
| TH 27 | RP 174 | N | 4.3 |
| TH 9 | RP 208 | O | 4.2 |
| TH 9 | RP 214 | P | 4.2 |
| TH 28 | RP 81 | Q | 4.2 |
| TH 28 | RP 88 | R | 4.2 |
| TH 6 | RP 53 | S | 4.4 |
| TH 10 | RP 75 | T | 4.3 |
| CSAH 30 | Jct TH 95 | U | 4.4 |
| TH 10 | RP 159 | V | 5.3 |
| TH 10 | RP 161 | W | 5.3 |

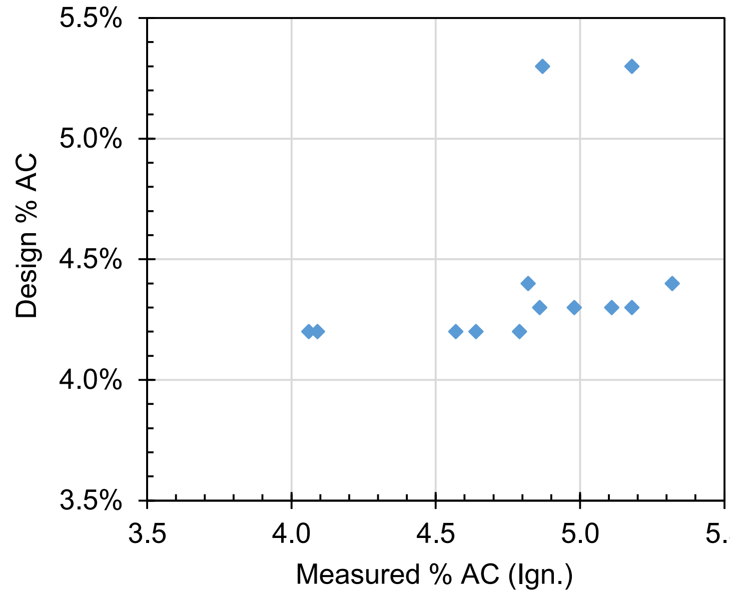



**Figure 4.3: Comparison of Design and Measured Asphalt Content**

The results from the gradation analysis of the ignition oven residue is presented in Table 4.8: Ignition oven residue gradation results.. The aggregate gradation requirements put forth by MnDOT are specified in the MnDOT 3139 specifications. These are also shown in Table 4.8: Ignition oven residue gradation results.. It should be noted that there have been previous studies that have shown degradation of aggregate in ignition oven, resulting in measurements of higher amounts of fines than what are actually present in the mixture.

**Table 4.8: Ignition oven residue gradation results.**

| Section | RP / Landmark | Specimen Letter | Sieve Size (Percent Passing) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 3/4 in | 1/2 in | 3/8 in | #4 | #8 |
| MnDOT Requirements (MnDOT 3139) | | | 100 | 85 - 100 | 35 - 90 | 30 - 80 | 25 - 65 |
| TH 220 | RP 12 | K | 100.0 | 94.5 | 81.0 | 50.7 | 35.8 |
| CSAH 10 | Jct 445B | L | 100.0 | 98.0 | 89.5 | 59.7 | 44.1 |
| TH 27 | RP 171 | M | 100.0 | 90.4 | 76.6 | 51.7 | 39.5 |
| TH 27 | RP 174 | N | 100.0 | 88.7 | 74.6 | 50.0 | 37.2 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| TH 9 | RP 208 | O | 100.0 | 93.5 | 77.8 | 51.7 | 43.2 |
| TH 9 | RP 214 | P | 99.4 | 91.9 | 76.4 | 50.1 | 42.7 |
| TH 28 | RP 81 | Q | - | - | - | - | - |
| TH 28 | RP 88 | R | 100.0 | 94.9 | 82.7 | 55.7 | 44.3 |
| TH 6 | RP 53 | S | 99.7 | 96.4 | 87.9 | 63.9 | 50.4 |
| TH 10 | RP 75 | T | 100.0 | 95.9 | 83.6 | 60.6 | 42.3 |
| CSAH 30 | Jct TH 95 | U | 100.0 | 96.3 | 85.9 | 54.1 | 39.6 |
| TH 10 | RP 159 | V | 100.0 | 94.1 | 81.6 | 55.4 | 42.8 |
| TH 10 | RP 161 | W | 100.0 | 93.6 | 79.9 | 56.8 | 46.2 |

## 4.4 SUMMARY

This task of the project focused on laboratory testing of field cored samples of coarse asphalt mixtures from thirteen pavement section from Minnesota. The testing spanned across variety of tests to determine asphalt mixtures' permeability, fracture energy, volumetric properties, asphalt content, and gradation. On basis of the test results following points can be summarized:

- The asphalt content measured using ignition oven tests on the post-test DCT specimens showed considerably higher asphalt binder amounts as opposed to the designed values. It is anticipated that this is due to the lack of calibration using the chemical extraction method.
- The results from permeability testing indicated that eight of the thirteen mixtures have higher permeability than typical ranges for dense graded asphalt mixtures. Specifically, six of the mixtures have significantly higher permeability. These mixtures are anticipated to have inferior durability and might be more prone to moisture induced damage and distresses like raveling.
- The DCT fracture energy results for the field cored specimens showed greater variability than typically experienced. The reasoning behind this can be hypothesized to be due to thin test specimens (typical specimen thickness is 50 mm, several specimens in this study were in range of 30 mm thickness), mixtures that have been field aged, and specimens sampled along 1000 ft. length of pavement that might be representative of different days of paving and mix production. After conducting data trimming to remove apparent outliers, the variability for majority of sections dropped to typical range.
- Only two out of thirteen mixtures have fracture energies that are above the recommended threshold of 400 J/m$^2$. Nine sections have substantially lower fracture energies, even after consideration of lowering fracture energies due to the pavement being in service for several years. These sections are expected to have significantly inferior transverse cracking performance and shortened service lives.

# CHAPTER 5: LABORATORY TESTING PART 2 (TASK-3B)

## 5.1 INTRODUCTION

### 5.1.1 Introduction and Scope

Understanding of the stress-strain behavior of pavement materials under repetitive traffic loading is necessary to predict the pavement's performance and service life. The dynamic modulus test is accepted by pavement agencies as a critical parameter for pavement design, and a dynamic modulus master curve for asphalt concrete is an important input for flexible pavement design in the mechanistic-empirical pavement design guide developed in NCHRP Project 1-37A (Kim, et al., 2004). In this research, this property was chosen to determine material stiffness and understand its behavior according to temperature (environment) and time of loading. For this work, three replicate specimens are tested at three temperatures (0.4°C, 17.1°C, and 33.8°C) and nine frequencies between 25 Hz and 0.1 Hz. The master curves and shift factors are then developed from this database using numerical optimization.

One of the issues related to the role of the dynamic modulus in pavement management is its use in forensic studies and pavement rehabilitation design. It is often impossible to obtain 4-inch (101.6 mm) diameter and 6-inch (152.4 mm) tall asphalt concrete specimens from individual pavement layers for use in dynamic modulus testing because many asphalt layers are less than a few inches thick. Therefore, the indirect tension (IDT) mode testing of field cores is more appropriate for the evaluation of dynamic modulus in this case. In forensic studies, another challenge is designing asphalt mixes in a multi-layered system. These layers have different aggregate gradation, binder content, and stiffnesses, typically resulting in different dynamic modulus values. In the uniaxial dynamic modulus test this difference is often not considered, but it is possible to measure a layers' dynamic modulus values separately using the IDT mode and create master curves for each layer. To use dynamic modulus prediction models, volumetrics and binder results, such as G*, are invaluable. Another focus of this work is to evaluate whether the Modified Witczak model compares well against the experimentally shifted dynamic results (Bari and Witczak, 2006).

## 5.2 MATERIALS AND METHODS

### 5.2.1 Materials

Within this research work, performance evaluation took place on coarse-graded field cores from 9 different pavements located in five districts of Minnesota as shown in Figure 5.1: Locations of Pavement Sections in Minnesota and Table 5.1: Pavement Section Information. From each pavement's surface layer, 3 specimens were used for testing.

| | |
|---|---|
| Group 1: K-TH220 | (District 2) |
| Group 2: L-CSAH10 | (District 1) |
| Group 3: M, N-TH27 | (District 3) |
| Group 4: O, P-TH9 | (District 2) |
| Group 5: Q, R-TH28 | (District 4) |
| Group 6: S-TH6 | (District 2) |
| Group 7: T- TH10 | (District 4) |
| Group 8: U-CSAH30 | (Metro) |
| Group 9: W, V-TH10 | (District3) |

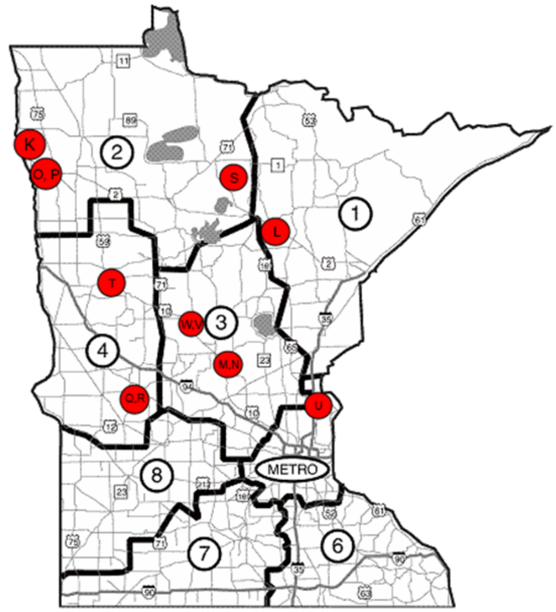



**Figure 5.1: Locations of Pavement Sections in Minnesota**

**Table 5.1: Pavement Section Information**

| Section | MnDOT District | Construction Year | Specimen Letter | Group No. | Construction Type |
|---|---|---|---|---|---|
| TH 220 | 2 | 2012 | K | 1 | 3" M/O |
| CSAH 10 | 1 | 2012 | L | 2 | 1.5" O/L on old AC |
| TH27 | 3 | 2010 | M, N | 3 | 3" M/O |
| TH 9 | 2 | 2011 | O, P | 4 | 3" O/L on reclaimed AC |
| TH 28 | 4 | 2012 | Q, R | 5 | 4.5" M/O |
| TH 6 | 2 | 2010 | S | 6 | 1.5" M/O |
| TH 10 | 4 | 2013 | T | 7 | 3.5" M/O |
| CSAH 30 | Metro | 2012 | U | 8 | 6" M/O |
| TH 10 | 3 | 2005 | V | 9 | 4" M/O (sealed cracks) |
| TH 10 | 3 | 2005 | W | 9 | 4" M/O (cracks not sealed) |

Note: M/O = Mill and Overlay; O/L = Overlay

### 5.2.2 Methods

The complex dynamic modulus |E*| is a complex number that describes the relationship between stress and strain for a linear viscoelastic material under sinusoidal loading. It is defined as the ratio of amplitude of the sinusoidal stress and sinusoidal strain in a steady state response as shown in Equation 5.1 (Dougan, et al., 2003, Schwartz, 2005).

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_0 . e^{i\omega t}}{\varepsilon_0 . e^{i(\omega t - \delta)}} = \frac{\sigma_0 . \sin(\omega t)}{\varepsilon_0 . \sin(\omega t - \delta)} \qquad (5.1)$$

Where E* = complex modulus; $\sigma_0$= peak (maximum) stress; $\varepsilon_0$ = peak (maximum) strain; δ = phase angle, degrees; ω = angular velocity; t = time, seconds; e = exponential; and i = imaginary component of the complex modulus. Thus, the dynamic modulus is in Equation 5.2 defined as:

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \qquad (5.2)$$

The dynamic modulus is a performance related property that can be used for mixture evaluation and characterizing the stiffness of hot mix asphalt (HMA) for use in mechanistic-empirical pavement design. The indirect tension (IDT) mode dynamic modulus test protocol was evaluated by Kim (Kim, et al., 2004) using 6-inch (152.4 mm) diameter, 1.5-inch (38.1 mm) thick specimens cut from Superpave gyratory compacted (SGC) specimens. Sinusoidal loading is applied in controlled stress mode. Horizontal and vertical deformations are measured from two loose core-type miniature linear variable differential transformers (LVDT)s with a 50.8mm gauge length located on each side of a specimen's face. Based on the AASHTO TP 62-07 specification, testing must take place on at least two replicate specimens at five temperatures between 14°F and 130°F (-10°C and 54.4°C) and six loading rates between 0.1 and 25 Hz (AASHTO, 2006). Due to the number of temperatures, this specification is more time consuming and costly.

In a recent study, Li and Williams found that five test temperatures are not necessary to build an accurate, smooth master curve. From this study it was found that with three temperatures and nine frequencies, an equivalent master curve comparable to one made using results from testing at five temperatures and six frequencies could be developed (Li and Williams, 2012).

### 5.2.3 Modified Witzak Model

The modified Witczak model is a semi-empirical method used for asphalt concrete dynamic modulus estimation. It is based on nonlinear regression and was formulated through historical data taken from 346 mixtures (7,400 data points). This model was made in response to the limitations identified by the original Witczak model (Bari and Witczak, 2006, Witczak, et al., 1999). A main limitation of the original Witczak model was its dependence on needing other models to convert binder complex shear modulus values into binder viscosity. Furthermore, the original model was not sensitive to changes in volumetrics, such as voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), binder content, and air voids. Some of these limitations are addressed in the modified model through use of the following parameters: $V_a$ = percentage of air voids (by volume of mix), $V_{beff}$ = percentage of effective binder content (by volume of mix), $|G_b{}^*|$= complex shear modulus of binder (psi), and $\delta_b$= phase angle of binder associated with$|G_b{}^*|$(degrees). The modified Witczak model is shown below in Equation 5.3 (Bari and Witczak, 2006).

$$\log_{10}|E^*| = -0.349 + 0.754(|G_b{}^*|^{-0.0052}) \times \left(6.65 - 0.032\rho_{200} + 0.0027\rho_{200}{}^2 + 0.011\rho_4 - 0.0001\rho_4{}^2 + 0.006\rho_{38} - 0.00014\rho_{38}{}^2 - 0.08V_a - 1.06\left(\frac{V_{beff}}{V_a+V_{beff}}\right)\right) + \frac{2.56+0.03V_a+0.71\left(\frac{V_{beff}}{V_a+V_{beff}}\right)+0.012\rho_{38}-0.0001\rho_{38}{}^2-0.01\rho_{34}}{1+e^{(-0.7814-0.5785\log|G_b{}^*|+0.8834 log\delta_b)}} \quad (5.3)$$

Where, $|E^*|$= dynamic modulus (psi), $\rho_{200}$ = percentage of aggregate passing no. 200 sieve, $\rho_4$ = percentage of aggregate retained on no.4 sieve, $\rho_{3/8}$ = percentage of aggregate retained on no.3/8” sieve, and $\rho_{3/4}$ = percentage of aggregates retained on no.3/4” sieve.

As part of this study the E* values are predicted using $G_b$* values, and volumetrics using the Modified Witczak Model. As such, the predicted E* values will be compared with laboratory results to see how well the Modified Witczak Model compares against experimental data gained in the IDT mode for dynamic modulus testing.

## 5.3 DISCUSSION OF RESULTS AND ANALYSIS

Before binder extraction and recovery was done, volumetrics in conjunction with testing was completed. After testing was finished, binder was extracted and recovered from one specimen of each group. The binder content was determined based on the amount of binder extracted and recovered and the amount of additional binder via an NCAT ignition oven. The recovered aggregate from each group were then sieved according to AASHTO C136/C136M-14. Other properties such as $\%V_{beff}$, %VMA, %VFA, $G_{mm}$, and air voids were determined from previous work done on the cores collected at the same time from the same section of roadways as the ones used in this study (Helmer, 2015). This information is shown in Table 5.2: Sieve analysis results and mix properties..

**Table 5.2: Sieve analysis results and mix properties.**

| | Group No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Sieve Size (%) passing | 3/4” | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | 1/2” | 93.9 | 96.4 | 87.2 | 93.5 | 95.1 | 96.4 | 94.1 | 94.4 | 94.2 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 3/8" | 77.5 | 84.6 | 73.7 | 76.4 | 83.1 | 87.3 | 83.4 | 82 | 80.9 |
| | #4 | 49.8 | 53.1 | 48.4 | 52.2 | 52.2 | 60.9 | 63.8 | 48.2 | 58.6 |
| | #8 | 34.4 | 38.4 | 35.1 | 43.6 | 38.8 | 46.9 | 47.1 | 34.9 | 46.0 |
| | #30 | 16.7 | 18.7 | 17.9 | 20.9 | 18.8 | 23.4 | 21.7 | 19.2 | 25.9 |
| | #50 | 10.3 | 10.8 | 10.9 | 11.4 | 9.9 | 12.4 | 11.9 | 11.8 | 13.8 |
| | #100 | 6.1 | 5.9 | 6.4 | 5.8 | 5.4 | 6.1 | 6.6 | 6.1 | 7.2 |
| | #200 | 3.6 | 3.3 | 6.2 | 3.3 | 3.5 | 3.4 | 4.0 | 3.1 | 4.0 |

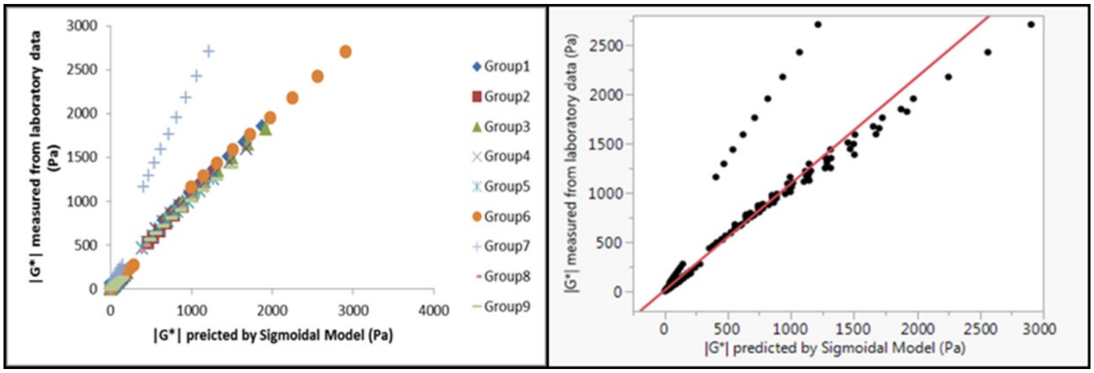
| | **Group No.** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
|---|---|---|---|---|---|---|---|---|---|---|
| Mix Property | % RAP | 23.8 | 23.3 | 37.2 | 26.2 | 23.8 | 36.4 | 23.3 | 11.4 | 45.3 |
| | % AC | 4.5 | 5.2 | 5.6 | 4.8 | 4.8 | 4.9 | 5.6 | 5.3 | 5.0 |
| | % $V_{beff}$ | 4.2 | 4.1 | 4.1 | 3.9 | 3.5 | 4.3 | 4.2 | 4.0 | 4.6 |
| | %VMA | 13.5 | 13.5 | 13.6 | 13.1 | 12.5 | 13.9 | 13.7 | 13.4 | 14.4 |
| | % VFA | 70.3 | 70.4 | 70.6 | 69.6 | 68.1 | 71.2 | 70.8 | 70.2 | 72.3 |
| | $G_{mb}$ | 2.3 | 2.4 | 2.4 | 2.4 | 2.5 | 2.4 | 2.4 | 2.4 | 2.3 |
| | $G_{mm}$ | 2.4 | 2.5 | 2.5 | 2.5 | 2.6 | 2.5 | 2.5 | 2.5 | 2.4 |
| | % $V_A$ | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |

Master curves were developed for $G_b$* using the sigmoidal model. The model coefficients and shift factors for each group are shown in Table 5.3: G* sigmoidal model coefficients and shift factors.. These values can be used to reconstruct the curves.

**Table 5.3: G* sigmoidal model coefficients and shift factors.**

| Group No. | δ | α | β | γ | *a* | *b* | *c* |
|---|---|---|---|---|---|---|---|
| **1** | -6.253 | 12.421 | -0.942 | 0.248 | 0.000339 | -0.113 | 1.825 |
| **2** | -5.861 | 11.656 | -0.949 | 0.257 | 0.000497 | -0.122 | 1.944 |
| **3** | -6.292 | 12.407 | -0.973 | 0.245 | 0.000404 | -0.118 | 1.906 |
| **4** | -6.106 | 12.508 | -0.836 | 0.241 | 0.000292 | -0.103 | 1.680 |
| **5** | -6.103 | 12.530 | -0.766 | 0.253 | 0.000440 | -0.115 | 1.840 |
| **6** | -6.190 | 12.467 | -0.979 | 0.254 | 0.000372 | -0.118 | 1.906 |
| **7** | -6.284 | 12.400 | -0.881 | 0.247 | 0.000312 | -0.105 | 1.710 |
| **8** | -6.178 | 12.490 | -0.792 | 0.250 | 0.000443 | -0.115 | 1.834 |
| **9** | -6.271 | 12.410 | -0.900 | 0.260 | 0.000362 | -0.111 | 1.800 |

For comparison purposes, $|G_b^*|$ from lab was plotted against the predicted $|G_b^*|$ results using the sigmoidal model for each of the nine different groups as shown in Figure 5.2 (a). Figure 5.2 (b) displays an overall comparison of all the results of the groups for the lab $|G_b^*|$ versus sigmoidal predicted $|G_b^*|$. Table 5.4: R2 and R from fitting lab |Gb*| values against sigmoidal predicted |Gb*|. shows the $R^2$ and correlation coefficient (R) values calculated from fitting lab $|G_b^*|$ values against $|G_b^*|$ predicted by sigmoidal model.




a. b.

**Figure 5.2: Laboratory Data vs. Predicted (a) each group, (b) all groups together.**

**Table 5.4: $R^2$ and R from fitting lab $|G_b^*|$ values against sigmoidal predicted $|G_b^*|$.**

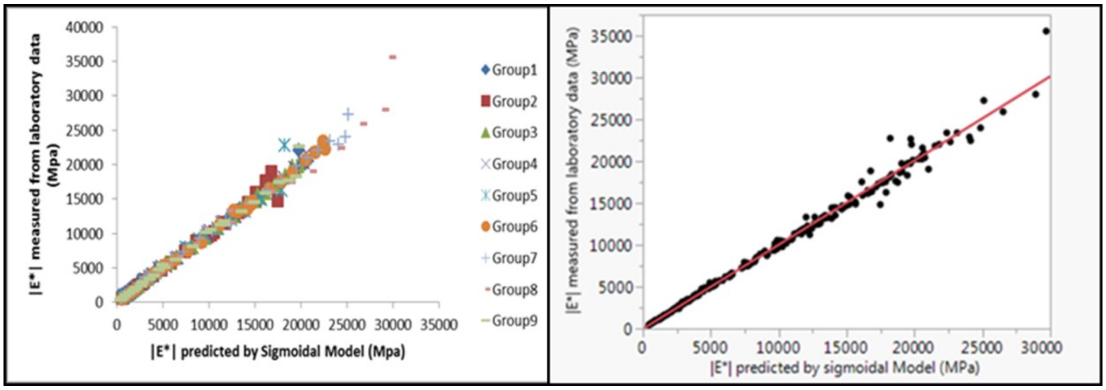
| Group No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | All Groups |
|---|---|---|---|---|---|---|---|---|---|---|
| $R^2$ | 0.995 | 0.998 | 0.995 | 0.994 | 0.996 | 0.995 | 0.993 | 0.997 | 0.994 | 0.91 |
| Correlation Coefficient | 0.998 | 0.999 | 0.998 | 0.997 | 0.998 | 0.998 | 0.997 | 0.997 | 0.997 | 0.954 |

From the results shown, the sigmoidal model shows an extremely good fit for the experimental data of each group as well as the data from all the groups put together. This is apparent as both R and $R^2$ are in the range of 0.91 to 0.999. Dynamic modulus master curves were developed for E* using the sigmoidal model as well. The model coefficients and shift factors for each group's model are shown in Table 5.5.

**Table 5.5: E* sigmoidal model coefficients and shift factors.**

| Group No. | δ | α | β | γ | *a* | *b* | *c* |
|---|---|---|---|---|---|---|---|
| ***1*** | 1.617 | 2.778 | -1.32 | 0.626 | 2.171 | 0.000 | -1.849 |
| ***2*** | 2.363 | 1.938 | -0.762 | 0.699 | 2.472 | 0.000 | -2.11 |
| ***3*** | 2.073 | 2.288 | -1.618 | 0.659 | 1.546 | 0.000 | -2.312 |
| ***4*** | 1.957 | 2.465 | -1.128 | 0.625 | 1.734 | 0.000 | -1.828 |
| ***5*** | 2.51 | 1.855 | -0.31 | 0.75 | 1.947 | 0.000 | -1.698 |
| ***6*** | 1.145 | 3.301 | -1.589 | 0.565 | 2.104 | 0.000 | -1.932 |
| ***7*** | 1.274 | 3.217 | -1.267 | 0.488 | 3.267 | 0.000 | -2.199 |
| ***8*** | 0.79 | 4.046 | -0.985 | 0.353 | 2.375 | 0.000 | -1.715 |
| ***9*** | 1.345 | 3.041 | -1.254 | 0.638 | 2.089 | 0.000 | -1.453 |

To compare the sigmoidal model with the experimentally gained dynamic modulus values shifted to reduce frequencies, Figure 5.3: Laboratory Data vs. Predicted (a) each group, (b) all groups together.. Figure 5.3: Laboratory Data vs. Predicted (a) each group, (b) all groups together. is split into two parts (a) separated groups, and (b) all groups data pooled together. From the plots it appears that the sigmoidal model does a very good job fitting the experimental results. The $R^2$ and R values were determined for each group and for all data from all groups pooled together with results shown in Table 5.6: R2 and R from fitting lab |E*| values against sigmoidal predicted |E*|..



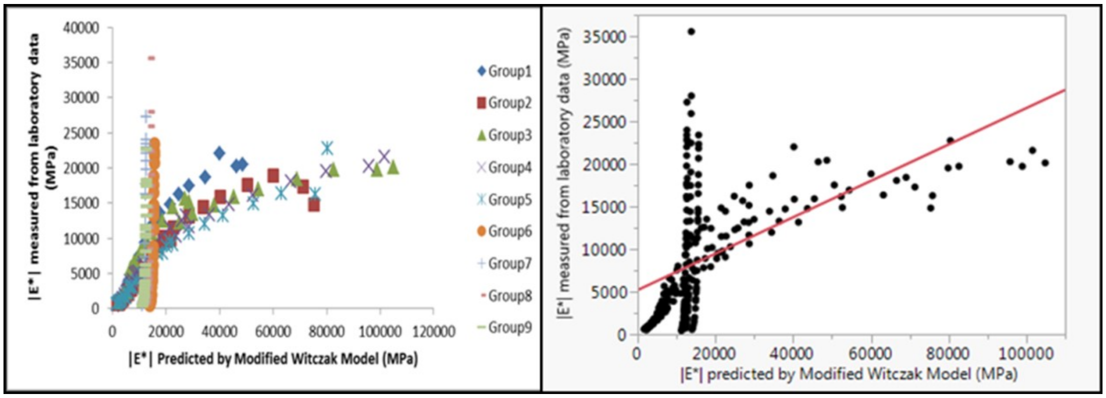

a. b.

**Figure 5.3: Laboratory Data vs. Predicted (a) each group, (b) all groups together.**

**Table 5.6: $R^2$ and R from fitting lab |E*| values against sigmoidal predicted |E*|.**

| Group No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | All Groups |
|---|---|---|---|---|---|---|---|---|---|---|
| $R^2$ | 0.995 | 0.984 | 0.998 | 0.998 | 0.972 | 0.998 | 0.995 | 0.980 | 0.990 | 0.990 |
| Correlation Coefficient | 0.998 | 0.992 | 0.999 | 0.999 | 0.990 | 0.999 | 0.998 | 0.990 | 0.990 | 0.995 |

The sigmoidal model shows very good agreement with the experimentally shifted |E*| results from both Figure 5.3: Laboratory Data vs. Predicted (a) each group, (b) all groups together. (a) and (b) as both the R and $R^2$ values are in the range of 0.972 to 0.999. Using the $|G_b^*|$ master curve results in combination with volumetrics shown in Table 5.2, the dynamic modulus master curves were developed using the Modified Witczak Model. Comparison between the experimentally shifted data and Modified Witczak Model predicted data were made for each group and for all the groups pooled together. The results are presented in Figure 5.4: Laboratory Data vs. Predicted (a) each group, (b) all groups together. parts (a) and (b). From the results it is fairly clear that the Modified Witczak Model predicted results do not fit well with the experimentally shifted results for all the groups together as shown in Figure 5.4: Laboratory Data vs. Predicted (a) each group, (b) all groups together. (b). However, it is not clear from visual inspection if the Modified Witczak Model fits well or poorly with the experimentally shifted data for each individual group (Figure 5.4: Laboratory Data vs. Predicted (a) each group, (b) all groups together. (a)). To better examine the best fit models, the R and $R^2$ values were determined for each group and the all the groups data pooled together as shown in Table 5.7: R2 and R for lab |E*| vs. |E*| predicted values by Modified Witczak model..




a. b.

**Figure 5.4: Laboratory Data vs. Predicted (a) each group, (b) all groups together.**

**Table 5.7: $R^2$ and R for lab |E*| vs. |E*| predicted values by Modified Witczak model.**

| Group No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | All Groups |
|---|---|---|---|---|---|---|---|---|---|---|
| **$R^2$** | 0.89 | 0.82 | 0.74 | 0.87 | 0.93 | 0.79 | 0.78 | 0.76 | 0.77 | 0.30 |
| **Correlation Coefficient** | 0.94 | 0.91 | 0.86 | 0.93 | 0.96 | 0.88 | 0.88 | 0.87 | 0.88 | 0.54 |

From the results shown, the Modified Witczak Model works fairly well for each group individually as the R and $R^2$ range from 0.74 to 0.96. However, looking at the overall fit of all the data together, the R and $R^2$ ranged from 0.54 and 0.30. Examining the fitted plots in Figure 5.4: Laboratory Data vs. Predicted (a) each group, (b) all groups together. does not explain what is happening, so Figure 5.5: Sigmoidal model results vs. Modified Witczak Model results for group 3. is shown to illustrate why the R and $R^2$ could be low for the overall fit of all data. Figure 5.5: Sigmoidal model results vs. Modified Witczak Model results for group 3. shows a comparison between the sigmoidal model and Modified Witczak Model against experimentally shifted data for group 3.

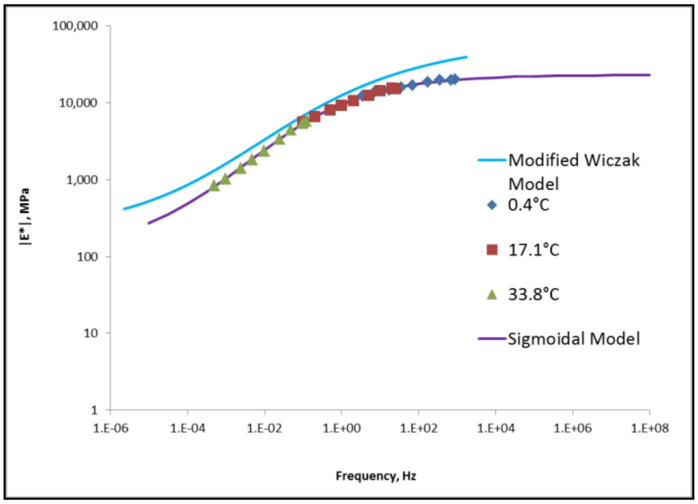



**Figure 5.5: Sigmoidal model results vs. Modified Witczak Model results for group 3.**

From the resulting master curves shown in Figure 5.5: Sigmoidal model results vs. Modified Witczak Model results for group 3. it can be seen that the Modified Witczak Model over estimates the dynamic modulus values from low to high frequencies. This is most likely due to the Modified Witczak Model creation based on historical data gained from testing 4-inch diameter by 6-inch high dynamic modulus specimens.

## 5.4 SUMMARY AND CONCLUSIONS

The IDT dynamic modulus test results showed that all nine mix groups have very high stiffness values. Typical dynamic modulus value for asphalt mixtures of same binder grade and mix size evaluated in this study range from 10 to 1000 MPa for the loading frequencies and temperatures used herein, the coarse lower asphalt mixtures were measured to have dynamic modulus to be in 500 to 10,000 MPa range. The $R^2$ and R values gained from fitting experimental results against predicted data using the sigmoidal model were close to 1, and thus means the sigmoidal model can be developed and used to predict both $|E^*|$ and $|G_b^*|$ values very well. For the IDT mode of testing, although the Modified Wiczak model can predict $|E^*|$ values using $|G_b^*|$ and other inputs for the more commonly used uniaxial test configuration for determining dynamic modulus values, it is not as accurate in predicting IDT $|E^*|$ values as the sigmoidal model. Due to the ability of the IDT dynamic modulus test to more accurately measure the dynamic modulus in asphalt concrete layers collected from field cores, the Modified Witczak Model should be modified for IDT mode in future studies.

# CHAPTER 6: DATA ANALYSIS (TASK-4A)

## 6.1 INTRODUCTION AND SCOPE

Task-4A of the MnDOT research contract number 99008 work order number 100 (Impact of Lower-Asphalt Binder for Coarse Hot Mix Asphalt Mixtures) involved the field cracking performance evaluation of thirteen pavement test sections and data analysis a between laboratory measured properties, asphalt mix designs and the field performance. This report presents the results and findings from these efforts in order to evaluate the impacts of lower-asphalt content coarse hot-mix asphalt mixes.

The selection of the field sections and collection of mix design records (MDR) was completed as Task-1 of this project. The field sampling plans and sample procurement were conducted as Task-2 of this project. The laboratory testing of field procured specimens using disk-shaped compact tensions (DCT) test, lab permeability measurements, mix volumetric information and asphalt content as well as aggregate gradations from ignition oven testing were completed and reported in Chapter 4. For purposes related to selection of pavement sections, details on mix designs and laboratory test results the readers are encouraged to refer to Chapters 2,3, and 4

This chapter is organized into four sections. The second section presents the field cracking performance of all the pavement sections, the third section presents the comparisons between field performance and asphalt mix designs as well as lab measured parameters, and finally the last section summarizes the task and presents the findings from analysis presented in this report. The appendix provides the notes from the field visits of each section along with pictorial summary of the sections.

## 6.2 PAVEMENT CRACKING SECTION PERFORMANCE

### 6.2.1 Pavement Sections

The pavement sections that are being studied through this research project are listed in Table 6.1: Field section highway and project information.. In several instances each study site has more than one pavement profile.  For example, a part of the section is constructed as an overlay on milled pavement and the other part is constructed over a reclaimed base. In such instances or in cases where the project yielded significantly different performance over its length, two pavement sections were selected. All of these sites have been visited by the researchers and on basis of the site visits, 1000 ft. long pavement sections were identified. Typically, the sections were identified to be beginning at a mile post (RP) so that they could be easily identified for purposes of sampling and also to ensure that performance data from pavement management system (PMS) is easily accessible. Field sampling plans have been developed for each of those sections. In addition to development of field sampling plans, the visual distress surveys and crack counts were also performed.

The information about the highway where pavement sections are located is presented in Table 6.1. The table describes the highway location, project number, mix design record information as well as the date of crack count and visual distress survey. The specific information regarding the location of pavement section on the highways indicated in Table 6.1: Field section highway and project information. is shown in Table 6.2: Summary of pavement sections.. This table also shows the information regarding the lane where sections are located, the year of construction, qualitative performance on basis of visual observations during site visits and the type of pavement construction. From these two tables it can be seen that this study captures a breadth of asphalt pavements in terms of their location, pavement types, and years in service. Please note that while TH25 and TH220 were visited by researchers and the sampling plans were prepared and delivered, after communication with the staff at MnDOT, it was decided to not core these sections as the total number of sections to be cored and studied already exceeded the number decided during the early part of the project and in the contract for the study.

The performance data from the MnDOT's Pavement Management System (PMS) was also obtained for each section. The data was obtained from the year of construction onwards.

**Table 6.1: Field section highway and project information.**

| Highway | SP Number | MDR | MnDOT District | Date Visited |
|---|---|---|---|---|
| MN Trunk Highway 6 (TH 6) | 1103-25 | 3A-2010-128 | 3 | 07/30/2014 |
| MN Trunk Highway 9 (TH 9) | 6010-26 | 02-2011-063 | 2 | 01/02/2014 |
| Itasca County Rd 10 (CSAH 10) | 031-610-016 | 01-2012-128 | 1 | 07/30/2014 |
| MN Trunk Highway 10 (TH 10) | 0502-95 | 04-2013-033 | 4 | 07/29/2014 |
| MN Trunk Highway 10 (TH 10) | 5606-42 | | 3 | 10/17/2013 |
| MN Trunk Highway 25 (TH 25) | 7104-19 | 3A-2011-109 | 3 | 01/08/2014 |
| MN Trunk Highway 28 (TH 28) | 6104-11 | 04-2012-026 | 4 | 04/10/2014 |

| | | | | |
|---|---|---|---|---|
| MN Trunk Highway 210 (TH 210) | 1805-72 | 3A-2010-073 | 3 | 01/08/2014 |
| MN Trunk Highway 220 (TH 220) | 6016-37 | 02-2012-045 | 2 | 07/29/2014 |
| MN Trunk Highway 27 (TH 27) | 4803-19 | 3A-2010-045 | 3 | 04/10/2014 |
| MN Trunk Highway 95 (TH 95) / County Road 30 (CSAH 30) | 1306-44 | 0-2012-170 | Metro | 07/28/2014 |

**Table 6.2: Summary of pavement sections.**

| Section | RP / Landmark | Specimen Letter | Construction Year | Visual Performance | Lane | Construction Type |
|---|---|---|---|---|---|---|
| TH 220 | RP 12 | K | 2012 | Good/Fair | D | 3” M/O |
| CSAH 10 | Jct 445B | L | 2012 | Poor | D | 1.5" O/L on old AC |
| TH 27 | RP 171 | M | 2010 | Poor | D | 3" M/O |
| TH 27 | RP 174 | N | 2010 | Good | D | 3" M/O |
| TH 9 | RP 208 | O | 2011 | Poor | D | 3" O/L on reclaimed AC |
| TH 9 | RP 214 | P | 2011 | Good | D | 3" O/L on reclaimed AC |
| TH 28 | RP 81 | Q | 2012 | Poor | D | 4.5" M/O |
| TH 28 | RP 88 | R | 2012 | Good | D | 4.5" M/O |
| TH 6 | RP 53 | S | 2010 | Poor | D | 1.5" M/O |

| | | | | | | |
|---|---|---|---|---|---|---|
| TH 10 | RP 75 | T | 2013 | Poor | D/P | 3.5" M/O |
| CSAH 30 | Jct TH 95 | U | 2012 | Good/Fair | D | 6” M/O |
| TH 10 | RP 159 | V | 2005 | Poor | D/P | 4" M/O (sealed cracks) |
| TH 10 | RP 161 | W | 2005 | Good | D/P | 4" M/O (cracks not sealed) |
| M/O = Mill and Overlay; O/L = Overlay ; BAB = Bituminous on Aggregate Base<br>*Where the term “Jct” is referenced as a landmark, a signpost for the specific roadway is being specified. | | | | | | |

### 6.2.2 Cracking Performance Measure

The transverse cracking data in the PMS data is collected based on the severity of the cracks; low, medium and high. For each severity level, the data is reported in terms of percent cracking (% cracking), which is calculated as 2 times the number of cracks per 500 feet length of the survey section. For the purpose of conducting analysis between the amount of cracking and laboratory tests as well as asphalt mix parameters, a number of measures of field cracking performances can be calculated. In this study, the researchers looked at transverse amounts in terms of total cracking. This is the sum total of low, medium, and high severity cracks. Please note that all data presented in this report includes the crack counts that researchers collected during the site visits. Thus, the field visit information was incorporated with the PMS data providing the cracking performance information for the pavements from their construction until 2013/2014

The total cracking amounts for a given PMS section for each year of distress survey can be used to calculate additional cracking measures that are representative of field cracking performance. In a previous MnDOT research study, a number of different cracking measures were evaluated and assessed, such as, maximum transverse cracking amount, maximum transverse cracking rates, and average transverse cracking rates. More information on these measures can be found in the final report for that study (Dave et al., 2015). Three of the measures proposed in that previous study were used in the analysis of data in the current research. These are described in Table 6.3: Cracking performance measures and descriptions. The reasoning for use of these measures as opposed to others is that these measures captures the cracking amounts of the pavement in context of its performance. For example, a roadway experiencing 0% cracking for the first four years of the service life then cracking to a current amount of 50% is a superior performer to a roadway cracking at 50% in year one and staying at 50% until the current time period. If only current cracking amounts are used this performance difference is neglected. The calculation of these measures are described next, clarifying why these measures might be better suited as opposed to the use of current cracking amounts.

**Table 6.3: Cracking performance measures and descriptions.**

| Measure | Description | Unit |
|---|---|---|
| **Total Transverse Cracking (TCTotal)** | Sum of the total transverse cracking (low + medium + high) work over the service life. Total area is then normalized against the square of number of years for which pavement section has been in service. | % cracking/year |
| **Maximum Total Transverse Cracking Rate (MTCRTotal)** | Maximum increase in total transverse cracking amounts (low + medium + high) between any two consecutive years of service. | % cracking/year |
| **Average Total Transverse Cracking (ATCTotal)** | Sum of total transverse cracking (low + medium + high) for every survey year of a pavement section normalized against number of years for which pavement section has been in service. | % cracking/year |

If we assume that the transverse cracking amount in a pavement section is as shown in Figure 6.1, the Total Transverse Cracking (TCTotal) is the area under the percent cracking versus years in service curve (total cracking performance) divided by the total years in service. For reference, if a pavement section has TCTotal of 5%/year that would roughly translate into section reaching 100% cracking in 10 years, whereas a TCTotal of 10%/yr. will translate into 100% transverse cracking in 5 years. The MTCRTotal will be 12%/yr. as that indicates the highest transverse cracking rate experience by this pavement between any two consecutive years, which in this instance happens to be during the first year of pavement's service. Finally, ATCTotal will be 5.4%/yr. (59% / 11 year) as that is the average rate of cracking experienced by this pavement over its life.

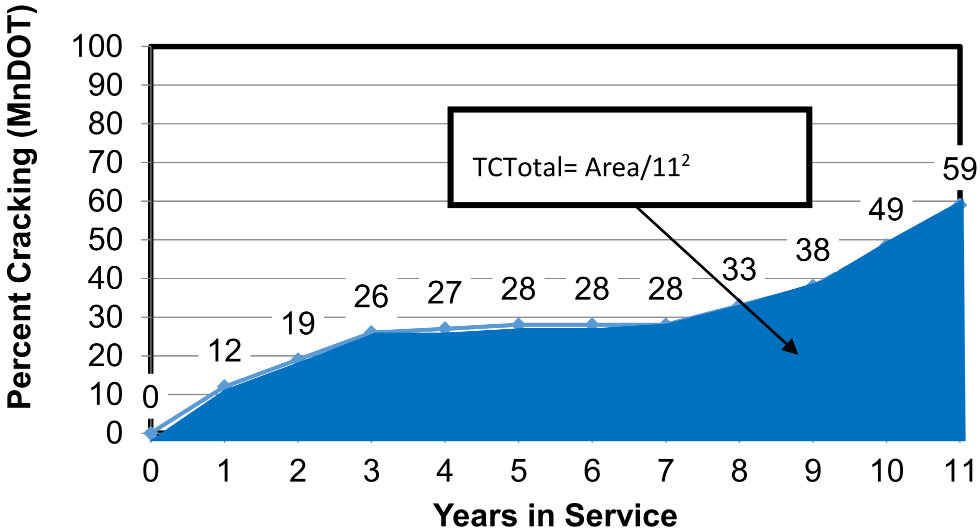



**Figure 6.1: Example showing calculation of TCTotal and other cracking measures.**

### 6.2.3 Cracking Performance of Field Sections

The amounts of transverse cracking with respect to time for each of the study site is presented in this section. Basic notes taken during the site visits are also provided. Note that all percent cracking measures defined on the y-axis in these figures are designated "MnDOT". In other words, the cracking measure is presented here in the same units as utilized by the MnDOT Pavement Management System. The details on the field notes and the select pictures of the sections are presented in the Appendix of this report.

#### 6.2.3.1 TH6 – SP1103-25 – RP53 (Specimen Letter S)

The project on Trunk Highway 6 (SP 1103-25) has been in service for four years. During the first year of service, the roadway deteriorated to nearly 20% transverse cracking (Figure 6.2: Cracking performance of TH 6 (SP 1103-25)). Since that time, the cracking rate has tapered off slightly. While the roadway is still experiencing annual increases in transverse cracking amounts, there has not been an overly drastic increase between two years.

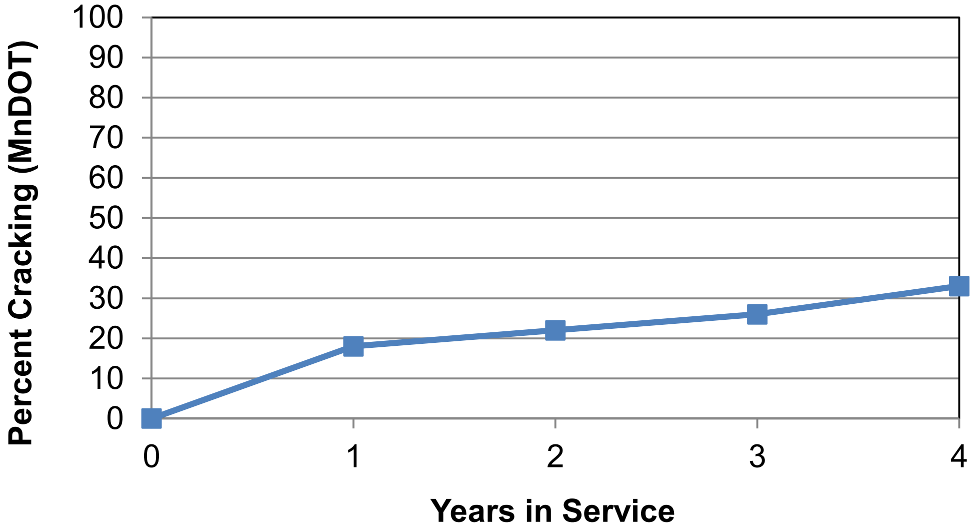



**Figure 6.2: Cracking performance of TH 6 (SP 1103-25)**

#### 6.2.3.2 TH9 – SP6010-25 – RP208 (Specimen Letter O) and RP214 (P)

Trunk Highway 9 (SP 6010-26) had two study sections. Both of these sections were constructed as 3" overlays on reclaimed asphalt. As can be seen in Figure 6.3: Cracking performance of TH 9 (SP 6010-26), the section at RP 214 has performed slightly better than the section at RP 208. The main purpose a section was considered poor performing (RP 208) was due to ride quality. Overall, both sections are performing well.

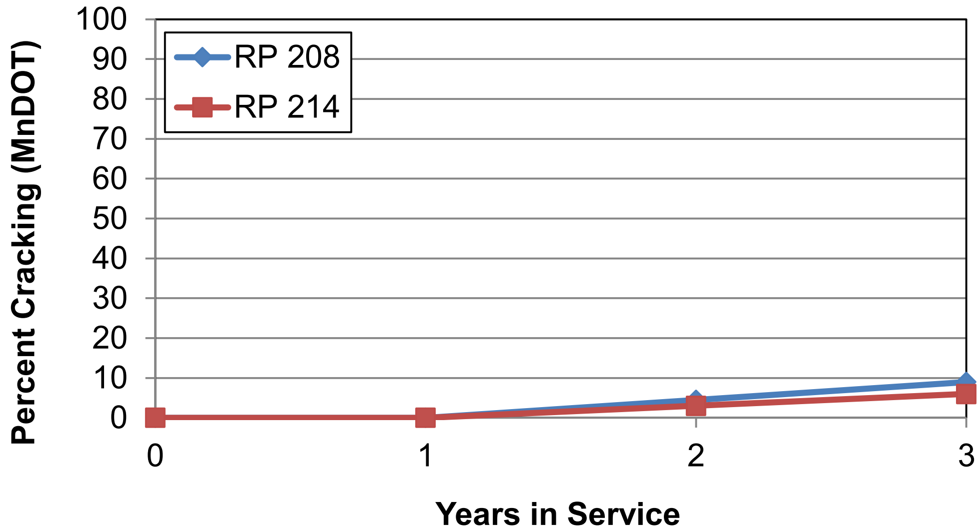



Figure 6.3: Cracking performance of TH 9 (SP 6010-26)

#### 6.2.3.3 CSAH10– SP031-610-016– Jct 445B (Specimen Letter L)

County State Aid Highway (CSAH) 10 (SAP 031-610-016) has both a poor performing (JCT 445B) and good performing (JCT 446) sections. The performance of each can be seen in Figure 6.4: Cracking performance of CSAH 10 (SAP 031-610-016). The section at JCT 446 is a 3” mill and overlay, while the JCT 445B section is a 1.5” overlay on old asphalt. The service life of two years is short, but the drastic difference between the two sections is apparent.

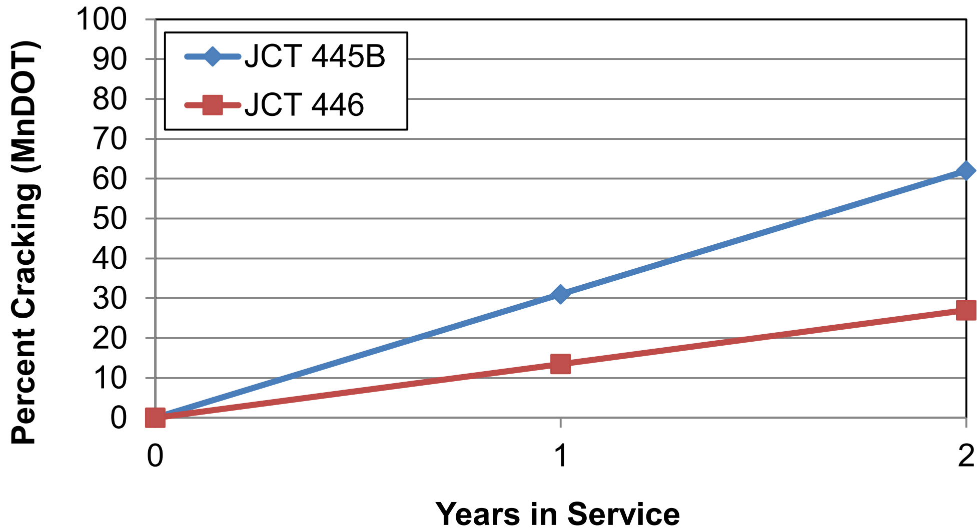



**Figure 6.4: Cracking performance of CSAH 10 (SAP 031-610-016)**

#### 6.2.3.4 TH10 – SP0502-95 – RP159 (Specimen Letter V) and RP161 (W)

The study area on Trunk Highway 10, a divided four lane highway, contained two different pavement sections. The cracking amounts are separated into driving lane (D) and passing lane data (P) (Figure 6.5: Cracking Performance of TH 10 (SP 0502-95)). Both sections, RP 159 and RP 161, were constructed using a 4" mill and overlay. The cracks in the section beginning at RP 159 were sealed at the time of site visit where, as for the section beginning at RP 161 the cracked were not sealed.

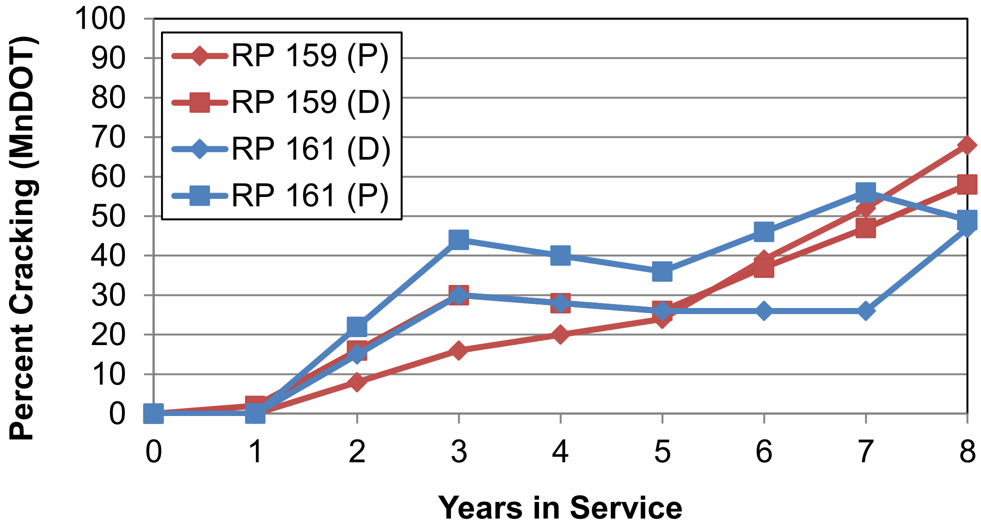



**Figure 6.5: Cracking Performance of TH 10 (SP 0502-95)**

### 6.2.3.5 TH10 – SP5606-42 – RP75 (Specimen Letter T)

Trunk Highway 10 (SP 5606-42) consists of one section and two lanes. The project is a 3.5" mill and overlay. Over the first year of service, this roadway experienced a substantial deterioration (Figure 6.6: Cracking performance of TH 10 (SP 5606-42)). The reason for this is unclear, as most of the mill and overlay sections in this research feature significantly better resistance to transverse cracking in year 1. The analysis of this project should provide clarity for the severe cracking experienced by this section.

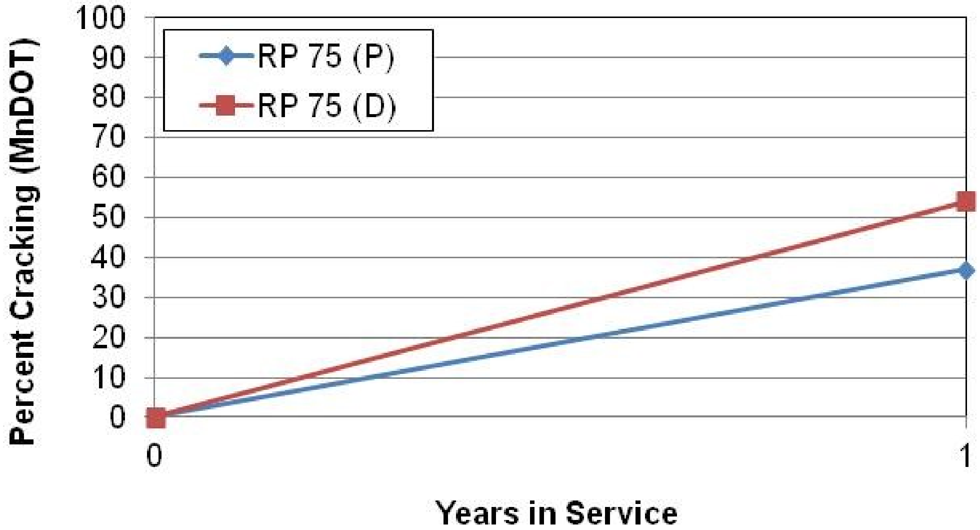



Figure 6.6: Cracking performance of TH 10 (SP 5606-42)

### 6.2.3.6 TH27 – SP4803-19 – RP171 (Specimen Letter M) and RP174 (N)

Trunk Highway 27 (SP 4803-19) data represents four-year service life. Two sections were observed for this project. RP 171 and RP 174 are both 3" mill and overlay construction. The sections feature similar cracking amounts, with both currently exhibiting roughly 35% transverse cracking (Figure 6.7: Cracking performance of TH 27 (SP 4803-19)).

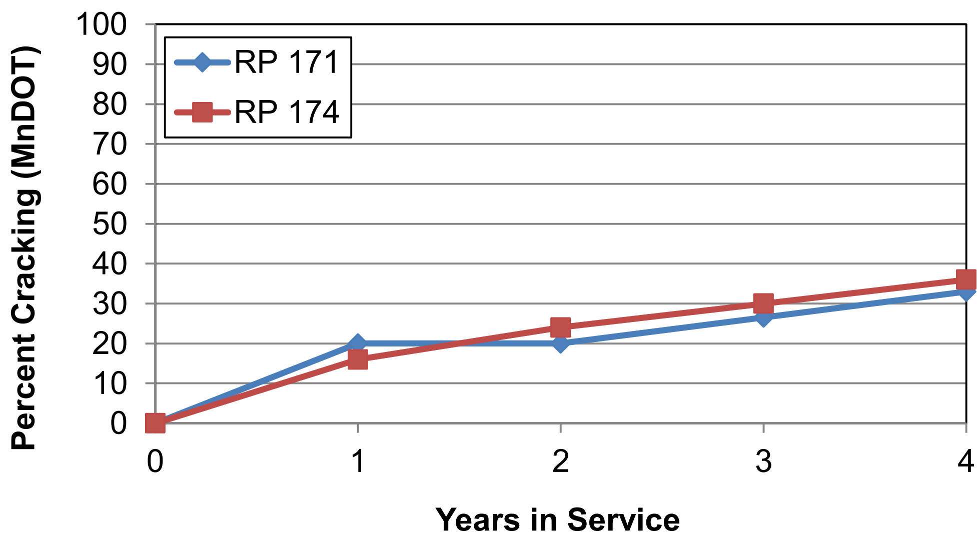



Figure 6.7: Cracking performance of TH 27 (SP 4803-19)

### 6.2.3.7 TH28 – SP6104-11 – RP81 (Specimen Letter Q) and RP88 (R)

Trunk Highway 28 (SP 6104-11) performance can be found in Figure 6.8: Cracking performance of TH 28 (SP 6104-11). Two sections of the same 4.5" mill and overlay construction were observed. Similar to previous sections of same construction types, both study corridors are performing nearly identical. The current transverse cracking levels are at approximately 30% over a two-year service life. This is a fairly substantial increase over that time period, especially considering the majority of this deterioration occurred over the second year of the service life.

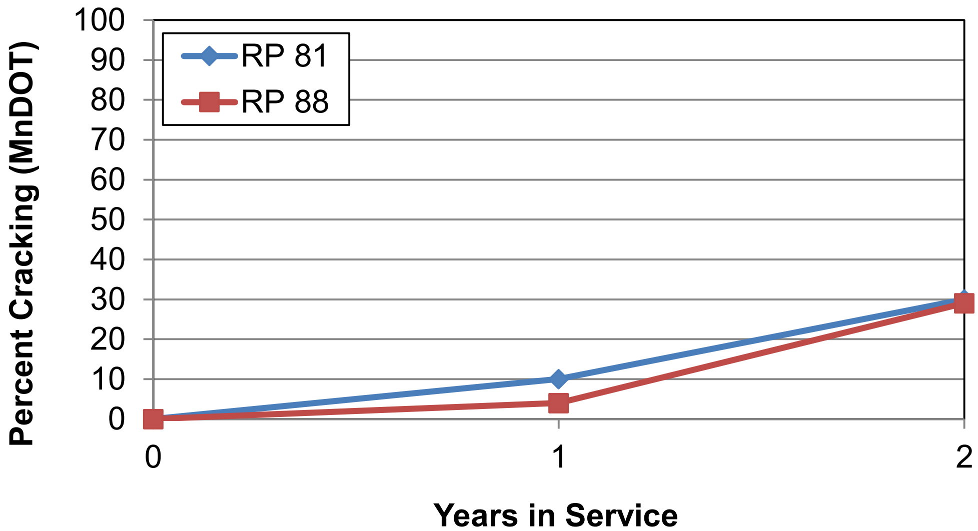



**Figure 6.8: Cracking performance of TH 28 (SP 6104-11)**

### 6.2.3.8 CSAH30 – SP1306-44 – Jct TH95 (Specimen Letter U)

The service life performance of County State Aid Highway 30 (SP 1306-44) can be seen in Figure 6.9: Cracking performance of CSAH 30 (SP 1306-44). Still early in the service life, the roadway has seen a gradual increase in cracking performance since the construction year. Future observation of this roadway should monitor if this gradual trend is maintained.

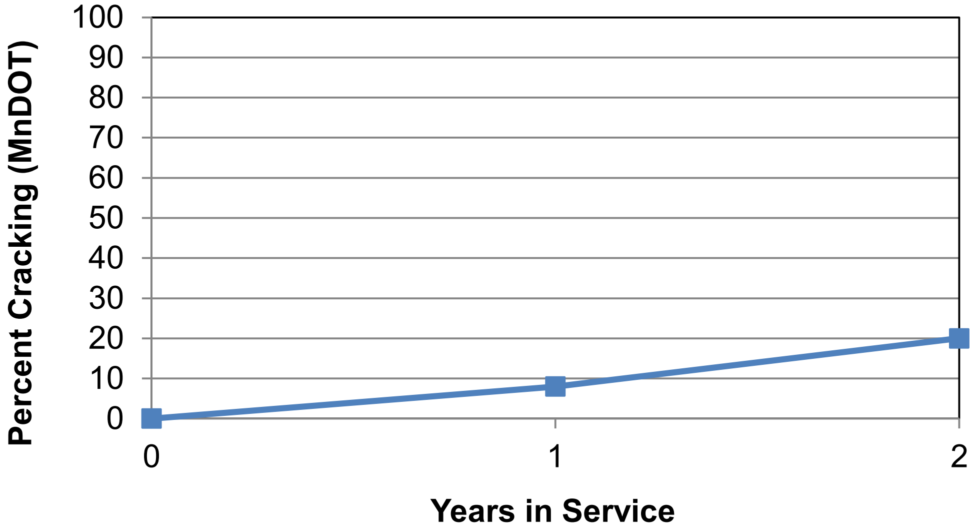



**Figure 6.9: Cracking performance of CSAH 30 (SP 1306-44)**

### 6.2.3.9 TH220 – SP6016-37 – RP 12 (Specimen Letter K)

Trunk Highway 220 (SP 6016-37) is a 3" mill and overlay project. As seen in Figure 6.10: Cracking performance of TH 220 (SP 6016-37), a small amount of transverse cracking has occurred on this roadway, with all of the deterioration occurring after the first year of service. No substantial cracking has occurred on this roadway thus far in the two-year service life.

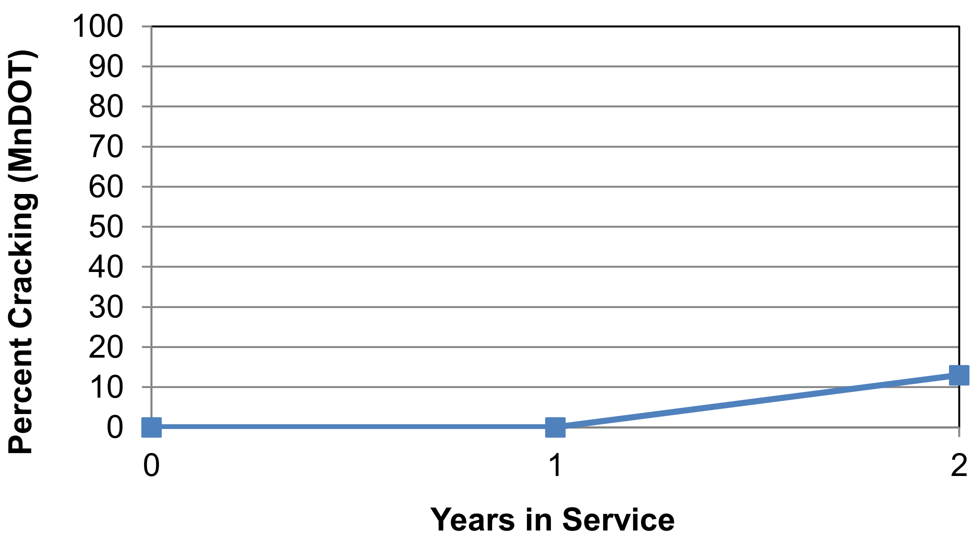



**Figure 6.10: Cracking performance of TH 220 (SP 6016-37)**

### 6.2.4 Transverse Cracking Performance of All Study Sections

The transverse cracking performance of all pavement sections studied in this project is presented here. The TCTotal parameter for all pavement sections is shown in Figure 6.11: TCTotal for all study sections.. As previously described, a pavement with TCTotal of 5%/year will reach 100% cracking in approximately 10 years. It can be seen that two of the pavements have substantially poor cracking performance as compared to others. There are several pavements with TCTotal near the 5% mark with average of all sections to be approximately 6.65%/yr. It should be noted that large number of sections in this study have only been in service for 2 years at the time of data collection and analysis, anecdotal evidence has shown that it is usually 5-8 years before clear distinction is seen between the transverse cracking performances of good and poor performing sections.

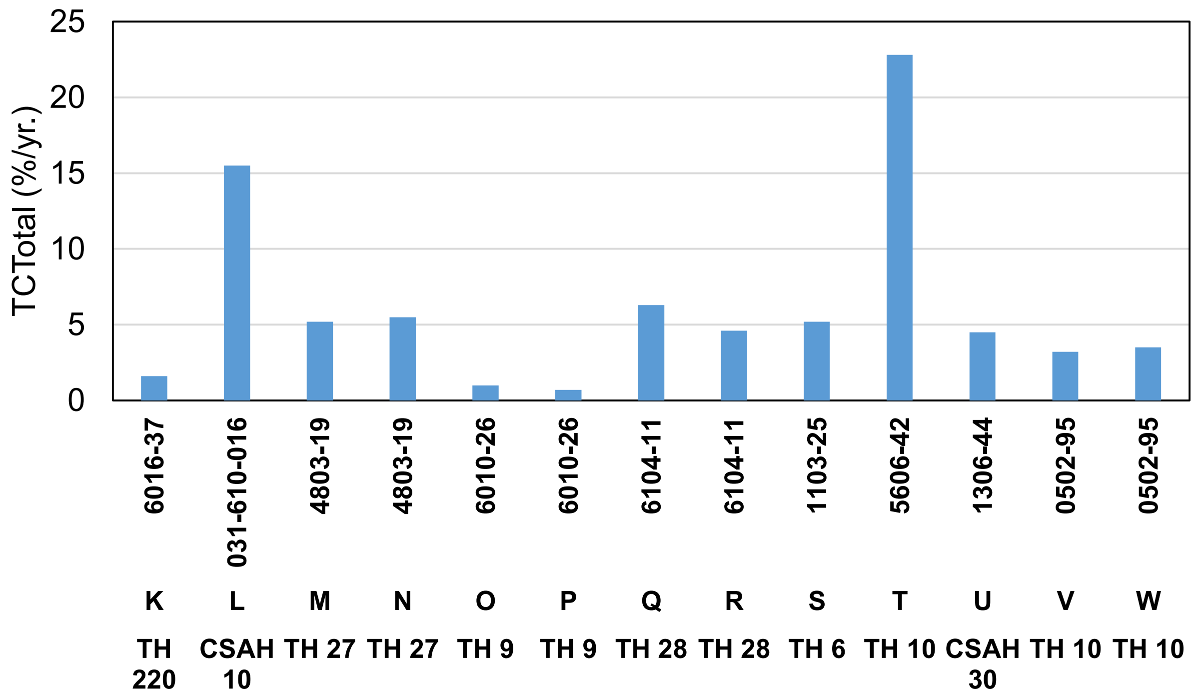



Figure 6.11: TCTotal for all study sections.

The maximum transverse cracking rate (MTCRTotal) for all sections is presented in Figure 6.12: MTCRTotal for all study sections.. Once again there is wide range of performance represented by these sections. The maximum rates are over 30% indicating pavements that will be significantly inferior cracking performance. The average MTCRTotal for all sections is approximately 17.2%/yr. The average cracking rates (ATCTotal) is shown in Figure 6.13: ATCTotal for all study sections.. It can be seen that seven out of thirteen sections have average transverse cracking rates at or above 20%, indicating that these pavements will reach 100% transverse cracking conditions in span of 5 years from construction. The average of all sections for average transverse cracking rate is 20.6%/yr.

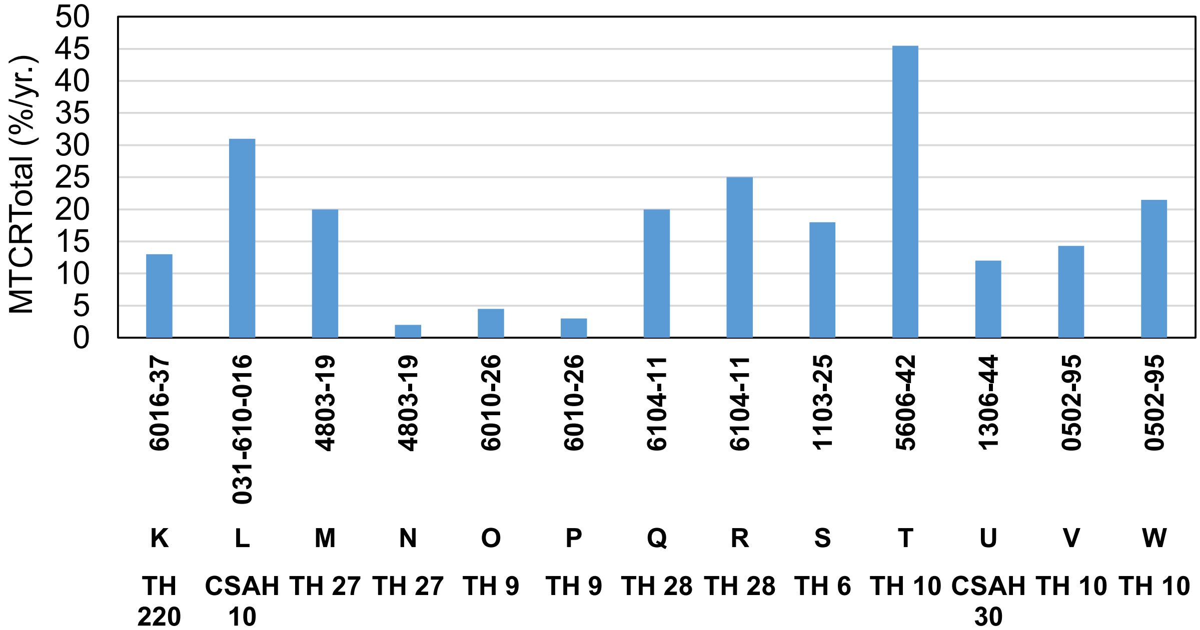



Figure 6.12: MTCRTotal for all study sections.

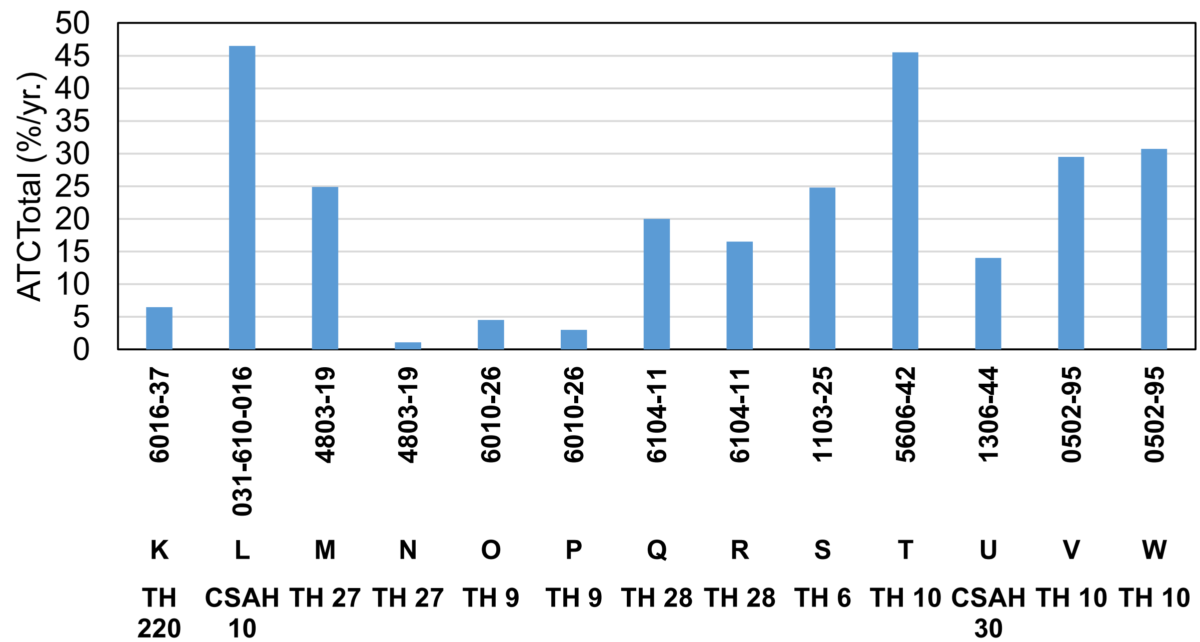



Figure 6.13: ATCTotal for all study sections.

## 6.3 DATA ANALYSIS, RESULTS AND DISCUSSION

This section discusses the comparison between the field cracking performance and the laboratory tested parameters. The field cracking performance is also compared with the asphalt mix design parameters.

### 6.3.1 Comparison of Design Mixture Properties with Field Performance

The asphalt mix properties of the wear course mixtures of the various pavement sections under study are presented in Table 6.4: Section mix design properties.. The table shows the pertinent parameters that are typically used for purposes of characterizing asphalt mixtures. The asphalt binder grade used for the virgin binder component of the mixture is shown along with the amount of binder contribution to the mixes form recycled sources. The three most commonly used volumetric parameters for characterization and specification of asphalt mixtures in practice at present are adjusted asphalt film thickness (Adj. AFT), voids in mineral aggregates (VMA) and voids filled with asphalt (VFA). At present, the MnDOT 2360 specification for plant produced asphalt mixtures utilizes Adj. AFT as a control parameter. The field core samples were tested as per the AASHTO T166 specifications to measure the bulk specific gravities of the asphalt mixtures. These are also reported in Table 6.4.

**Table 6.4: Section mix design properties.**

| Section | Specimen Letter | PG Grade | PG Spread | Asphalt Content | Recycled Asphalt Content | Adj. AFT | Voids in Mineral Aggregate (VMA) | Voids Filled with Asphalt (VFA) | Average Bulk Specific Gravity($G_{mb}$) |
|---|---|---|---|---|---|---|---|---|---|
| TH 220 | K | 58-28 | 86 | 4.2% | 23.80% | 9.5 | 13.50% | 70.3% | 2.307 |
| CSAH 10 | L | 58-28 | 86 | 4.3% | 23.30% | 9.1 | 13.50% | 70.4% | 2.382 |
| TH 27 | M | 58-28 | 86 | 4.3% | 37.20% | 8.8 | 13.60% | 70.6% | 2.399 |
| TH 27 | N | 58-28 | 86 | 4.3% | 37.20% | 8.8 | 13.60% | 70.6% | 2.401 |
| TH 9 | O | 58-34 | 92 | 4.2% | 26.20% | 8.9 | 13.10% | 69.6% | 2.370 |
| TH 9 | P | 58-34 | 92 | 4.2% | 26.20% | 8.9 | 13.10% | 69.6% | 2.379 |
| TH 28 | Q | 58-34 | 92 | 4.2% | 23.80% | 9.4 | 12.50% | 68.1% | 2.343 |
| TH 28 | R | 58-34 | 92 | 4.2% | 23.80% | 9.4 | 12.50% | 68.1% | 2.340 |
| TH 6 | S | 58-28 | 86 | 4.4% | 36.40% | 9.2 | 13.90% | 71.2% | 2.365 |
| TH 10 | T | 58-28 | 86 | 4.3% | 23.30% | 8.9 | 13.70% | 70.8% | 2.356 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| CSAH 30 | U | 64-34 | 98 | 4.4% | 11.40% | 9.0 | 13.40% | 70.2% | 2.512 |
| TH 10 | V | 64-28 | 92 | 5.3% | 45.30% | 7.8 | 14.40% | 72.3% | 2.339 |
| TH 10 | W | 64-28 | 92 | 5.3% | 45.30% | 7.8 | 14.40% | 72.3% | 2.536 |

Since a major focus of this study is to evaluate the impact of low asphalt binder content of the mixtures on its cracking performance, comparisons plots are generated between cracking performance measures and design asphalt contents. The results showing comparisons between the design binder content and various cracking performance measures is shown in Figure 6.14: Cracking performance versus design asphalt content.. It can be seen from the plot that the design asphalt content by itself may not be a good indicator of the pavement's cracking performance as no clear trends are evident.

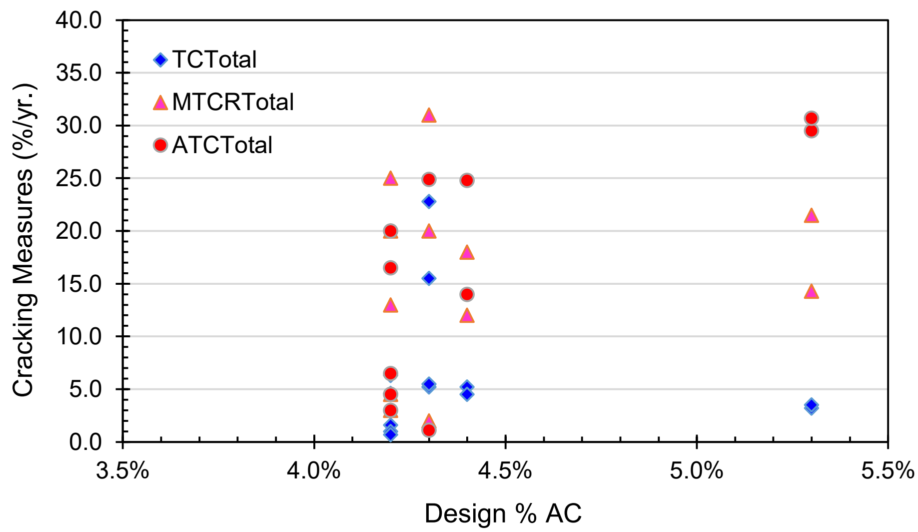



Figure 6.14: Cracking performance versus design asphalt content.

The cracking performance measures are plotted against VMA and adjusted AFT in Figure 6.15: Cracking performance versus voids in mineral aggregates (VMA) (trend-line fitted to ATCTotal) and Figure 6.16: Cracking performance versus adjusted asphalt film thickness (AFT) (trend-line fitted to ATCTotal) respectively. In both instances, trend-lines are fitted between ATCTotal and the volumetric parameters. Please note that the intent of these trend-lines is simply to show the weakness of the relationship and they are only for purposes of graphical display. Trends are relatively weak for both VMA and AFT. In case of VMA, the trend is actually reversed as compared to general consensus of improved cracking performance with increased VMA. AFT trend is in agreement with general consensus but still it is very weak relationship. This further reinforces that use of volumetric measures as a predictor of asphalt mixture's field cracking performance may not be adequate by itself.

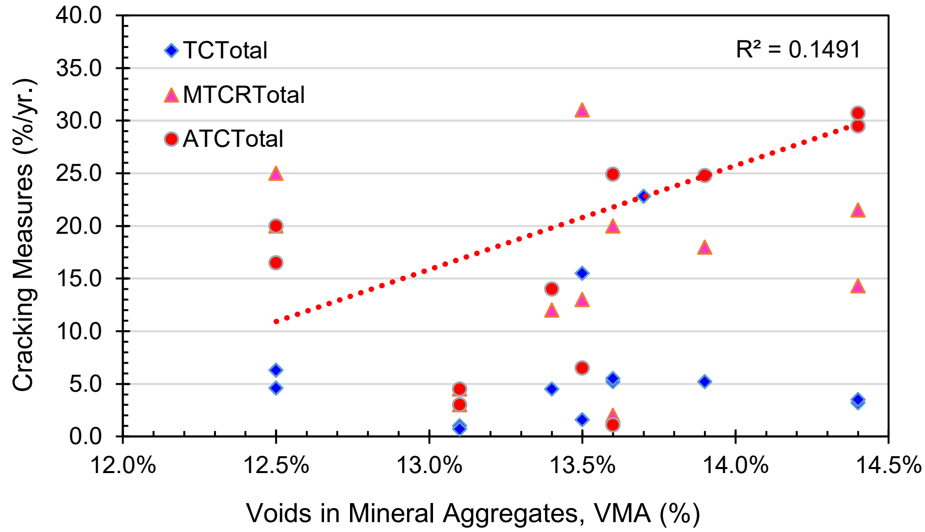



**Figure 6.15: Cracking performance versus voids in mineral aggregates (VMA) (trend-line fitted to ATCTotal)**

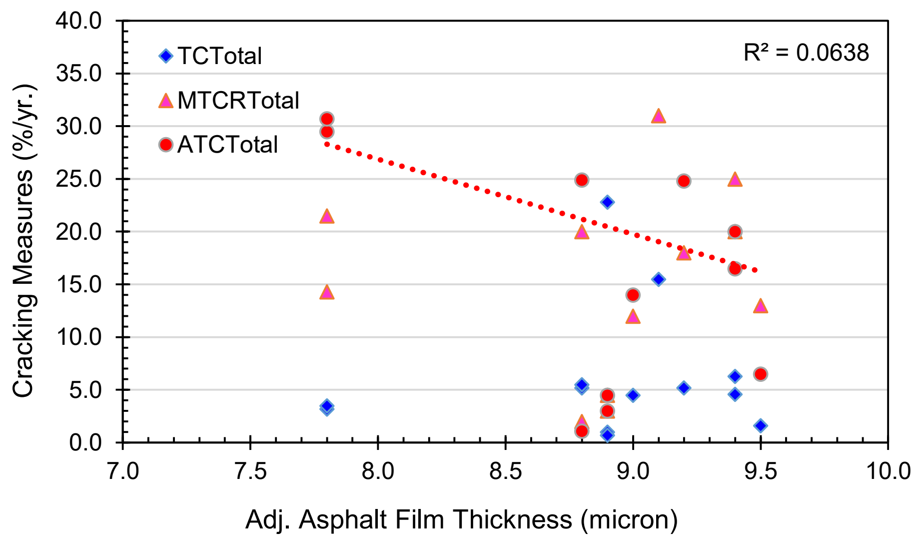



**Figure 6.16: Cracking performance versus adjusted asphalt film thickness (AFT) (trend-line fitted to ATCTotal)**

The performance grade of the asphalt binder is compared next with field performance measures. The binder grade used in this comparison represents the specified grade for the mixture and typically represents the virgin binder component of the mixture. Figure 6.17: Total transverse cracking (TCTotal) performance versus PG spread. compares the spread of asphalt binder grade (difference between high and low grade temperatures) versus the TCTotal. From the data it can be seen that in an averaged manner as the spread of the binder grade increases, so does the transverse cracking performance. The low temperature grade (referred to as PGLT) of the binders are compared with TCTotal and ATCTotal, this is presented in Figure 6.18: Total transverse cracking (TCTotal) performance versus PGLT. and Figure 6.19: Average transverse cracking rate (ATCTotal) versus PGLT. respectively. It can be seen from the fitted trend-lines that the PGLT has an effect on the cracking performance with -34 graded binders showing significantly better cracking performance. The observation of the ATCTotal data indicates that the average cracking rate for all mixtures with PGLT of -28 ºC is approximately 26.2 %/yr. as opposed to 11.6%/yr. for mixes with PGLT of -34 ºC, this would translate in pavement life to 100% cracking for -28 ºC binders in under 4 years and approximately 9 years for -34 ºC binders. Majority of -34 ºC binders were used on asphalt wear courses placed on full depth reclamation projects. Thus, pavement type is also an influencing factor in the results presented here. This observation is consistent with other recent studies of MnDOT pavements.

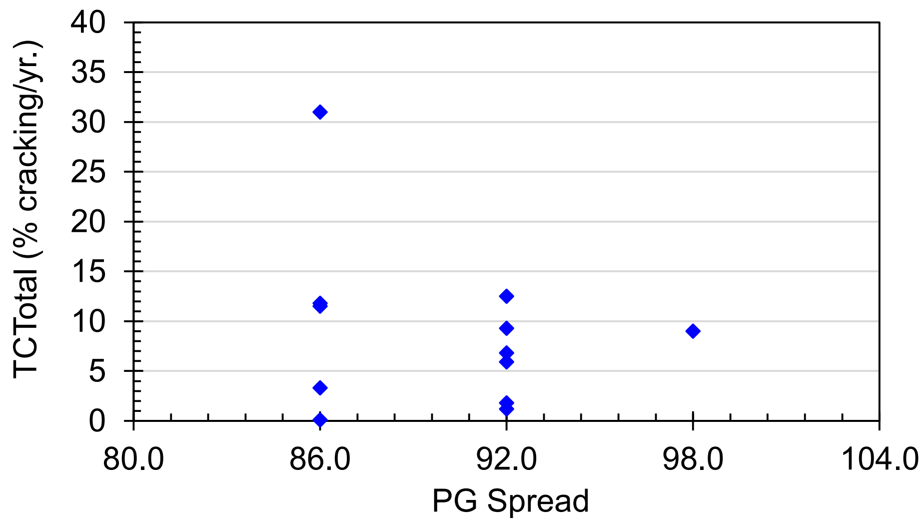



**Figure 6.17: Total transverse cracking (TCTotal) performance versus PG spread.**

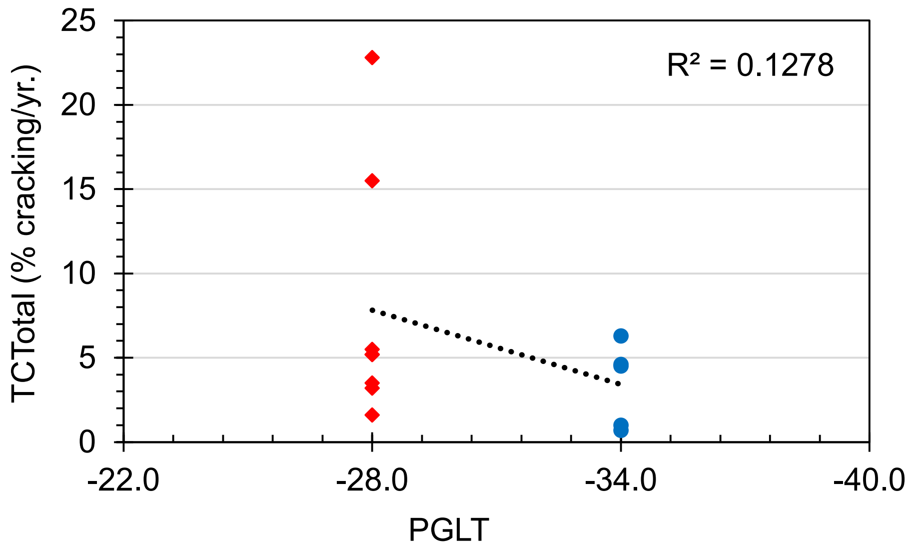



**Figure 6.18: Total transverse cracking (TCTotal) performance versus PGLT.**

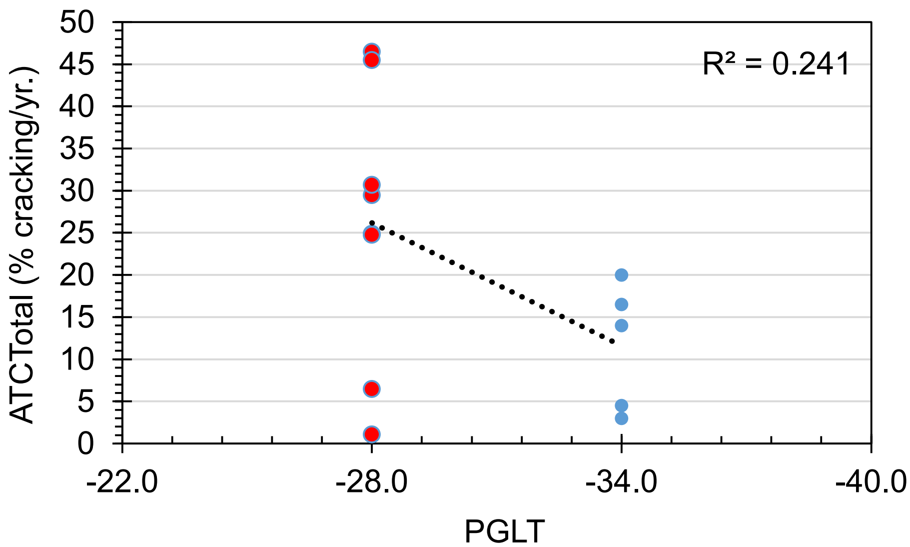



**Figure 6.19: Average transverse cracking rate (ATCTotal) versus PGLT.**

The amount of recycled binder as a percent of total binder amount is compared with field cracking performance next. The comparison in terms of TCTotal is presented in Figure 6.20: Total transverse cracking (TCTotal) performance versus percent recycled binder.. Note that the data does not show an increasing or decreasing trend, similar results were observed for other cracking measures (ATCTotal and MTCRTotal). Once again, it should be noted that majority of evaluated pavements are asphalt overlays with some wear courses on full depth reclamation, thus direct comparison of mixture effects to cracking performance cannot be made.

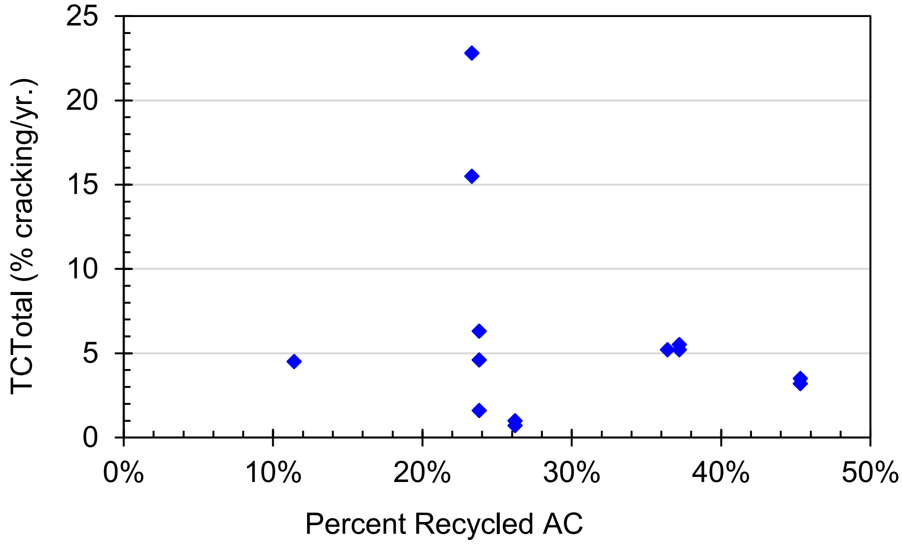



**Figure 6.20: Total transverse cracking (TCTotal) performance versus percent recycled binder.**

Finally, the type of pavement construction (thin mill and overlay versus thick mill and overlay versus reclaim and overlay) was compared with the transverse cracking performance. The thin mill and overlay sections are defined here as overlays with thickness of less than 3”. The comparison between cracking performance and the construction type is shown in Figure 6.21: Total transverse cracking (TCTotal) versus construction type.. As seen in previous studies the type of construction has a very significant effect on the cracking performance. In this study, the average cracking rate for thin overlay construction is found to be 35.65%/yr. as opposed to 21%/yr. for thick overlays and 3.75%/yr. for reclaim sections.

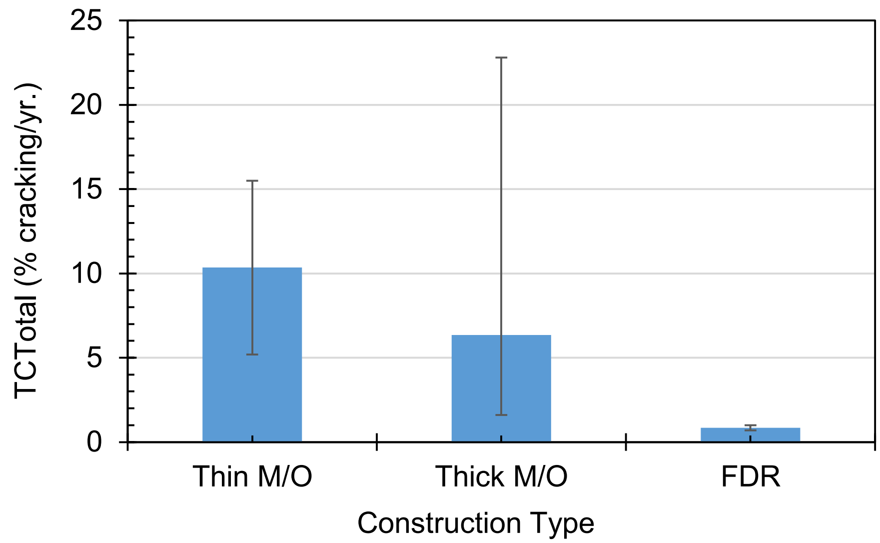



**Figure 6.21: Total transverse cracking (TCTotal) versus construction type.**

## 6.3.2 Comparison of Laboratory Measured Mixture Properties with Field Performance

In this section, the field transverse cracking performance is compared with the lab measured parameters. The lab measurements were conducted on cored samples obtained from the pavement sections. The details on the laboratory testing and results are presented in Chapter 4. The comparisons are presented for permeability, DCT fracture energy and gradation measures from ignition oven residue testing.

### 6.3.2.1 Permeability

The permeability of asphalt mixtures has been hypothesized to have significant effect on the durability and performance of the mixtures. The cause of high permeability is primarily presence of interconnected voids. The use of permeability over air void level has been recommended by researchers in past as a better measure of asphalt mixture's durability. The comparisons between lab measured permeability (using Karol-Warner permeameter and Florida DOT test procedure) and cracking performance are plotted in Figure 6.22: Total transverse cracking (TCTotal) versus permeability (shaded box indicates typical permeability range for dense graded asphalt mixtures). and Figure 6.23: Average transverse cracking rate (ATCTotal) versus permeability (shaded box indicates typical permeability range for dense graded asphalt mixtures). In general, it can be seen that as the permeability increases the cracking performance deteriorates. The comparison between ATCTotal and permeability show that of eight mixtures with permeability greater than typical range for dense graded asphalt mixtures, six have very high average cracking rates.

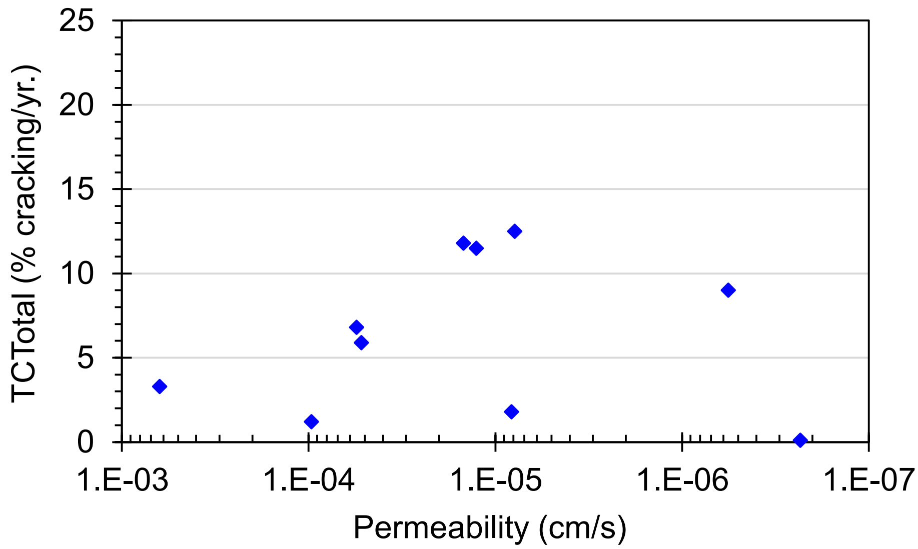



**Figure 6.22: Total transverse cracking (TCTotal) versus permeability (shaded box indicates typical permeability range for dense graded asphalt mixtures).**

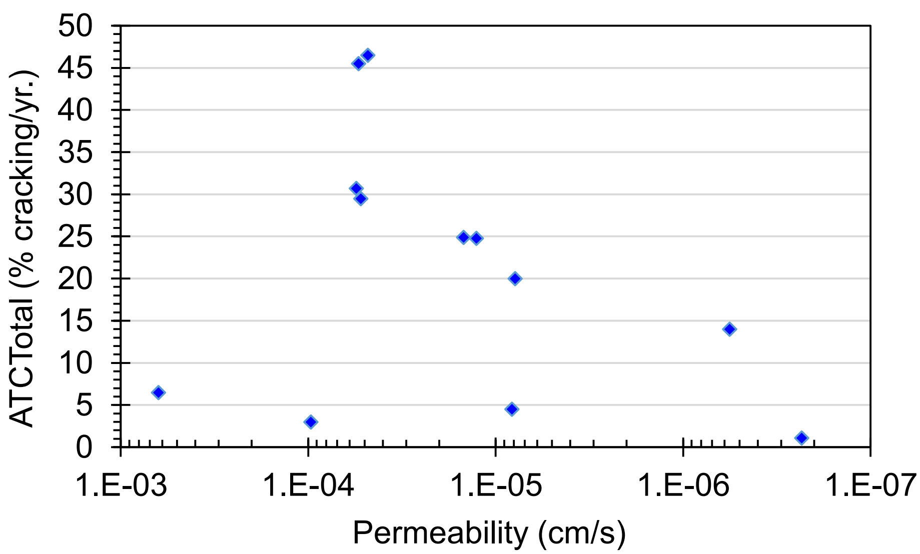



**Figure 6.23: Average transverse cracking rate (ATCTotal) versus permeability (shaded box indicates typical permeability range for dense graded asphalt mixtures).**

### 6.3.2.2 Disk-shaped Compact Tension (DCT) Test

The disk-shaped compact tension (DCT) fracture energy tests were conducted on samples from each pavement section. The DCT fracture energy is being closely evaluated by MnDOT and several other transportation agencies as a cracking performance prediction parameter for asphalt mixtures. Several agencies including MnDOT have conducted pilot implementations of minimum fracture energy requirements in the asphalt mixture specifications.

The comparison between the DCT fracture energies and current cracking amounts of the pavement sections is presented in Figure 6.24: Current cracking amount versus DCT fracture energy.. The recommended minimum threshold value of 400 J/m$^2$ is also indicated on the plot. While a trend between DCT fracture energy and current cracking amount is not evident, it can be seen that out of twelve mixtures that are below the recommended threshold, eight are above or approaching substantial transverse cracking amount of 30%. The comparison between DCT fracture energy and average transverse cracking rate (ATCTotal) is plotted in Figure 6.25: Average transverse cracking rate (ATCTotal) versus DCT fracture energy.. Once again it can be seen that of twelve mixtures below the recommended fracture energy threshold of 400 J/m$^2$ eight have very high average cracking rates. It should be noted that only one mixture meets the recommended threshold and thus from this dataset it cannot be concluded that once fracture energy increases above 400 J/m$^2$ the pavement cracking performance improves dramatically.

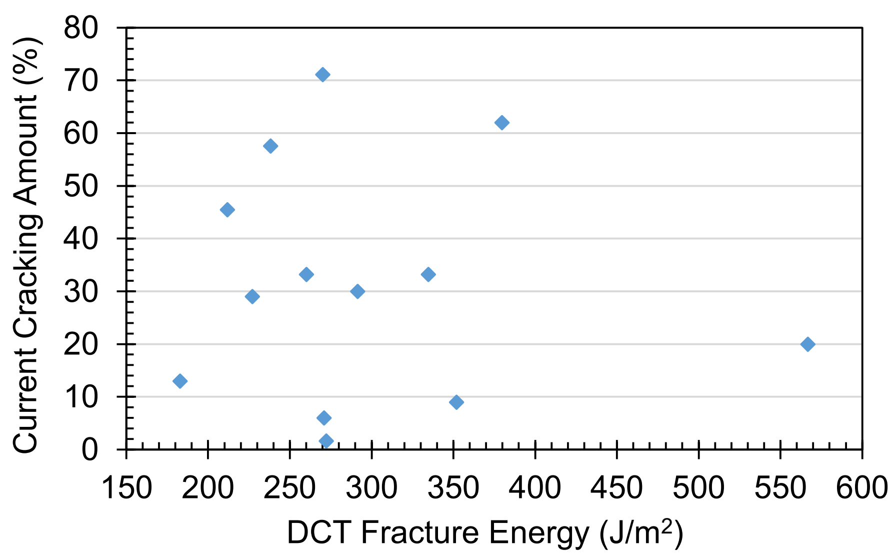



**Figure 6.24: Current cracking amount versus DCT fracture energy.**

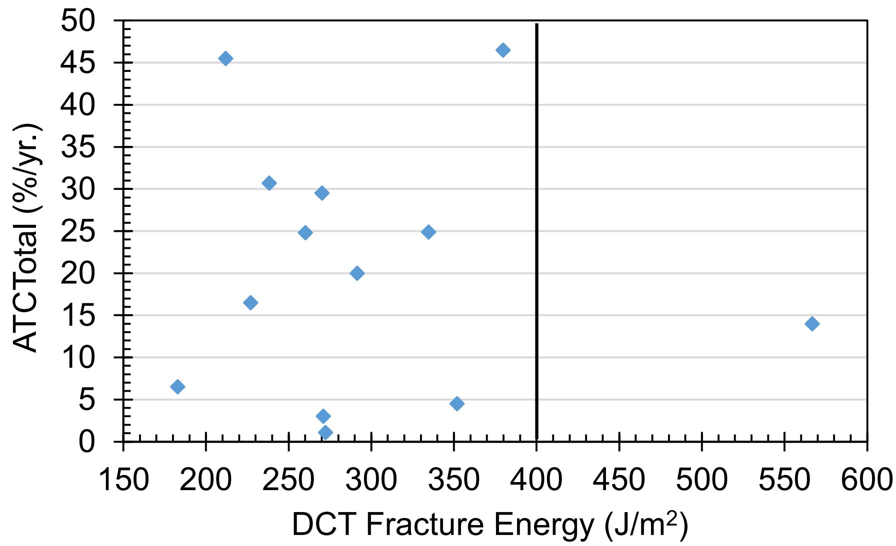



**Figure 6.25: Average transverse cracking rate (ATCTotal) versus DCT fracture energy.**

#### 6.3.2.3 Aggregate Gradation

The comparison between cracking performance and the gradation of recovered aggregates from ignition oven residue of field samples is presented in this sub-section. The gradation measures in terms of amount of aggregate passing on various MnDOT control sieves was conducted. After a thorough analysis, two set of comparisons showed the highest correlations. Figure 6.26 shows the average transverse cracking rates plotted against the fraction of aggregate passing ½ inch sieve and retained on #4 sieve. It can be seen that a relatively strong correlation exists between this parameters and average cracking rate, with cracking rate decreasing as this intermediate portion of aggregate gradation increases. Similarly, a comparison is plotted between average cracking rate and aggregate fraction passing #4 sieve and retained on #200 sieve in Figure 6.27: Average transverse cracking rate (ATCTotal) versus percent aggregate

between #4 and #200 sieve sizes. Please note that majority of tests exhibited that the asphalt mixtures had very high amount of fraction passing #200 sieve (c.f. Chapter 4), it is hypothesized that this is partially due to break-down of aggregate in ignition oven. Nonetheless, a strong trend is once again seen whereby as the fraction of aggregate between #4 and #200 sieve increases the field cracking rate also increases.

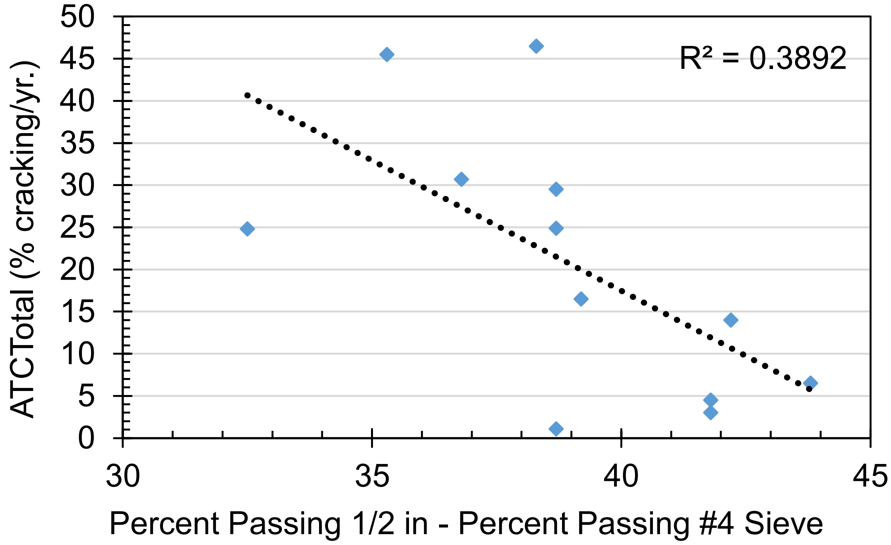



**Figure 6.26: Average transverse cracking rate (ATCTotal) versus percent aggregate between 1/2 in and #4 sieve sizes.**

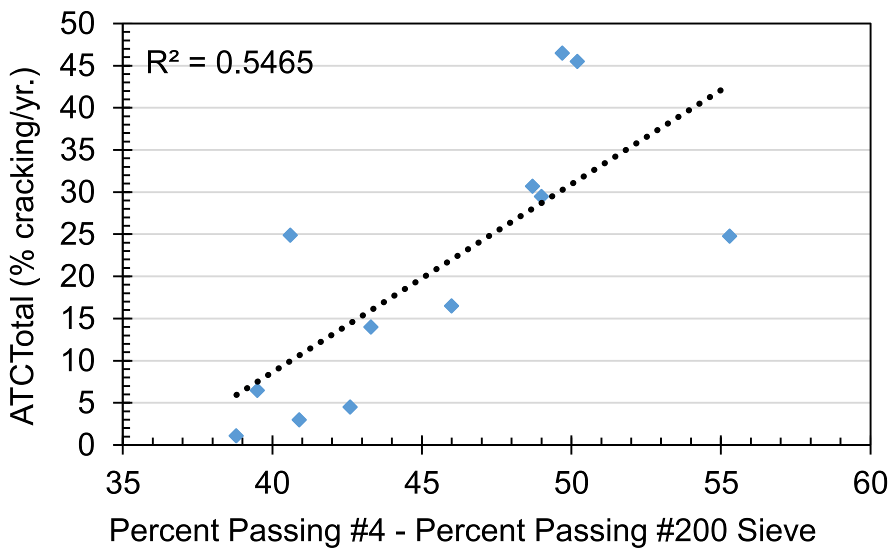



**Figure 6.27: Average transverse cracking rate (ATCTotal) versus percent aggregate between #4 and #200 sieve sizes.**

### 6.3.3 Effects of Mix Parameters and Permeability on Fracture Energy

This section discusses the comparisons between the asphalt mix designs and two of the performance related lab parameters used in this research, i.e. disk-shaped compact tension fracture energy and permeability.

The comparisons between the design asphalt content and the DCT fracture energy from all twelve pavement study sections is plotted in Figure 6.28: Design asphalt content versus DCT fracture energy.. The data presented herein do not show any apparent trend between these two parameters. It should be noted that the extent of data is limited and only focusses primarily on mixtures that are coarser in gradation and with lower asphalt contents than typical Superpave dense-graded mixtures. Furthermore, the test results here only show results from field procured samples which were all collected at different pavement lives, for example, the two of the higher asphalt content mixtures (design asphalt content = 5.3%) were in service for nine years before sampling where as some of the lower asphalt content mixtures had been in service only for 2-3 years.

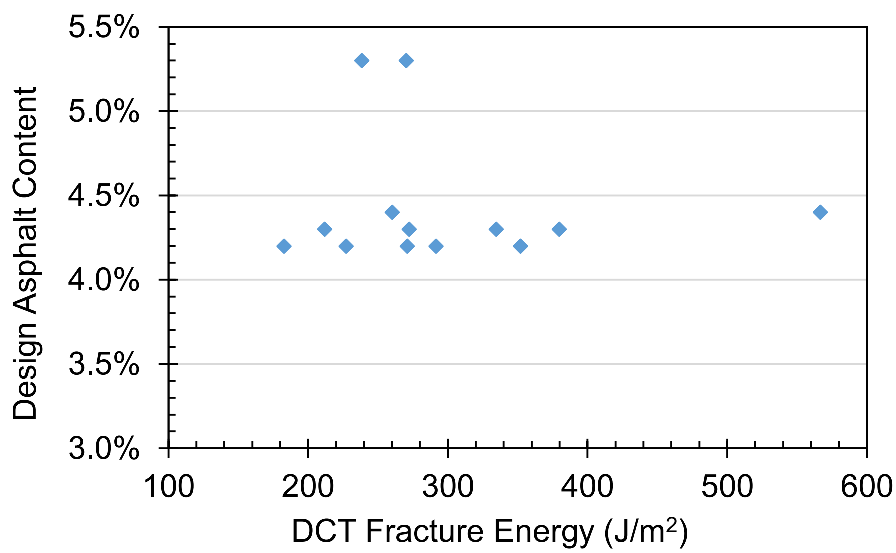



Figure 6.28: Design asphalt content versus DCT fracture energy.

On conclusion of DCT testing the specimens were tested using the ignition oven to estimate the actual asphalt binder content in the mixtures. As previously indicated in Chapter 4, the ignition oven procedure requires extensive calibration and the results from it should be considered suspect in absence of such calibration. At present, MnDOT OM&RR is in process of testing three mixtures using chemical extraction method to get an accurate measure of the amount of asphalt binder. The comparison between the estimate (un-calibrated) amount of asphalt binder from ignition oven tests and DCT fracture energies is shown in Figure 6.29: Asphalt content (ignition oven) versus DCT fracture energy.. The results show a very weak trend of increasing fracture energy with increasing binder amounts.

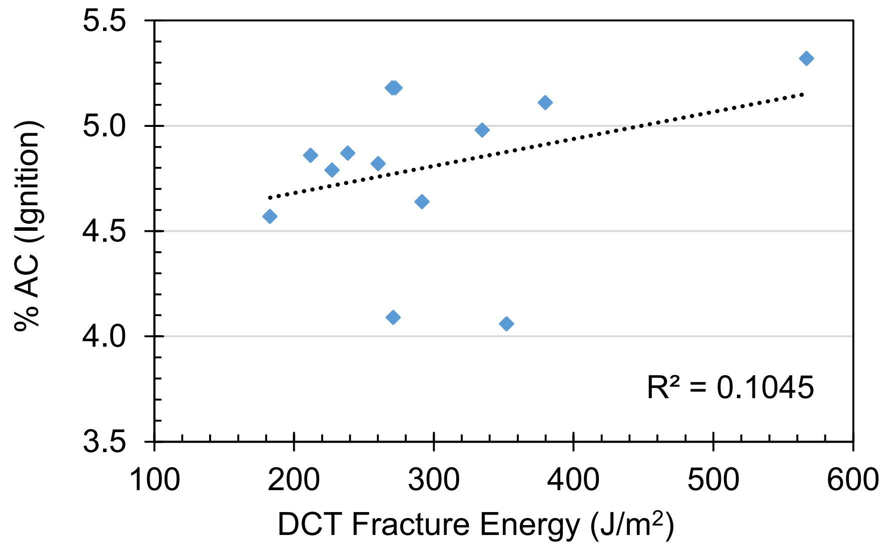



Figure 6.29: Asphalt content (ignition oven) versus DCT fracture energy.

The amount of recycled asphalt binder is compared with the DCT fracture energy next, which is shown in Figure 6.30: Percent recycled AC versus DCT fracture energy.. As seen in the plot there is a weak trend between the recycled asphalt amount and the DCT fracture energy. Note that the current MnDOT 2360 specifications limits the amount of recycled binder to be no more than 20 or 30% for wear courses. The limit of 20% is imposed on mixtures with -34 PGLT and 30% for all other binders.

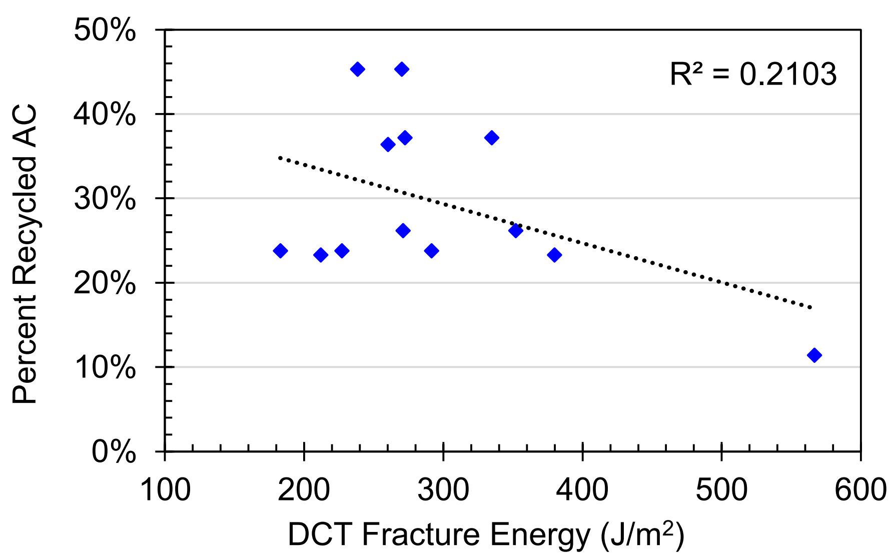



Figure 6.30: Percent recycled AC versus DCT fracture energy.

The last comparison that is presented here is between permeability and DCT fracture energy. The plot of DCT fracture energy and logarithm of the measured permeability is shown in Figure 6.31: DCT fracture energy versus logarithm (base=10) of permeability.. The data shows moderate trend and indicates that as permeability decreases the fracture energy increases. This trend does agree with general consensus that as permeability increasing the durability of asphalt mixtures decreases.  The DCT fracture energy is showing trend that is in agreement with the durability of the mixture.

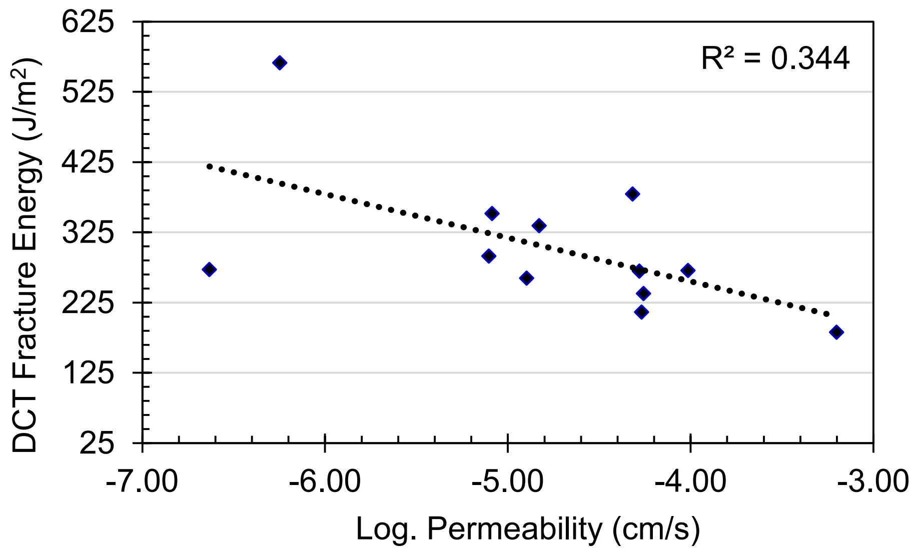



**Figure 6.31: DCT fracture energy versus logarithm (base=10) of permeability.**

## 6.4 SUMMARY AND FINDINGS

The Task-4A of the MnDOT contract 99008 work order 100 study spanned across topics of field performance evaluation and documentation, comparisons between field performance and asphalt mix designs and comparisons between field performance and lab measured performance parameters. This report provides field cracking performance for twelve pavement study sections on basis of the data from MnDOT pavement management system as well as site visits by the researchers. The cracking performance results are presented using three performance indicators developed through a previous MnDOT research study. The cracking performance is compared with various asphalt mix design parameters (such as, asphalt content, gradation measures and binder type). Comparisons are also drawn between cracking performance and the DCT fracture energy as well as the permeability.

On basis of the results and the discussion presented in this report, the following observations can be made:

- In general, the pavement sections studied in this project show poor transverse cracking performance with anticipated pavement age to reach 100% cracking average for these mixtures to be approximately 7.75 years and the average transverse cracking rate of 20.6% per year. Often times the cracking rate tapers off and hence the number of years to 100% cracking is expected to be 7.75 years and not 5 years.
- The construction type continues to show a very strong correlation with the transverse cracking performance. A recently completed MnDOT research on asphalt pavement performance made a very similar conclusion. In the present study of twelve pavement sections, the milling and thin overlays exhibit average transverse cracking rate of 35.65% as compared to 21% for milling and thick overlays and 3.75% for reclaim sections. Thin overlays are designated as ones below 3-inch thickness.
- From perspective of asphalt mix designs, the only two parameters showing a strong trend are the low temperature grade of the asphalt binder and the gradation.
    - The binders with -34 grade show approximately 12% average transverse cracking rate as opposed to approximately 26% for mixtures with -28 low temperature grade. Please note that these values are substantially influenced by the pavement structure, a large number of -28 grade mixtures in this study represented asphalt overlays, versus -34 grade mixtures represented wear courses on full-depth reclamation.
    - All mixtures in this study are ¾ inch sized mixtures as per MnDOT 2360 specifications. For these mixtures, as the amount of aggregate fraction between ½ inch and #4 sieve increases the average cracking rate decreases and as the fraction between #4 and #200 sieve increases the cracking rate increases. In other words, for these coarse mixtures as the intermediate size material on coarse side increases, the cracking performance improves and the trend is reversed on the finer sieves. It is recommended that the gradation bands be reevaluated to accomplish this goal.
    - The typically used volumetric measures for ensuring the performance of asphalt mixtures, i.e. asphalt film thickness and voids in mineral aggregates, did not show a consistent trend with cracking performance. This is in agreement with previous research results of MnDOT studies.
- The majority of sections with high cracking rates have DCT fracture energies that are under the recommended threshold of 400 J/m$^2$. However, there is limited data for mixtures with fracture energy that meets the threshold, thus it cannot be conclusively reported that a trend between DCT fracture energy and cracking performance is seen in this study. It should be noted that the samples tested in this study are all from field cores and procured at different pavement ages, thus the lack of trend is not entirely unexpected.
- The DCT fracture energy and the permeability results show a reasonable trend with mixtures with higher permeability having lower fracture energies.
- The results presented herein will be used in conducting pavement performance evaluation using tools such as, PavementME which will allow for making fair comparisons between the sections in terms of their anticipated cracking performances.

# CHAPTER 7: PAVEMENT PERFORMANCE (TASK-4B)

## 7.1 INTRODUCTION AND SCOPE

The purpose of Task-4B was to expand upon lab testing results from previous tasks of the "Impact of Lower Asphalt Binder for Coarse Hot Mix Asphalt Mixtures" project by predicting the performance of the study's nine field sections using AASHTO Pavement ME Design. The results from Pavement ME Design can then be compared to both the trends observed from lab testing as well as the cracking performance from the field sections. This compilation of data, predicted performance, and field recorded performance helps in determining the impacts of lower asphalt contents of coarse graded hot mix asphalt mixtures in Minnesota on pavement life.

Pavement ME Design requires three categories of inputs: traffic data, climatic data, and pavement layer material thicknesses and properties. Most of the important traffic data and material properties were readily available from previous tasks of this study. If any required input values were not readily available, either the values were calculated from existing data (if available) or reasonable assumptions were made. Once each pavement section was fully defined with inputs, Pavement ME Design was used to simulate the performance of the various pavement sections over a 20-year period. The results of primary concern were the predicted thermal cracking performance and the predicted International Roughness Index (IRI) over the lifetime of the pavement section. These results were then compared to the lab testing results and field data previously reported in this study.

The primary results that are presented in this memo are the predicted thermal cracking performance and the predicted IRI of each pavement section from Pavement ME Design. These two predicted performance measures are also compared to measured field cracking results in the report.

## 7.2 INPUT DATA AND ANALYSIS

### 7.2.1 Pavement Sections

In previous tasks of this study, field cores were taken from nine field sections. Various laboratory tests were then conducted by researchers. The ones most pertinent to Pavement ME analysis include: the dynamic modulus of the field cores, the complex shear modulus of extracted binder from the field cores, and volumetric properties of the field cores. Table 7.1 provides background information on the six field sites which have been analyzed in the present task.

**Table 7.1: General Information on Field Sites.**

| Section | RP / Landmark | Specimen Letter/Group | Construction Year | Visual Performance | Lane | Construction Type |
|---|---|---|---|---|---|---|
| TH 220 | RP 12 | K/1 | 2012 | Good/Fair | D | 3” M/O |
| TH 27 | RP 171 | M/3 | 2010 | Poor | D | 3" M/O |
| TH 9 | RP 208 | O/4 | 2011 | Poor | D | 3" O/L on reclaimed AC |
| TH 6 | RP 53 | S/6 | 2010 | Poor | D | 1.5" M/O |
| TH 10 | RP 75 | T/7 | 2013 | Poor | D/P | 3.5" M/O |
| TH 10 | RP 159 | V/9 | 2005 | Poor | D/P | 4" M/O (sealed cracks) |
| M/O = Mill and Overlay; O/L = Overlay | | | | | | |

The dynamic modulus testing previously performed in this study was done on field core specimens from the pavement sections. The specimens were tested in the Indirect Tension (IDT) mode due to the challenge of extracting six-inch-tall standard dynamic modulus specimens from field sections. The dynamic modulus tests on the field core specimens were then tested at three temperatures (0.4$^{o}$C, 17.1$^{o}$C, and 33.8$^{o}$C) and nine frequencies (25Hz, 20Hz, 10Hz, 5Hz, 2Hz, 1Hz, 0.5Hz, 0.2Hz, and 0.1Hz). The dynamic modulus data was then used to construct a dynamic modulus master curve for each field section using a sigmoidal model. The fitted master curves would be used to predict dynamic modulus values for Pavement ME Design inputs.

Volumetric properties were also measured on the field core specimens. The measurements included asphalt content (%AC), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), effective asphalt content (%$V_{beff}$), bulk specific gravity ($G_{mb}$), maximum theoretical specific gravity ($G_{mm}$), and air voids (%$V_a$). Out of these volumetric properties, Pavement ME Design only requires that the %AC, %$V_a$, and $G_{mb}$ (converted into a density) values as inputs. After binder was extracted from the field core specimens, a sieve analysis was performed on the aggregate mixtures for each field core specimens. The resulting gradation was not used as a Pavement ME Design input because the available dynamic modulus data was used instead. Table 7.2: Lab Measured Volumetric Properties of Field Specimens.

summarizes the volumetric measurements required for Pavement ME Design as well as those of interest in this study.

**Table 7.2: Lab Measured Volumetric Properties of Field Specimens.**

| Section | Specimen Letter/Group | PG Grade | PG Spread | Asphalt Content | Recycled Asphalt Content | Adj. AFT | Voids in Mineral Aggregate (VMA) | Voids Filled with Asphalt (VFA) | Average Bulk Specific Gravity($G_{mb}$) |
|---|---|---|---|---|---|---|---|---|---|
| TH 220 | K/1 | 58-28 | 86 | 4.2% | 23.80% | 9.5 | 13.50% | 70.3% | 2.307 |
| TH 27 | M, N/3 | 58-28 | 86 | 4.3% | 37.20% | 8.8 | 13.60% | 70.6% | 2.399 |
| TH 9 | O, P/4 | 58-34 | 92 | 4.2% | 26.20% | 8.9 | 13.10% | 69.6% | 2.370 |
| TH 6 | S/6 | 58-28 | 86 | 4.4% | 36.40% | 9.2 | 13.90% | 71.2% | 2.365 |
| TH 10 | T/7 | 58-28 | 86 | 4.3% | 23.30% | 8.9 | 13.70% | 70.8% | 2.356 |
| TH 10 | V, W/9 | 64-28 | 92 | 5.3% | 45.30% | 7.8 | 14.40% | 72.3% | 2.339 |

Extracted binder testing was performed to characterize the asphalt binder properties of the various field core specimens. The extracted binders were tested using a dynamic shear rheometer (DSR) to determine the complex shear modulus of the binder at various temperatures. Similar to the dynamic modulus results, the complex shear modulus results were also fit with a sigmoidal model to construct a master curve. The master curve with time-temperature superposition was used to predict complex shear modulus values at various temperatures, which are needed as inputs in Pavement ME Design.

Using the dynamic modulus data, creep compliance was also calculated for each of the field core specimens using the Abatech RHEA software. The data input for Pavement ME Design requires creep compliance at 3 temperatures and 7 loading times.

### 7.2.2 Use of Master-curves to Develop Inputs for Pavement ME Design

To accurately predict the performance of the field sections in Pavement ME Design, a level 1 dynamic modulus input was chosen. Level 1 input requires two properties of the asphalt mixture: Dynamic modulus of the mix over a range of temperatures and frequencies as well as complex shear modulus and phase angle of the binder at various temperatures. Both of these required inputs were calculated using the existing lab testing data from Task-3B conducted by the Iowa State University.

When inputting dynamic modulus values in Pavement ME Design, it is recommended that a broad range of temperatures and frequencies be used to fully characterize the material. In terms of temperatures, it is recommended that dynamic modulus data from testing a temperature higher than 130$^{o}$F, one between 100$^{o}$F and 60$^{o}$F, and one lower than 32$^{o}$F be used. The data from Iowa State did not include testing temperatures above 130$^{o}$F and below 32$^{o}$F so the values were calculated using the sigmoidal models constructed for the various specimen groups. The two extra temperatures selected were 50$^{o}$C and -10$^{o}$C. The dynamic modulus values at these temperatures were calculated by first using a fitted shift factor equation to find the shift factors for the two temperatures. These shift factors were then used determine the equivalent "reduced" frequencies from the standard testing frequencies using the time-temperature superposition principle. The dynamic modulus values were then calculated using the sigmoidal equation, Equation 7.1, with the given sigmoidal fit parameters and the previously determined shift factors.

$$\log E^*(\omega) = D + A[1 + Te^{-B(\log \omega - M)}]^{-1/T} \quad (7.1)$$

where,

*E*(ω)* = Dynamic modulus *E** at frequency *ω*

*T* = Temperature

*A, B, D and M* = Sigmoidal model fitting parameters

After the dynamic modulus values were calculated for the five chosen frequencies (25Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz), a full array of dynamic modulus values for each group of specimens was input into Pavement ME Design. Unfortunately, the Pavement ME Design software was not able to construct a master curve with the data from three of the nine pavement sites (CSAH10 – L; TH28 – Q, R; CSAH30 - U) so those sections could not be simulated in the program.

Similar to dynamic modulus values, the complex shear modulus values for the binders of the field core specimens could be calculated using the existing sigmoidal model. The main difference compared to the dynamic modulus calculations is that complex shear modulus testing is only performed at one frequency, dropping the need to calculate shift factors. Complex shear modulus values were calculated for each binder at a range of standard PG grading temperatures (52$^{o}$C, 58$^{o}$C, 64$^{o}$C, and 70$^{o}$C). No phase angle data was provided, necessitating reasonable assumptions, which are shown in Appendix A.

### 7.2.3 Traffic and Section Inputs for Pavement ME

Three categories of inputs are required to accurately predict performance of the various pavement sections: Traffic measurements and information, Climatic data, and material property and thicknesses.

Traffic measurements such as average annual daily traffic (AADT) and percent trucks were available from the previous tasks of this study. Data from the site visits as well as from construction plans readily provided information such as the number of lanes and the operational speeds. For multi-lane roadways, it was assumed that 95% of trucks are driving in the design lane. All of the other inputs in Pavement ME Design were left with the default values. This included traffic growth, truck class distributions, and truck class seasonal variations. Table 7.3: Traffic and Climate Station Information for Pavement ME Design. shows the traffic and climate inputs for the six simulated field sections.

Climatic data is built into Pavement ME Design through the use of historical data from weather stations all over the country. For each of the field sections, the nearest available weather station (based off latitude-longitude) was selected to provide the climatic information. Pavement ME Design uses the historical data from the weather station to predict the climatic conditions of each field section.

**Table 7.3: Traffic and Climate Station Information for Pavement ME Design.**

| Roadway | AADT | Percent Trucks | AADTT | Ratio of Percent Trucks in Design Direction to Percent Trucks in Design Lane | Growth Rate | Nearest Weather Station in Pavement ME |
|---|---|---|---|---|---|---|
| TH 220 Group 1 | 434 | 26.30% | 114 | 50/100 | 3% | Park Rapids, MN |
| TH 27 Group 3 | 1484 | 2.80% | 42 | 50/100 | 3% | Brainerd, MN |
| TH10 Group 7 | 7265 | 10.20% | 741 | 50/95 | 3% | Park Rapids, MN |
| TH 9 Group 4 | 564 | 15.80% | 89 | 50/100 | 3% | Park Rapids, MN |
| TH 6 Group 6 | 1408 | 7.60% | 107 | 50/100 | 3% | Brainerd, MN |
| TH 10 Group 9 | 20700 | 8.00% | 1656 | 50/95 | 3% | Brainerd, MN |

Material property inputs in Pavement ME Design are either in the form of volumetric properties or mechanical properties. The important mechanical properties such as dynamic modulus, binder complex shear modulus, and creep compliance were discussed in previous section. The important volumetric properties such as percent asphalt content, percent air voids, and bulk specific gravity were also available and are presented earlier in this report (Table 7.2: Lab Measured Volumetric Properties of Field Specimens.).

Pavement layer thicknesses were determined using construction drawings and verified on basis of the field core specimens that have been previously tested in the earlier tasks of this study. Since all of the projects studied herein are in the category of pavement rehabilitation, the construction drawings only provide information on the thickness of the asphalt layer(s) with no information on the underlying base material or subgrade. In order to be consistent, a 10 inch crushed stone base was assumed for all of the field sections. For all of the field sites, the subgrade material was found by using the AASHTO soil classification tool in web soil survey at the exact location of the field core using latitude-longitude coordinates. Table 7.4: Pavement ME Layer Thicknesses and Properties. shows the various layer thicknesses and material inputs for the Pavement ME Design simulations.

**Table 7.4: Pavement ME Layer Thicknesses and Properties.**

| Roadway | TH 220 | TH 27 | TH 10 | TH 9 | TH 6 | TH 10 |
|---|---|---|---|---|---|---|
| **Specimen Group** | **Group 1** | **Group 3** | **Group 7** | **Group 4** | **Group 6** | **Group 9** |
| **Layer 1** | 3 inch Asphalt Overlay | 3 inch Asphalt Overlay | 3.5 inch Asphalt | 3 inch Asphalt | 1.5 inch Asphalt Overlay | 4 inch Asphalt |
| **Layer 2** | 2 inch Existing Asphalt | 2 inch Existing Asphalt | - | - | 2.5 inch Existing Asphalt | - |
| **Layer 3** | 10 inch Crushed Stone Base | 10 inch Crushed Stone Base | 10 inch Crushed Stone Base | 10 inch Crushed Stone Base | 10 inch Crushed Stone Base | 10 inch Crushed Stone Base |
| **Subgrade (AASHTO Classification)** | A-7-5 | A-4 | A-4 | A-7-5 | A-4 | A-3 |

## 7.3 RESULTS

### 7.3.1 Presentation Scheme for Results

The two Pavement ME Design outputs this report will focus on is the predicted thermal cracking and IRI over time. In Pavement ME Design, thermal cracking performance outputs are given in units of linear feet of thermal cracking per mile of roadway. Pavement ME Design outputs IRI values in inches of roughness per mile of pavement. This value quantifies the overall roughness of the pavement which can be due to thermal cracking as well as other common pavement distresses such as rutting and fatigue cracking. The performance outputs from Pavement ME design are plotted to compare the field sites to each other and a previously determined failure threshold value.

The predicted IRI of the six field sections analyzed here are presented in Figure 7.1: IRI Curves Generated for the Field Sections in Pavement ME.. The chosen failure threshold was the default value in Pavement ME Design which is 172 inch/mile. All of the field sections experienced a relatively linear, gradual increase in IRI over time. Over the twenty-year analysis period, all six field sections exceed the failure threshold. The failures occurred between approximately 13 and 20 years. The one section with relatively higher asphalt binder content of 5.3% (TH10, Group 9) showed approximately 18 years of service life as opposed to its low asphalt content counterpart (TH10, Group 7) with 4.3% binder content predicting to have 13 years of service life.

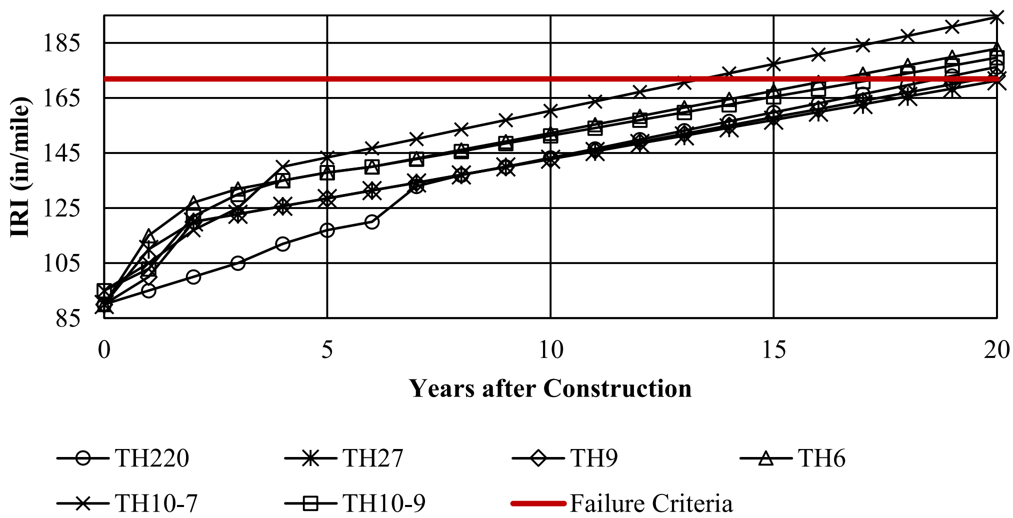



Figure 7.1: IRI Curves Generated for the Field Sections in Pavement ME.

Figure 7.2: Pavement ME Predicted Thermal Cracking for Field Sections. shows the predicted thermal cracking of the six field sections. The default Pavement ME Design failure threshold of 1000ft/mile was used. In general, the field sections experienced a very rapid increase in thermal cracking during the first few years of service. After a few years of rapid crack growth, most of the field sections cracking growth either slowed down or completely stopped. All of the field sections exceeded the failure threshold after only few years of service. TH220 predicted to have the best thermal cracking performance with approximately 6 years of service before reaching the failure threshold.

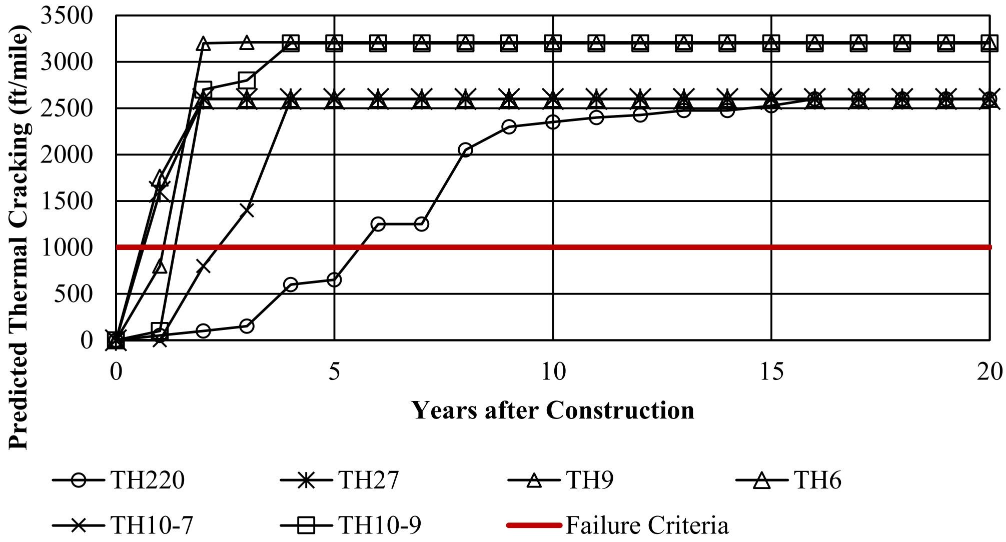



Figure 7.2: Pavement ME Predicted Thermal Cracking for Field Sections.

A predicted thermal cracking rate was calculated using the Pavement ME output. This parameter is calculated by dividing the thermal cracking failure threshold value (1000 ft./mile) by the amount of time, as predicted by Pavement ME Design, for a pavement section to reached that failure threshold value. This parameter was chosen so that comparisons could be made with the field cracking performance calculated as the TCTotal. A detailed description of TCTotal and other field cracking measures are presented in the Chapter 3 of this report. The TCTotal is a sum of the total transverse cracking (low + medium + high) work over the service life. Transverse cracking work is calculated by taking area under the transverse cracking versus service life curve. The total area is then normalized against the square of number of years for which pavement section has been in service.

### 7.3.2 Comparison between Performance of Different Sites

Table 7.5 summarizes the comparative performance of the six field sites. The table also includes the field sites ranked in terms of IRI and thermal cracking performance.

**Table 7.5: Predicted Performance of Field Sections in Pavement ME**

| Site | IRI Failure Year | Thermal Cracking Failure Year | Terminal IRI (in/mile) | Terminal Thermal Cracking (ft/mile) | Predicted Thermal Cracking Rate (ft/mile/yr) | IRI Performance Rank | Thermal Cracking Performance Rank |
|---|---|---|---|---|---|---|---|
| **TH 220** | 18.5 | 5.5 | 176.3 | 2600 | 182 | 3 | 1 |
| **TH 27** | 20 | 0.7 | 172.3 | 2600 | 1429 | 1 | 3 |
| **TH 9** | 19 | 1.5 | 173 | 3210 | 667 | 2 | 5 |
| **TH 6** | 17 | 0.5 | 182.9 | 2600 | 2000 | 5 | 4 |
| **TH 10-7** | 14 | 2.5 | 194.4 | 2600 | 400 | 6 | 2 |
| **TH 10-9** | 17 | 1.6 | 179.6 | 3210 | 625 | 4 | 6 |

In terms of thermal cracking, the TH 220 site performed considerably better than the other five field sites. It took more than twice as long as any of the other sites to reach the failure criteria and it reached its terminal thermal cracking amount years after any of the other sites. The other five field sites performed similarly, failing between 0.5 and 2.5 years. Out of the five, TH27, TH6, and TH10-7 performed slightly better as their terminal thermal cracking amount was less than the TH9 and TH10-9 sites.

In general, the field sites performed very similarly in terms of IRI. The field sites experience a rapid initial growth which eventually slowed down into a steady, linear growth. The only exception to this was the TH 220 site, which deteriorated much slower initially compared to the other sites. This is likely due to the significantly better early life thermal cracking performance previously mentioned.

### 7.3.3 Discussion of Results

The actual field transverse cracking performance of the sections is compared with the predicted thermal cracking failure rate of the field sites in Figure 7.3: Predicted Thermal Cracking Rate vs Measured Cracking Performance.. While it is difficult to discern clear trends using only six data points, it can be seen that the one best performing section also is predicted to have the lowest thermal cracking rate as well as the two sections with high predicted thermal cracking rate corresponded to high TCtotal values.

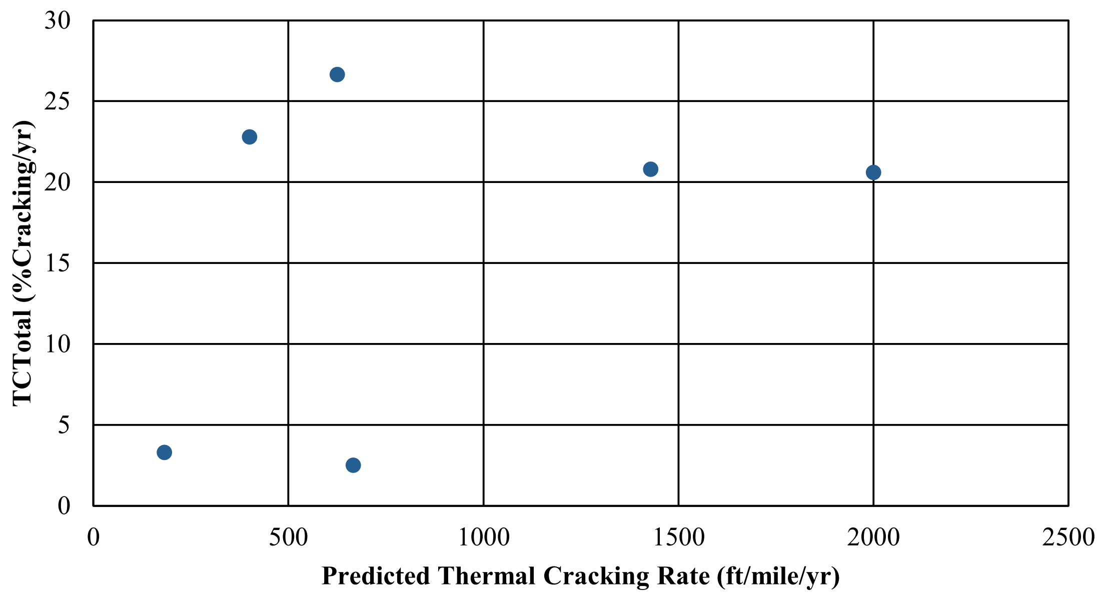



Figure 7.3: Predicted Thermal Cracking Rate vs Measured Cracking Performance.

The predicted thermal cracking rate and the PG low temperature grade of the field sections are plotted in Figure 7.4: Predicted Thermal Cracking Rate vs PG Low Temperature Grade.. From this plot, there does not appear to be a clear correlation between the two factors. However, it should be noted that except for one section all other were constructed with same low temperature PG grade of -28.

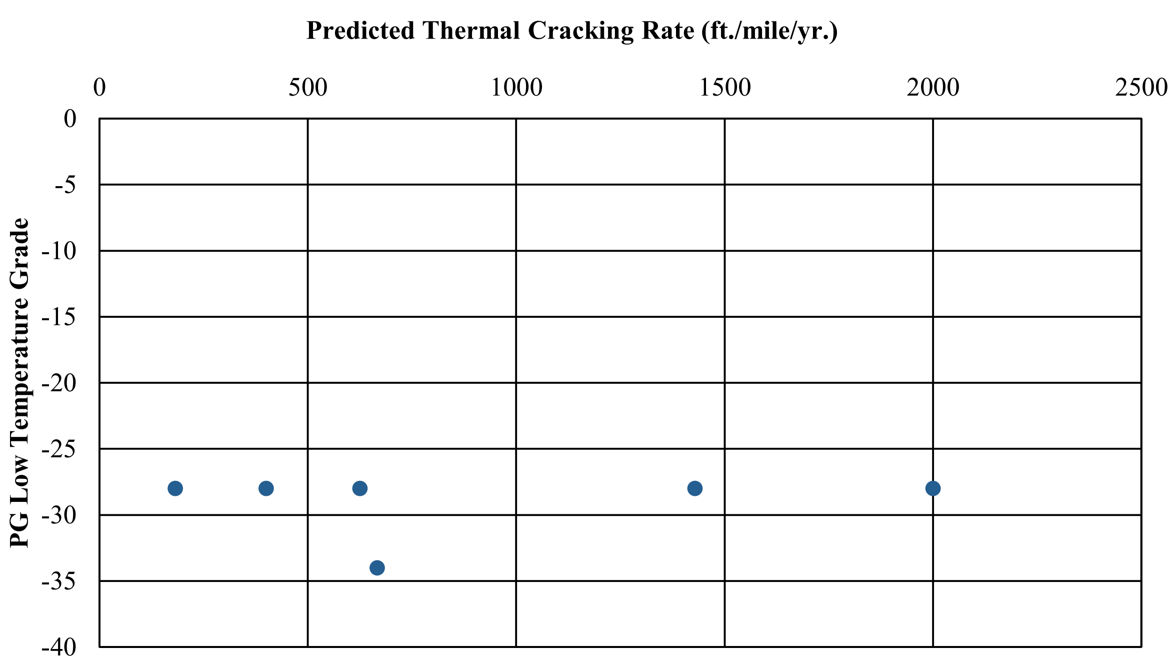



Figure 7.4: Predicted Thermal Cracking Rate vs PG Low Temperature Grade.

Since a major focus of this study is to determine the impacts of lower asphalt content mixes on the field cracking performance, the asphalt binder content of the mixes in study sections are compared with the predicted thermal cracking performance in Figure 7.5: Predicted Thermal Cracking Rate vs Asphalt Content.. With exception of one mix, all other mixes are designed with a relatively low asphalt binder content. Overall in this limited data set no significant trend appears between the asphalt binder content and the predicted thermal cracking rate.

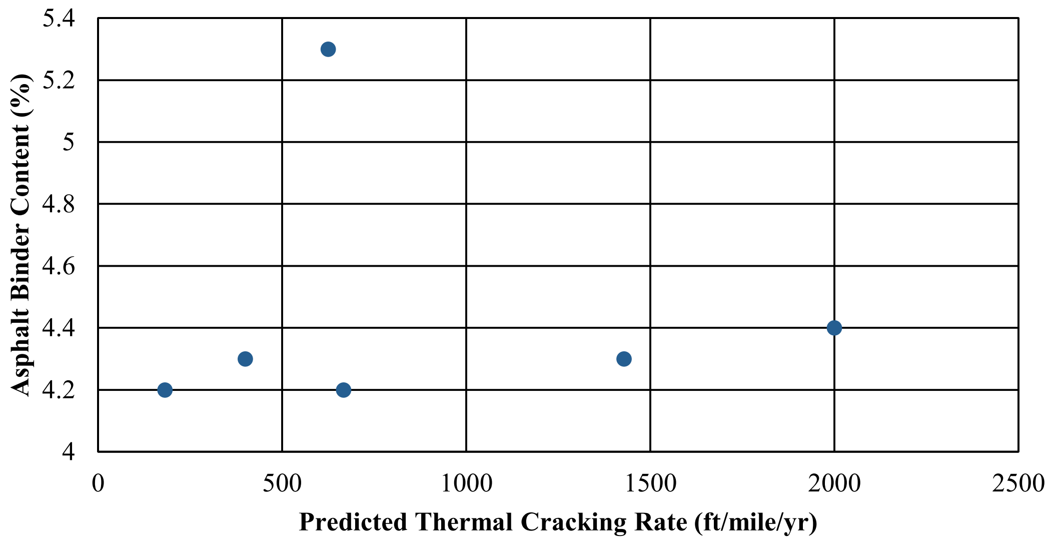



**Figure 7.5: Predicted Thermal Cracking Rate vs Asphalt Content.**

At present, MnDOT 2360 specification for asphalt mix design as well as the quality assurance based acceptance process utilizes adjusted asphalt film thickness (AFT) as one of the criteria. Figure 7.6: Predicted Thermal Cracking Rate vs Adjusted Asphalt Film Thickness (AFT). shows the relationship between the predicted thermal cracking rate and the average AFT of the field core specimens. It should be noted that at present MnDOT requires a minimum AFT value of 8.5 micron. The comparison shows that for the four mixes with high thermal cracking rates (first four points to the left hand side on the plot), the performance deteriorated as AFT increased. However, for the two mixes with very high cracking rates (two points towards right hand side of the plot) the trends are reversed. Thus for the limited set presented here either the AFT did not show a correlation with the thermal cracking rate or the Pavement ME Design failed capture this effect in the simulations.

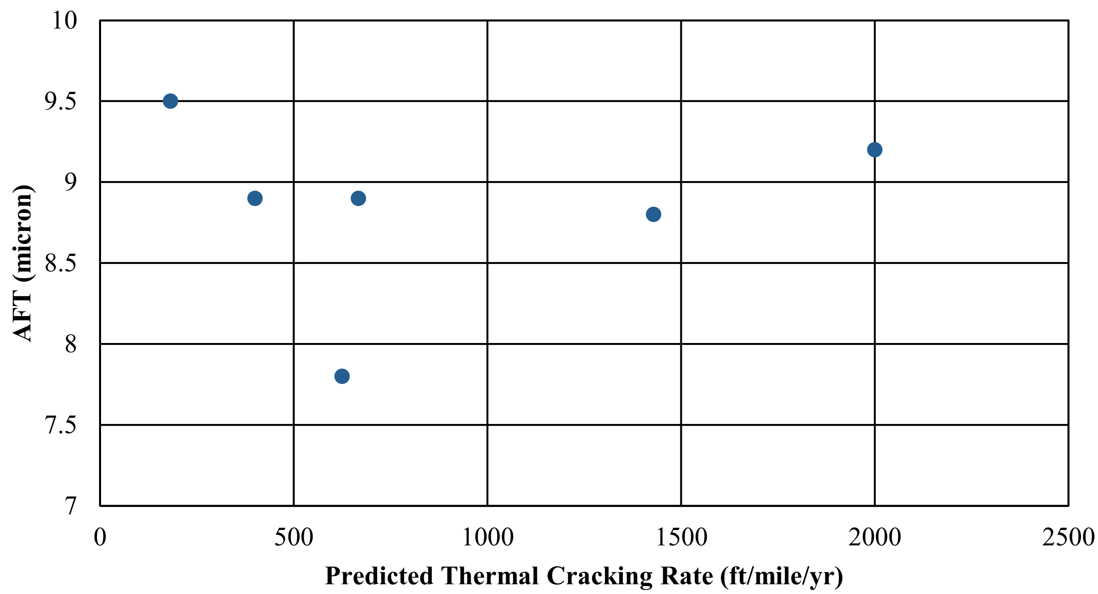



**Figure 7.6: Predicted Thermal Cracking Rate vs Adjusted Asphalt Film Thickness (AFT).**

A nationally used volumetric control for design and acceptance of asphalt mixtures is the voids in mineral aggregate (VMA) measure. The predicted thermal cracking rate and the voids in mineral aggregates (VMA) of the field specimens are compared in Figure 7.7: Predicted Thermal Cracking Rate vs % VMA.. As with AFT, there appears to be no significant correlation between the two parameters.

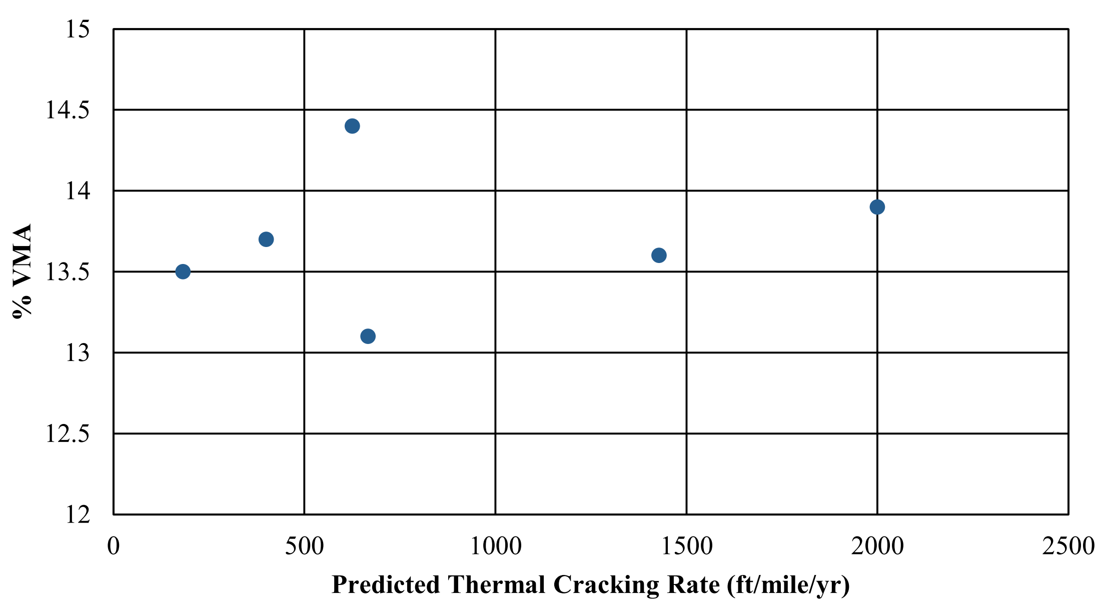



**Figure 7.7: Predicted Thermal Cracking Rate vs % VMA.**

## 7.4 SUMMARY AND FINDINGS

In this task researchers conducted Pavement ME Design simulations of the pavement sections studied in this research project. The simulations were conducted using the material properties measured in previous tasks using the field core specimens. The simulation results were compared with some of the asphalt mix parameters as well as the actual field cracking performance. It should be noted that the thermal cracking performance in the Pavement ME Design software is primarily determined using strength of material based approach where the thermal stresses calculated using the linear viscoelastic properties are compared with the tensile strength of the material to simulate formation of cracks. The software does not take into account the quasi-brittle cracking behavior of asphalt concrete using the fracture mechanics based principles. Use of fracture energy based analysis that account for quasi-brittle cracking in asphalt is recommended to be undertaken for supplementing the information gathered through this study.

On basis of the Pavement ME Design analysis conducted and presented herein following observations can be made:

- The coarse graded low-asphalt content sections are predicted to have a poor thermal cracking performances on the basis of the material properties measured using the field cores (specifically very high dynamic modulus combined with lower fracture energies).
- The results show a loose correlation between the actual field cracking performance (TCTotal) and the Pavement ME Design predicted thermal cracking performance. One of the good performing sections and two of the poor performing sections in actual service were predicted to have similar ranking in Pavement ME Design predictions.
- The predicted thermal cracking performances did not correlate well with the traditional asphalt mix design control criteria (asphalt binder content, AFT and VMA). It should be noted that the correlations are made for relatively small set sections and cannot be used to draw general conclusions regarding all asphalt mixes.
- Another observation from the results is that it appears that none of the volumetric properties provide good predictions of thermal cracking performance in Pavement ME. The plotted relationships between the various volumetric properties (%VMA, Asphalt Content, AFT) show no correlation to the predicted field performance.

# CHAPTER 8: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

## 8.1 SUMMARY

A brief summary of the research conducted through this project can be presented by describing key highlights of the efforts from each of the project tasks. Task 1 and Task 2 (Chapters 2 and 3) dealt with the determination of field sections and the material sampling plan, respectively. These tasks led to Tasks 3A and 3B (Chapters 4 and 5) which consisted of the laboratory testing for this project. Task 3A included testing the mixtures in each section for mixture-based volumetric properties such as adjusted asphalt film thickness (Adj. AFT), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), asphalt content, and gradation. Task 3A also included mechanical testing in the form of the disk-shaped compact tension (DCT) test as well as permeability testing using the Karol-Warner laboratory device. Continuing with the laboratory testing, Task 3B measured the field section mixture's dynamic modulus in the indirect tensile (IDT) mode and then compared these results to values predicted with the modified Witczak model. Using the various laboratory measured mixture properties, Task 4A (Chapter 6) measured the field cracking performance of the multiple sections and compared each section's performance to corresponding mixture properties. Finally, Task 4B (Chapter 7) used Pavement ME Design to predict the performance of the field sections. The predicted performance was then compared to both mixture properties and actual, measured field performance. The project proposes use of performance-based specifications to alleviate challenges of volumetric control-based specifications that can potentially lead to inferior performing mixtures or mixtures that are unbalanced in context of their rutting or cracking performances. Researchers recommend fracture energy from the disk-shaped compact tension (DCT) to be added to currently practiced asphalt mixture specifications.

Individual task summaries are as following:

- Task-1 (Chapter 2: Mix Design Record Data Collection and Selection of Field Sections for Evaluation) undertook the selection of field sections that were studied for determination of the impact of lower-asphalt content, coarse hot-mix asphalt mixes. The selection of the field sections was made in two steps. The researchers as well as staff at MnDOT Office of Materials and Road Research (OM&RR) evaluated the mix design records (MDR) from the past several years and identified potential candidate mixes. Next a meeting was held between the researchers and the technical advisory panel (TAP) for the project. The aforementioned lists were discussed during this meeting and a final list of nine (9) field sections was selected.
- Task-2 (Chapter 3: Sampling Plan) developed the sampling plans for obtaining field cores for volumetric and performance testing to determine the impacts of lower-asphalt content, coarse hot-mix asphalt mixes.
- Task-3A (Chapter 4: Laboratory Testing Part-1) focused on laboratory testing of field-cored samples of coarse asphalt mixtures from 13 pavement sections from Minnesota. The testing spanned a variety of tests to determine the asphalt mixtures' permeability, fracture energy, volumetric properties, asphalt content, and gradation.

- Task-3B (Chapter 5: Laboratory Testing Part-2) focused on the performance evaluation of coarse graded pavement using dynamic modulus in IDT mode and making comparisons between laboratory data and Modified Witczak Model outputs for dynamic modulus in the IDT mode for the 13 pavement sections from Minnesota.
- Task-4A (Chapter 6: Data Analysis) spanned various topics of field performance evaluation and documentation, comparisons between field performance and asphalt-mix designs, and comparisons between field performance and lab-measured performance parameters. This study provided field cracking performance for 12 pavement study sections on the basis of the data provided by the MnDOT pavement management system as well as site visits by the researchers. The cracking performance results are presented using three performance indicators developed through a previous MnDOT research study. The cracking performance is compared with various asphalt mix design parameters (such as, asphalt content, gradation measures, and binder type). Comparisons are also drawn between cracking performance and the DCT fracture energy as well as the permeability.
- Task-4B (Chapter 7: Pavement Performance) conducted Pavement ME Design simulations of the pavement sections studied in this research project. The simulations were conducted using the material properties measured in previous tasks using the field core specimens. The simulation results were compared with some of the asphalt mix parameters as well as the actual field cracking performance.

## 8.2 CONCLUSIONS AND RECOMMENDATIONS

On the basis of various research tasks undertaken in this study the following conclusions and recommendations are drawn.

- In general, the low-asphalt content, coarse graded asphalt overlay pavement sections studied in this project show poor transverse cracking performance, with the anticipated pavement age with a 100% transverse cracking average to be approximately 7.75 years and an average transverse cracking rate of 20.6% per year. Often the cracking rate tapers off, and hence the number of years until 100% cracking is expected to be 7.75 years and not 5 years.
- The construction type continues to show a very strong correlation with the transverse cracking performance. A recently completed MnDOT research report on asphalt pavement performance made very similar conclusions. In the present study of 12 pavement sections, the milling and thin overlays exhibit an average transverse cracking rate of 35.65% as compared to 21% for milling and thick overlays and 3.75% for reclaimed sections. Thin overlays are defined as those below 3-inch thickness.
- From the perspective of asphalt mix designs, the only two parameters showing a strong trend to transverse cracking rates and amounts are the low temperature grade of the asphalt binder and the gradation.
    - The binders with a -34 grade show an approximately 12% average transverse cracking rate as opposed to approximately 26% for mixtures with a -28 low-temperature grade on overlays.
    - All mixtures in this study are ¾ inch sized mixtures as per MnDOT 2360 specifications. For these mixtures, as the amount of aggregate fraction between ½ inch and #4 sieve increases, the average cracking rate decreases, and as the fraction between #4 and #200 sieve increases, the cracking rate increases. In other words, for these coarse mixtures, as the

intermediate size material becomes coarser, the cracking performance improves, and the trend is reversed on the finer sieves. Thus, it is recommended that the mixtures be designed with more uniform gradations to improve cracking resistance. It is recommended that the gradation bands be reevaluated to accomplish this goal.

- The typically used volumetric measures for ensuring the performance of asphalt mixtures, i.e., asphalt film thickness and voids in mineral aggregates did not show a consistent trend with cracking performance. This is in agreement with previous research results of MnDOT studies.
- The majority of sections with high cracking rates have DCT fracture energy that is under the recommended threshold of 400 J/m2. However, there is limited data for mixtures with fracture energy that meets the threshold, thus it cannot be conclusively reported that a trend between DCT fracture energy and cracking performance is seen in this study. It should be noted that the samples tested in this study are all from field cores and procured at different pavement ages, thus the lack of trend is not entirely unexpected.
- The DCT fracture energy and permeability show a reasonable trend, and mixtures having higher permeability have lower fracture energies.
- The results from permeability testing indicated that eight of the 13 mixtures have higher permeability than typical ranges for dense graded asphalt mixtures. Specifically, six of the mixtures have significantly higher permeability. These mixtures have inferior durability and are more prone to moisture-induced damage and distresses such as raveling.
- The overall findings from this Task are that the IDT dynamic modulus test results showed that all nine mix groups have very high stiffness values. The $R^2$ and R values gained from fitting experimental results against predicted data using the sigmoidal model were close to 1, and this means the sigmoidal model can be developed and used to predict both $|E^*|$ and $|G_b^*|$ values very well. For the IDT mode of testing, although the Modified Wiczak model can predict $|E^*|$ values using $|G_b^*|$ and other inputs for the more commonly used uniaxial test configuration for determining dynamic modulus values, it is not as accurate in predicting IDT $|E^*|$ values as the sigmoidal model. Due to the ability of the IDT dynamic modulus test to more accurately measure the dynamic modulus in asphalt concrete layers collected from field cores, the Modified Witczak Model should be modified for IDT mode in future studies.
- The Pavement ME simulations show that the coarse graded low-asphalt content sections are predicted to have significantly inferior thermal cracking performance on the basis of the material properties measured using the field cores.
- The results show a loose correlation between the actual field cracking performance (TCTotal) and the Pavement ME Design predicted thermal cracking performance. One of the good performing sections and two of the poor performing sections in actual service were predicted to have similar rankings in Pavement ME Design predictions.
- The predicted thermal cracking performances did not correlate well with the traditional asphalt mix design control criteria (asphalt binder content, AFT and VMA). It should be noted that the correlations are made for a relatively small set of sections and cannot be used to draw general conclusions regarding all asphalt mixes.
- Another observation from the results is that it appears that none of the volumetric properties provide good predictions of thermal cracking performance in Pavement ME. The plotted relationships between the various volumetric properties (%VMA, Asphalt Content, AFT) show no correlation to the predicted field performance.

# REFERENCES


1. AASHTO (2006). TP 62 - Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixture. *AASHTO TP 62-07*, American Association of State Highway and Transportation Officials, Washington, DC.

2. Bari, J., and Witczak, M. W. (2006). "Development of a new revised version of the Witczak E* predictive model for hot mix asphalt mixtures (with discussion)." *Journal of the Association of Asphalt Paving Technologists*, 75, 381-423.

3. Dave et al. (2015) "Laboratory Performance Test for Asphalt Concrete," Resear4ch Project Final Report 2015-24, Minnesota Department of Transportation, St. Paul, MN.

4. Dougan, C. E., Stephens, J., Mahoney, J., and Hansen, G. (2003). "E*-Dynamic Modulus: Test Protocol-Problems and Solutions."(No. CT-SPR-0003084-F-03-3).

5. Helmer, B. W. (2015). "Impact of asphalt mixture design parameters on transverse cracking performance and laboratory testing results." M.S., University of Minnesota, Duluth.

6. Kim, Y., Seo, Y., King, M., and Momen, M. (2004). "Dynamic modulus testing of asphalt concrete in indirect tension mode." *Transportation Research Record: Journal of the Transportation Research Board*(1891), 163-173.

7. Li, X. J., and Williams, R. C. (2012). "A Practical Dynamic Modulus Testing Protocol." *J Test Eval*, 40(1), 100-106.

8. Schwartz, C. W. "Evaluation of the Witczak dynamic modulus prediction model." *Proc., Proceedings of the 84th Annual Meeting of the Transportation Research Board, Washington, DC*, (No. 05-2112).

9. Witczak, M., Andrei, D., and Mirza, W. (1999). "Development of revised predictive model for the dynamic (complex) modulus of asphalt mixtures." *Inter-team Technical Report prepared for the NCHRP 1-37A Project*, Department of Civil Engineering, University of Maryland, College Park, MD.

# APPENDIX A: CONSTRUCTION PLANS

# MINNESOTA DEPARTMENT OF TRANSPORTATION

CONSTRUCTION PLAN FOR BITUMINOUS OVERLAY, GRADE & BIT. SURFACE, BIT. RECLAMATION, AND BOX CULV.

LOCATED ON T.H. 6 FROM 0.95 MILES N. TALMOON TO 1200' N. OF JCT. T.H. 1

STATE PROJ. NO. 3107-42

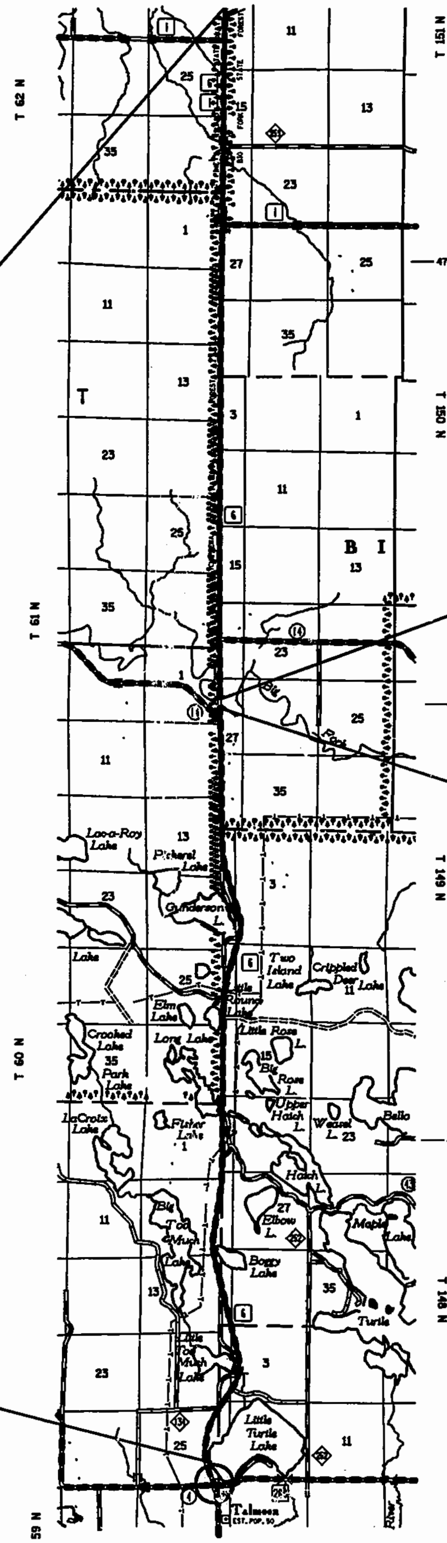
GROSS LENGTH 99165.00 FEET 18.781 MILES
BRIDGES-LENGTH 193.00 FEET 0.034 MILES
EXCEPTIONS-LENGTH 193.00 FEET 0.034 MILES
NET LENGTH 98972.00 FEET 18.747 MILES
REF. POINT 110+00.123 TO REF. POINT 128+00.704

| R.P. | STA. |
|---|---|
| 110 | 1096+24 |
| 111 | ??? |
| 112 | 1201+85 |
| 113 | 1254+54 |
| 114 | 1307+11 |
| 115 | 1359+87 |
| 116 | 1412+65 |
| 117 | 1465+65 |
| 118 | 1518+44 |
| 119 | 1571+03 |
| 120 | 1590+72 |
| 121 | 1643+08 |
| 122 | 1695+89 |
| 123 | 1748+54 |
| 124 | 1801+34 |
| 125 | 1853+98 |
| 126 | 1906+81 |
| 127 | 1959+69 |
| 128 | 2012+36 |

EQUATIONS:

1153+00.78 = 1153+70.45
1238+60.35 = 1238+70.04
1309+56.25 = 1309+70.33
1418+04.49 = 1418+56.80
1579+98.71 = 1580+00.00
1622+85.90 = 1590+04.70
1878+86.04 = 1879+06.41
2037+67.50 = 82+83.60

END S.P. 3107-42
STA. 94+84
R.P. 128+00.704




EXCEPTION LENGTH 193'
BRIDGE NO. 31001

BEGIN S.P. 3107-42
STA. 1102+74
R.P. 110+00.123

SCALE
INDEX MAP 1 MILE

GOVERNING SPECIFICATIONS

THE 2000 EDITION OF THE MINNESOTA DEPARTMENT OF TRANSPORTATION "STANDARD SPECIFICATIONS FOR CONSTRUCTION", SHALL GOVERN.

FED. PROJ. NO. HPP-STPMN52(100)

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| DESIGN DETAILS | 12 |
| TEMPORARY EROSION CONTROL DETAILS | 13-15 |
| PERMANENT EROSION CONTROL DETAILS | 16 |
| GUARDRAIL DETAILS | 17-19C |
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| INTERIM PAVEMENT MARKING | 22 |
| TRAFFIC CONTROL PLAN | 23-27 |
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| CROSS-SECTION SHEETS | X1-X127 |


THIS PLAN CONTAINS 193 SHEETS

I HEREBY CERTIFY THAT THIS PLAN WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

PRINT NAME: JOSEPH S. McKINNON LICENSE # 18965

DATE: 1-7-2004 SIGNATURE: Joseph S McKinnon

PROJECT MANAGER M. COLEMAN DESIGN SQUAD B. PEMBERTON

RECOMMENDED FOR APPROVAL [signature] DISTRICT TRANSPORTATION ENGINEER 1/7 20 04

For RECOMMENDED FOR APPROVAL [signature] DISTRICT MATERIALS ENGINEER 1/07 20 04

RECOMMENDED FOR APPROVAL William Pill DISTRICT HYDRAULICS ENGINEER 1/8/ 20 04

RECOMMENDED FOR APPROVAL Michael L. Kammohn DISTRICT TRAFFIC ENGINEER 1/7 20 04

FOR RECOMMENDED FOR APPROVAL TRS R. Swanson STATE PRE-LETTING ENGINEER 1/15 20 04

OFFICE OF LAND MANAGEMENT APPROVAL [signature] DIRECTOR, LAND MANAGEMENT 1/20 20 04

APPROVED Jan 21 20 04 [signature] STATE DESIGN ENGINEER

I HEREBY CERTIFY THAT THE FINAL FIELD REVISIONS, IF ANY, WERE PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

PRINT NAME: LICENSE #

DATE: SIGNATURE:

FOR PLANS AND UTILITIES SYMBOLS SEE TECHNICAL MANUAL

| STATE PROJ. NO. | CHARGE IDENTIFIER |
|---|---|
| 3107-42 | |
| | |
| | |
| | |

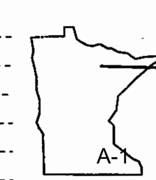
DESIGN DESIGNATION

Design ESALS 2024 = 777,000
ADT (Current Year) 2004 = 710
ADT (Future Year) 2024 = 1200
DHV (Design Hr. Vol.) =
D (Directional Distr.) = %
T (Heavy Commercial) = %

Design Speed 60 MPH
Based on STOPPING Sight Distance
Height of eye 3.5' Height of object 0.5'
Design Speed not achieved at:
STA. TO STA. MPH
STA. TO STA. MPH

PLAN REVISIONS

| DATE | SHEET NO. | APPROVED BY |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |




PROJECT LOCATION
COUNTY : ITASCA
DISTRICT : 2-BEMIDJI

STATE PROJ. NO. 3107-42 (T.H. 6= 061) SHEET NO. 1 OF 63 SHEETS

PLOTTED/REVISED: 1/7/2004

DISTRICT #: DISTRICT 2 - BEMIDJI.MN
IPLOT NAME:
PATH & FILENAME: S:\Projects\006\3107-42\Plan\2d3107-42.tsh

OK 1-21-04

PLOTTED AND/OR REVISED: 1/14/2004

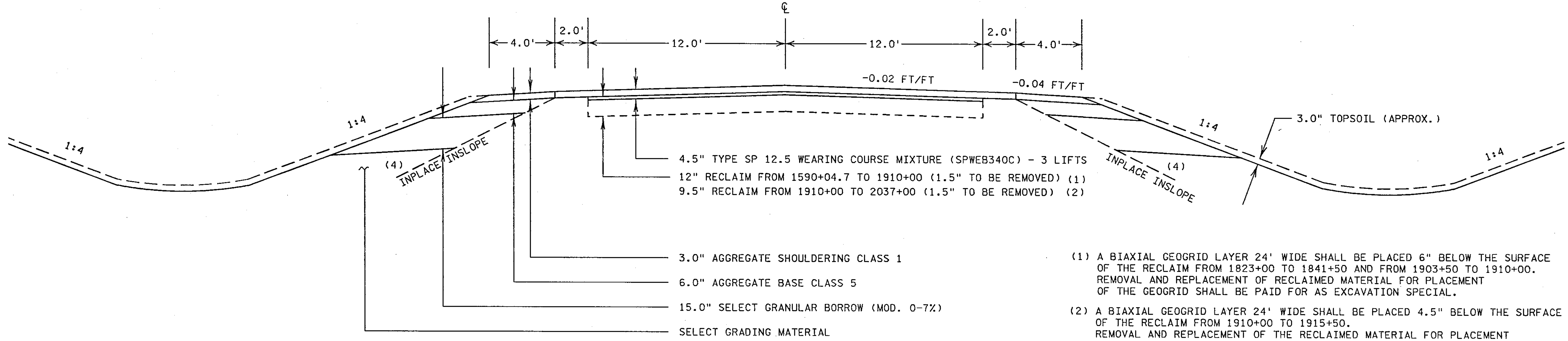
(4) A GEOTEXTILE FABRIC TYPE VI SHALL BE PLACED FROM A POINT 7' DOWNSLOPE OF THE SHOULDER P.I. TO THE TOE OF THE FILL PRIOR TO THE PLACEMENT OF THE EMBANKMENT IN THE FOLLOWING AREAS:
1783+50 - 1789+50 LT.
1829+50 - 1832+50 LT.
1714+50 - 1715+50 RT.
1784+50 - 1787+50 RT.
1790+50 - 1791+50 RT.
1822+50 - 1823+50 RT.
1830+50 - 1831+50 RT.

# T.H. 6

1590+04.70 - 2037+00.00

THE CONTRACTOR SHALL ROUND THE DITCH BOTTOMS, TOP EDGES OF THE BACKSLOPES AND THE TOE OF THE FILL SLOPES, REGARDLESS OF THE SECTIONS SHOWN ON THE CROSS-SECTION SHEETS.

SELECTED GRADING MATERIALS SHALL INCLUDE ALL MINERAL SOILS OTHER THAN DEBRIS, ORGANIC SOILS.



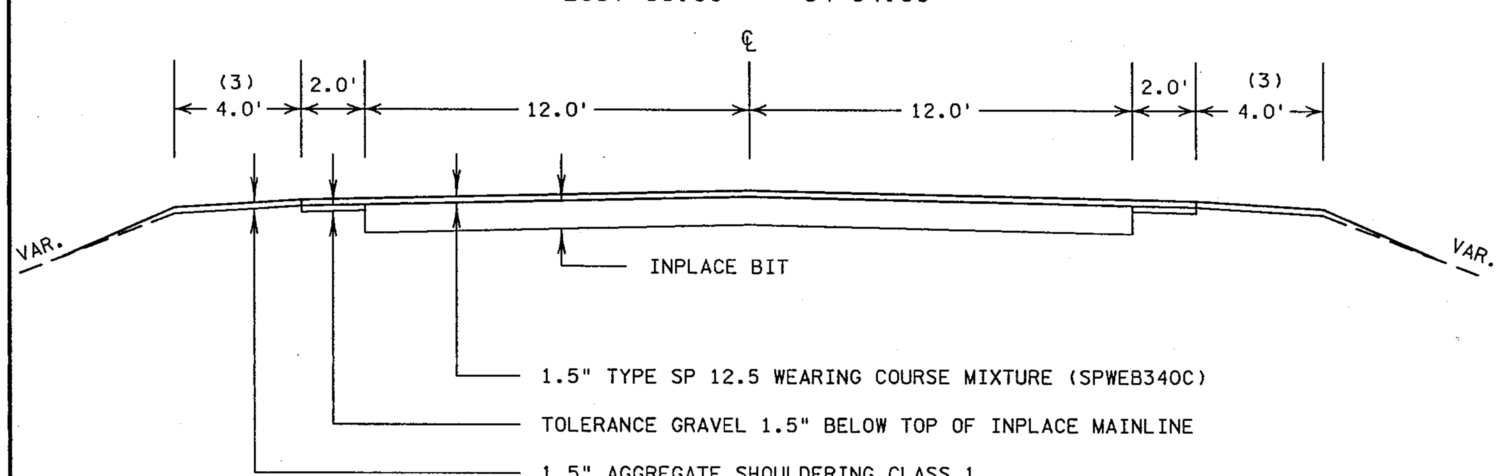

(1) A BIAXIAL GEOGRID LAYER 24' WIDE SHALL BE PLACED 6" BELOW THE SURFACE OF THE RECLAIM FROM 1823+00 TO 1841+50 AND FROM 1903+50 TO 1910+00. REMOVAL AND REPLACEMENT OF RECLAIMED MATERIAL FOR PLACEMENT OF THE GEOGRID SHALL BE PAID FOR AS EXCAVATION SPECIAL.

(2) A BIAXIAL GEOGRID LAYER 24' WIDE SHALL BE PLACED 4.5" BELOW THE SURFACE OF THE RECLAIM FROM 1910+00 TO 1915+50. REMOVAL AND REPLACEMENT OF THE RECLAIMED MATERIAL FOR PLACEMENT OF THE GEOGRID SHALL BE PAID FOR AS EXCAVATION SPECIAL.

NOTE: MATCH INPLACE CROSS SLOPES.

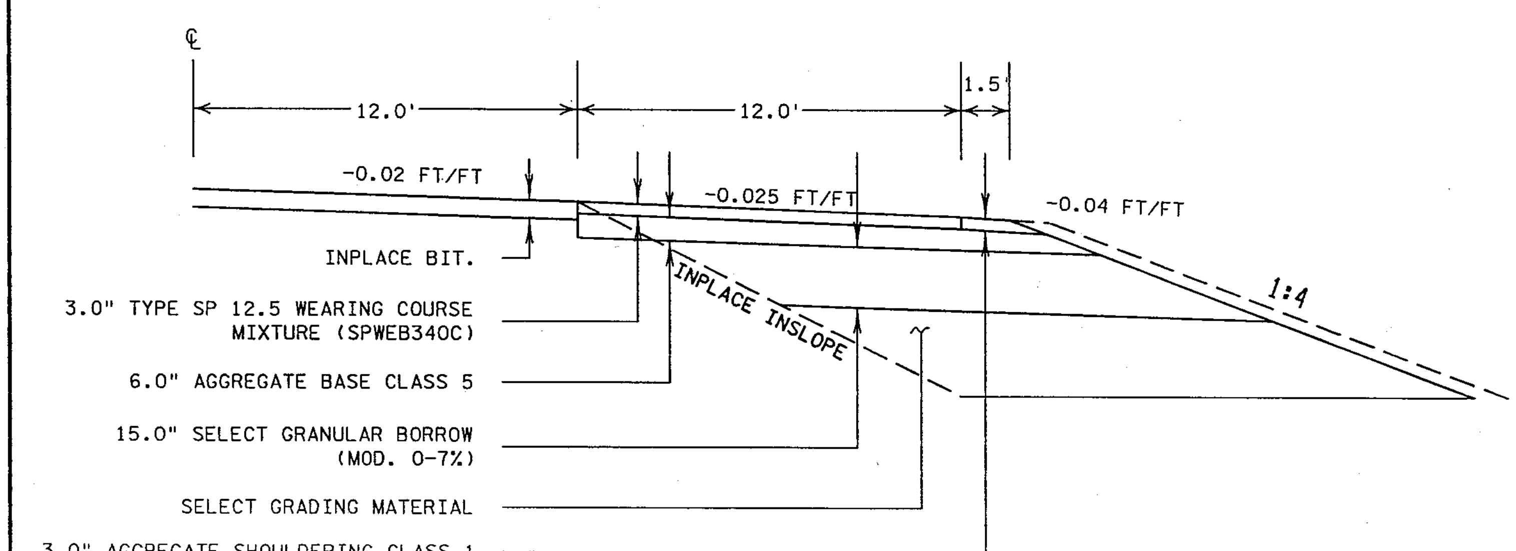
# T.H. 6

1102+74.00 - 1622+85.90
2037+00.00 - 94+84.00




(3) SHOULDER WIDTH SHALL MATCH EXISTING FROM 2037_00 TO 94+84.

# T.H. 1
# RIGHT TURN LANE




DISTRICT 2 - BEMIDJI, MN
PATH & FILENAME: S:\Projects\006\3107\42\Plan\2d310742.tsl

I HEREBY CERTIFY THAT THIS PLAN SHEET WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

A-2

ENGINEER Joseph S. McKinnon LIC. NO. 18965

TYPICAL SECTIONS

S.P. 3107-42 (T.H. 6)

FED. PROJ. NO. STPX 6011 (082)

# MINNESOTA DEPARTMENT OF TRANSPORTATION

CONSTRUCTION PLAN FOR BITUMINOUS RECLAIM & OVERLAY AND CULVERT REPLACEMENT

LOCATED ON TH 9 FROM NORMAN/POLK COUNTY LINE TO TH 2

STATE PROJ. NO. 6010-26 (TH 9)

| | | | | |
|---|---|---|---|---|
| GROSS LENGTH | 95,381.75 | FEET | 18.061 | MILES |
| BRIDGES-LENGTH | 140.00 | FEET | 0.027 | MILES |
| EXCEPTIONS-LENGTH | 140.00 | FEET | 0.027 | MILES |
| NET LENGTH | 95,241.75 | FEET | 18.034 | MILES |

REF. POINT 207+00.460 TO REF. POINT 225+00.494

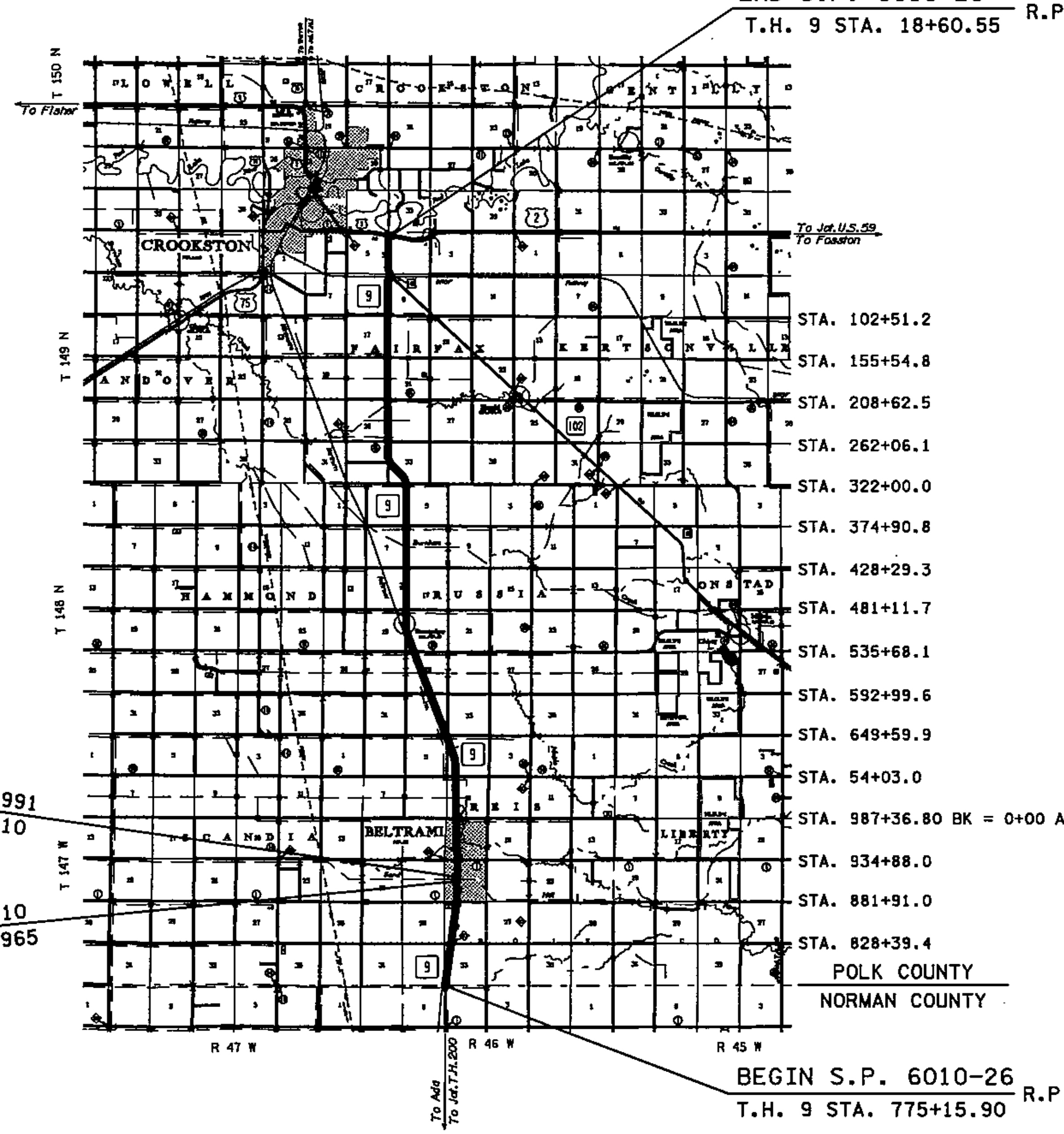
T.H. 9

| | | |
|---|---|---|
| R.P. 207 | = | 750+92 |
| R.P. 208 | = | 803+67 |
| R.P. 209 | = | 857+05 |
| R.P. 210 | = | 909+75 |
| R.P. 211 | = | 962+63 |
| R.P. 212 | = | 28+00 |
| R.P. 213 | = | 80+80 |
| R.P. 214 | = | 623+83 |
| R.P. 215 | = | 570+34 |
| R.P. 216 | = | 517+54 |
| R.P. 217 | = | 464+74 |
| R.P. 218 | = | 411+80 |
| R.P. 219 | = | 359+00 |
| R.P. 220 | = | 306+75 |
| R.P. 221 | = | 253+95 |
| R.P. 222 | = | 201+15 |
| R.P. 223 | = | 148+35 |
| R.P. 224 | = | 95+55 |
| R.P. 225 | = | 6+70 |

EQUATIONS
S.P. 6010-26 (T.H. 9)

| | | | |
|---|---|---|---|
| | STA. 907+52.09 BK | = STA. 907+57.96 AH | - R.P. 209+00.960 |
| | STA. 917+54.80 BK | = STA. 917+61.60 AH | - R.P. 210+00.148 |
| | STA. 928+70.80 BK | = STA. 928+63.80 AH | - R.P. 210+00.359 |
| | STA. 940+74.10 BK | = STA. 940+81.92 AH | - R.P. 210+00.587 |
| | STA. 956+00.00 BK | = STA. 955+90.33 AH | - R.P. 210+00.873 |
| | STA. 987+36.80 BK | = STA. 0+00.00 AH | - R.P. 211+00.469 |
| | STA. 97+23.12 BK | = STA. 660+34.61 AH | - R.P. 213+00.311 |
| | STA. 513+17.21 BK | = STA. 513+11.86 AH | - R.P. 216+00.083 |
| | STA. 329+62.56 BK | = STA. 328+84.45 AH | - R.P. 219+00.556 |
| | STA. 8+01.91 BK | = STA. 59+73.37 AH | - R.P. 224+00.678 |
| 17.52' RT. | STA. 15+58.75 BK | = STA. 0+00.00 AH | - R.P. 224+00.832 |
| | STA. 40+25.34 BK | = STA. 2+28.60 AH | - R.P. 225+00.084 |

END S.P. 6010-26
T.H. 9 STA. 18+60.55 R.P. 225+00.494




BRIDGE NO. 60008 EXCEPTION
R.P. 209+00.991
STA. 909+28.10
STA. 907+88.10
R.P. 209+00.965

BEGIN S.P. 6010-26
T.H. 9 STA. 775+15.90 R.P. 207+00.460

N

SCALES

| | | |
|---|---|---|
| PLAN | 50' | |
| PROFILE | 50' HORIZ. | 5' VERT. |
| INDEX MAP | 2 MILES | |

PLAN REVISIONS

| DATE | SHEET NO. | APPROVED BY |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |

## DESIGN DESIGNATION

Design ESALS 2029 = 1,411,000
ADT (Current Year) 2009 = 1900
ADT (Future Year) 2029 = 2400
DHV (Design Hr. Vol.) = ______
D (Directional Distr.) = ______ %
T (Heavy Commercial) = 14.2 %

Design Speed 60 MPH
Based on STOPPING Sight Distance 2.0'
Height of eye 3.5' Height of object
Design Speed not achieved at:
STA. ______ TO STA. ______ MPH
STA. ______ TO STA. ______ MPH

PROJECT LOCATION
COUNTY : POLK
DISTRICT : 2 BEMIDJI

FOR PLANS AND UTILITIES SYMBOLS SEE TECHNICAL MANUAL

| STATE PROJ. NO. | CHARGE IDENTIFIER |
|---|---|
| 6010-26 | [illegible] |

## GOVERNING SPECIFICATIONS

THE 2005 EDITION OF THE MINNESOTA DEPARTMENT OF TRANSPORTATION 'STANDARD SPECIFICATIONS FOR CONSTRUCTION', SHALL GOVERN.

## INDEX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EROSION CONTROL - STANDARD PLANS ........ 15-17
TRAFFIC CONTROL ........ 18-21
PLAN SHEET ........ 22
EROSION CONTROL & TURF ESTABLISHMENT SHEET ........ 23
BOX CULVERT PLAN SHEETS ........ B1-B7
CROSS-SECTIONS SHEETS ........ X1-X8


THIS PLAN CONTAINS 38 SHEETS

I HEREBY CERTIFY THAT THIS PLAN WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

PRINT NAME: JOHN T. ANDERSON LICENSE # 26462

DATE: 9-2-10 SIGNATURE: John T Anderson

DESIGN SQUAD SCOTT DOWERS

RECOMMENDED FOR APPROVAL [signature] 9/10 20 10 DISTRICT TRANSPORTATION ENGINEER

RECOMMENDED FOR APPROVAL [signature] 9/8 20 10 DISTRICT MATERIALS ENGINEER

RECOMMENDED FOR APPROVAL John Wingard 9-9- 20 10 DISTRICT WATER RESOURCES/HYDRAULICS ENGINEER

RECOMMENDED FOR APPROVAL [signature] 9/8 20 10 DISTRICT TRAFFIC ENGINEER

RECOMMENDED FOR APPROVAL [signature] 11/2 20 10 STATE PRE-LETTING ENGINEER

OFFICE OF LAND MANAGEMENT APPROVAL [signature] 11/9 20 10 DIRECTOR, LAND MANAGEMENT

APPROVED 11/10 20 10 [signature] For STATE DESIGN ENGINEER

I HEREBY CERTIFY THAT THE FINAL FIELD REVISIONS, IF ANY, WERE PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

PRINT NAME: ______ LICENSE # ______

DATE: ______ SIGNATURE: ______

STATE PROJ. NO. 6010-26 (TH 9 = 6 ) SHEET NO. 1 OF 23 SHEETS

PLOTTED/REVISED: 9/1/2010

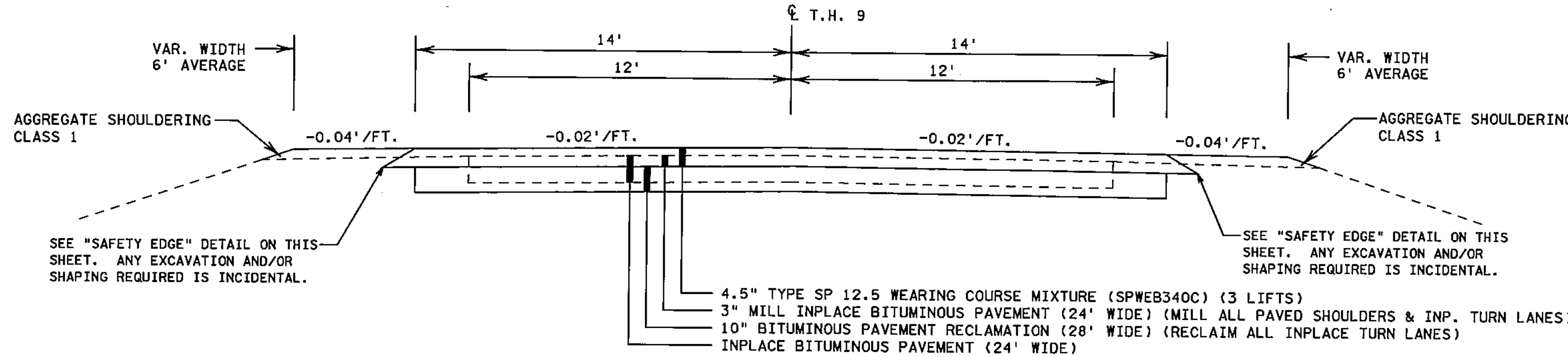
DISTRICT #: DISTRICT 2 - BEMIDJI,MN
IPLOT NAME:
PATH & FILENAME: IP_PWP:d0982487\2d601026_tsh.dgn

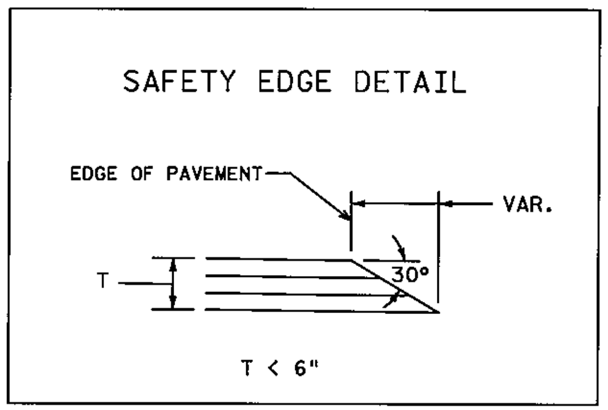
PLOTTED/REVISED: 10/25/2010

## PROPOSED TYPICAL SECTION

S.P. 6010-26

STA. 775+15.9 TO STA. 881+91 R.P. 207+00.460 TO R.P. 209+00.471
STA. 987+36.8 TO STA. 0+00 R.P. 211+00.469 TO R.P. 224+00.800



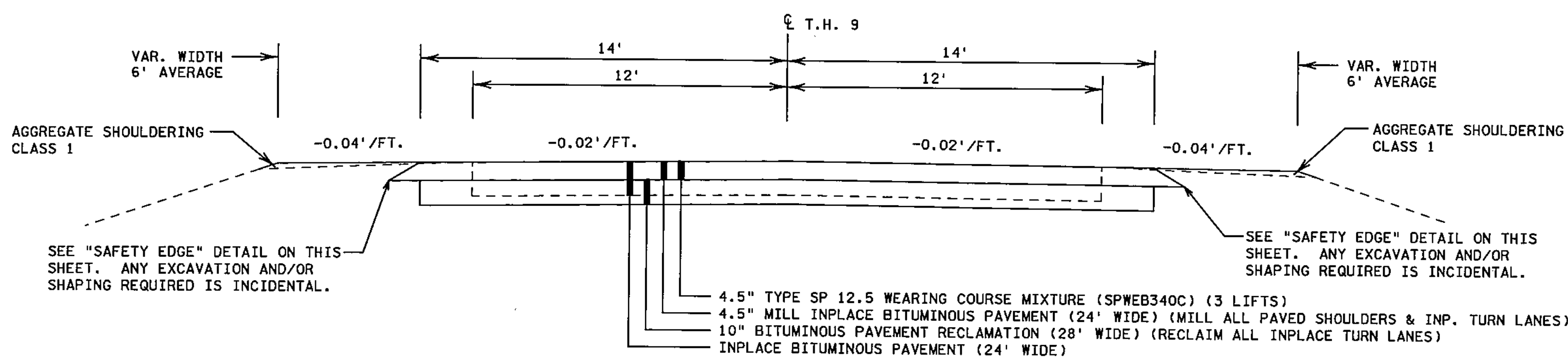



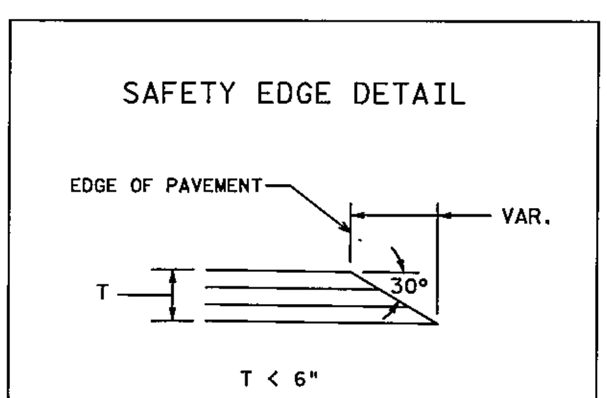

NOTE: FINISHED CENTERLINE GRADE AFTER FINAL BITUMINOUS PLACEMENT SHALL BE 1.5" HIGHER THAN INPLACE CENTERLINE ELEVATION. RECLAIM MATERIAL SHALL BE USED TO TOLERANCE INPLACE GRADE AND SHOULDERS. RECLAIM MATERIAL NOT USED ON THE PROJECT SHALL BECOME THE PROPERTY OF THE CONTRACTOR.

## PROPOSED TYPICAL SECTION

S.P. 6010-26

STA. 881+91 TO STA. 925+25 R.P. 209+00.471 TO R.P. 210+00.294
STA. 942+42 TO STA. 987+36.8 R.P. 210+00.619 TO R.P. 211+00.469




NOTE: MILL INP. BIT. APPROACHES 1.5".

NOTE: FINISHED CENTERLINE GRADE AFTER FINAL BITUMINOUS PLACEMENT SHALL BE THE SAME AS INPLACE CENTERLINE ELEVATION. RECLAIM MATERIAL SHALL BE USED TO TOLERANCE INPLACE GRADE AND SHOULDERS. RECLAIM MATERIAL NOT USED ON THE PROJECT SHALL BECOME THE PROPERTY OF THE CONTRACTOR.

DISTRICT #: DISTRICT 2 - BEMIDJI,MN
IPLOT NAME:
PATH & FILENAME: IP_PWP:d0982487\2d601026_ts1.dgn

I HEREBY CERTIFY THAT THIS PLAN SHEET WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

ENGINEER [signature] LIC. NO. 26462

TYPICAL SECTIONS

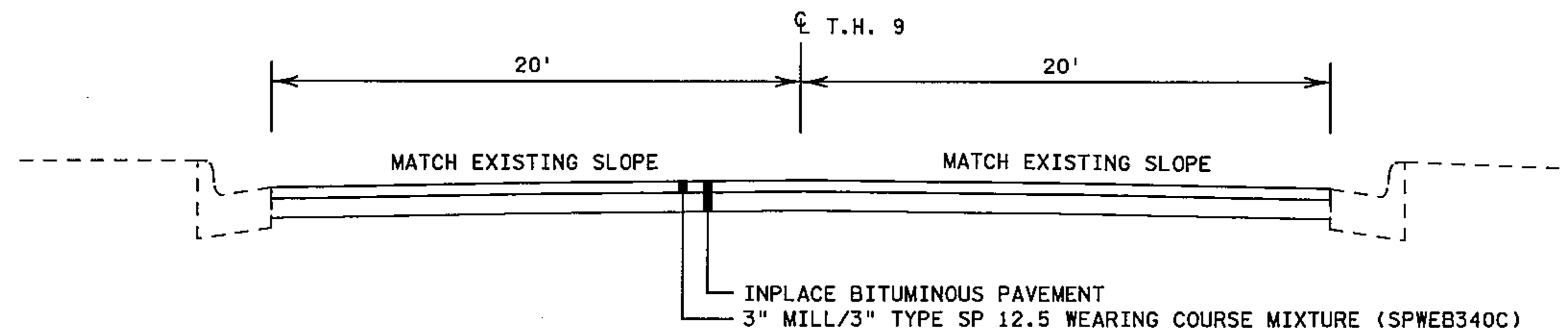
STATE PROJ. NO. 6010-26 (TH 9 ) SHEET NO. 5 OF 23 SHEETS

PLOTTED/REVISED: 8/24/2010

## PROPOSED TYPICAL SECTION

S.P. 6010-26
IN BELTRAMI

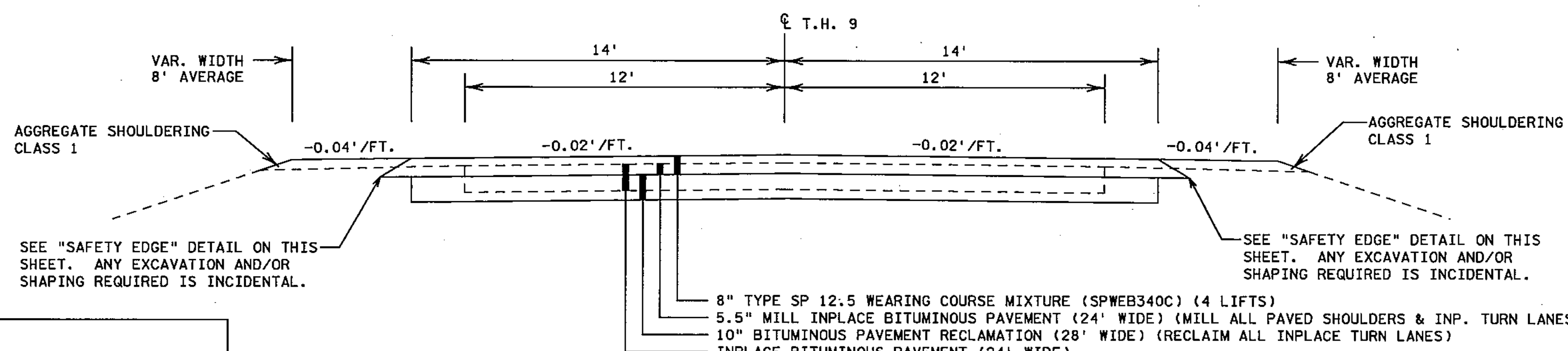
STA. 925+25 TO STA. 942+42 R.P. 210+00.294 TO R.P. 210+00.619




## PROPOSED TYPICAL SECTION

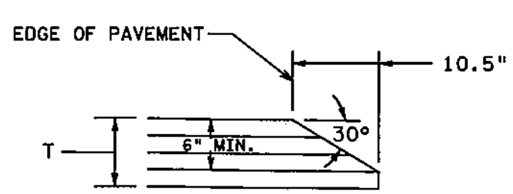
S.P. 6010-26

STA. 0+00 (JCT. TH 102) TO STA. 18+60.55 R.P. 224+00.800 TO R.P. 225+00.494




NOTE: FINISHED CENTERLINE GRADE AFTER FINAL BITUMINOUS PLACEMENT SHALL BE 2.5" HIGHER THAN INPLACE CENTERLINE ELEVATION. RECLAIM MATERIAL SHALL BE USED TO TOLERANCE INPLACE GRADE AND SHOULDERS. RECLAIM MATERIAL NOT USED ON THE PROJECT SHALL BECOME THE PROPERTY OF THE CONTRACTOR.

### SAFETY EDGE DETAIL




T >= 6"

DISTRICT *: DISTRICT 2 - BEMIDJI,MN
IPLOT NAME:
PATH & FILENAME: IP_PWP:d0982487\2d601026_ts.dgn

I HEREBY CERTIFY THAT THIS PLAN SHEET WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

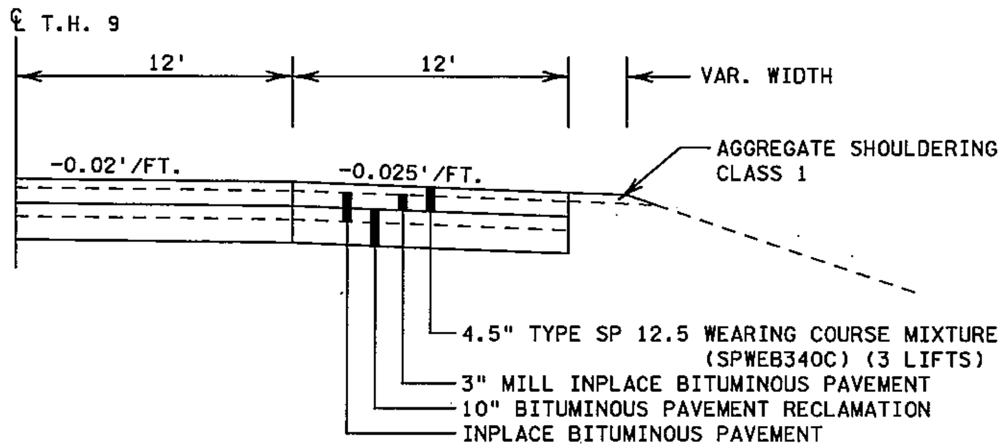
ENGINEER John A.T. [signature] LIC. NO. 26462

TYPICAL SECTIONS

STATE PROJ. NO. 6010-26 (TH 9 ) SHEET NO. 6 OF 23 SHEETS

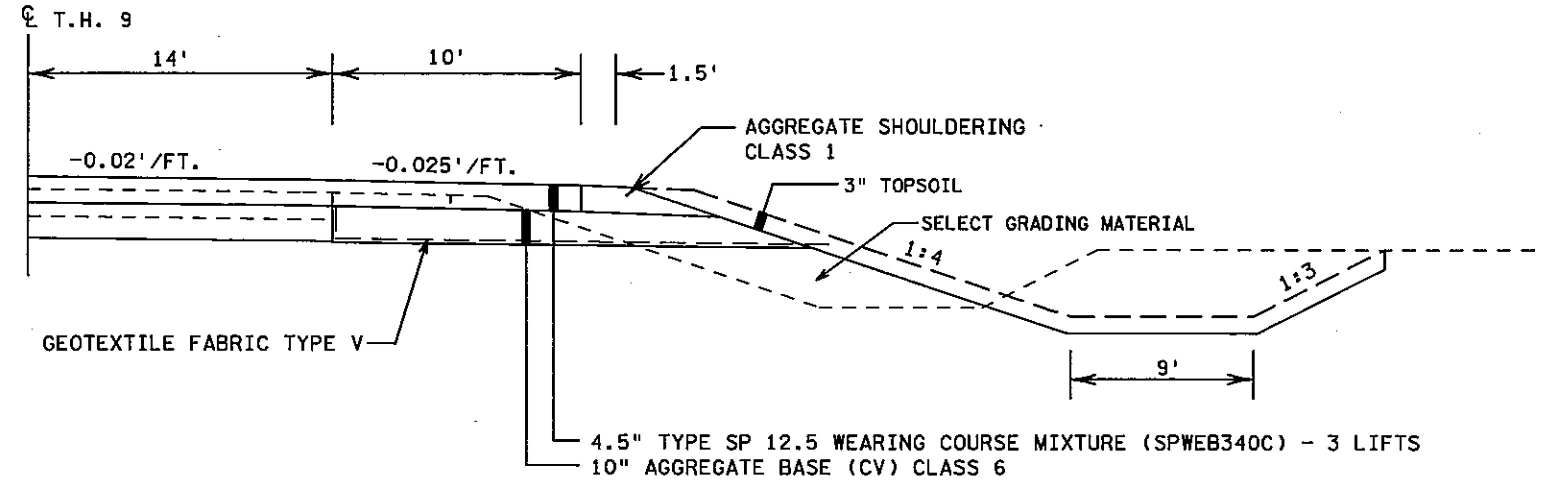
PLOTTED/REVISED: 10/1/2010

## EXISTING TURN LANES



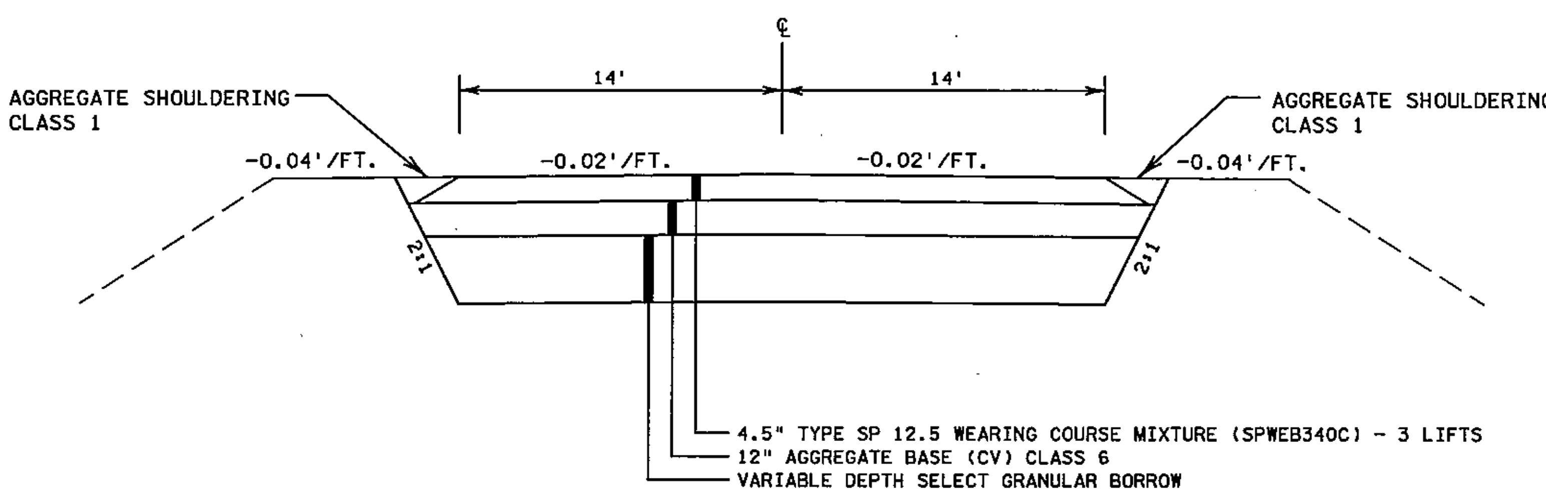

## PROPOSED TURN LANE

NBL AT JCT. TH 102
STA. 4+80 TO STA. 0+00
R.P. 224+00.710 TO R.P. 224+00.800



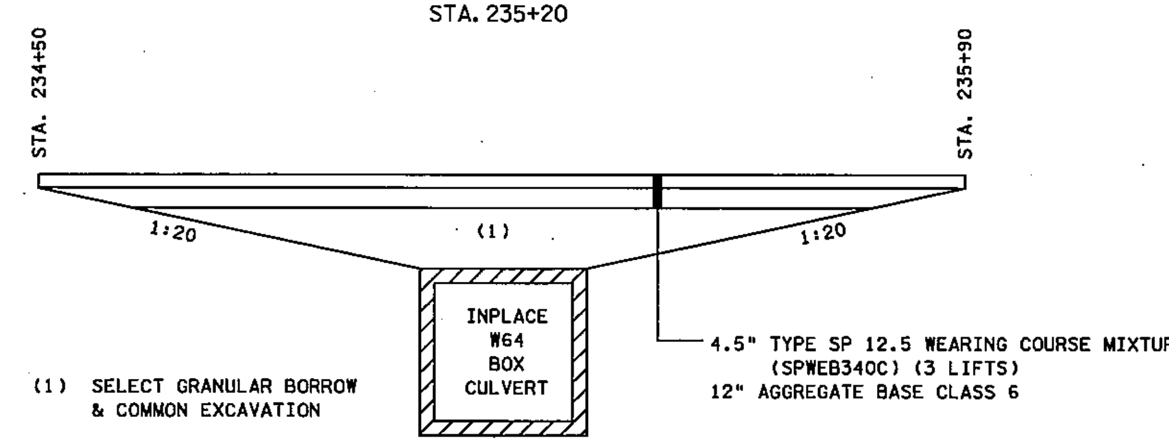

## BOX CULVERT REPAIR TYPICAL SECTION

STA. 235+20




## BOX CULVERT REPAIR TREATMENT DETAILS

STA. 235+20




DISTRICT •: DISTRICT 2 - BEMIDJI,MN
IPLOT NAME:
PATH & FILENAME: IP_PWP:d0982487\2d601026_tsl.dgn

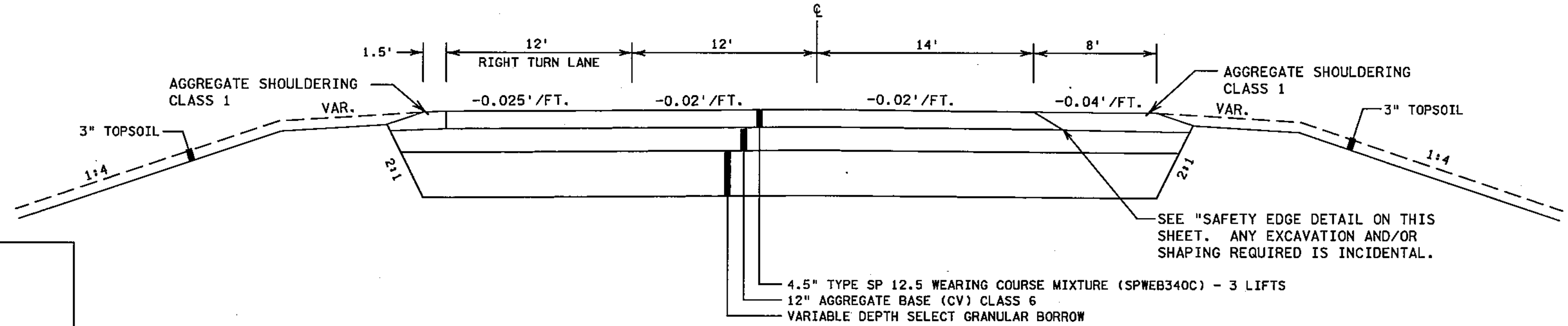
I HEREBY CERTIFY THAT THIS PLAN SHEET WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

ENGINEER ____________ LIC. NO. 26462

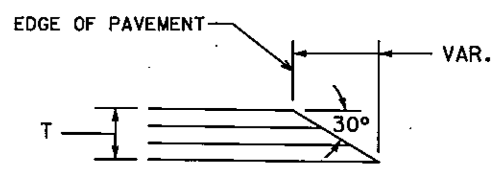
TYPICAL SECTIONS

## BOX CULVERT REPLACEMENT TYPICAL SECTION

STA. 375+04 TO STA. 376+45



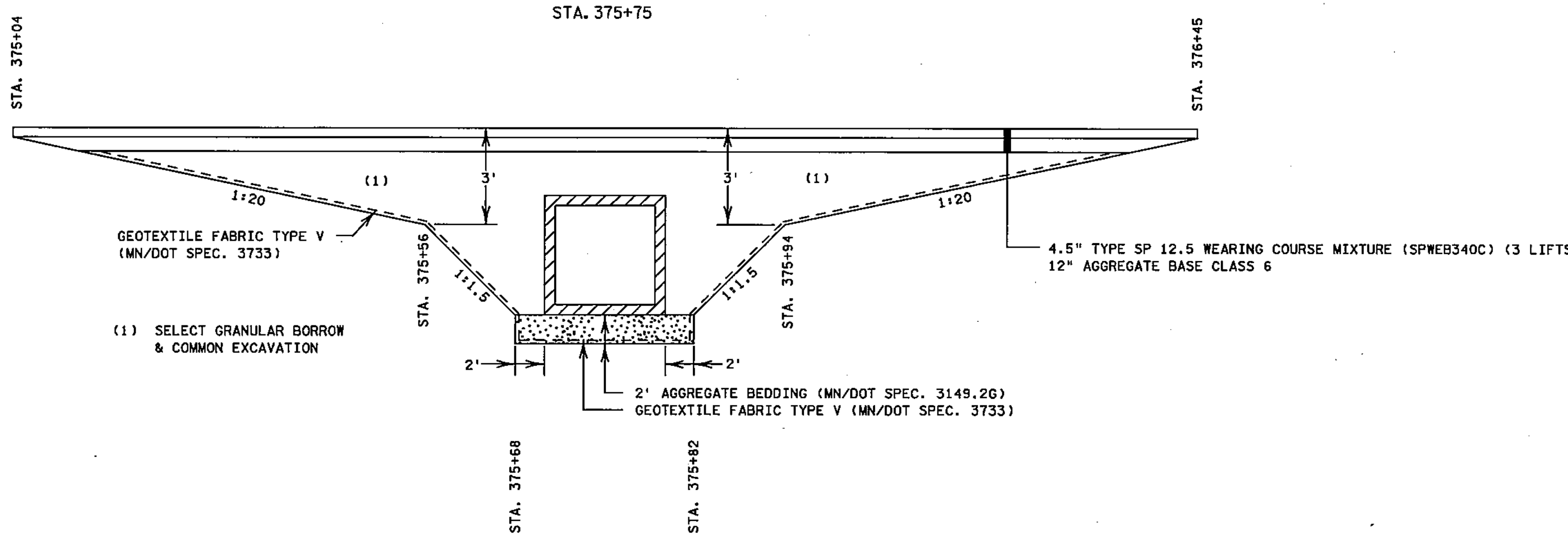

### SAFETY EDGE DETAIL




T < 6"

## BOX CULVERT TREATMENT DETAILS

STA. 375+75




PLOTTED/REVISED: 8/24/2010

DISTRICT #: DISTRICT 2 - BEMIDJI,MN
IPLOT NAME:
PATH & FILENAME: IP_PWP:d0982487\2d601026_tsl.dgn

I HEREBY CERTIFY THAT THIS PLAN SHEET WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

ENGINEER [signature] LIC. NO. 26462

TYPICAL SECTIONS

STATE PROJ. NO. 6010-26 (TH 9 ) SHEET NO. 8 OF 23 SHEETS

PLANS SYMBOLS

STATE LINE
COUNTY LINE
TOWNSHIP OR RANGE LINE
SECTION LINE
QUARTER LINE
SIXTEENTH LINE
RIGHT-OF-WAY LINE
PRESENT RIGHT-OF-WAY LINE
CONTROL OF ACCESS LINE
PROPERTY LINE (Except Land Lines)
VACATED PLATTED PROPERTY
CORPORATE OR CITY LIMITS
TRUNK HIGHWAY CENTER LINE
RETAINING WALL
RAILROAD
RAILROAD RIGHT-OF-WAY LINE
RIVER OR CREEK
DRY RUN
DRAINAGE DITCH
DRAIN TILE
CULVERT
DROP INLET
GUARD RAIL
BARBED WIRE FENCE
WOVEN WIRE FENCE
CHAIN LINK FENCE
RAILROAD SNOW FENCE
STONE WALL OR FENCE
HEDGE
RAILROAD CROSSING SIGN
RAILROAD CROSSING BELL
ELECTRIC WARNING SIGN
CROSSING GATE
MEANDER CORNER
SPRINGS
MARSH
TIMBER
ORCHARD
BRUSH
NURSERY
CATCH BASIN
FIRE HYDRANT
CATTLE GUARD
OVERPASS (Highway Over)
UNDERPASS (Highway Under)
BRIDGE
BUILDING (One Story Frame)
F-FRAME C-CONCRETE
S-STONE T-TILE
B-BRICK ST-STUCCO
IRON PIPE OR ROD
MONUMENT (STONE, CONCRETE, OR METAL)
WOODEN HUB
GRAVEL PIT
SAND PIT
BORROW PIT
ROCK QUARRY
SLOPE EASEMENT

UTILITIES SYMBOLS

POWER POLE LINE
TELEPHONE OR TELEGRAPH POLE LINE
JOINT TELEPHONE AND POWER ON POWER POLES
ON TELEPHONE POLES
ANCHOR
STEEL TOWER
STREET LIGHT
PEDESTAL (TELEPHONE CABLE TERMINAL)
GAS MAIN
WATER MAIN
CONDUIT
TELEPHONE CABLE IN CONDUIT
ELECTRIC CABLE IN CONDUIT
TELEPHONE MANHOLE
ELECTRIC MANHOLE
BURIED TELEPHONE CABLE
BURIED ELECTRIC CABLE
AERIAL TELEPHONE CABLE
SEWER, (SANITARY OR STORM)
SEWER MANHOLE
CURB STOP & BOX
GATE VALVE & BOX

N:\CSAH 10\1016\DWG\TITLE

# MINNESOTA DEPARTMENT OF TRANSPORTATION
# ITASCA COUNTY HIGHWAY DEPARTMENT

CONSTRUCTION PLAN FOR BITUMINOUS PAVING, CONSTRUCT TURN LANES AND SHOULDERING WORK

LOCATED ON CSAH NO. 10 BETWEEN US HWY NO. 2 AND TH NO. 169 (GEOGRAPHIC DESCRIPTION)

FROM APPROX. 150' N. OF 1/4 COR. COM. TO SECS. 28 & 29, T. 54 N., R. 23 W. TO APPROX. 1,550' W. & 90' N. OF 1/4 COR. COM. TO SECS. 32 & 33, T. 56 N., R. 24 W. (LEGAL DESCRIPTION)

STATE AID PROJ. NO. 031-610-016

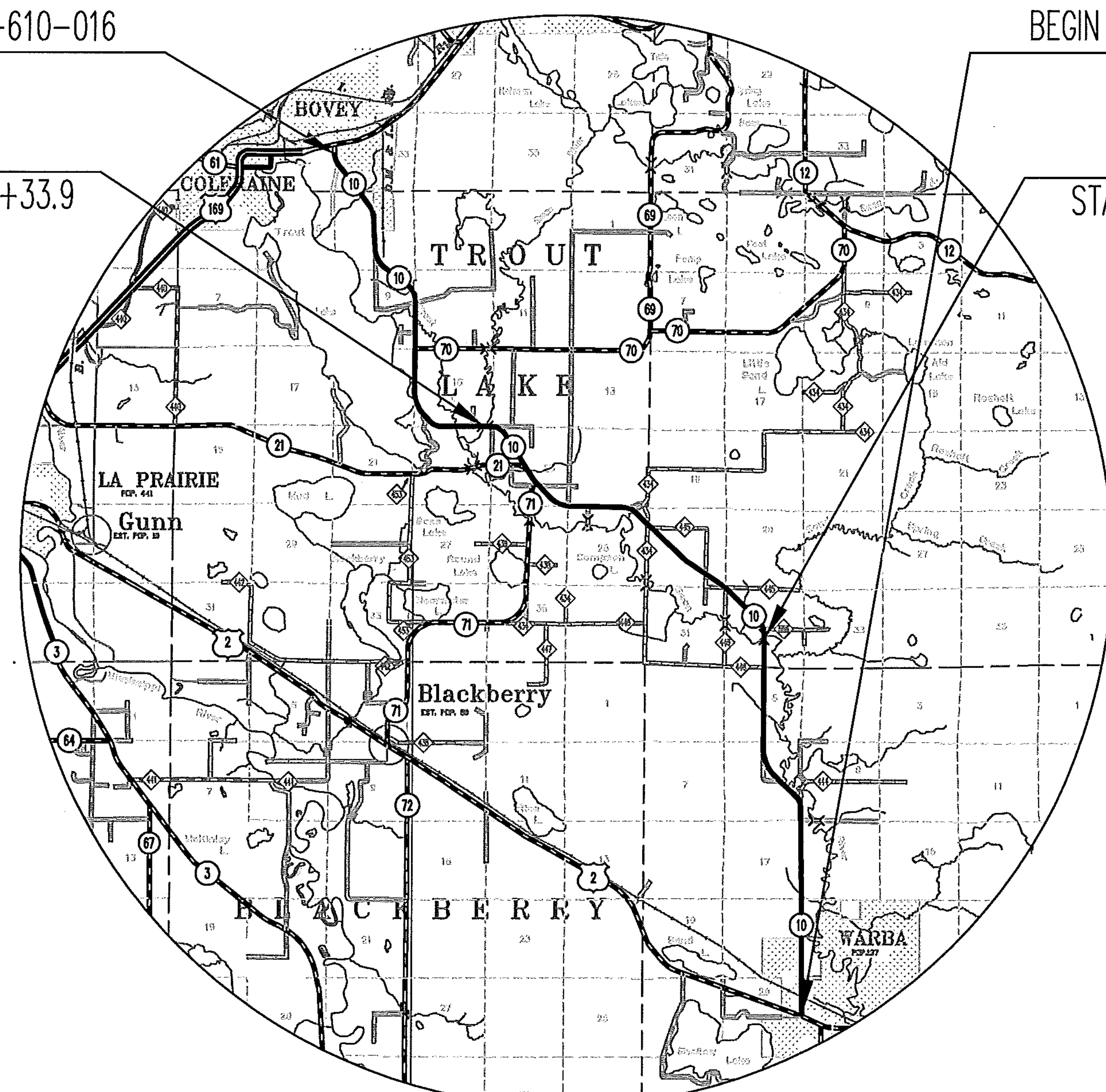
| | | | | |
|---|---|---|---|---|
| GROSS LENGTH | 14.396 | MILES | 76,012 | FEET |
| BRIDGES-LENGTH | 0.051 | MILES | 270.5 | FEET |
| EXCEPTIONS-LENGTH | 0.051 | MILES | 270.5 | FEET |
| NET LENGTH | 14.345 | MILES | 75,741.5 | FEET |

END PROJECT S.A.P. 031-610-016
STA. 760+12

BRIDGE EXCEPTION:
STA 512+10 TO STA 513+33.9

BEGIN PROJECT S.A.P. 031-610-016
STA. 0+00

BRIDGE EXCEPTION:
STA 262+40 TO STA 263+86.6




N

ITASCA COUNTY ENGINEERING DEPT.
Grand Rapids Minnesota

SCALES

| | |
|---|---|
| PLAN | NA |
| PROFILE | NA |
| INDEX MAP | 5,280' |
| GENERAL LAYOUT | NA |

A-8

STATE AID PROJECT 031-610-016

GOVERNING SPECIFICATIONS

THE 2005 EDITION OF THE MINNESOTA DEPARTMENT OF TRANSPORTATION "STANDARD SPECIFICATIONS FOR CONSTRUCTION".

| SHEET NO. | DESCRIPTION |
|---|---|
| 1 | TITLE SHEET |
| 2 | ESTIMATED QUANTITIES, STANDARD PLATES |
| 3 - 8 | TYPICAL SECTIONS |
| 9 - 11 | PLAN SHEETS |
| 12 - 14 | CROSS-SECTIONS |
| 15 - 16 | TRAFFIC PLAN |

THIS PLAN CONTAINS 16 SHEETS

DESIGN DESIGNATION - RECONDITIONING

$N18_{20}$ N/A
R Value N/A
ADT(Current Year) 2012 = 1,150
ADT(Projected) 2032 = 1,150
Proj. HCADT = N/A
Ton Design = N/A

Roadway Classification = RURAL UNDIVIDED
No. of Traffic Lanes: 2
No. of Parking Lanes: N/A
Shoulder Width (This Plan) 6'
(Future) N/A
Design Speed N/A miles/hr.
Based on N/A Sight Distance
Height of eye N/A Height of object N/A
Design Speed not achieved at: ______

I HEREBY CERTIFY THAT THIS PLAN WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

DATE 4-11-12 REG. NO. 24035 ENGR. Karin Grandia
KARIN GRANDIA
TRANSPORTATION ENGINEER

Karin Grandia DATE 4-11-12
for: APPROVED: ITASCA COUNTY ENGINEER

DATE 4/13/12
District State Aid Engineer: Reviewed for Compliance with State Aid Rules/Policy

DATE 4/13/12
State Aid Engineer:
Approved for State Aid and Federal Aid Funding

STATE AID PROJ. NO. S.A.P. 031-610-016 SHEET NO. 1 OF 16 SHEETS

| PIT DATA |
|---|
| COUNTY: BENTON<br>SOURCE NO: 05017<br>LOCATION: E 1/2 SW 1/4 S11 T36 R30<br>MAT. AVAIL: CL-6 |
| COUNTY: MORRISON<br>SOURCE NO.: 49027<br>LOCATION: NW 1/4 SW 1/4 S7 T40 R31<br>MAT. AVAIL: CL-6, BIT. AGG. |
| COUNTY: MORRISON<br>SOURCE AVAIL: 49069<br>LOCATION: NW 1/4 SW 1/4 S20 T40 R30<br>MAT. AVAIL: SELECT GRANULAR |

# MINNESOTA DEPARTMENT OF TRANSPORTATION

CONSTRUCTION PLAN FOR BITUMINOUS MILLING & SURFACING, TURN LANE CONSTRUCTION, CULVERTS AND GUARDRAIL

LOCATED ON T.H. 10 FROM 1350' NORTH OF C.S.A.H. 35 TO 1 MI. S. OF WATAB RD (CR 79)

| STATE PROJ. NO. 0502-95 (T.H. 10) | STATE PROJ. NO. 4901-73 (T.H. 10) |
|---|---|
| GROSS LENGTH 68862.63 FEET 13.04 MILES | GROSS LENGTH 45252.44 FEET 8.57 MILES |
| BRIDGES-LENGTH 274.56 FEET 0.052 MILES | BRIDGES-LENGTH 0.0 FEET 0.0 MILES |
| EXCEPTIONS-LENGTH 274.56 FEET 0.052 MILES | EXCEPTIONS-LENGTH 0.0 FEET 0.0 MILES |
| NET LENGTH 68588.07 FEET 12.99 MILES | NET LENGTH 45252.44 FEET 8.57 MILES |
| REF. POINT 156+00.961 TO REF. POINT 170+00.091 | REF. POINT 148+00.637 TO REF. POINT 156+00.961 |

LENGTH BASED ON W.B. ALIGNMENT

PLOTTED/REVISED: 2/16/2005

## T.H. 10 EQUATIONS

### BENTON COUNTY

W.B.

| | | |
|---|---|---|
| PT 416+74.74 R 5 BK | = | POT 416+72.52 R 6 AH |
| PT 561+71.74 R 6 BK | = | POT 561+68.30 R 7 AH |
| PT 580+00.00 R 7 BK | = | POT 580+00.02 R 8 AH |
| PT 583+43.80 R 8 BK | = | POT 583+44.28 R 9 AH |
| PT 654+92.44 R 9 BK | = | POT 654+91.88 R 10 AH |
| PT 670+42.70 R 10 BK | = | POT 670+40.26 R 11 AH |
| PT 750+88.68 R 11 BK | = | POT 750+90.85 R 12 AH |
| ST 802+23.65 R 12 BK | = | POT 802+25.00 R 13 AH |
| ST 849+01.38 R 13 BK | = | POT 842+29.13 R 14 AH |
| POT 889+73.40 R 14 BK | = | POT 889+76.87 R 15 AH |
| POT 1091+02.30 R 15 BK | = | POT 2+11.56 R 16 AH |

E.B.

| | | |
|---|---|---|
| PT 416+74.55 R 8 BK | = | POT 416+72.82 R 9 AH |
| POT 543+89.56 R 9 BK | = | TS 544+04.50 R 10 AH |
| ST 562+84.52 R 10 BK | = | POT 563+28.18 R 11 AH |
| POT 583+43.77 R 11 BK | = | POT 583+44.28 R 12 AH |
| POT 654+96.97 R 12 BK | = | POT 654+87.90 R 13 AH |
| POT 664+19.71 R 13 BK | = | PC 664+24.10 R 14 AH |
| PT 670+43.10 R 14 BK | = | POT 670+44.81 R 15 AH |
| POT 734+40.11 R 15 BK | = | TS 734+40.02 R 16 AH |
| POT 751+42.48 R 16 BK | = | POT 750+90.85 R 17 AH |
| POT 780+36.51 R 17 BK | = | TS 780+36.37 R 18 AH |
| POT 849+53.78 R 18 BK | = | POT 842+29.13 R 19 AH |
| POT 889+73.43 R 19 BK | = | POT 889+76.82 R 20 AH |
| POT 1091+39.00 R 20 BK | = | POT 2+46.99 R 21 AH |

### MORRISON COUNTY

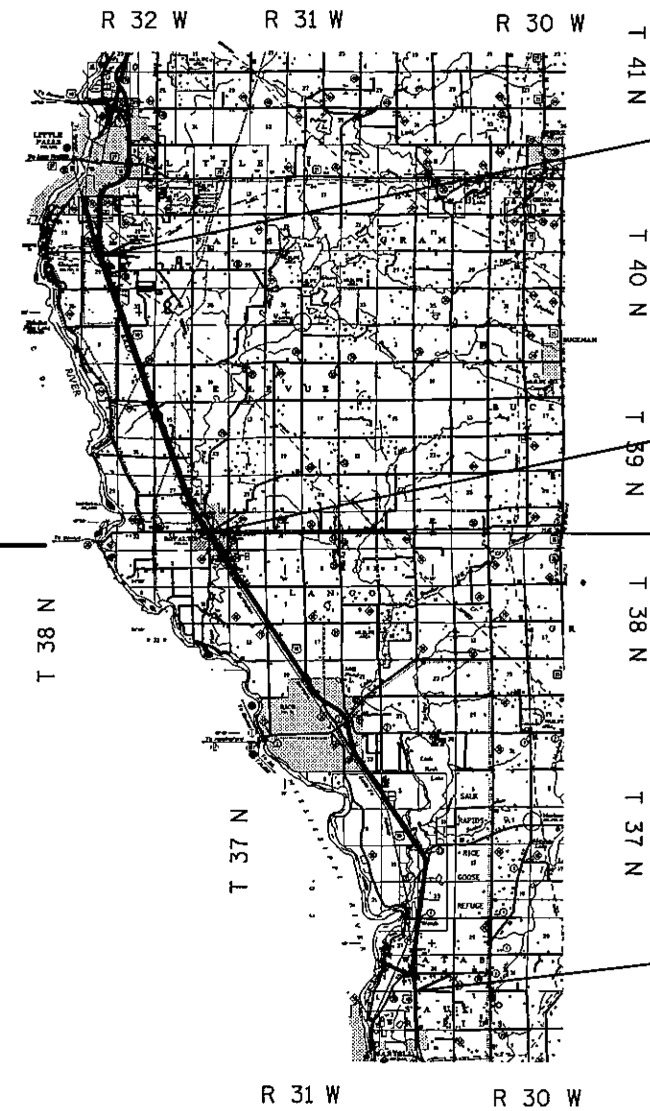
W.B.

| | | |
|---|---|---|
| PT 1154+49.50 R 1 BK | = | POT 65+63.38 R 2 AH |
| PT 81+03.30 R 2 BK | = | POT 81+27.10 R 3 AH |
| POT 160+71.30 R 3 BK | = | POT 160+71.21 R 4 AH |
| POT 204+20.50 R 4 BK | = | POT 204+16.23 R 5 AH |
| POT 274+62.40 R 5 BK | = | POT 274+63.80 R 6 AH |
| POT 296+22.20 R 6 BK | = | POT 296+10.00 R 7 AH |
| POT 327+87.70 R 7 BK | = | POT 327+88.50 R 8 AH |
| POT 383+97.70 R 8 BK | = | POT 384+18.08 R 9 AH |
| POT 412+29.90 R 9 BK | = | POT 412+34.10 R 10 AH |
| POT 444+11.10 R 10 BK | = | POT 444+08.46 R 11 AH |

E.B.

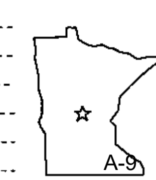
| | | |
|---|---|---|
| PT 1094+21.96 R 1 BK | = | POT 1094+20.82 R 2 AH |
| PT 1119+45.95 R 2 BK | = | POT 1119+42.77 R 3 AH |
| PT 1126+50.65 R 3 BK | = | POT 1126+53.52 R 4 AH |
| POT 1153+33.63 R 4 BK | = | POT 64+52.69 R 5 AH |
| PT 80+45.71 R 5 BK | = | POT 80+48.60 R 6 AH |
| POT 204+18.50 R 6 BK | = | POT 204+13.96 R 7 AH |
| POT 296+16.00 R 7 BK | = | POT 296+09.81 R 8 AH |
| POT 383+98.40 R 8 BK | = | POT 384+17.90 R 9 AH |

WARNING: PETROLEUM PRODUCTS PIPELINE WITHIN PROJECT LIMITS




## DESIGN DESIGNATION

Design ESALS 20 YR. = 8,794,000
ADT (Current Year) 2005 = 20,700 Design Speed 70 MPH
ADT (Future Year) 2025 = 32,200 Based on ______ Sight Distance ______
DHV (Design Hr. Vol.) = ______ Height of eye ______ Height of object ______
D (Directional Distr.) = ______ % Design Speed not achieved at: ______
T (Heavy Commercial) = ______ % STA. ______ TO STA. ______ MPH
STA. ______ TO STA. ______ MPH




PROJECT LOCATION
COUNTY: MORRISON/BENTON
DISTRICT: 3 BRAINERD

FOR PLANS AND UTILITIES SYMBOLS SEE TECHNICAL MANUAL

| STATE PROJ. NO. | CHARGE IDENTIFIER |
|---|---|
| 0502-95 | T39 |
| 4901-73 | T39 |

| PLAN REVISIONS | | |
|---|---|---|
| DATE | SHEET NO. | APPROVED BY |
| | | |
| | | |
| | | |
| | | |
| | | |

DISTRICT #: $$DISTRICT$$
IPLOT NAME:
PATH & FILENAME: S:\pr\0\0502\95\design\d050295_tsh.dgn

FED. PROJ. NO. NH-STP 0010(314)

## GOVERNING SPECIFICATIONS

THE 2000 EDITION OF THE MINNESOTA DEPARTMENT OF TRANSPORTATION "STANDARD SPECIFICATIONS FOR CONSTRUCTION", SHALL GOVERN.

## INDEX


| | |
|---|---|
| 1 | TITLE SHEET |
| 2 - 4 | ESTIMATED QUANTITIES |
| 5 - 9 | TABULATED QUANTITIES |
| 10 | SOILS & CONST. NOTES AND STANDARD PLATES |
| 11 - 15 | TYPICAL SECTIONS |
| 16 - 17 | PUBLIC UTILITIES TABULATIONS |
| 18 - 57 | PLAN SHEETS |
| 58 - 59 | MISCELLANEOUS DETAILS |
| 60 - 77 | STANDARD PLANS |
| 78 - 80 | DRAINAGE PLAN & TABULATIONS |
| 81 - 82 | ACCELERATION LANE PLAN & PROFILE |
| 83 - 84 | TURF ESTABLISHMENT & EROSION CONTROL SHEETS |
| 85 - 87 | TRAFFIC CONTROL SHEETS |
| 88 - 94 | PAVEMENT MARKING DETAILS & TABULATIONS |
| 95 - 104 | SIGNING DETAILS & TABULATIONS |
| 105 - 108 | LOOP DETECTOR SHEETS |
| 109 - 120 | ROAD/WEATHER/INFORMATION SHEETS |
| 121 | EARTHWORK TABULATIONS |
| 122 - 131 | CROSS SECTIONS |


THIS PLAN CONTAINS 131 SHEETS

I HEREBY CERTIFY THAT THIS PLAN WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

PRINT NAME: ROBERT MILLER LICENSE # 23164
DATE: 2/16/05 SIGNATURE: Robert Miller

DESIGN SQUAD MARY SCHILLING, JEREMY BJORGAARD, STEVE DESMITH, JASON LEE AND CHAD DEMENGE

RECOMMENDED FOR APPROVAL Bob Busch 2/16/2005 DISTRICT TRANSPORTATION ENGINEER
RECOMMENDED FOR APPROVAL 2/16 2005 DISTRICT MATERIALS ENGINEER
RECOMMENDED FOR APPROVAL 2/16 2005 DISTRICT HYDRAULICS ENGINEER
RECOMMENDED FOR APPROVAL A P Durlam 2/16 2005 DISTRICT TRAFFIC ENGINEER
RECOMMENDED FOR APPROVAL Janet Blanch 3-11 2005 STATE PRE-LETTING ENGINEER
OFFICE OF LAND MANAGEMENT APPROVAL 3/14 2005 DIRECTOR, LAND MANAGEMENT
APPROVED 3/14 2005 Timothy P Quinn STATE DESIGN ENGINEER

I HEREBY CERTIFY THAT THE FINAL FIELD REVISIONS, IF ANY, WERE PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

PRINT NAME: ______ LICENSE # ______
DATE: ______ SIGNATURE: ______

STATE PROJ. NO. 0502-95 (T.H. 10 = 27) 4901-73 (T.H. 10 = 27) SHEET NO. 1 OF 131 SHEETS

AR 3-15-05

## PROPOSED TYPICAL SECTION NO.1

T.H. 10

BENTON COUNTY

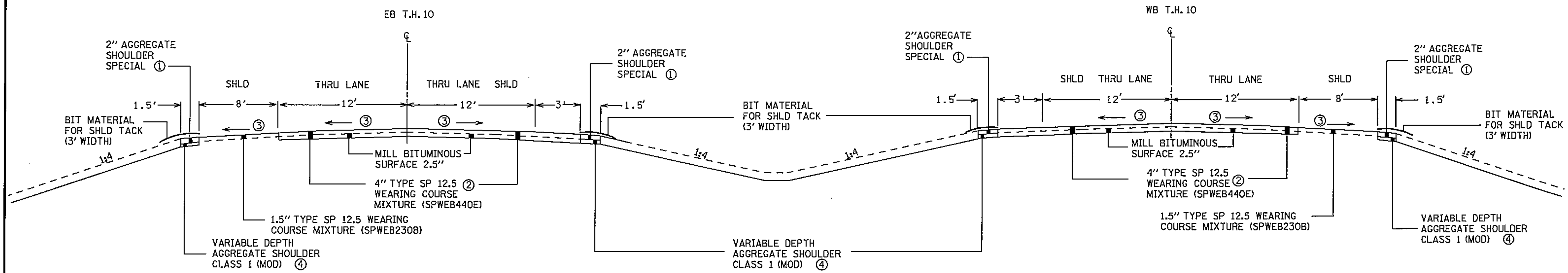
WB STA. 409+13.09 R 5 TO 1091+02.30 R 15

EB STA. 466+56.50 R 9 TO 1091+39.00 R 20

MORRISON COUNTY

WB STA. 1087+06.61 R 1 TO 1093+77.39 R 1
WB STA. 68+17.64 R 2 TO 447+50.00 R 11

EB STA. 68+24.52 R 5 TO 447+50 R 9




VARIABLE DEPTH
AGGREGATE SHOULDER
CLASS 1 (MOD) ④

## PROPOSED TYPICAL SECTION NO.2

T.H. 10 CITY OF ROYALTON

MORRISON COUNTY

WB STA. 1093+77.39 R 1 TO 1096+43.39 R 1
WB STA. 1141+00.00 R 1 TO 1146+46.84 R 1
WB STA. 1149+16.43 R 1 TO 65+63.38 R 2

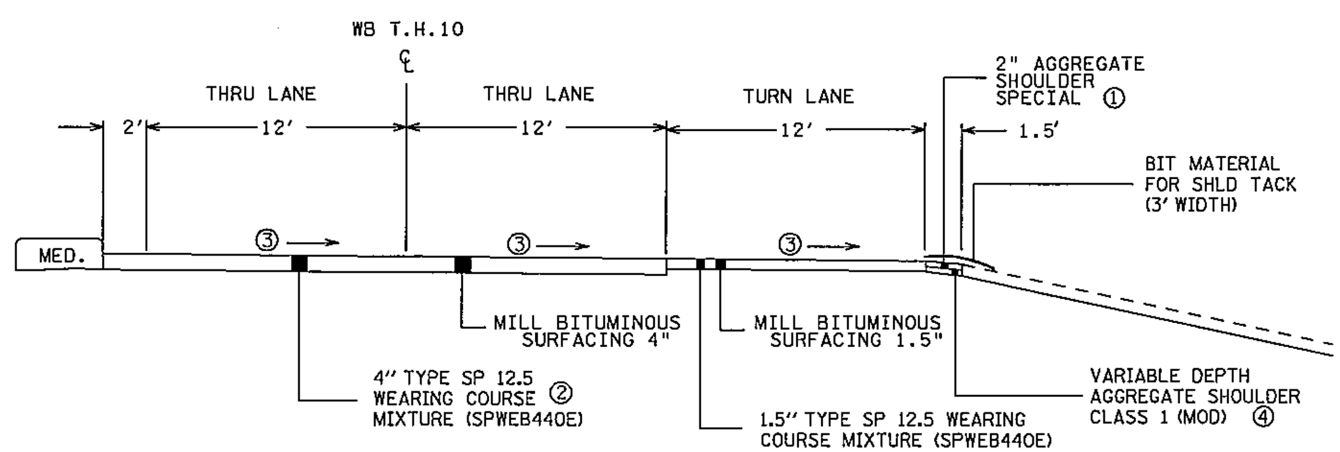
NOTES:

① SHALL BE 100% BIT MILLING

② SHALL BE PLACED IN LIFTS OF 2.5" & 1.5"

③ MATCH EXISTING SLOPE

④ MODIFIED TO 12% - 20% PASSING THE NO. 200 SIEVE




CERTIFIED BY ______ LICENSED PROFESSIONAL ENGINEER LIC. NO. 23164

FILE NAME: S:\prj\10\0502\95\design\d050295_ts.dgn 2/16/2005

TYPICAL SECTIONS

STATE PROJ. NO. 0502-95, ETC (T.H. 10)

SHEET NO. 11 OF 131 SHEETS

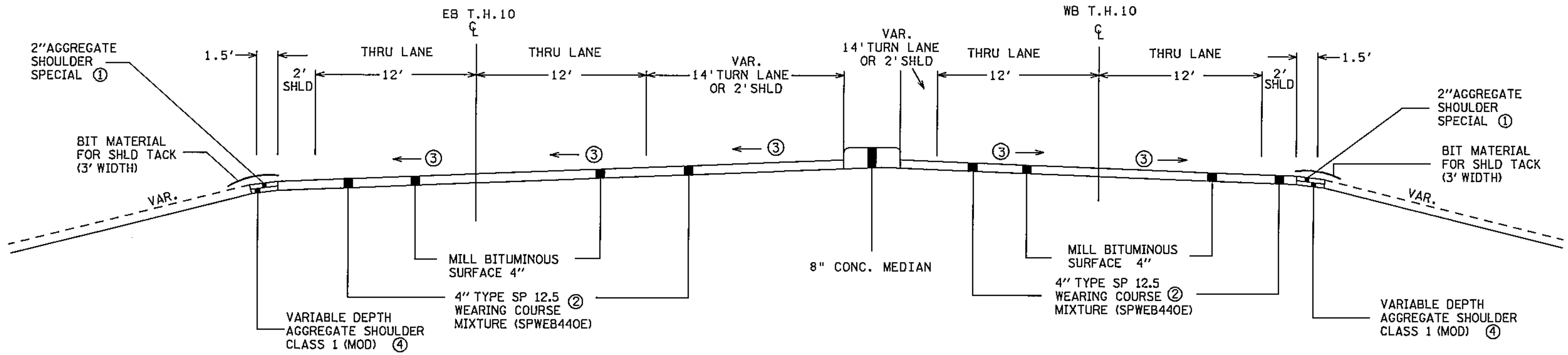
## PROPOSED TYPICAL SECTION NO.3

T.H. 10 CITY OF ROYALTON

MORRISON COUNTY

WB STA. 1096+43.39 R 1 TO 1114+00.00 R 1
WB STA. 1134+36.30 R 1 TO 1141+00.00 R 1
WB STA. 1146+46.84 R 1 TO 1149+16.43 R 1

EB STA. 1088+65.11 R 1 TO 1119+18.58 R 2
EB STA. 1139+00.00 R 4 TO 1151+82.74 R 4




## PROPOSED TYPICAL SECTION NO.4

T.H. 10 CITY OF ROYALTON

MORRISON COUNTY

WB STA. 1114+00.00 R 1 TO 1119+66.27 R 1
WB STA. 1130+18.81 R 1 TO 1134+36.30 R 1

EB STA. 1119+18.58 R 2 TO 1119+65.52 R 3
EB STA. 1130+18.48 R 1 TO 1139+00.00 R 4

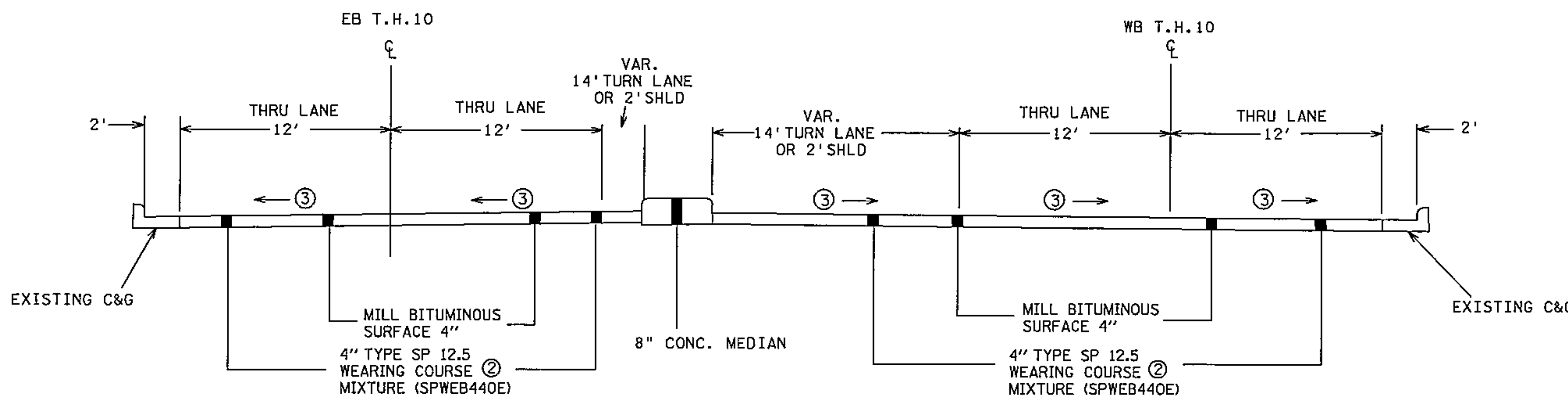
NOTES:

① SHALL BE 100% BIT MILLING

② SHALL BE PLACED IN LIFTS OF 2.5" & 1.5"

③ MATCH EXISTING SLOPE

④ MODIFIED TO 12% - 20% PASSING THE NO. 200 SIEVE




CERTIFIED BY ______ LIC. NO. 23164
LICENSED PROFESSIONAL ENGINEER

TYPICAL SECTIONS

FILE NAME: S:\prj\10\0502\95\design\d050295_ts.dgn 2/16/2005

STATE PROJ. NO. 0502-95, ETC (T. H. 10) SHEET NO. 12 OF 131 SHEETS

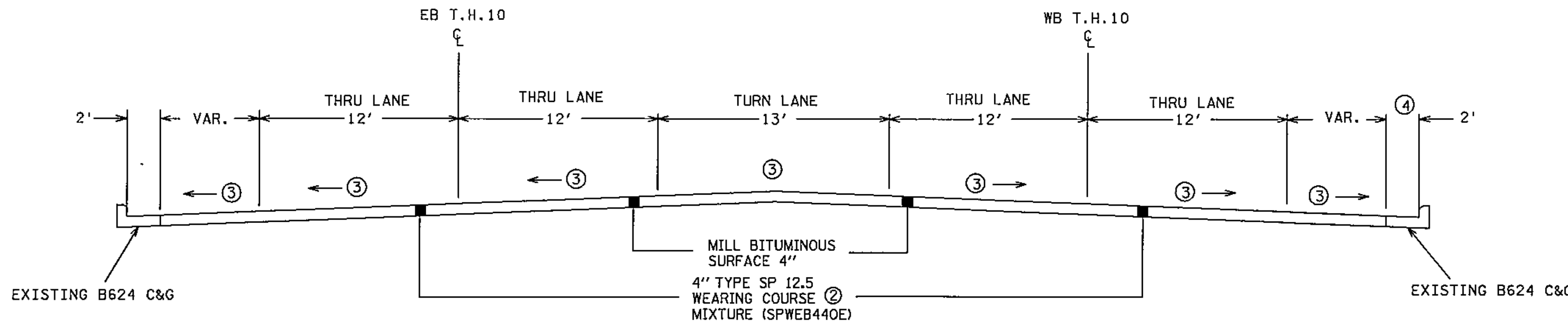
## PROPOSED TYPICAL SECTION NO.5

T.H. 10 CITY OF ROYALTON

MORRISON COUNTY

WB STA. 1119+66.27 R 1 TO 1130+18.81 R 1

EB STA. 1119+65.52 R 3 TO 1130+18.48 R 4




NOTES:

① SHALL BE 100% BIT MILLING

② SHALL BE PLACED IN LIFTS OF 2.5" & 1.5"

③ MATCH EXISING SLOPE

④ NO CURB & GUTTER WB STA. 1123+92.00 R 1 TO 1125+00.00 R 1 SIDEWALK ONLY

⑤ MODIFIED TO 12% - 20% PASSING THE NO. 200 SIEVE

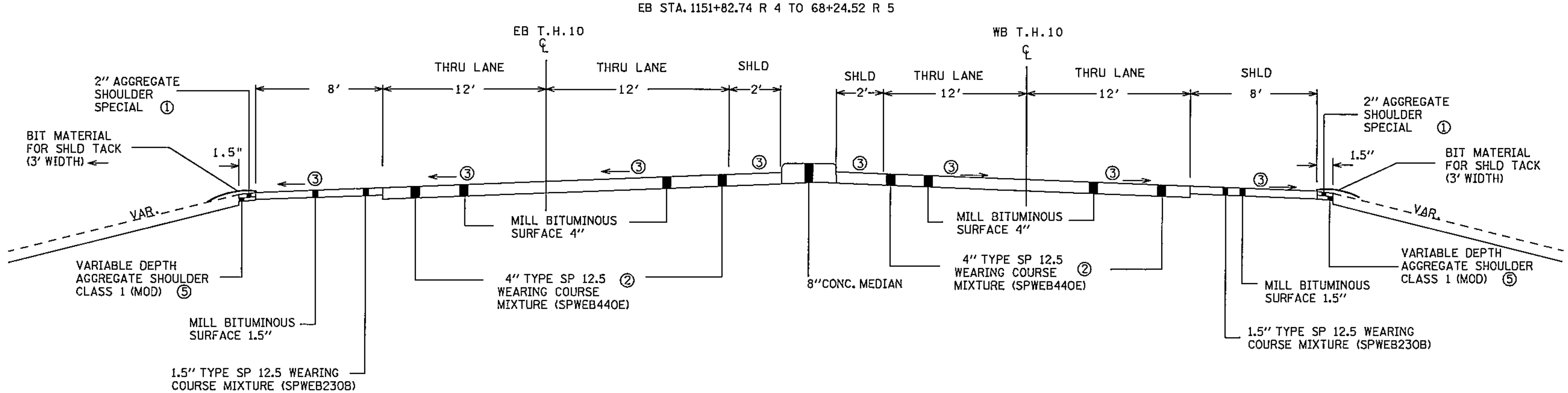
## PROPOSED TYPICAL SECTION NO.6

T.H. 10 CITY OF ROYALTON

MORRISON COUNTY

WB STA. 65+63.38 R 2 TO 68+17.64 R 2

EB STA. 1151+82.74 R 4 TO 68+24.52 R 5



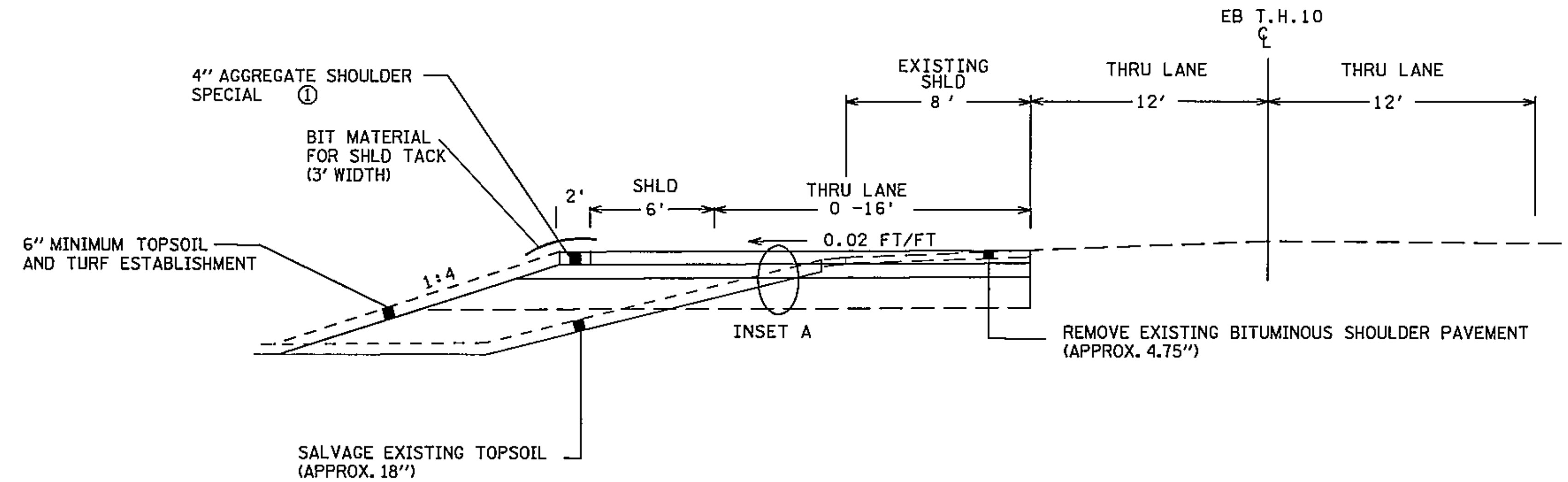

| | | |
|---|---|---|
| CERTIFIED BY ______ LICENSED PROFESSIONAL ENGINEER LIC. NO. 23164 | FILE NAME: S:\prj\10\0502\95\design\d050295_ts.dgn | 2/16/2005 |
| | STATE PROJ. NO. 0502-95, ETC (T.H. 10) | SHEET NO. 13 OF 131 SHEETS |

TYPICAL SECTIONS

## PROPOSED TYPICAL SECTION NO.7

ACCELERATION LANE

STA. 725+40.19 R 1 TO 739+24.89 R 1

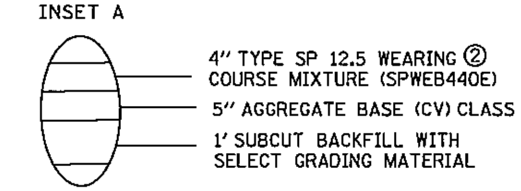



NOTES:

① SHALL BE 100% BIT MILLING

② SHALL BE PLACED IN LIFTS OF 2.5" & 1.5"

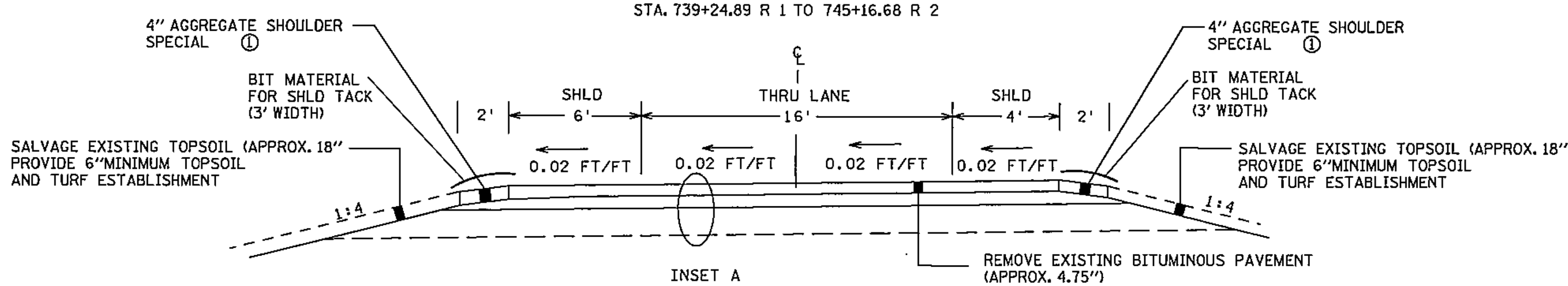
INSET A




## PROPOSED TYPICAL SECTION NO.8

ACCELERATION LANE

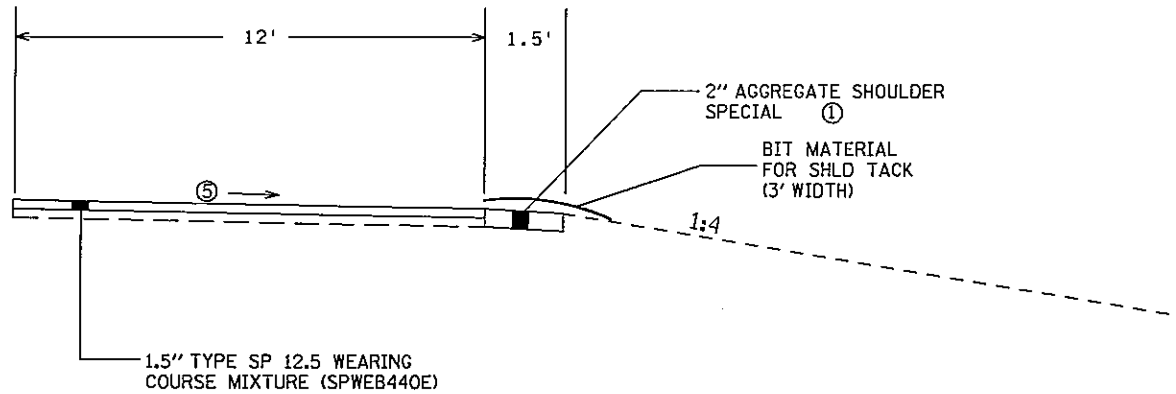
STA. 739+24.89 R 1 TO 745+16.68 R 2




| | | |
|---|---|---|
| CERTIFIED BY ______ LICENSED PROFESSIONAL ENGINEER LIC. NO. 23164 | FILE NAME: S:\prj\10\0502\95\design\d050295_ts.dgn | TYPICAL SECTIONS 3/8/2005 |
| | STATE PROJ. NO. 0502-95, ETC (T.H. 10) | SHEET NO. 14 OF 131 SHEETS |

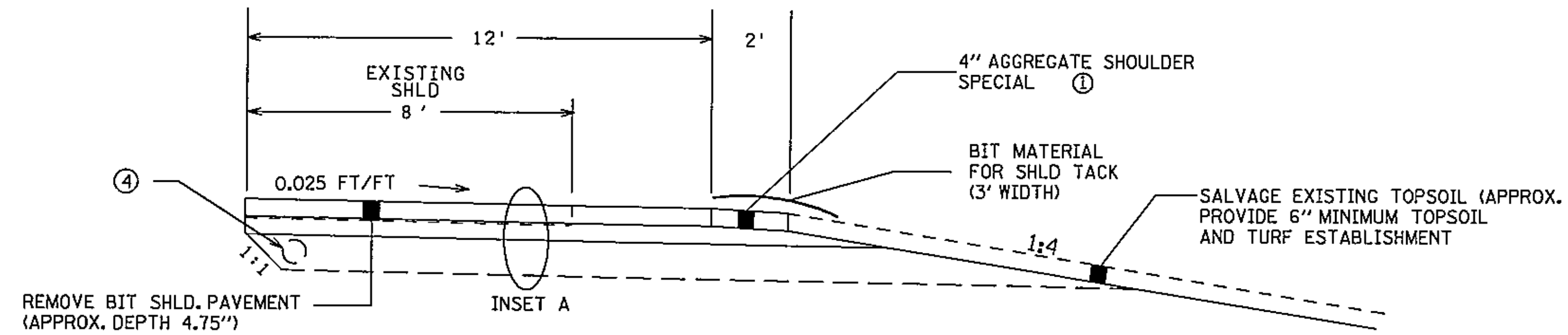
## PROPOSED TYPICAL SECTION NO.9

EXISTING RIGHT TURN LANE



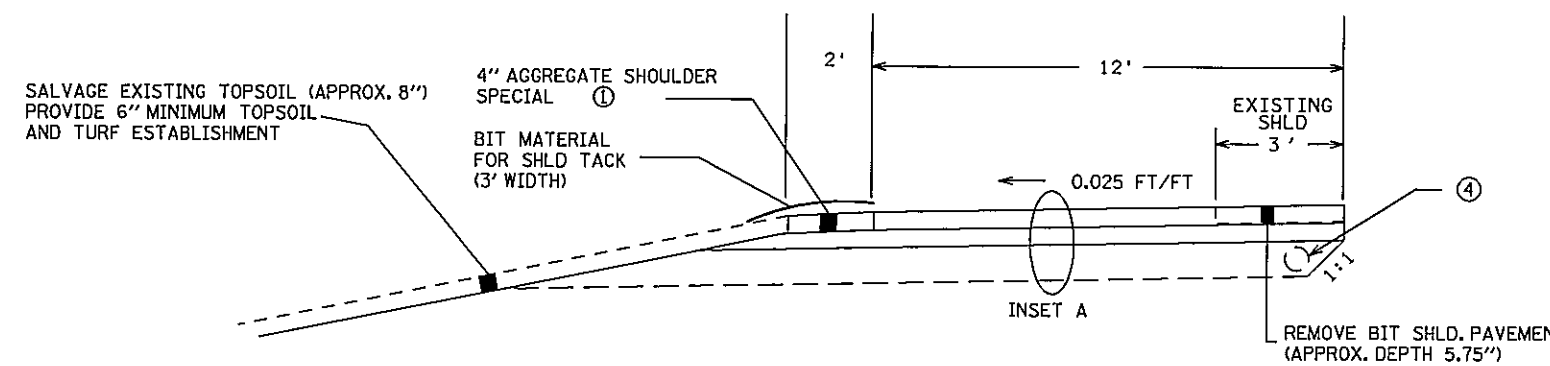

## PROPOSED TYPICAL SECTION NO.11

RIGHT TURN LANE ③



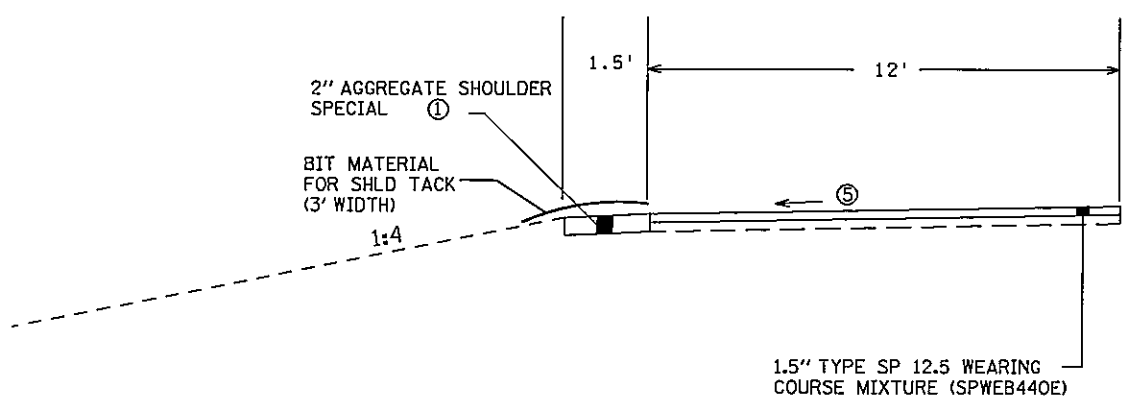

## PROPOSED TYPICAL SECTION NO.12

LEFT TURN LANE ③




## PROPOSED TYPICAL SECTION NO.10

EXISTING LEFT TURN LANE




NOTES:

① SHALL BE 100% BIT MILLING

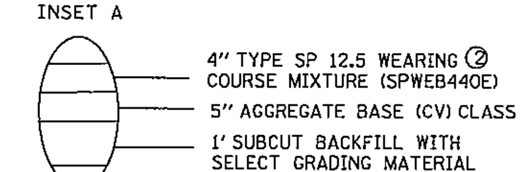
② SHALL BE PLACED IN LIFTS OF 2.5" & 1.5"

③ SEE SHEETS NO. 6-7 CHARTS 'E' AND 'F' FOR LOCATIONS

④ EDGE DRAIN OUTLETS TO BE MOVED TO PROPER LOCATION IN TURNLANE CONSTRUCTION AREAS. SEE SHEET NO. 59 FOR DETAILS

⑤ MATCH EXISTING SLOPE

INSET A




CERTIFIED BY ______ LIC. NO. 23164
LICENSED PROFESSIONAL ENGINEER

FILE NAME: S:\prj\10\0502\95\design\d050295_ts.dgn

STATE PROJ. NO. 0502-95, ETC (T. H. 10)

TYPICAL SECTIONS

2/17/2005

SHEET NO. 15 OF 131 SHEETS

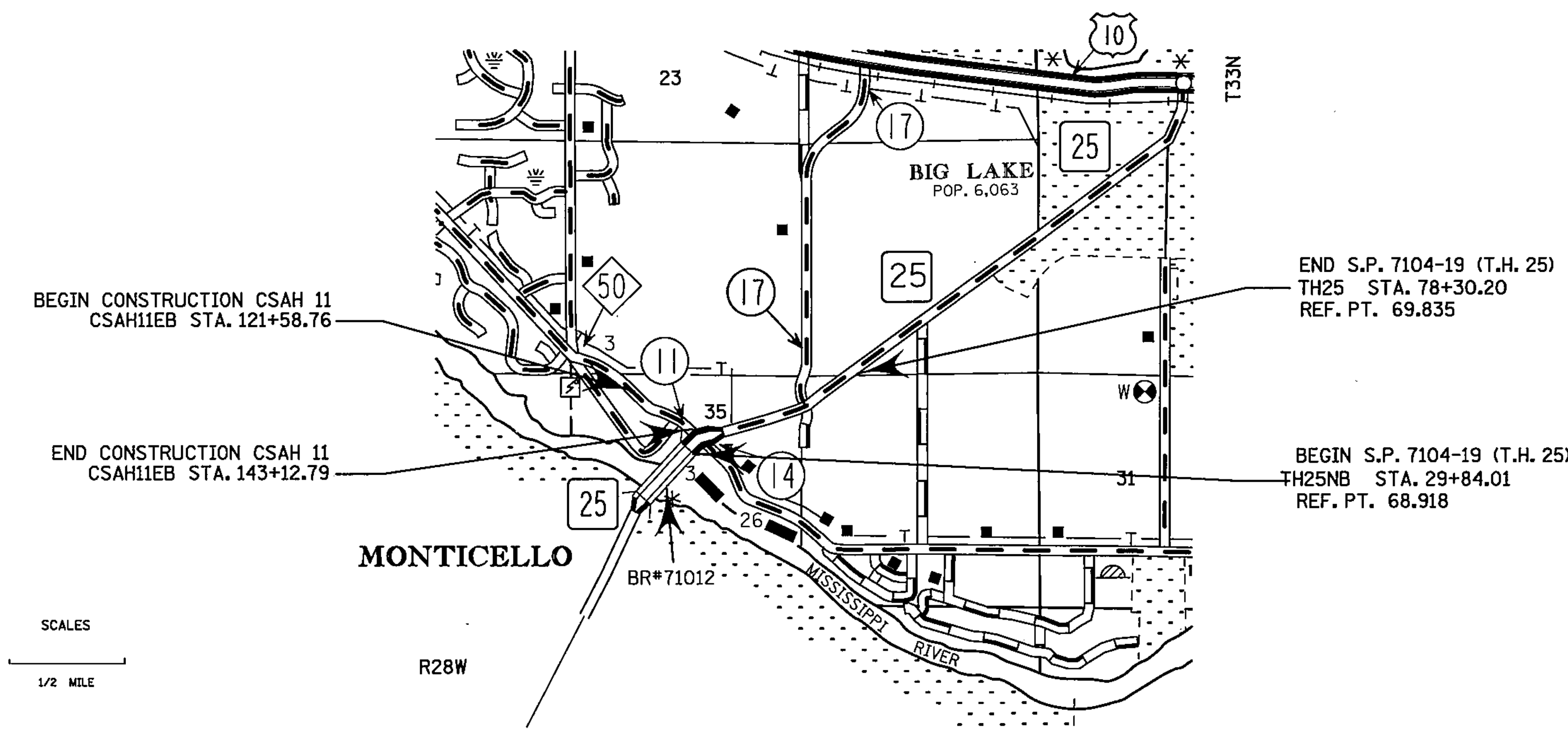
FED. PROJ. NO. STPX 7111(068)

# MINNESOTA DEPARTMENT OF TRANSPORTATION

CONSTRUCTION PLAN FOR GRADING, BITUMINOUS MILL & OVERLAY, BIT. SURFACING, LIGHTING & SIGNAL SYSTEM

LOCATED ON T.H. 25 FROM MISSISSIPPI RIVER TO 1600' NORTH OF C.S.A.H. 17

STATE PROJ. NO. 7104-19
GROSS LENGTH 4846.19 FEET 0.92 MILES
BRIDGES-LENGTH ______ FEET ______ MILES
EXCEPTIONS-LENGTH ______ FEET ______ MILES
NET LENGTH 4846.19 FEET 0.92 MILES
REF. POINT 68.918 TO REF. POINT 69.835
LENGTH & DESCRIPTION BASED ON TH25NB




## GOVERNING SPECIFICATIONS

THE 2005 EDITION OF THE MINNESOTA DEPARTMENT OF TRANSPORTATION "STANDARD SPECIFICATIONS FOR CONSTRUCTION", SHALL GOVERN.

## INDEX



| SHEET NO. | DESCRIPTION |
|---|---|
| 1 | TITLE SHEET |
| 2-3 | GENERAL LAYOUT |
| 4-6 | ESTIMATED QUANTITIES, AND STANDARD PLATES |
| 7 | SOILS AND CONSTRUCTION NOTES |
| 8 - 11 | TYPICAL SECTIONS |
| 12 - 14 | PUBLIC UTILITIES TABULATIONS |
| 15 - 19 | TABULATED QUANTITIES |
| 20-22A, 23-29 | MISCELLANEOUS & STANDARD DETAILS |
| 30 - 31 | STAKING INFO AND ALIGNMENT TABULATIONS |
| 32 - 57 | STAGING PLANS |
| 58 - 69 | INPLACE REMOVALS & CONSTRUCTION PLAN |
| 70 - 81 | PROFILES |
| 82 - 94 | DRAINAGE PLAN & DRAINAGE TABULATIONS |
| 95 - 96 | NPDES MAP & SWPPP |
| 97 - 107 | EROSION CONTROL AND TURF ESTABLISHMENT |
| 108 - 144 | DETOUR & TRAFFIC CONTROL |
| 145 - 151 | PAVEMENT MARKING DETAILS |
| 152 - 171 | SIGN TABULATION AND DETAILS |
| 172 - 183 | SIGNAL SYSTEM & TEMPORARY SIGNAL SYSTEM |
| 185 - 190 | LIGHTING PLAN |
| X1 - X70 | CROSS SECTIONS |



SHEET NO. 184 HAS BEEN DELETED.

THIS PLAN CONTAINS 260 SHEETS

I HEREBY CERTIFY THAT THIS PLAN WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

PRINT NAME: TERRENCE J. HUMBERT LICENSE # 17807

DATE: 1/4/11 SIGNATURE: Terrence J. Humbert

DESIGN SQUAD ADAM PITAN, STEVE DESMITH, TROY GRATKE, GREG RAMBERG,

RECOMMENDED FOR APPROVAL Bob Busch 1/4/ 2011 DISTRICT TRANSPORTATION ENGINEER

RECOMMENDED FOR APPROVAL 1/04 2011 DISTRICT MATERIALS ENGINEER

RECOMMENDED FOR APPROVAL 1/04 2011 DISTRICT WATER RESOURCES/HYDRAULICS ENGINEER

RECOMMENDED FOR APPROVAL 1-04 2011 DISTRICT TRAFFIC ENGINEER

TRS

RECOMMENDED FOR APPROVAL Valerie VA Duenson 2/17 2011 STATE PRE-LETTING ENGINEER

OFFICE OF LAND MANAGEMENT APPROVAL M.D. Stromberg 2/22 2011 DIRECTOR LAND MANAGEMENT

APPROVED 2/22 2011 STATE DESIGN ENGINEER

I HEREBY CERTIFY THAT THE FINAL FIELD REVISIONS, IF ANY, WERE PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

PRINT NAME: ______ LICENSE # ______

DATE: ______ SIGNATURE: ______

## DESIGN DESIGNATION

Design ESALS = 3,300,000
ADT (Current Year) 2011 = 37,300 Design Speed ______ MPH 55
ADT (Future Year) 2031 = 59,400 Based on ______ Sight Distance ______
DHV (Design Hr. Vol.) = ______ Height of eye ______ Height of object ______
D (Directional Distr.) = ______ % Design Speed not achieved at: ______
T (Heavy Commercial) = ______ % STA. ______ TO STA. ______ MPH ___
STA. ______ TO STA. ______ MPH ___

| PLAN REVISIONS | | |
|---|---|---|
| DATE | SHEET NO. | APPROVED BY |
| | | |
| | | |
| | | |
| | | |
| | | |

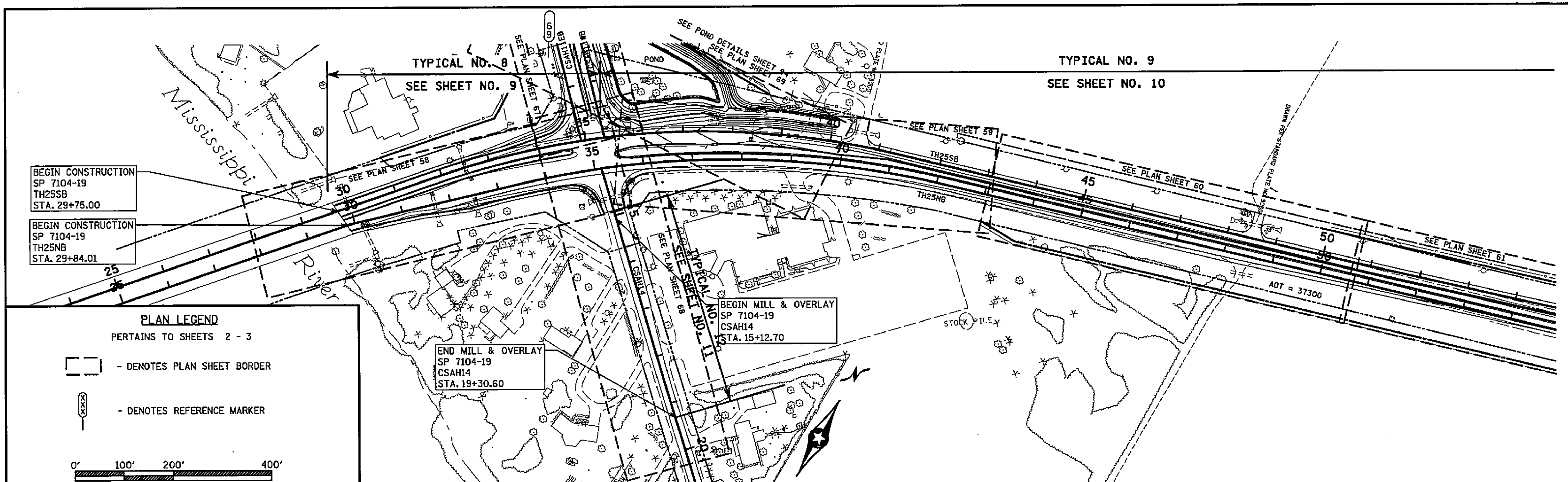
PROJECT LOCATION
COUNTY : SHERBURNE
DISTRICT : 3
A-15

FOR PLANS AND UTILITIES SYMBOLS SEE TECHNICAL MANUAL

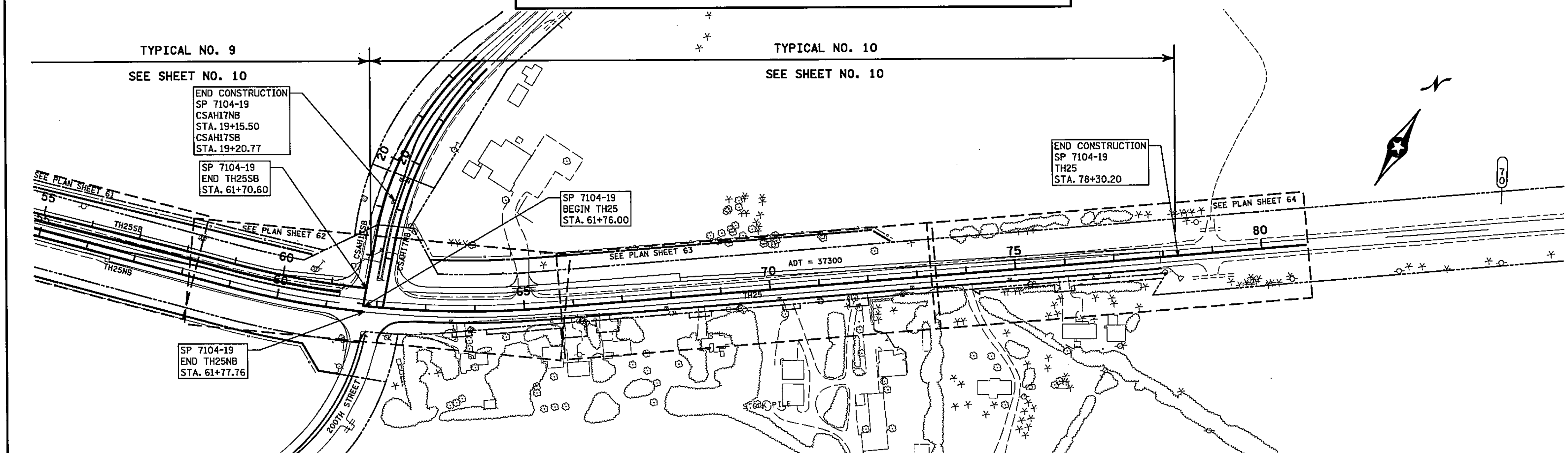
| STATE PROJ. NO. | CHARGE IDENTIFIER |
|---|---|
| 7104-19 | T39483 |
| | |
| | |
| | |

PLOTTED/REVISED: 30-DEC-2010

DISTRICT #: DISTRICT 3 - BAXTER, MN
IPLOT NAME: d710419_tsh
PATH & FILENAME: Projects/D3_BAX/025/7104/019/Design/d710419_tsh.dgn



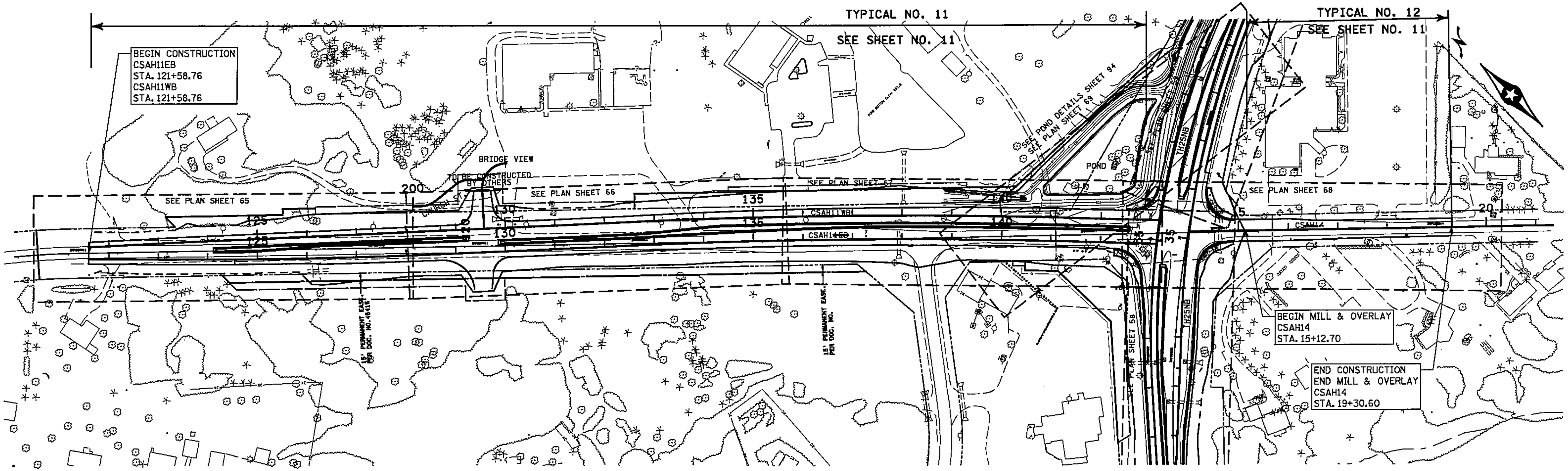

# T.H. 25 GENERAL LAYOUT
## (TH25NB, TH25SB, TH25, CSAH14, CSAH17NB, CSAH17SB)




CERTIFIED BY ______ LICENSED PROFESSIONAL ENGINEER LIC. NO. 17807

FILE NAME: Projects/D3_BAX/025/7104/019/Design/d710419_gl1.dgn 07-FEB-2011

STATE PROJ. NO. 7104-19 (T.H. 25) SHEET NO. 2 OF 190 SHEETS




CSAH11 & CSAH14 GENERAL LAYOUT

CERTIFIED BY [signature] LIC. NO. 17807
LICENSED PROFESSIONAL ENGINEER

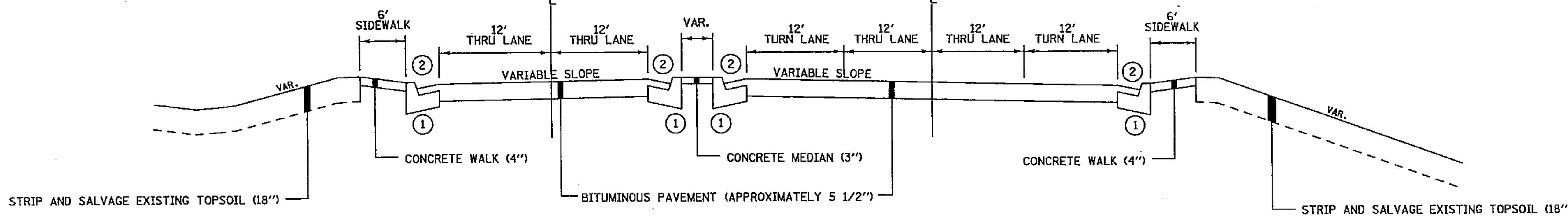
FILE NAME: Projects/D3_BAX/025/7104/019/Design/d710419_gl2.dgn 14-FEB-2011

STATE PROJ. NO. 7104-19 (T.H. 25) SHEET NO. 3 OF 190 SHEETS

## TYPICAL SECTION NO. 1

EXISTING T.H. 25

INPNB25M
STA. 29+84.01 R 4 - STA. 35+13.01 R 4

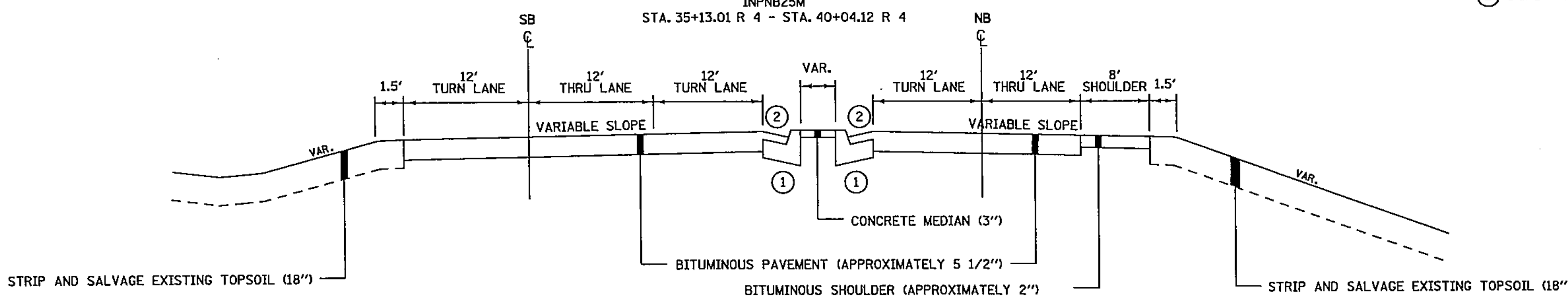



## TYPICAL SECTION NO. 2

EXISTING T.H. 25
INPNB25M
STA. 35+13.01 R 4 - STA. 40+04.12 R 4

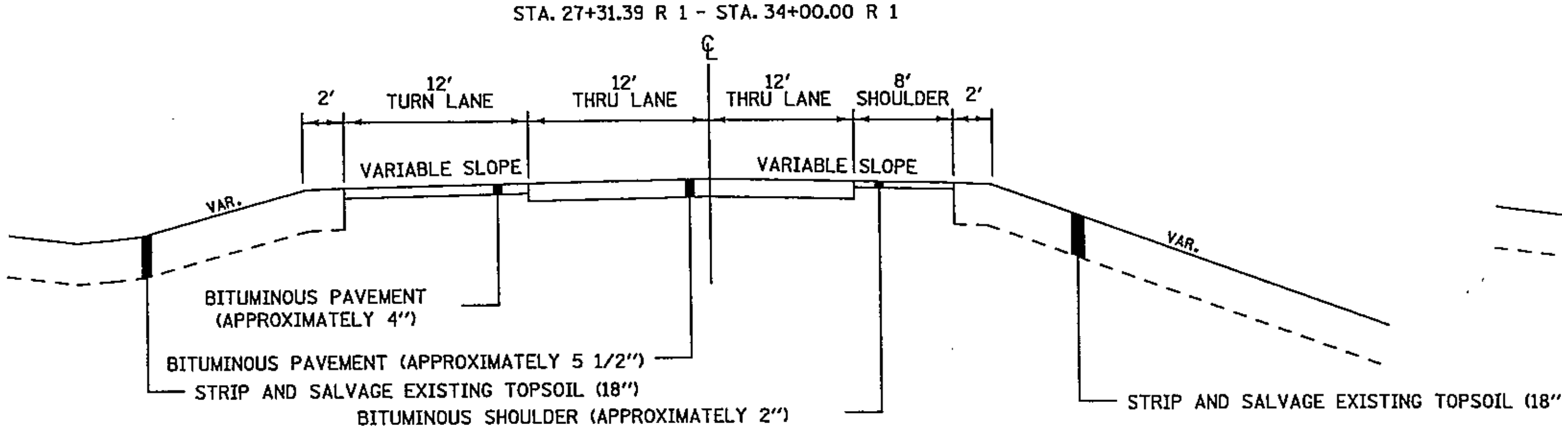
(1) EXISTING B624 CONCRETE CURB AND GUTTER

(2) 1 1/2" BITUMINOUS OVER CONCRETE GUTTER




## TYPICAL SECTION NO. 3

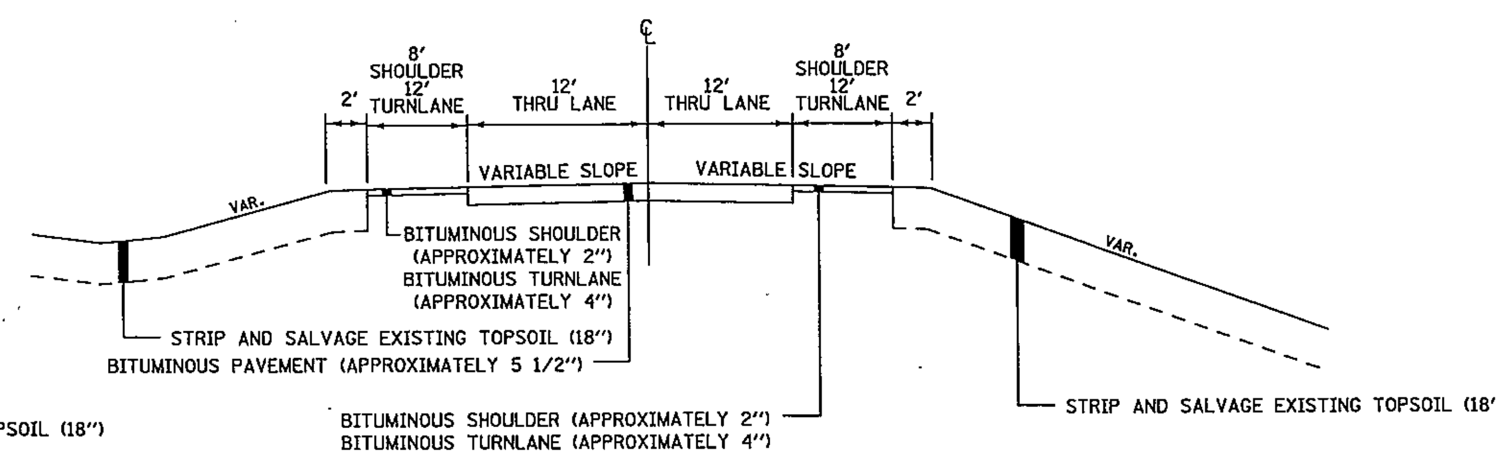
EXISTING T.H. 25
INPNB25M
STA. 40+04.12 R 4 - STA. 50+00.00 R 5
INP25
STA. 27+31.39 R 1 - STA. 34+00.00 R 1




## TYPICAL SECTION NO. 4

EXISTING T.H. 25

INP25
STA. 34+00.00 R 1 - STA. 41+88.20 R 1




EXISTING TYPICAL SECTIONS

A-18

CERTIFIED BY [signature] LIC. NO. 17807
LICENSED PROFESSIONAL ENGINEER

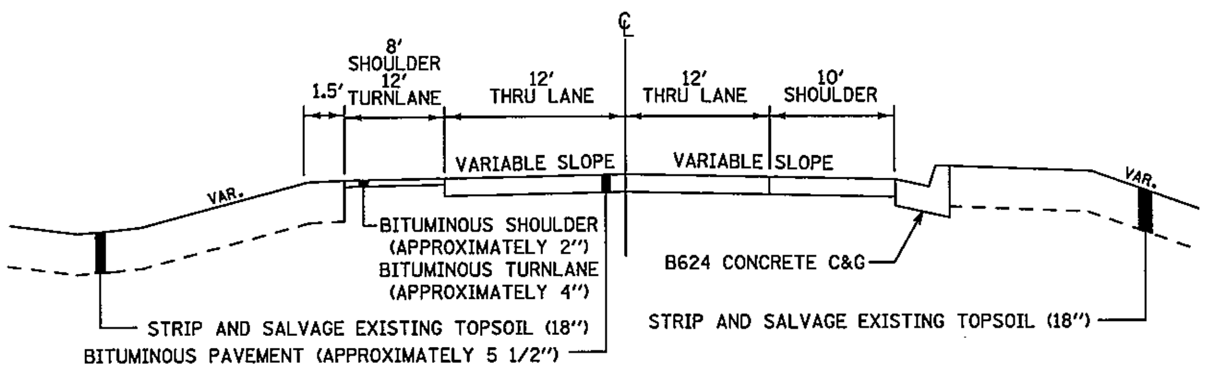
FILE NAME: Projects/D3_BAX/025/7104/019/Design/d710419_ts1.dgn 28-DEC-2010

STATE PROJ. NO. 7104-19 (T.H. 25) SHEET NO. 8 OF 190 SHEETS

## TYPICAL SECTION NO. 5

EXISTING T.H. 25

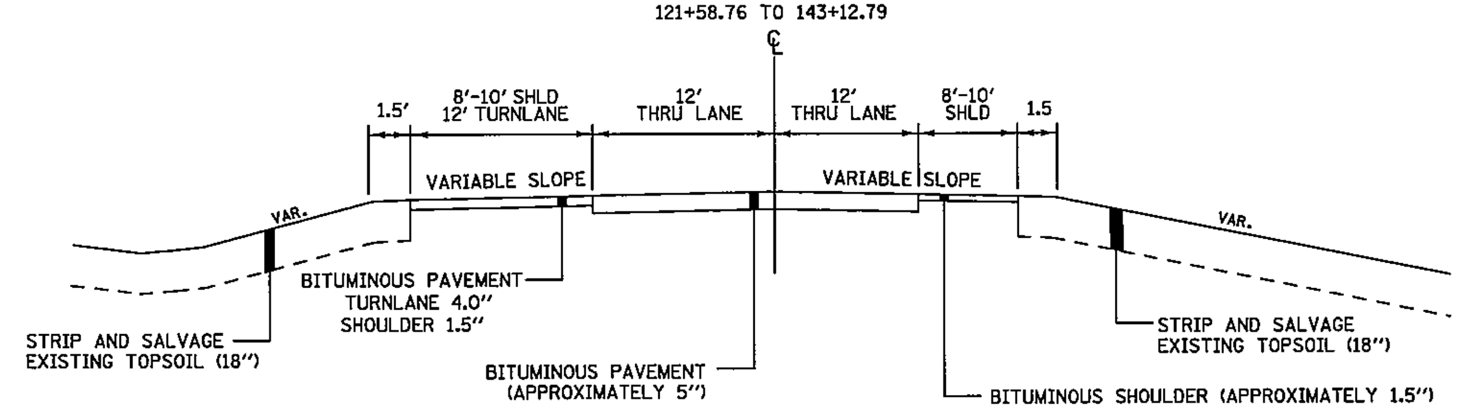
INP25
STA. 41+88.20 R 1 - STA. 57+41.25 R 2




## TYPICAL SECTION NO. 6

EXISTING CSAH 11

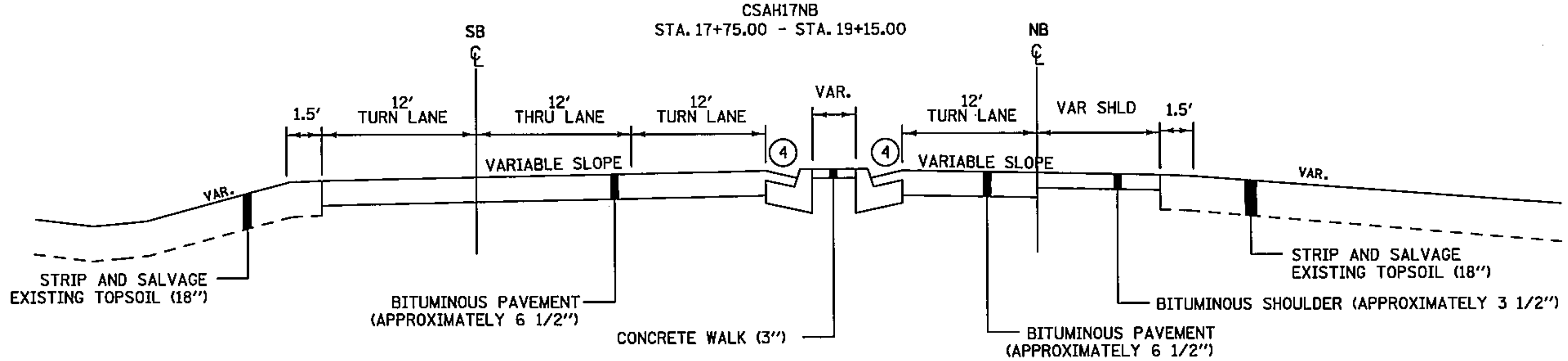
CSAH11EB
121+58.76 TO 143+12.79




## TYPICAL SECTION NO. 7

EXISTING CSAH 17

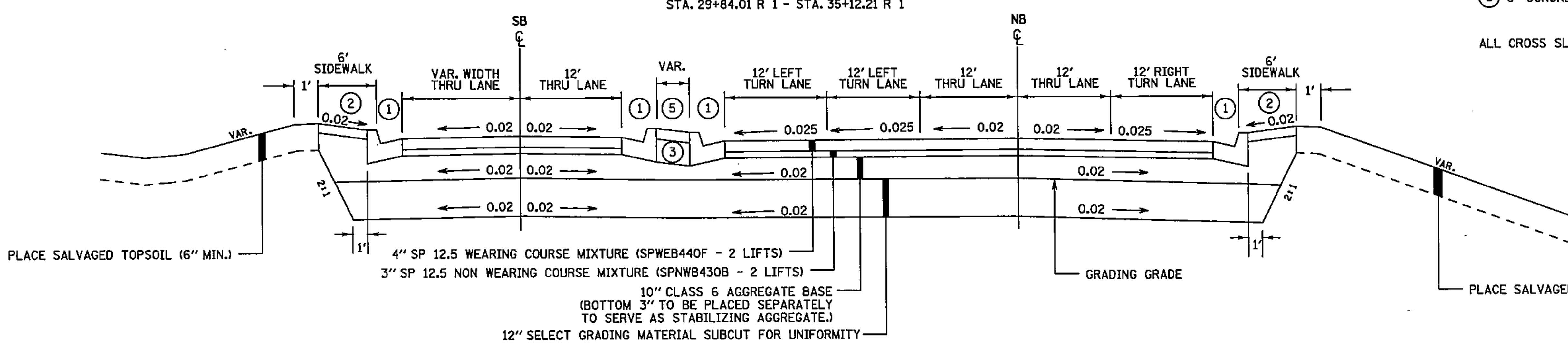
CSAH17NB
STA. 17+75.00 - STA. 19+15.00




## TYPICAL SECTION NO. 8

PROPOSED T.H. 25

TH25NB
STA. 29+84.01 R 1 - STA. 35+12.21 R 1




NOTES:

1. PROPOSED B424 CONCRETE CURB AND GUTTER (GUTTER SLOPE 0.03 FT/FT)
2. 4" CONCRETE WALK, 6" CONCRETE WALK UNDER PED RAMP
3. SELECT GRADING MATERIAL
4. EXISTING B424 CONCRETE CURB AND GUTTER
5. 6" CONCRETE WALK

ALL CROSS SLOPES ARE MEASURED FEET PER FOOT

EXISTING TYPICAL SECTIONS

CERTIFIED BY [signature] LIC. NO. 17807
LICENSED PROFESSIONAL ENGINEER

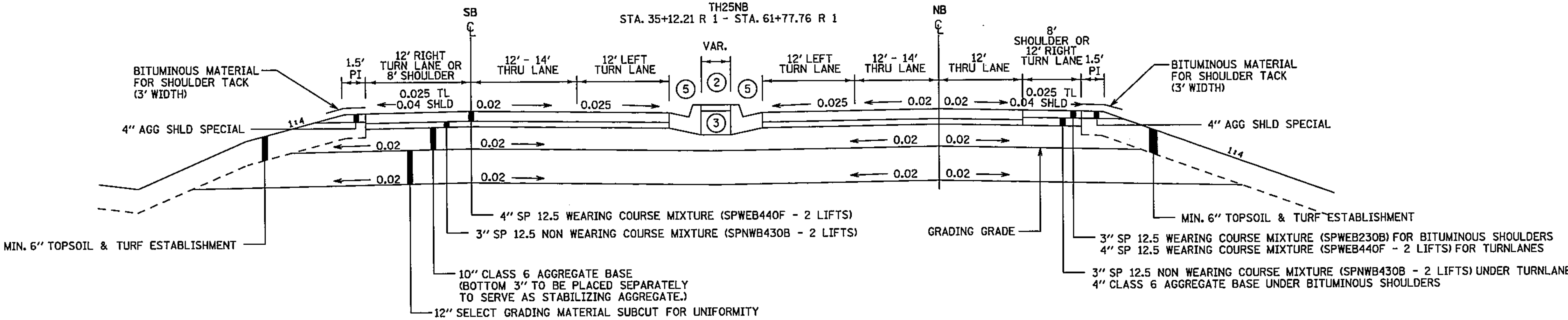
FILE NAME: Projects/D3_BAX/025/7104/019/Design/d710419_ts1.dgn 07-FEB-2011

STATE PROJ. NO. 7104-19 (T.H. 25)

## TYPICAL SECTION NO. 9

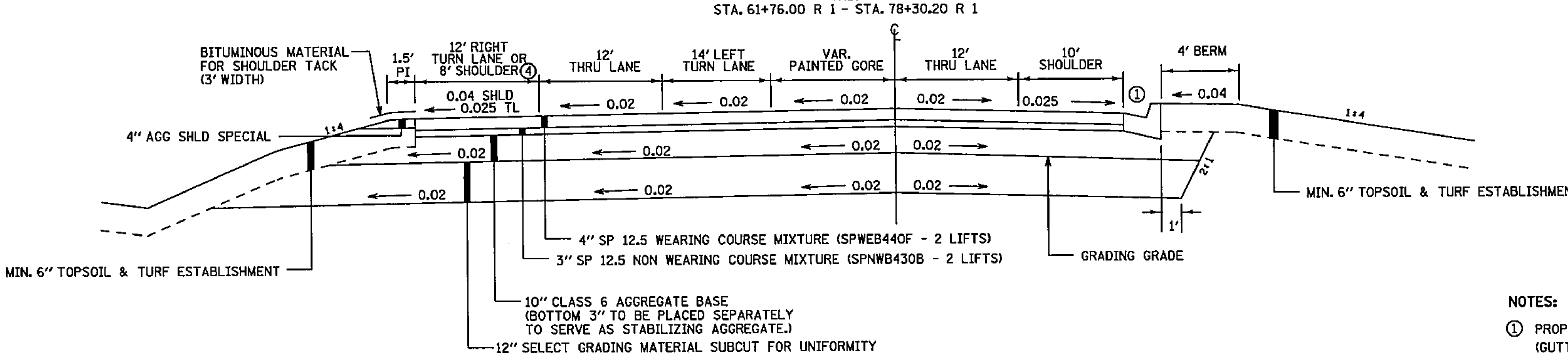
PROPOSED T.H. 25

TH25NB
STA. 35+12.21 R 1 - STA. 61+77.76 R 1




## TYPICAL SECTION NO. 10

PROPOSED T.H. 25
TH25
STA. 61+76.00 R 1 - STA. 78+30.20 R 1




NOTES:

① PROPOSED B624 CONCRETE CURB AND GUTTER. (GUTTER SLOPE 0.03 FT/FT)

② 6" CONCRETE WALK.

③ SELECT GRADING MATERIAL.

④ 14' SHOULDER WIDTH STATION 74+34 - 78+30. (EXTRA WIDTH TO BE USED IN STAGE 3)

⑤ PROPOSED B424 CONCRETE CURB AND GUTTER. (GUTTER SLOPE 0.03 FT/FT)

ALL CROSS SLOPES ARE MEASURED FOOT PER FOOT

PROPOSED TYPICAL SECTIONS

CERTIFIED BY [signature] LIC. NO. 17807
LICENSED PROFESSIONAL ENGINEER

A-20

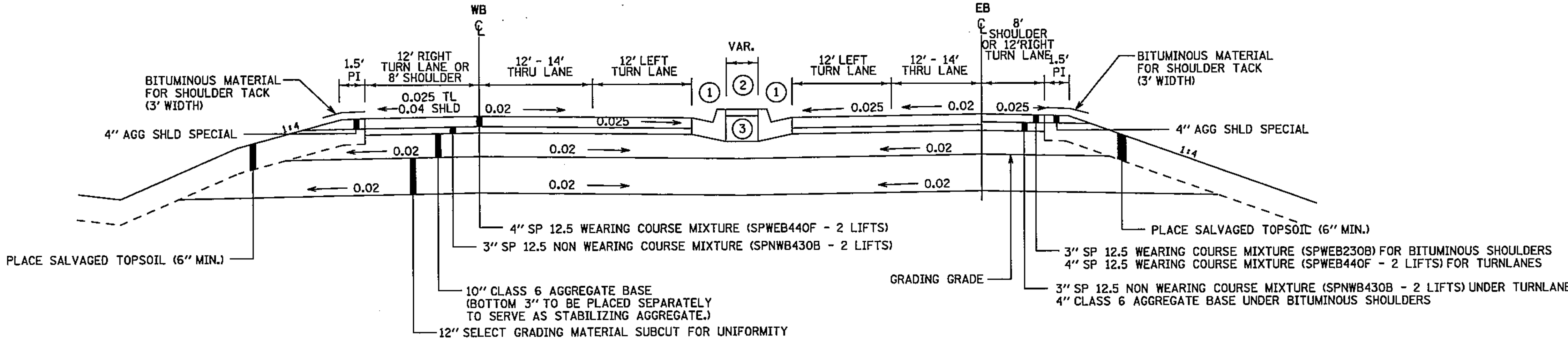
FILE NAME: Projects/D3_BAX/025/7104/019/Design/d710419_ts1.dgn 09-FEB-2011

STATE PROJ. NO. 7104-19 (T.H. 25) SHEET NO. 10 OF 190 SHEETS

## TYPICAL SECTION NO. 11

PROPOSED CSAH 11

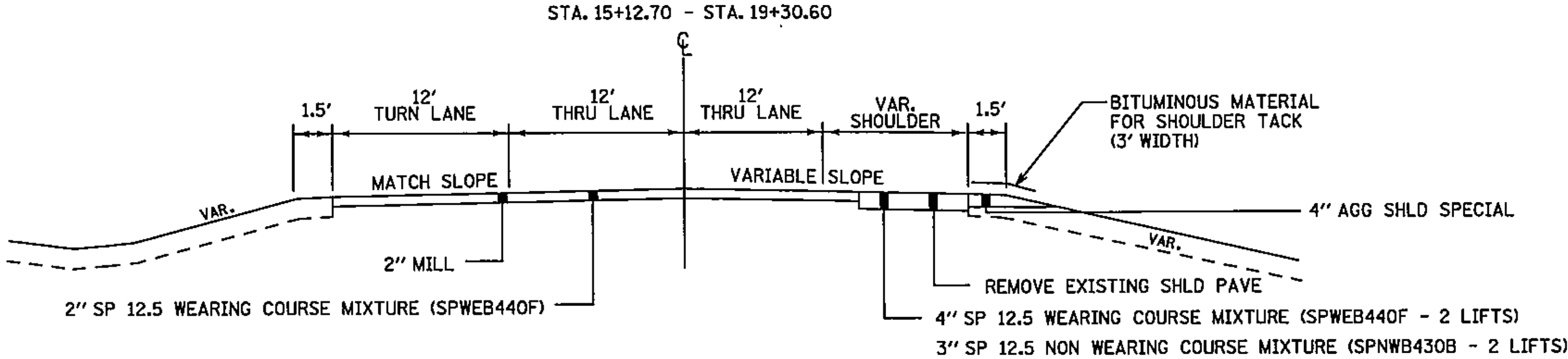
CSAH11EB
STA. 121+58.76 - STA. 143+12.79




## TYPICAL SECTION NO.12

PROPOSED CSAH 14

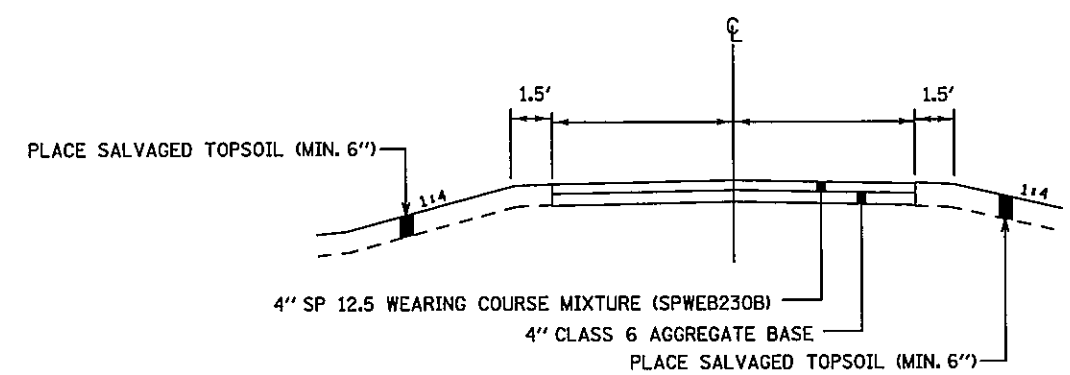
CSAH14
STA. 15+12.70 - STA. 19+30.60




## TYPICAL SECTION NO.13

PROPOSED BRIDGE VIEW

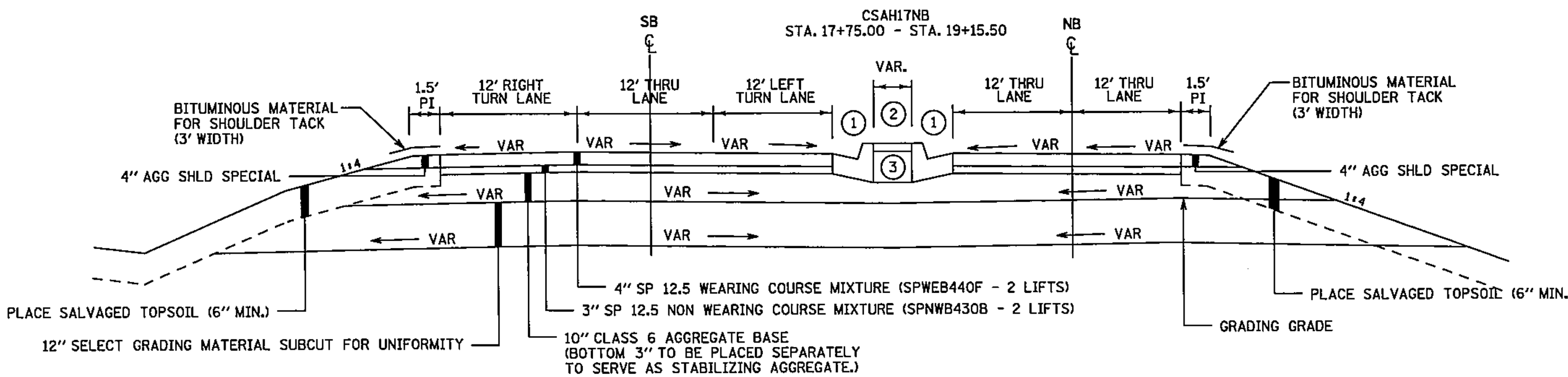
STA. 120+00 - STA. 120+77




## TYPICAL SECTION NO.14

PROPOSED CSAH 17

CSAH17NB
STA. 17+75.00 - STA. 19+15.50




NOTES:

1. PROPOSED B424 CONCRETE CURB AND GUTTER (GUTTER SLOPE 0.03 FT/FT)
2. 6" CONCRETE WALK
3. SELECT GRADING MATERIAL

ALL CROSS SLOPES ARE MEASURED FOOT PER FOOT

PROPOSED TYPICAL SECTIONS

CERTIFIED BY [signature] LIC. NO. 17807
LICENSED PROFESSIONAL ENGINEER

FILE NAME: Projects/D3_BAX/025/7104/019/Design/d710419_ts1.dgn 07-FEB-2011

STATE PROJ. NO. 7104-19 (T.H. 25) SHEET NO. 11 OF 190 SHEETS

# MINNESOTA DEPARTMENT OF TRANSPORTATION

## CITY OF BAXTER, MINNESOTA

**CONSTRUCTION PLAN FOR** GRADING, BITUMINOUS MILL & OVERLAY AND LIGHTING

LOCATED ON T.H. 210 FROM 400' WEST OF CASS/CROW WING COUNTY LINE TO 400' EAST OF THE WEST JCT. OF T.H. 371 IN BAXTER

PLAN SCALES

- 0 30 60 (IN FEET) — PLAN SHEETS: 29-32, 34-35, 42-43, 49-54
- 0 40 80 (IN FEET) — PLAN SHEETS: 19-21, 38-41
- 0 50 100 (IN FEET) — PLAN SHEETS: 23-28
- 5' 10' SCALE — CROSS SECTIONS

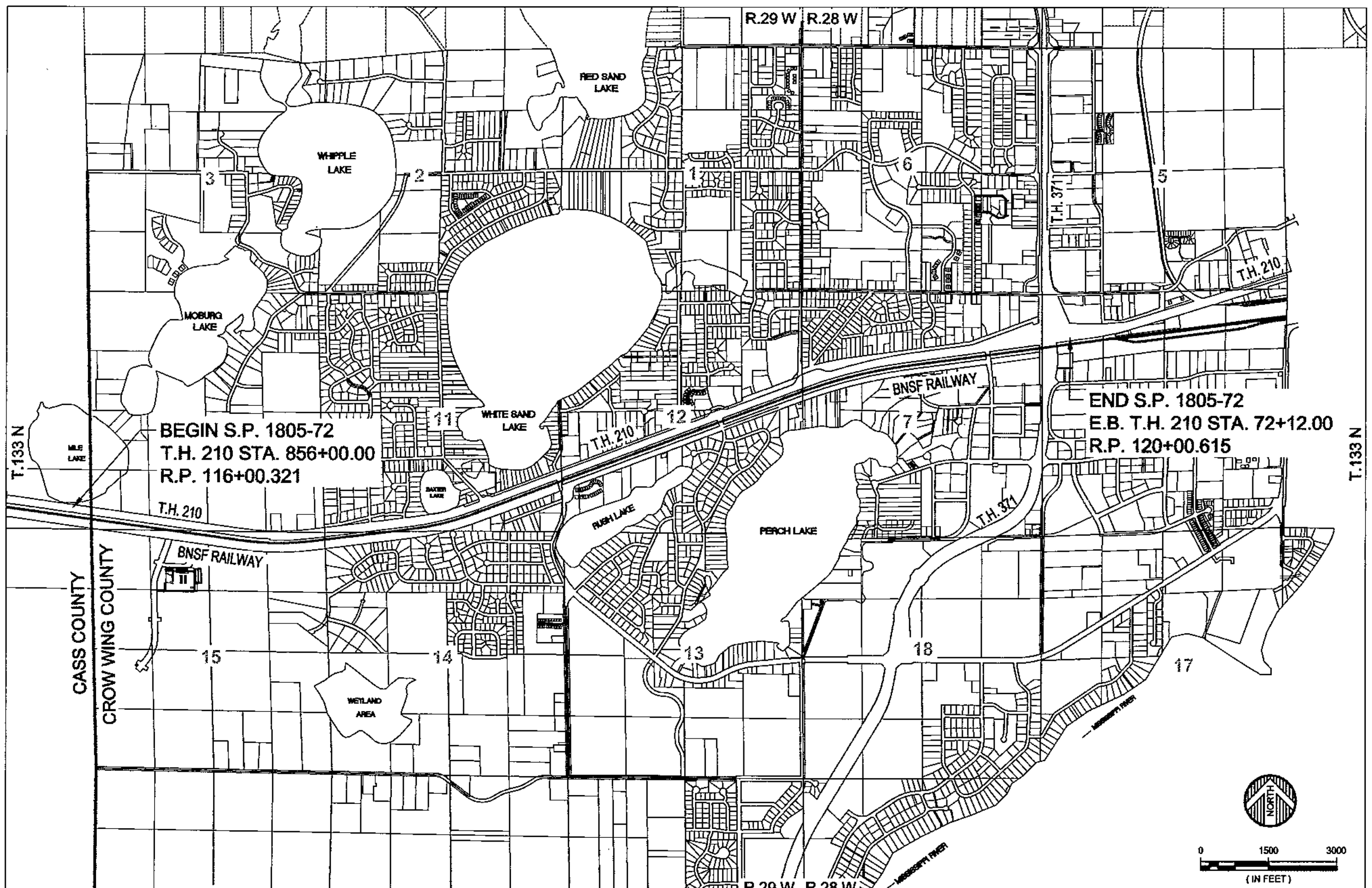
**STATE PROJECT NO. 1805-72 (T.H. 210)**

GROSS LENGTH 22,696.38 FEET 4.299 MILES
BRIDGES - LENGTH ______ FEET ______ MILES
EXCEPTIONS - LENGTH ______ FEET ______ MILES
NET LENGTH 22,696.38 FEET 4.299 MILES
REF. POINT 116+00.321 TO REF. POINT 120+00.615

AGREEMENT NO. 95474
CITY OF BAXTER
S.P. 1805-72 (T.H. 210=002)
STATE FUNDS
DISTRICT 3 (BAXTER)

PROJECT LOCATION
CASS COUNTY
CROW WING COUNTY
BAXTER, MINNESOTA
DISTRICT 3

EQUATION: E.B. T.H. 210 STA. 1045+71.36 BK = E.B. T.H. 210 STA. 34+86.98 AH




## STATE FUNDS

### GOVERNING SPECIFICATIONS

THE 2005 EDITION OF THE MINNESOTA DEPARTMENT OF TRANSPORTATION "STANDARD SPECIFICATIONS FOR CONSTRUCTION" SHALL GOVERN

### INDEX TO DRAWINGS



| SHEET NO. | DESCRIPTION |
|---|---|
| 1 | TITLE SHEET |
| 2-3 | GENERAL LAYOUT |
| 4 | STATEMENT OF ESTIMATED QUANTITIES |
| 5 | GENERAL NOTES |
| 6-9 | SOIL AND CONSTRUCTION NOTES & TYPICAL SECTIONS |
| 10 | EXISTING PUBLIC UTILITIES TABULATIONS |
| 11-16 | TABULATED QUANTITIES & DETAILS |
| 17-18 | SWPPP DOCUMENTS |
| 19-21 | T.H. 210 - CONSTRUCTION PLANS |
| 22-26 | T.H. 210 - TRAFFIC CONTROL |
| 27-32 | POTLATCH - CONSTRUCTION PLANS |
| 33-35 | STORM SEWER PLANS |
| 36-48 | SIGNING AND STRIPING PLANS |
| 49-53 | EROSION CONTROL |
| 54 | T.H. 210 LIGHTING PLAN |
| 55-73 | CROSS SECTIONS |
| | THIS PLAN CONTAINS 73 SHEETS |



### DESIGN DESIGNATION

ADT (Current Year) 2009 = 9,855 — Design Speed 60 MPH
ADT (Future Year) 2029 = 13,155 — Based on STOPPING Sight Distance
DHV (Design Hr. Vol.) = ______ — Height of eye 3.5' Height of object 2.0'
D (Directional Distr.) = ______%
T (Heavy Commercial) = ______%

### APPROVALS

I HEREBY CERTIFY THAT THIS PLAN WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

PRINT NAME: ARIC WELCH LICENSE#: 41983
DATE: 3-30-10 SIGNATURE: Aric Welch

RECOMMENDED FOR APPROVAL: Jim Watts, PE DATE: 3/31/10
PUBLIC WORKS DIRECTOR / CITY ENGINEER

RECOMMENDED FOR APPROVAL: Bob Busch DATE: 3/31/10
DISTRICT TRANSPORTATION ENGINEER

RECOMMENDED FOR APPROVAL: [signature] DATE: 3/31/10
DISTRICT TRAFFIC ENGINEER

RECOMMENDED FOR APPROVAL: Robert Witte DATE: 3/31/10
DISTRICT HYDRAULICS ENGINEER

RECOMMENDED FOR APPROVAL: Cal Ruttman ADE DATE: 3/31/10
for DISTRICT MATERIALS ENGINEER

RECOMMENDED FOR APPROVAL: T. R. Swanson DATE: 4/13/10
FOR STATE PRE-LETTING ENGINEER

OFFICE OF LAND MANAGEMENT APPROVAL: M. J. Stenberg DATE: 4/13/10
FOR DIRECTOR, LAND MANAGEMENT

APPROVED: [signature] DATE: 4/13/10
STATE DESIGN ENGINEER

TITLE SHEET
S.P. 1805-72 (T.H. 210 = 002) SHEET NO. 1 OF 73

ALEXANDRIA, MN · BEMIDJI, MN · BRAINERD, MN · CROOKSTON, MN · GRAND FORKS, ND · RED WING, MN · ROCHESTER, MN · SIOUX FALLS, SD
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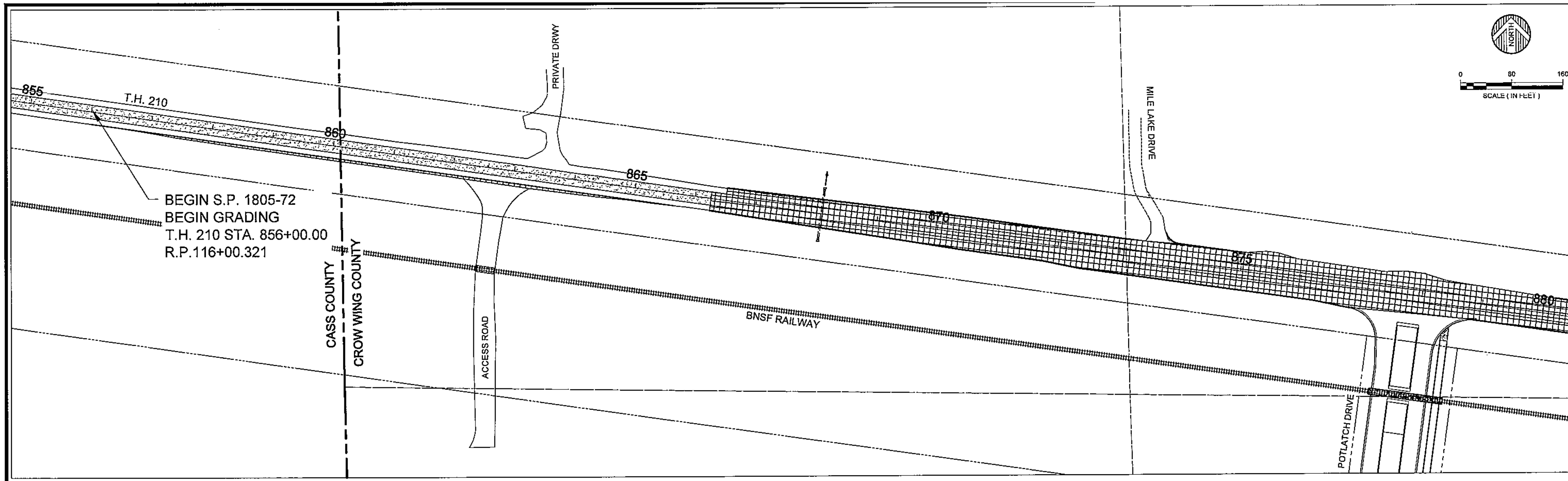
Aric Welch 3-30-10
ARIC WELCH DATE: LIC. NO. 41983

REVISIONS DESCRIPTION BY REV. DATE

DATE: MARCH 2009 · SCALE: AS SHOWN · DRAWN BY: M.A.S. · CHECKED BY: A.L.W. · JOB NUMBER: 010280318

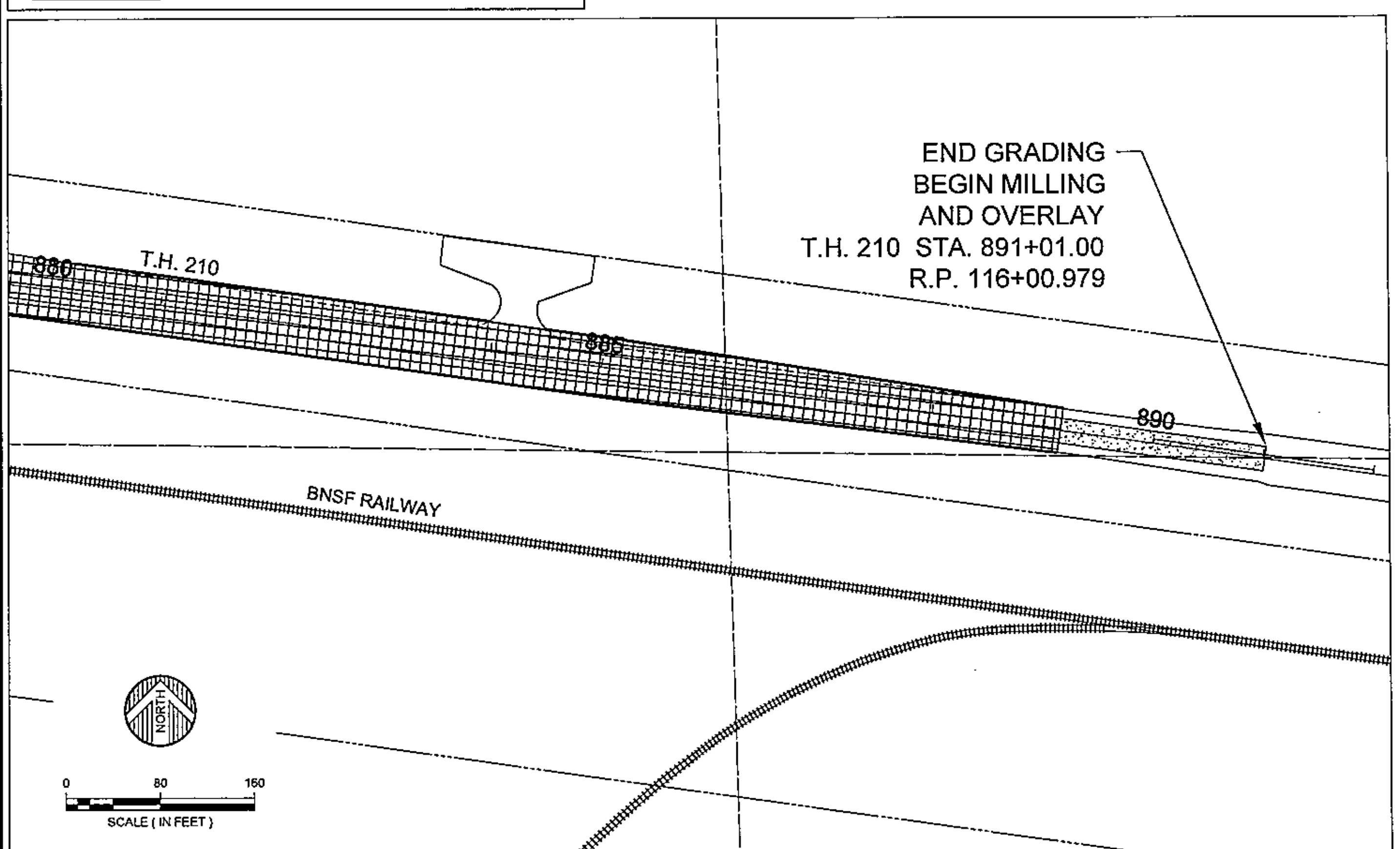
2008 POTLATCH ROADWAY EXTENSION
CITY OF BAXTER
BAXTER, MINNESOTA
TITLE SHEET

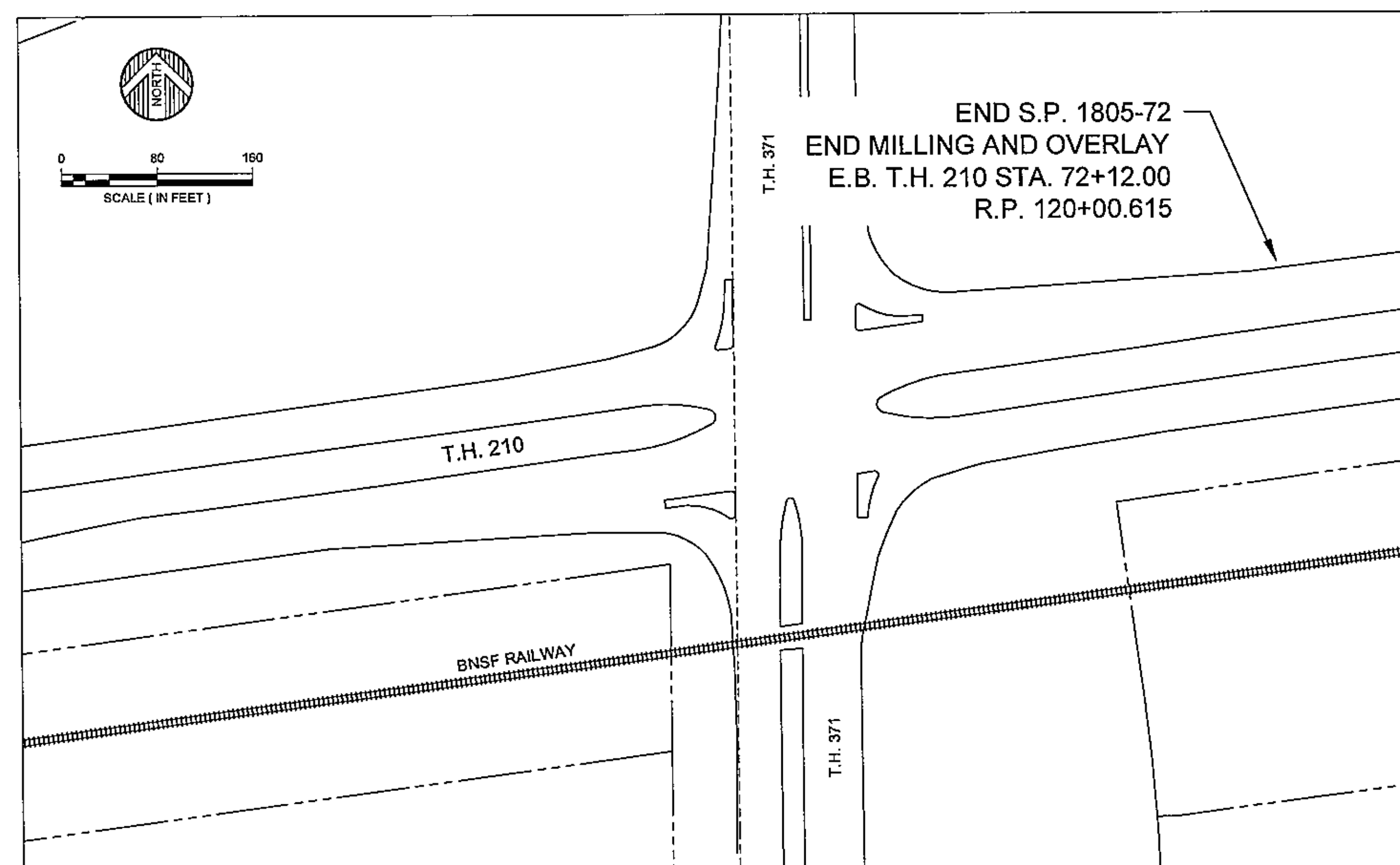
SHEET NO. 1
SHEET 1 OF 73




## LEGEND

- EXISTING TURN LANE REMOVAL
- TURN LANE CONSTRUCTION

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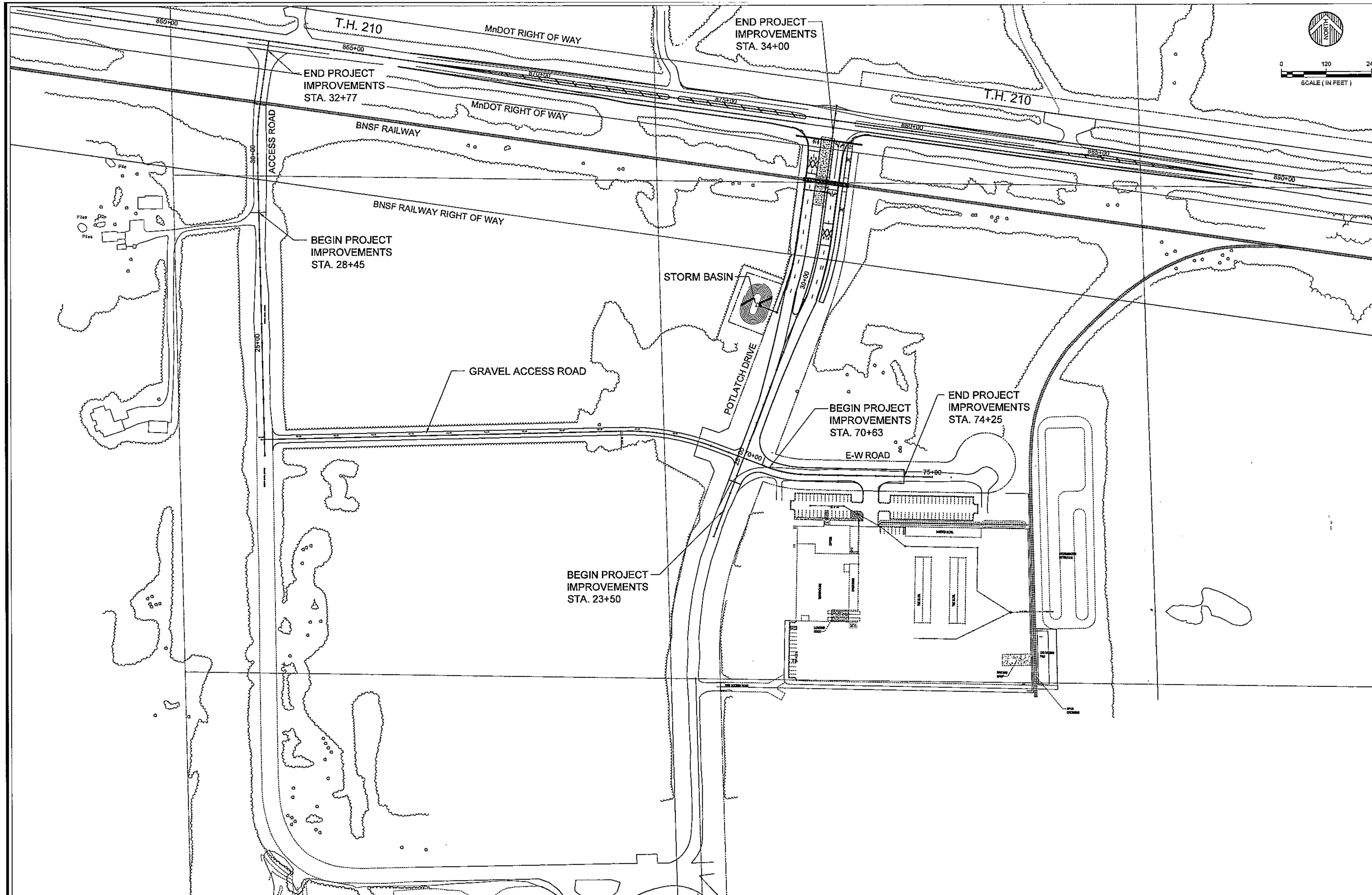
ARIC WELCH

DATE: MAY 2009
SCALE: AS SHOWN
DRAWN BY: MAS
CHECKED BY: ALW
JOB NUMBER: 0102B0318.000

2008 POTLATCH ROADWAY EXTENSION
CITY OF BAXTER
BAXTER, MINNESOTA
GENERAL LAYOUT - T.H. 210

SHEET NO. 2
SHEET 2 OF 73

GENERAL LAYOUT - T.H. 210
S.P. 1805-72 (T.H. 210)
SHEET NO. 2 OF 73




GENERAL LAYOUT
S.P. 1805-72 (T.H. 210)

SHEET NO. 3 OF 73

J:\0102B-City of Baxter\0102B0318-2008 Roadway Extension-Potlatch South\0102B0318.000-2008 Roadway Extension-Potlatch South\CADD\Civil\REVISED - Potlatch Road\REV-PP-102B0318-Revised.DWG Plotted by: Aric Welch 3/25/2010 9:12:59 AM © 2010 WIDSETH SMITH NOLTING

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Aric Welch 3-24-10

ARIC WELCH DATE: LIC. NO.41563

| DATE | REV# | REVISIONS DESCRIPTION | BY |
| --- | --- | --- | --- |
| | | | |

| | |
| --- | --- |
| DATE: | FEB. 2008 |
| SCALE: | AS SHOWN |
| DRAWN BY: | MAS |
| CHECKED BY: | ALW |
| JOB NUMBER: | 0102B0318 |

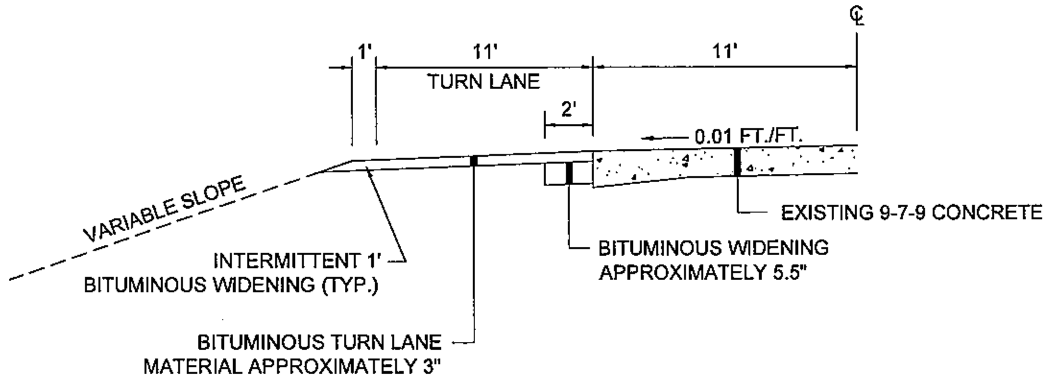
2008 POTLATCH ROADWAY EXTENSION
CITY OF BAXTER
BAXTER, MINNESOTA

GENERAL LAYOUT

SHEET NO.
3
SHEET 3 OF 73

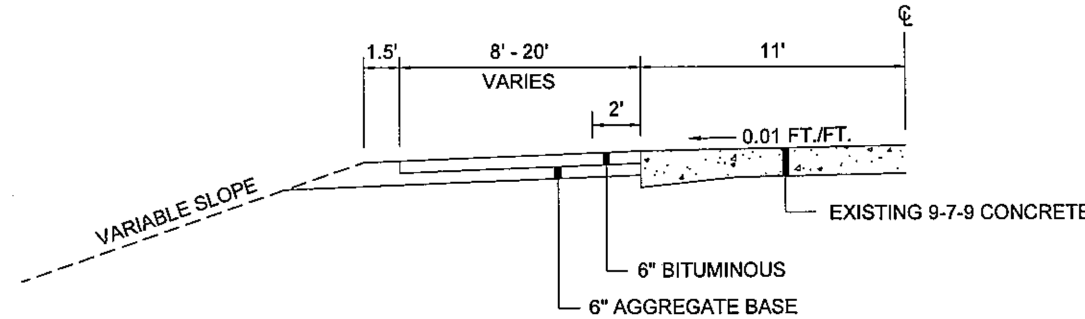
## EXISTING TYPICAL ROADWAY SECTION

TH 210 STA. 860+08 - 865+40 LT.



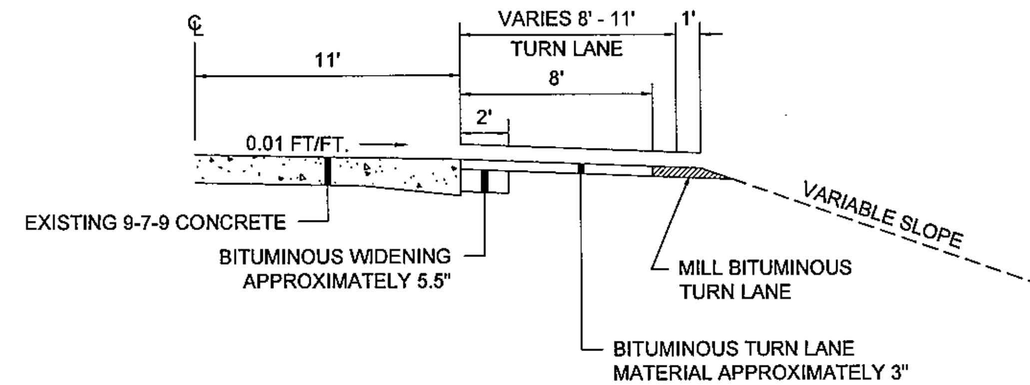

## EXISTING TYPICAL ROADWAY SECTION

TH 210 STA. 865+40 - 888+00 LT. LT.
TRUCK WEIGHING AND INSPECTION AREA



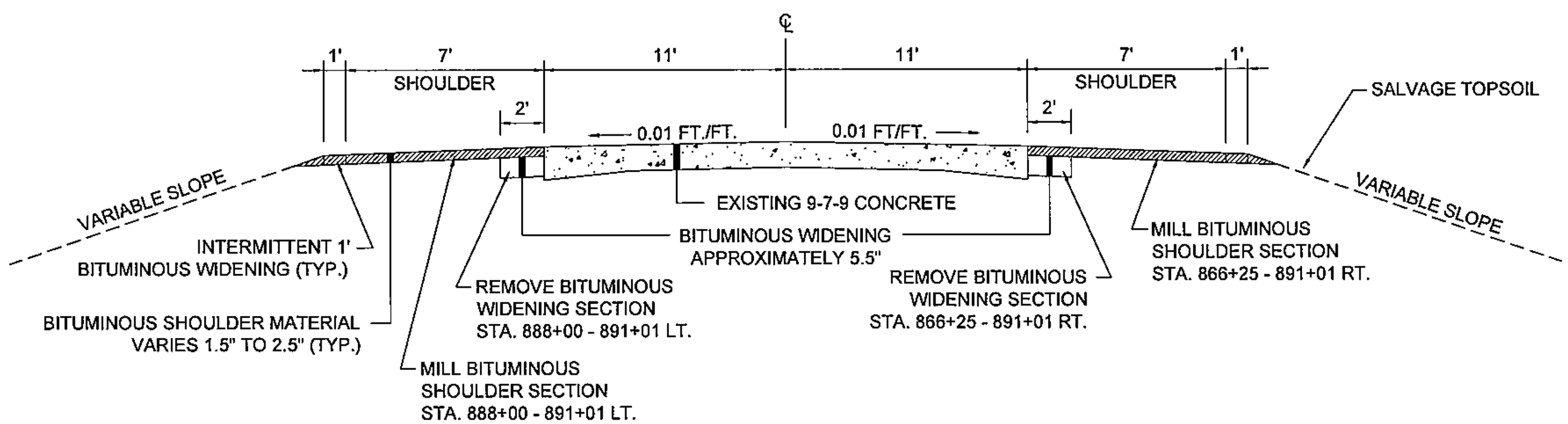

## EXISTING TYPICAL ROADWAY SECTION

TH 210 STA. 856+00 - 865+85 RT.



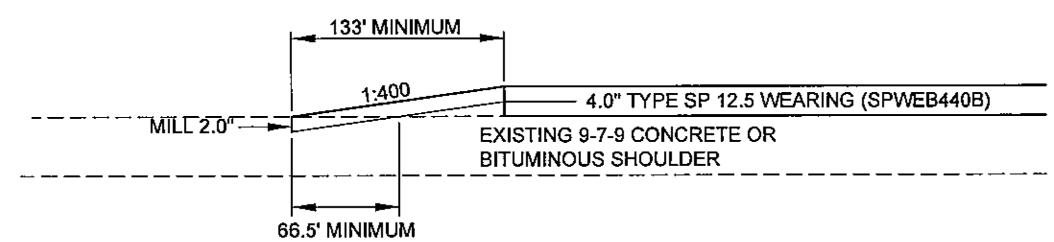

## EXISTING TYPICAL ROADWAY SECTION

TH 210 STA. 865+85 - 891+00 RT.
TH 210 STA. 856+00 - 860+08, 888+00 - 891+01 LT.



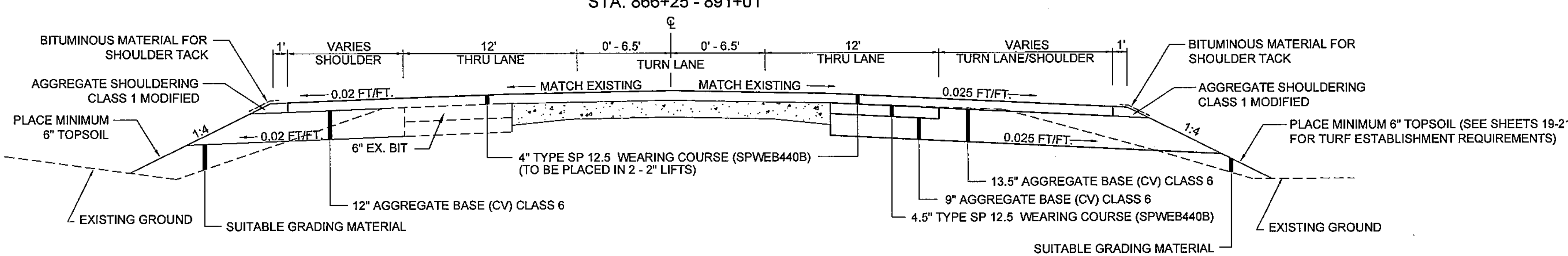

## TH 210 PAVEMENT TRANSITION DETAIL

TH 210 CONCRETE MAINLINE STA. 866+25 - 866+91.5, 890+34.5 - 891+01
TH 210 BITUMINOUS SHOULDER STA. 866.25 - 866+91.5 LT.




## TYPICAL NO. 1

PROPOSED T.H. 210 WIDENING
STA. 866+25 - 891+01

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ARIC WELCH 3-30-10 LIC. NO. 41983

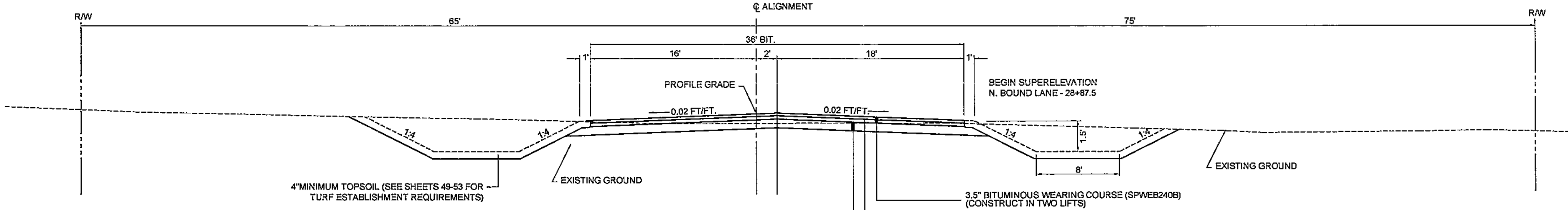
DATE: FEB. 2008
SCALE: AS SHOWN
DRAWN BY: MAS
CHECKED BY: ALW
JOB NUMBER: 010280318

2008 POTLATCH ROADWAY EXTENSION
CITY OF BAXTER
BAXTER, MINNESOTA

TYPICAL SECTIONS & PAVEMENT TRANSITION DETAIL

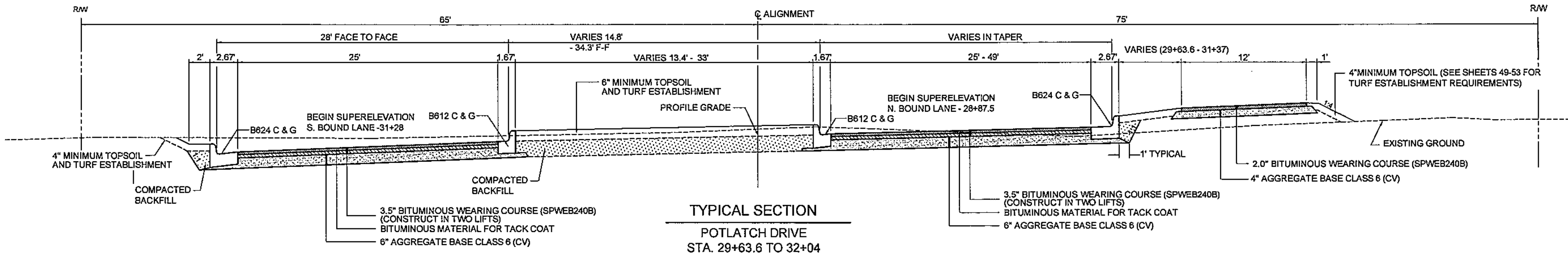
SHEET NO. 7
SHEET 7 OF 73

TYPICAL SECTIONS & PAVEMENT TRANSITIONAL DETAIL
S.P. 1805-72 (T.H. 210) SHEET NO. 7 OF 73



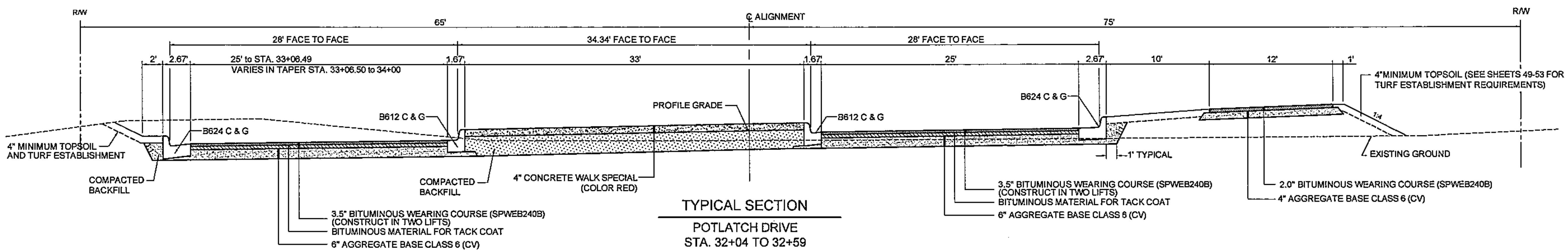

TYPICAL SECTION

POTLATCH DRIVE
STA. 24+32 TO 29+63.6



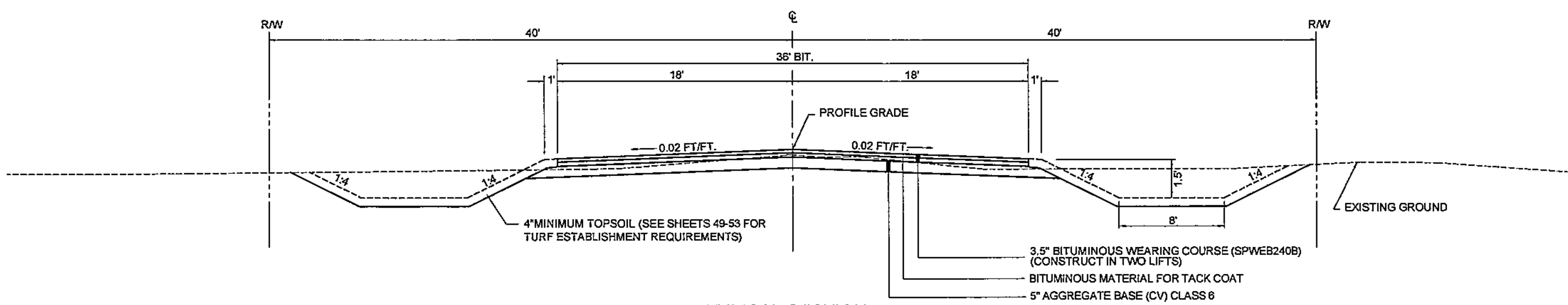

TYPICAL SECTION

POTLATCH DRIVE
STA. 29+63.6 TO 32+04




TYPICAL SECTION

POTLATCH DRIVE
STA. 32+04 TO 32+59
STA. 32+75 TO 33+85




TYPICAL SECTION

E-W ROAD
STA. 69+76 TO 74+25

J:\0102B-City of Baxter\0102B0318-2008 Roadway Extension-Potlatch South\0102B0318.000-2008 Roadway Extension-Potlatch South\CADD\Civil\REVISED - Potlatch Road\REVISED-TYPSECT.dwg Plotted by: Mark Skogen 3/24/2010 2:58:26 PM © 2010 WIDSETH SMITH NOLTING

TYPICAL SECTIONS
S.P. 1805-72 (T.H. 210)

SHEET NO. 8 OF 73

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ARIC WELCH DATE: 3-24-10 LIC. NO. 41983

| DATE | REV# | REVISIONS DESCRIPTION | BY |
|---|---|---|---|
| | | | |

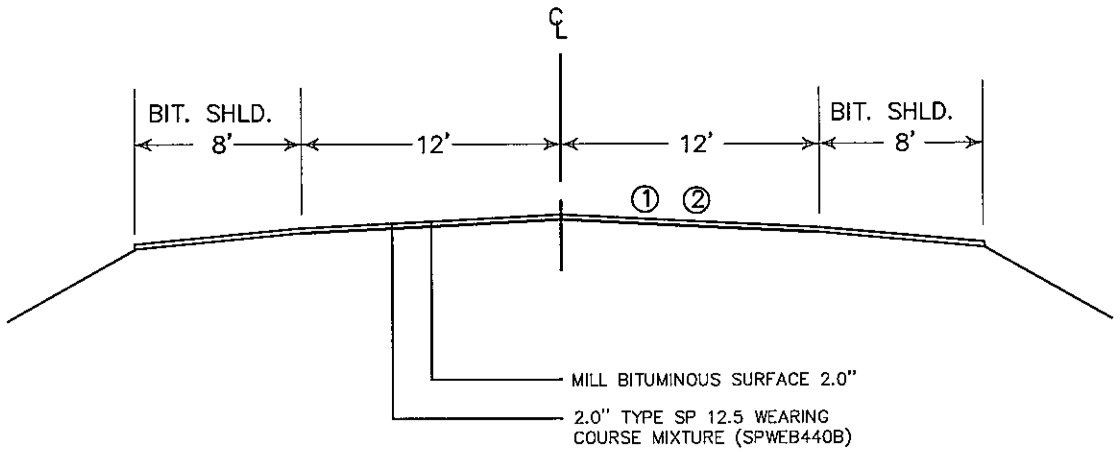
DATE: FEB. 2008
SCALE: AS SHOWN
DRAWN BY: MAS
CHECKED BY: AJW
JOB NUMBER: 0102B0318

2008 POTLATCH ROADWAY EXTENSION
CITY OF BAXTER
BAXTER, MINNESOTA

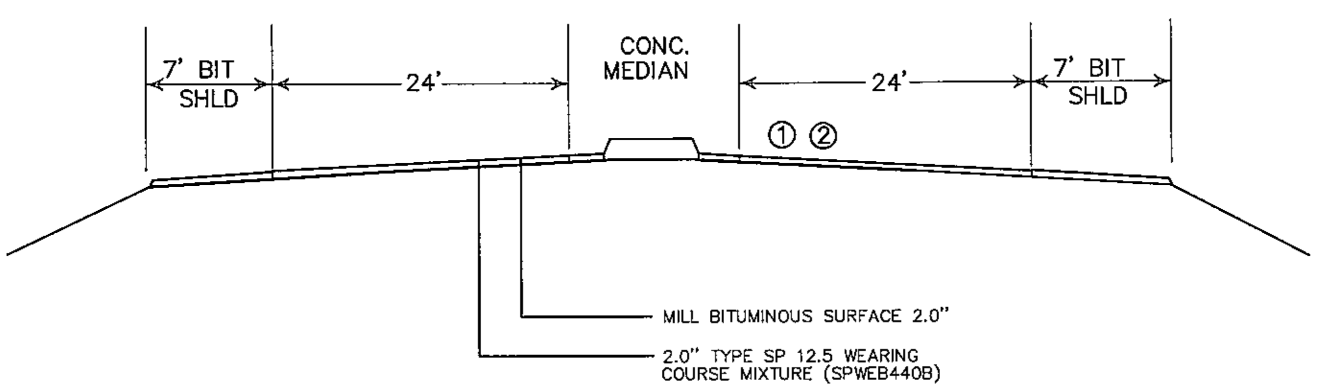
TYPICAL SECTIONS

SHEET NO. 8
SHEET 8 OF 73

## TYPICAL SECTION NO. 1
T.H. 210
R.P. 116.979 TO R.P. 117.346



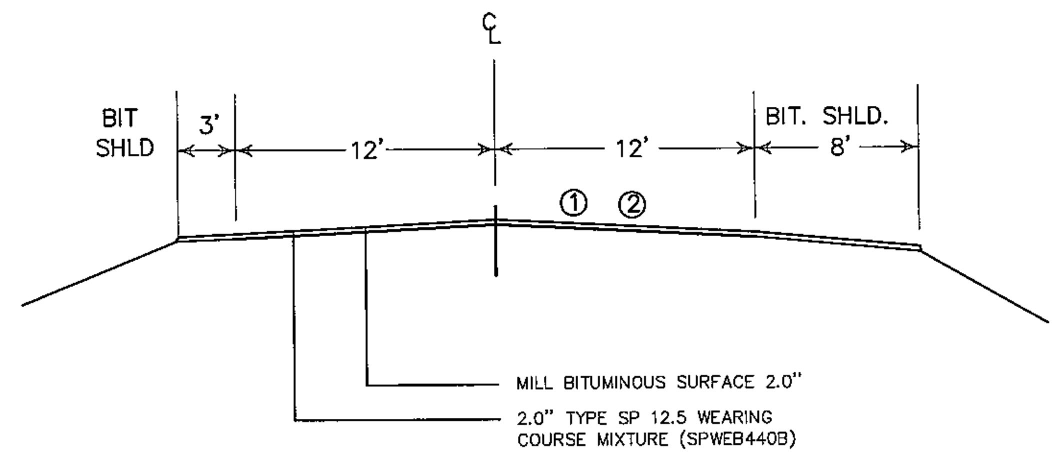

## TYPICAL SECTION NO. 2
T.H. 210
R.P. 117.346 TO R.P. 120.615




① MATCH EXISTING SLOPE

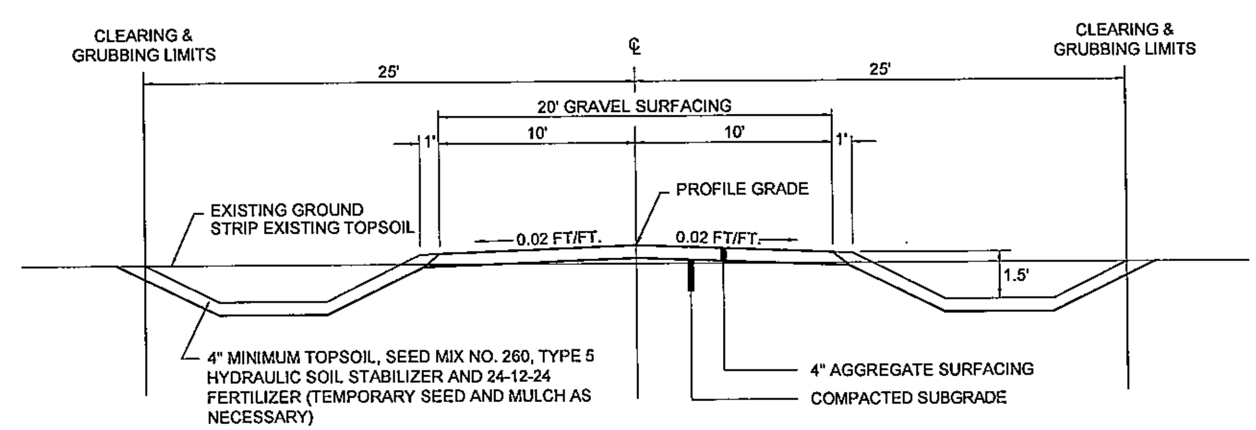
② EXISTING LEFT AND RIGHT TURN LANES SHALL ALSO BE MILLED 2.0" AND SURFACED WITH 2.0" TYPE SP12.5 WEARING COURSE MIXTURE (SPWEB440B)

## TYPICAL SECTION NO. 3
T.H. 210
EB & WB T.H. 210 (DIVIDED HIGHWAY)
R.P. 119.668 TO R.P. 120.615




① MATCH EXISTING SLOPE

② EXISTING LEFT AND RIGHT TURN LANES SHALL ALSO BE MILLED 2.0" AND SURFACED WITH 2.0" TYPE SP12.5 WEARING COURSE MIXTURE (SPWEB440B) EXCLUDING TURN LANES AT ELDER DRIVE.




## TYPICAL SECTION
GRAVEL ACCESS ROAD

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ARIC WELCH DATE: 4-8-13

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| --- | --- | --- | --- |

| | |
| --- | --- |
| DATE: | FEB. 2008 |
| SCALE: | AS SHOWN |
| DRAWN BY: | MAS |
| CHECKED BY: | ALW |
| JOB NUMBER: | 0102B0318 |

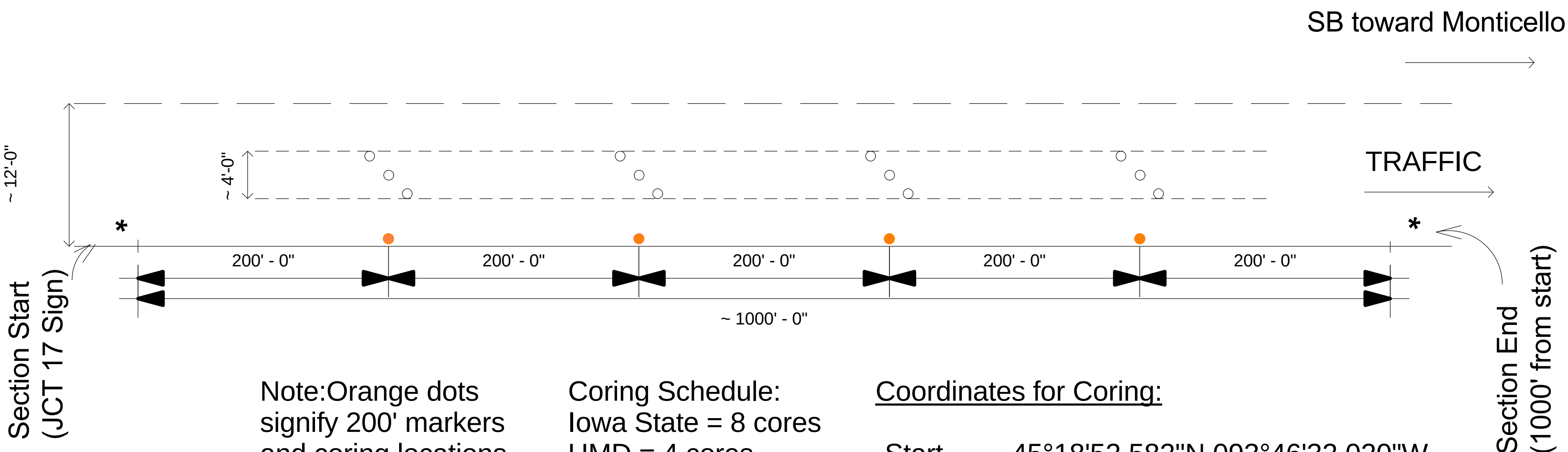
2008 POTLATCH ROADWAY EXTENSION
CITY OF BAXTER
BAXTER, MINNESOTA
TYPICAL SECTIONS

SHEET NO. 9
SHEET 9 of 73

TYPICAL SECTIONS
S.P. 1805-72 (T.H. 210)
SHEET NO. 9 OF 73

# APPENDIX B: FIELD SAMPLING PLANS

**TH 25:**
**S.P.# 7104-19**




Note:Orange dots signify 200' markers and coring locations

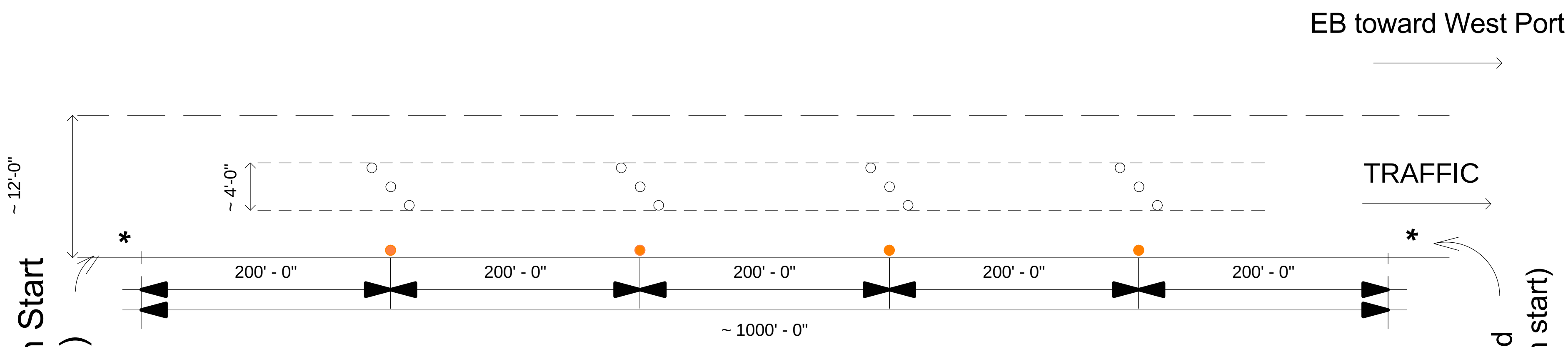
Coring Schedule:
Iowa State = 8 cores
UMD = 4 cores

Coordinates for Coring:

| | |
|---|---|
| -Start | 45°18'52.582"N 093°46'32.020"W |
| -1st Core | 45°18'51.358"N 093°46'34.249"W |
| -2nd Core | 45°18'50.295"N 093°46'36.798"W |
| -3rd Core | 45°18'49.137"N 093°46'38.774"W |
| -4th Core | 45°18'48.349"N 093°46'41.180"W |
| -End | 45°18'46.996"N 093°46'43.463"W |

RP (Start): Jct 17 Sign

**TH 28:**
**S.P.# 6104-11**




Note:Orange dots signify 200' markers and coring locations

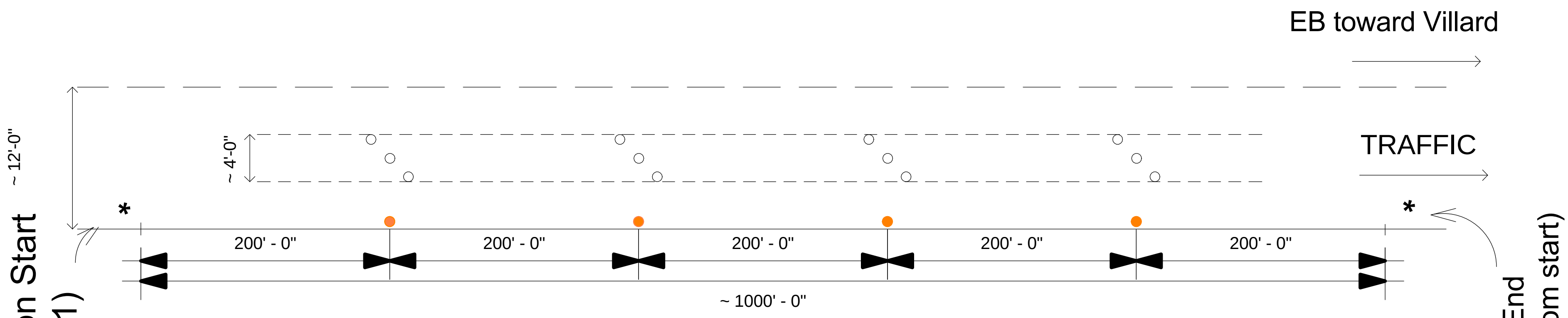
Coring Schedule:
Iowa State = 8 cores
UMD = 4 cores

Coordinates for Coring:

| | |
|---|---|
| -Start | 45°42'28.913"N 095°13'26.326"W |
| -1st Core | 45°42'29.057"N 095°13'24.068"W |
| -2nd Core | 45°42'29.124"N 095°13'20.671"W |
| -3rd Core | 45°42'29.029"N 095°13'18.023"W |
| -4th Core | 45°42'29.072"N 095°13'17.990"W |
| -End | 45°42'28.930"N 095°13'12.612"W |

RP (Start): 88

**<u>TH 28:</u>**
**S.P.# 6104-11**




Note:Orange dots
signify 200' markers
and coring locations

Coring Schedule:
Iowa State = 8 cores
UMD = 4 cores

<u>Coordinates for Coring:</u>

-Start 45°39'24.147"N 095°18'35.273"W

-1st Core 45°39'24.827"N 095°18'33.277"W

-2nd Core 45°39'26.271"N 095°18'30.750"W

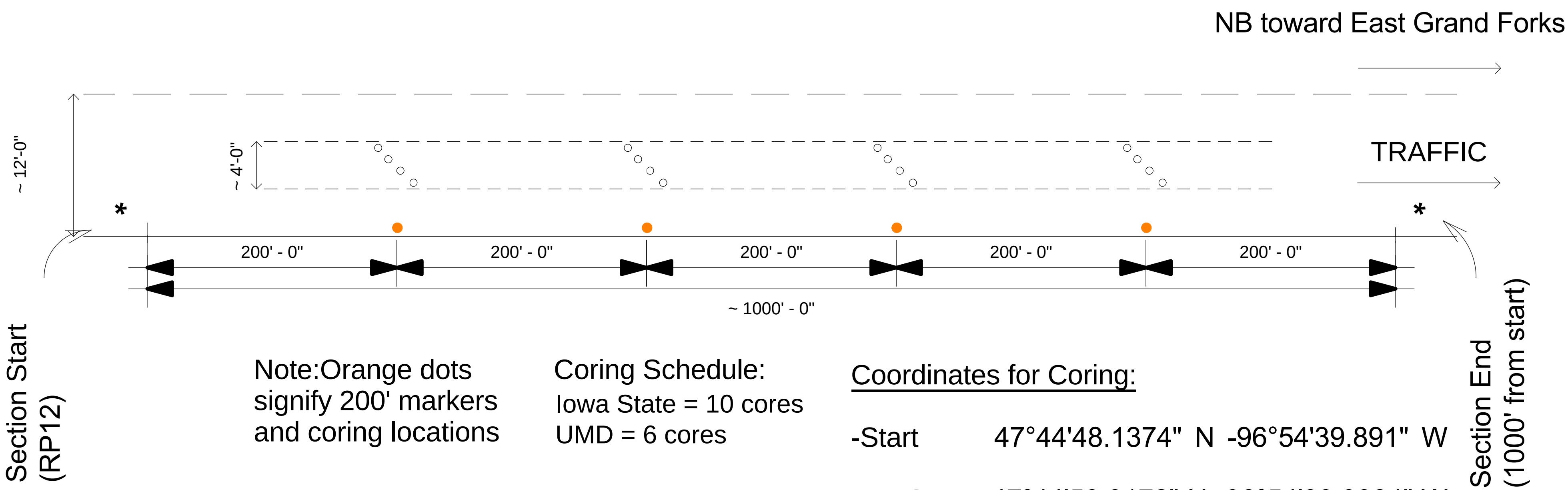
-3rd Core 45°39'27.437"N 095°18'28.490"W

-4th Core 45°39'28.467"N 095°18'26.222"W

-End 45°39'29.044"N 095°18'24.029"W

RP (Start): <u>81</u>

**TH 220:**
**SP #: 6016-37**




Note:Orange dots signify 200' markers and coring locations

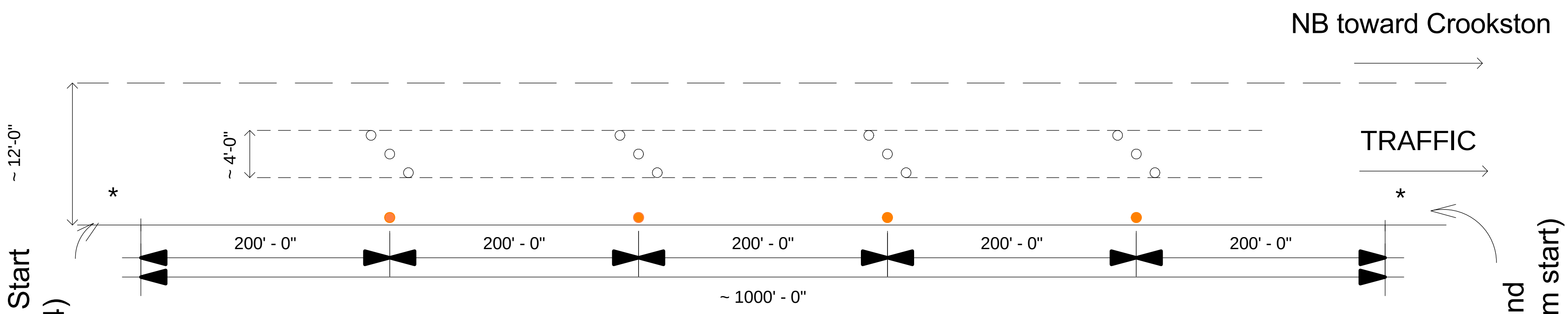
Coring Schedule:
Iowa State = 10 cores
UMD = 6 cores

Coordinates for Coring:

| | | |
|---|---|---|
| -Start | 47°44'48.1374" N | -96°54'39.891" W |
| -1st Core | 47°44'50.0172" N | -96°54'39.9384" W |
| -2nd Core | 47°44'51.8100" N | -96°54'39.6936" W |
| -3rd Core | 47°44'53.2608" N | -96°54'39.8082" W |
| -4th Core | 47°44'55.9932" N | -96°54'40.4202" W |
| -End | 47° 44' 57.9258" N | -96°54'40.0428" W |

(Start): RP 12

**TH 9:**
**S.P.# 6010-26**




Note:Orange dots signify 200' markers and coring locations

Coring Schedule:
Iowa State = 8 cores
UMD = 4 cores

Coordinates for Coring:

-Start 47°35'33.462"N 096°32'27.776"W

-1st Core 47°35'35.289"N 096°32'29.046"W

-2nd Core 47°35'36.980"N 096°32'29.959"W

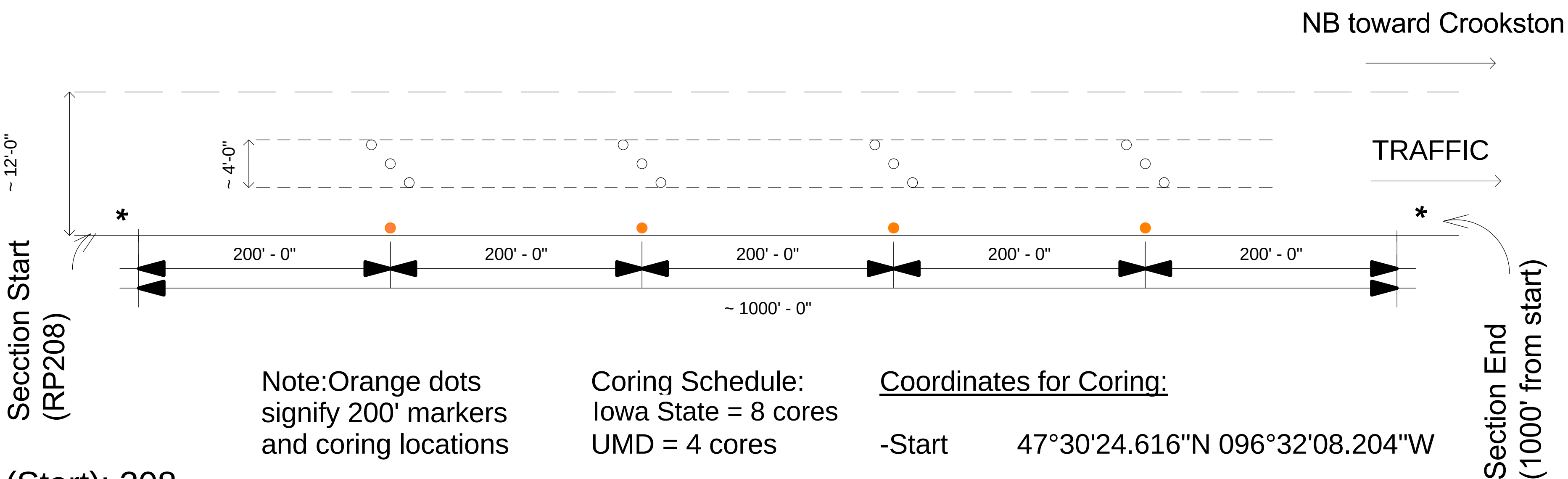
-3rd Core 47°35'38.900"N 096°32'30.950"W

-4th Core 47°35'40.889"N 096°32'32.161"W

-End 47°35'42.498"N 096°32'32.805"W

RP (Start): 214

**TH 9:**
**S.P.# 6010-26**




Note:Orange dots signify 200' markers and coring locations

Coring Schedule:
Iowa State = 8 cores
UMD = 4 cores

Coordinates for Coring:

-Start 47°30'24.616"N 096°32'08.204"W

-1st Core 47°30'26.612"N 096°32'07.807"W

-2nd Core 47°30'28.467"N 096°32'07.471"W

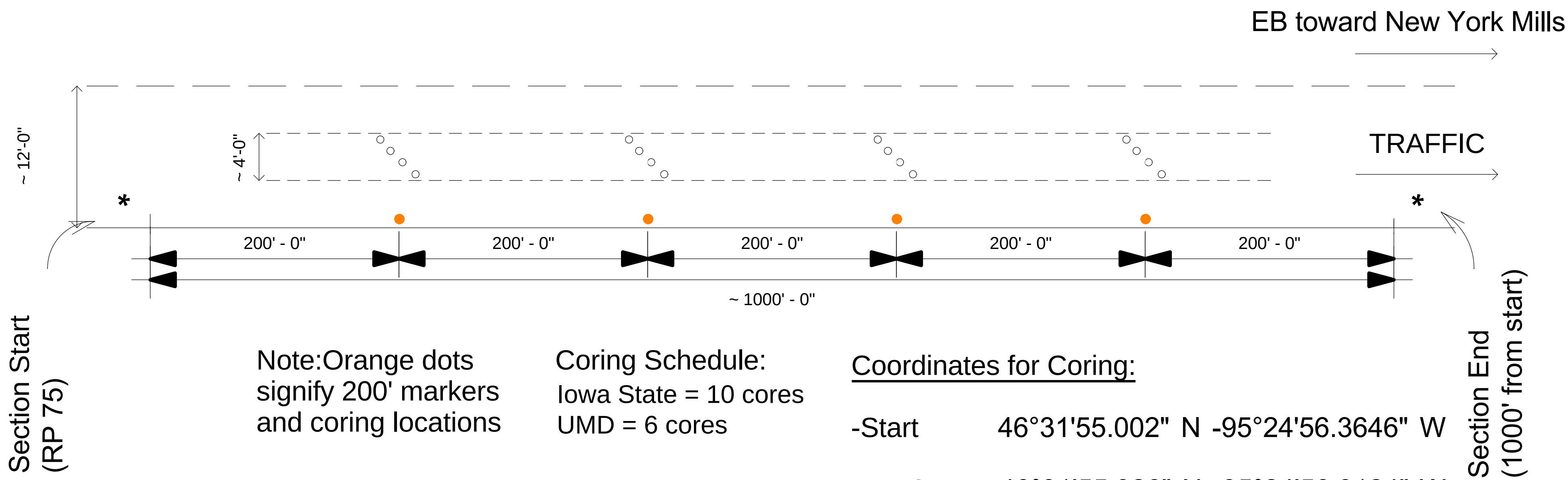
-3rd Core 47°30'30.577"N 096°32'07.074"W

-4th Core 47°30'32.471"N 096°32'06.642"W

-End 47°30'34.527"N 096°32'06.407"W

RP (Start): 208

**TH 10:**
**SP #: 5606-42**




Note:Orange dots signify 200' markers and coring locations

Coring Schedule:
Iowa State = 10 cores
UMD = 6 cores

Coordinates for Coring:

-Start 46°31'55.002" N -95°24'56.3646" W

-1st Core 46°31'55.326" N -95°24'56.0124" W

-2nd Core 46°31'53.3526" N -95°24'51.4398" W

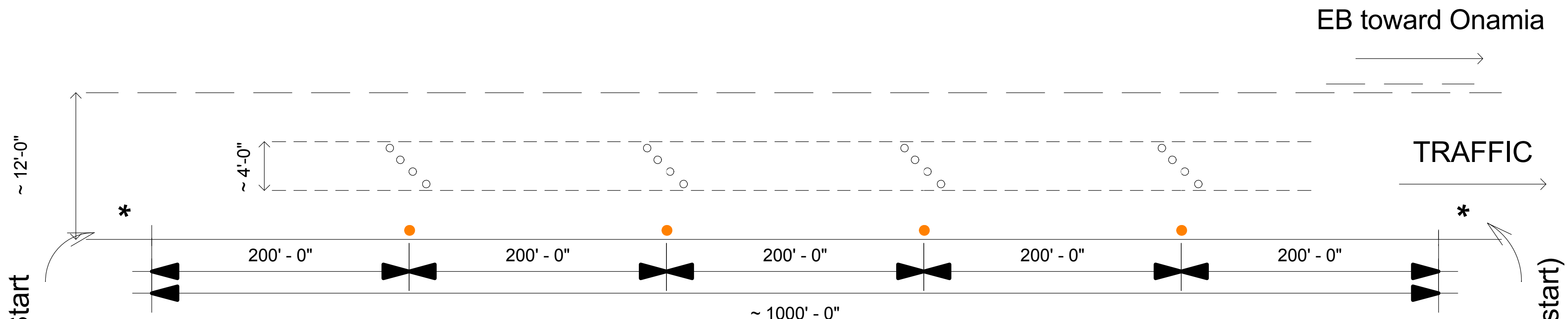
-3rd Core 46°31'52.9674" N -95°24'51.1632" W

-4th Core 46°31'51.8088" N -95°24'46.4004" W

-End NOT AVAILABLE

(Start): RP 75

**TH 27:**
**S.P. # 4803-19**




Note:Orange dots signify 200' markers and coring locations

Coring Schedule:
Iowa State = 10 cores
UMD = 6 cores

Coordinates for Coring:

-Start 46°04'17.648"N 093°41'19.9356"W

-1st Core 46°05'19.773"N 093°42'44.2764"W

-2nd Core 46°04'16.3344"N 093°41'16.2924"W

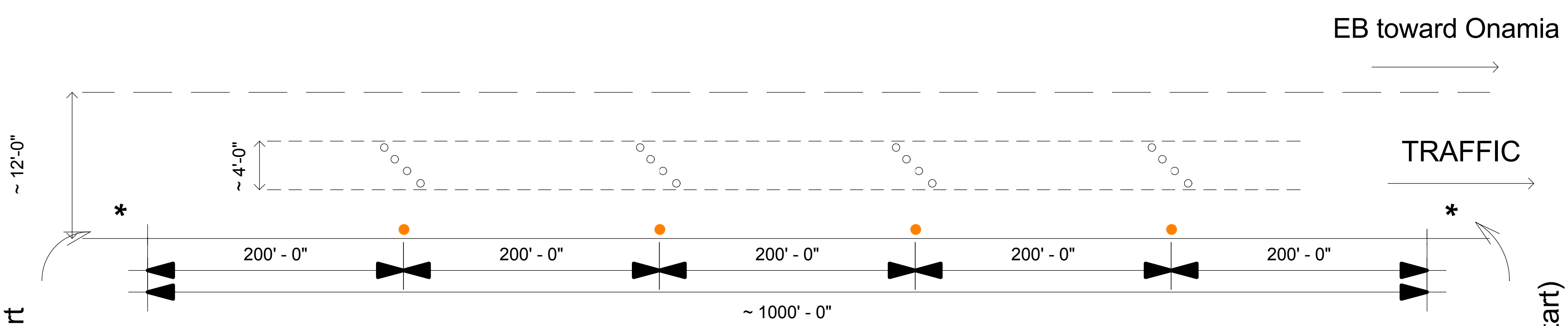
-3rd Core 46°04'14.019"N 093°41'13.3074"W

-4th Core 46°04'13.4976"N 093°41'10.3662"W

-End 46°04'13.3752"N 093°41'09.9132"W

RP (Start): 174

**<u>TH 27:</u>**
**S.P. # 4803-19**




Section Start
(RP 171)

Note:Orange dots signify 200' markers and coring locations

Coring Schedule:
Iowa State = 10 cores
UMD = 6 cores

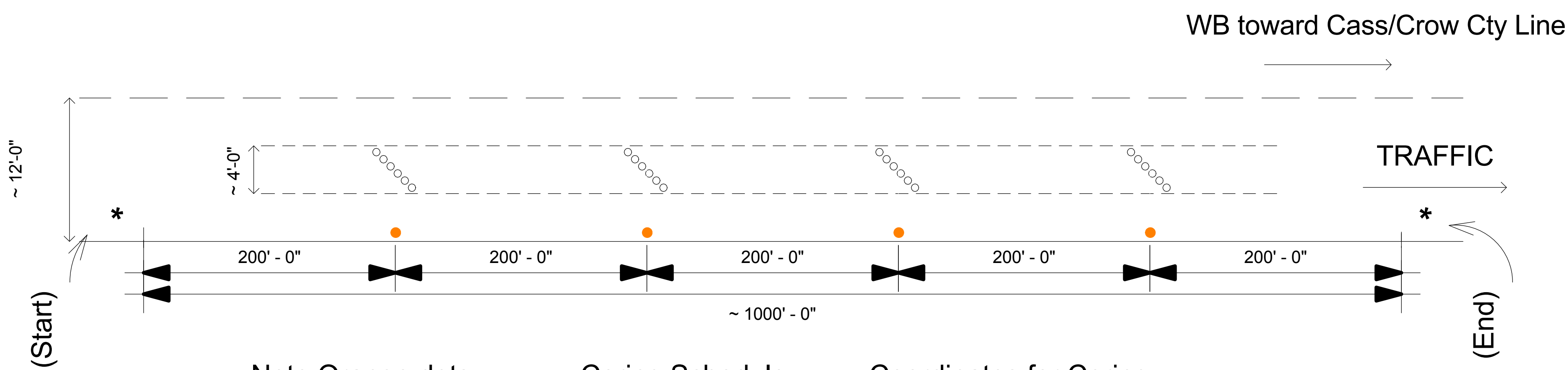
<u>Coordinates for Coring:</u>

| | |
|---|---|
| -Start | 46°04'38.0094"N 093°44'59.1468"W |
| -1st Core | 46°05'14.1606"N 093°44'57.6816"W |
| -2nd Core | 46°05'22.6885"N 093°44'49.2176"W |
| -3rd Core | 46°04'38.9418"N 093°44'50.9532"W |
| -4th Core | 46°04'38.841"N 093°44'49.8366"W |
| -End | 46°05'56.0214"N 093°44'53.232"W |

Section End
(1000' from start)

RP (Start): <u>171</u>

**TH 210:**
**S.P. # 1805-72**




Note:Orange dots
signify 200' markers
and coring locations

Coring Schedule:
MnDOT = 16 cores
UMD = 8 cores

Coordinates for Coring:

-Start 46°20'29.754"N 094°17'40.488"W

-1st Core 46°20'29.335"N 094°17'43.442"W

-2nd Core 46°20'28.830"N 094°17'46.324"W

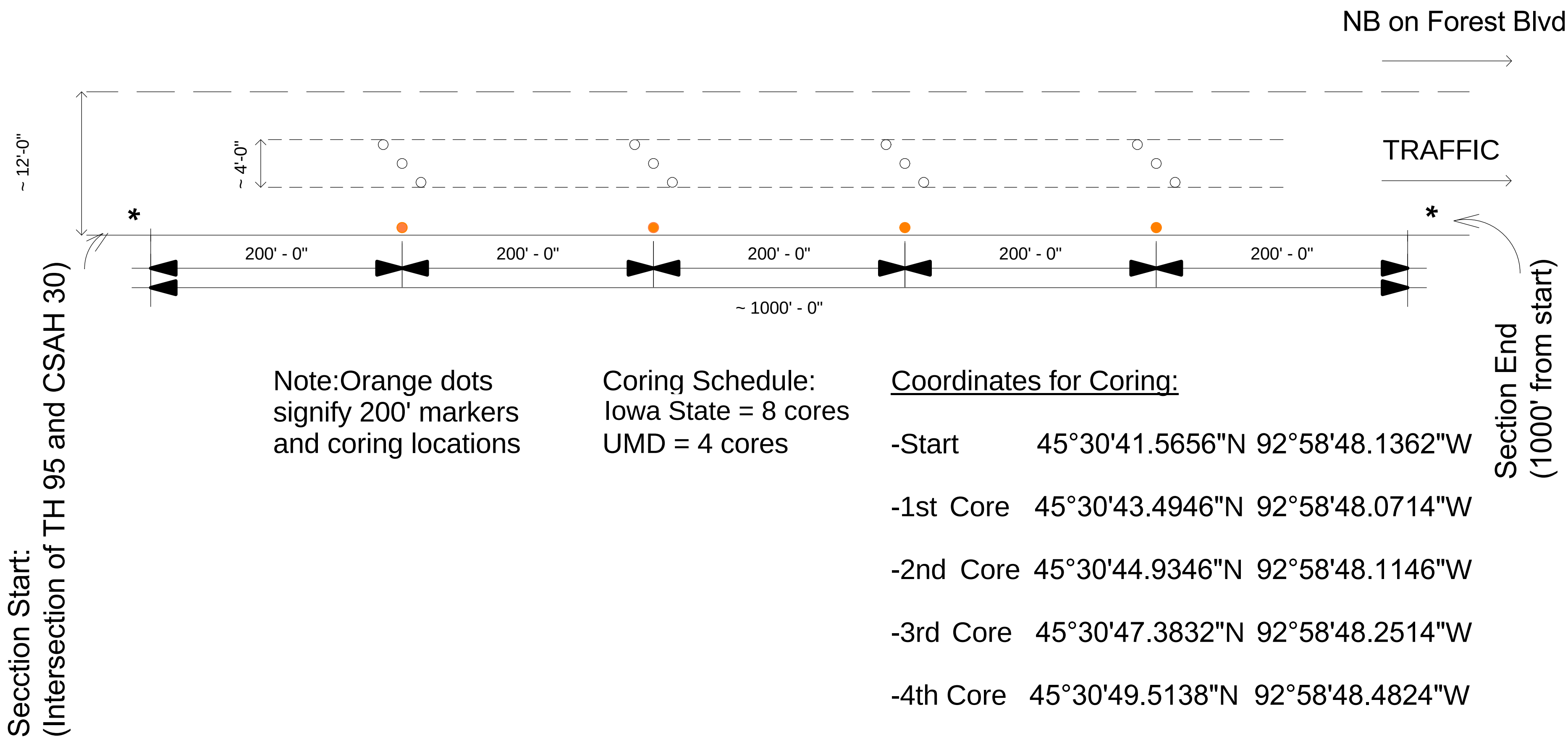
-3rd Core 46°20'28.264"N 094°17'48.862"W

-4th Core 46°20'28.087"N 094°17'51.588"W

-End 46°20'27.523"N 094°17'54.719"W

RP (Start): 118

**CSAH 30:**
**S.P.# 1306-44**



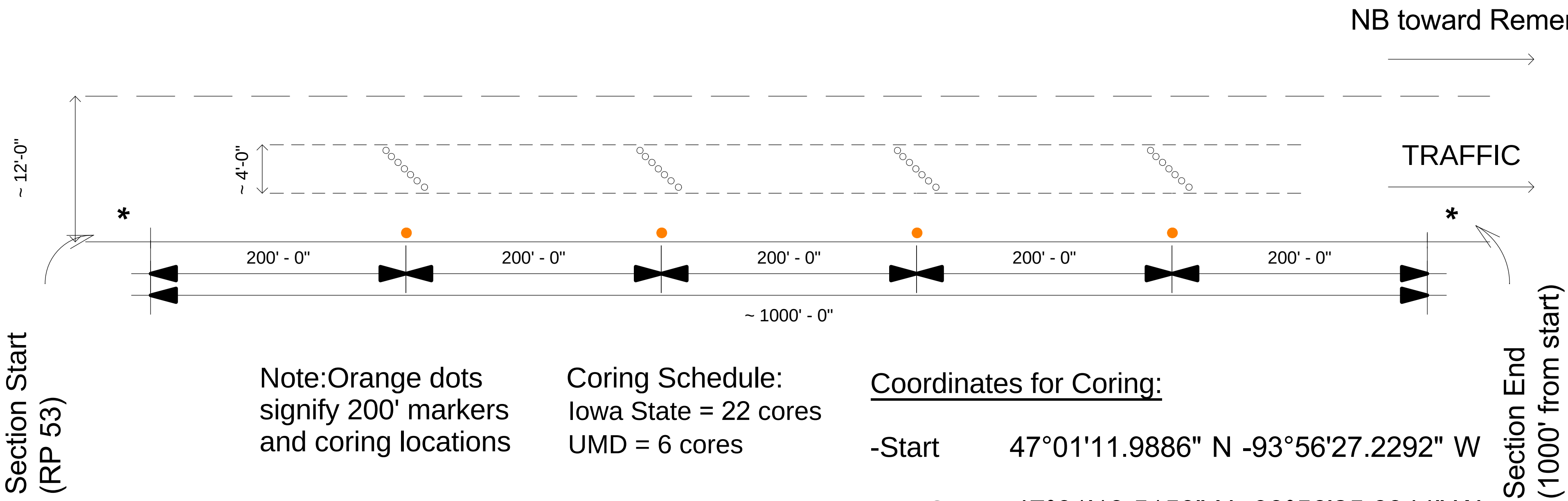

Note:Orange dots
signify 200' markers
and coring locations

Coring Schedule:
Iowa State = 8 cores
UMD = 4 cores

Coordinates for Coring:

| | | |
|---|---|---|
| -Start | 45°30'41.5656"N | 92°58'48.1362"W |
| -1st Core | 45°30'43.4946"N | 92°58'48.0714"W |
| -2nd Core | 45°30'44.9346"N | 92°58'48.1146"W |
| -3rd Core | 45°30'47.3832"N | 92°58'48.2514"W |
| -4th Core | 45°30'49.5138"N | 92°58'48.4824"W |
| -End | 45°30'51.1950"N | 92°58'48.1044""W |

**TH 6:**
**SP #: 1103-25**




Note:Orange dots signify 200' markers and coring locations

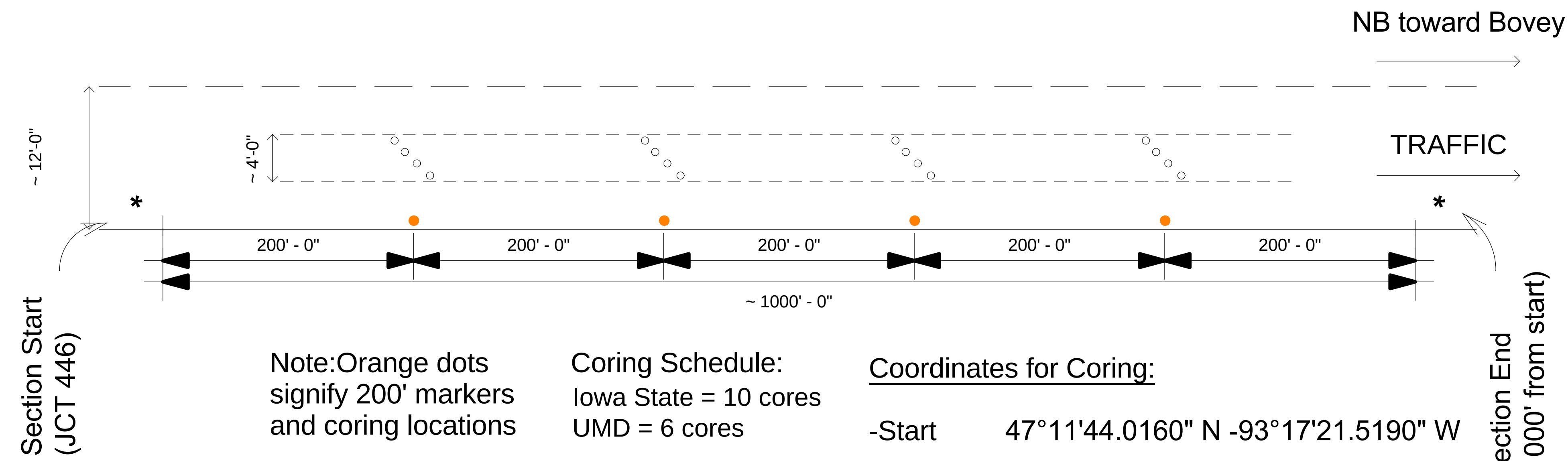
Coring Schedule:
Iowa State = 22 cores
UMD = 6 cores

Coordinates for Coring:

| | | |
|---|---|---|
| -Start | 47°01'11.9886" N | -93°56'27.2292" W |
| -1st Core | 47°01'13.5150" N | -93°56'25.6344" W |
| -2nd Core | 47°01'14.9946" N | -93°56'23.9850" W |
| -3rd Core | 47°01'16.8024" N | -93°56'22.7646" W |
| -4th Core | 47°01'18.0696" N | -93°56'20.7096" W |
| -End | 47°01'18.4074" N | -93°56'19.8234" W |

(Start): RP 53

**CR 10:**
**SAP #: 031-610-016**




Note:Orange dots signify 200' markers and coring locations

Coring Schedule:
Iowa State = 10 cores
UMD = 6 cores

Coordinates for Coring:

-Start 47°11'44.0160" N -93°17'21.5190" W

-1st Core 47°11'45.9342" N -93°17'21.4038" W

-2nd Core 47°11'48.0222" N -93°17'21.9906" W

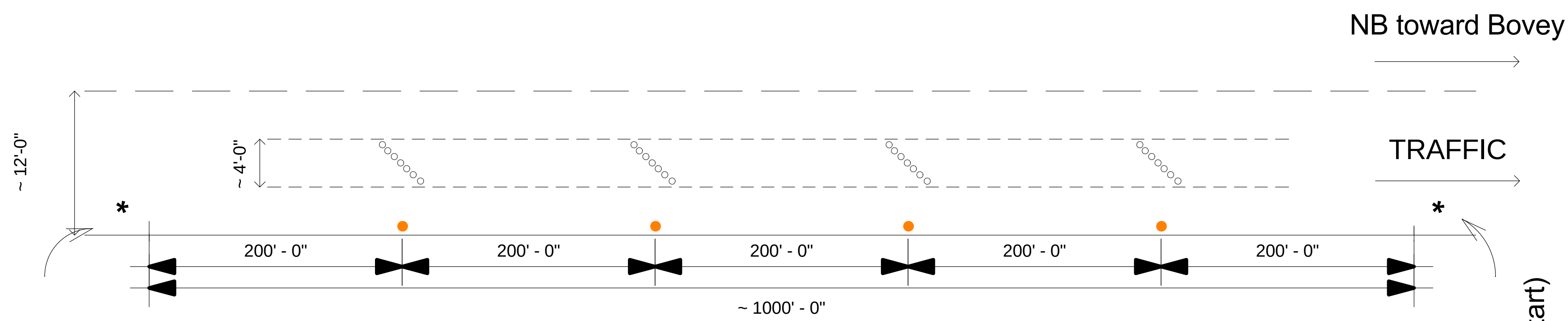
-3rd Core 47°11'49.7292" N -93°17'22.2138" W

-4th Core 47°11'51.9426" N -93°17'21.3030" W

-End 47°11'53.8188" N -93°17'21.7638" W

(Start): Itasca Cty 10 Sign

**CR 10:**
**SAP #: 031-610-016**




Section Start (JCT 445B)

Section End (1000' from start)

Note:Orange dots signify 200' markers and coring locations

Coring Schedule:
Iowa State = 22 cores
UMD = 6 cores

<u>Coordinates for Coring:</u>

-Start 47°12'45.4854" N -93°18'20.0226" W

-1st Core 47°12'46.7346" N -93°18'22.6974" W

-2nd Core 47°12'48.4992" N -93°18'24.7356" W

-3rd Core 47°12'48.3084" N -93°18'25.0086" W

-4th Core 47°12'49.6584" N -93°18'28.5804" W

-End 47°12'50.0430" N -93°18'29.5524" W

(Start): <u>Itasca Cty Rd 10 Sign</u>

# APPENDIX C: SECTION PICTURES AND FIELD VISIT NOTES

*Trunk Highway 6 (SP 1103-25)*

- Location: Spans between Remer and Outing
- Construction Year: 2010
- Construction Type(s):
  - 1-1/2 inch mill and overlay
  - Section Start: RP 53
- Section Length: 17.33 miles
- Site Notes:
  - Ride is generally smooth with a little uniform roughness due to thermal cracking
  - Majority of cracks have been sealed
  - Same construction type throughout project
  - Section has large amount of incline changes throughout


TH 6-section start

TH 6-overview

TH 6-surface profile

TH 6-typical crack configuration

TH 6-typical crack profile

***Trunk Highway 9 (SP 6010-26)***

- Location: South of Crookston to Beltrami
- Construction Year: 2011
- Construction Type(s):
    - 3-inch mill and overlay on reclaimed asphalt concrete (good and poor performers)
- Section Length: Roughly 18 miles
- Site Notes (Poor Performer):
    - Section Start: RP 208
    - Approximately 15 cracks per mile
- Site Notes (Good Performer):
    - Section Start: RP 214

- Approximately 11 cracks per mile
- Smoother ride than RP 208 section

***County State Aid Highway 10 (SAP 031-610-016)***

- Location: South of Bovey to Warba
- Construction Year: 2012
- Construction Type(s):
    - 1-1/2 inch overlay on old asphalt concrete (poor performer)
    - 3 inch mill and overlay (good performer)
- Section Length: Nearly 14.5 miles
- Site Notes (Poor Performer):
    - Section Start: JCT 445B sign
    - Visually more cracking than good performer
    - Centerline joint segregation


CSAH 10 poor performer-section start

CSAH 10 poor performer-overview

C-9

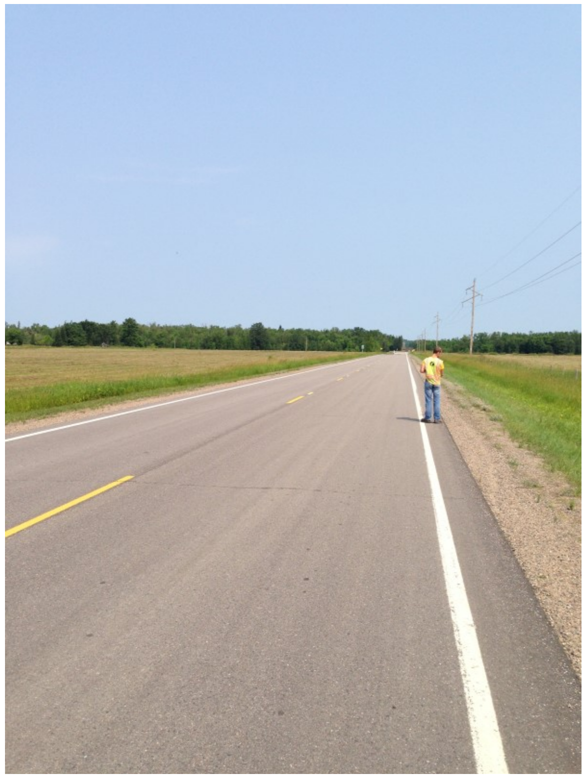
CSAH 10 poor performer-surface profile

CSAH 10 poor performer: typical crack configuration

CSAH 10 poor performer-typical crack profile

- Site Notes (Good Performer):
    - Section Start: JCT 446 sign
    - Smooth ride
    - Centerline joint segregation


CSAH 10 good performer-section start



CSAH 10 good performer-overview

CSAH 10 good performer-surface profile

CSAH 10 good performer: typical crack configuration

CSAH 10 good performer-typical crack profile

***Trunk Highway 10 (SP 0502-95)***

- Location: South of Little Falls, just outside Sartell
- Construction Year: 2005
- Construction Type(s):
    - 4-inch mill and overlay (good and poor performers)
    - Placed in two lifts 1-1/2 inch and 2-1/2 inch
    - Same mixture for both lifts
- Section Length: Slightly over 13 miles
- Site Notes (Poor Performer):
    - Section Start: RP 159
    - Cracks recently sealed
    - Inferior ride to RP 161

TH 10 poor performer-overview

TH 10 poor performer-typical crack configuration

TH 10 poor performer-typical crack profile and surface profile

- Site Notes (Good Performer):
    - Section Start: RP 161
    - Cracks are not sealed

- Rides better than RP 159

TH 10 good performer-overview

TH 10 good performer-typical crack configuration

TH 10 good performer-typical crack profile and surface profile

***Trunk Highway 10 (SP 5606-42)***

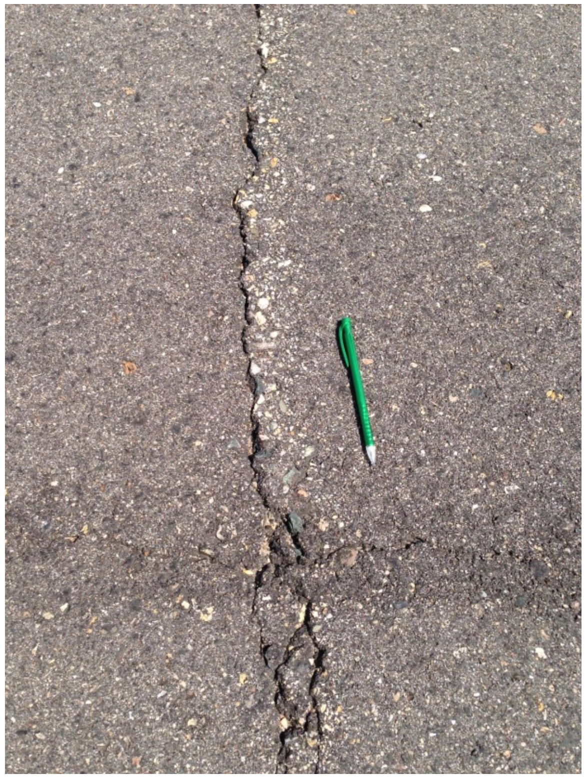
- Location: Spans through New York Mills
- Construction Year: 2013
- Construction Type(s):
    - 3-1/2 inch mill and overlay
- Section Length: Roughly 7 miles
- Site Notes:
    - Section Start: RP 75
    - Extensive shoulder cracking both longitudinal and transverse
    - Good ride quality
    - Centerline joint segregation apparent throughout most of section


TH 10-section start

TH 10-overview

TH 10-surface profile

TH 10-typical crack configuration



TH 10-typical crack profile

***Trunk Highway 25 (SP 7104-19)***

- Location: Between Monticello and Big Lake
- Construction Year: 2011
- Construction Type(s):
    - New construction-bituminous on aggregate base (BAB)
- Section Length: Nearly 1 mile
- Site Notes:
    - Section Start: Junction 17 sign
    - Zero thermal cracking
    - Very open surface
    - Poor construction joints

- Extremely dry and coarse mix

*Trunk Highway 27 (SP 4803-19)*

- Location: Starts in Onamia and spans west
- Construction Year: 2010
- Construction Type(s):
    - 3-inch mill and overlay (good and poor performers)
- Section Length: Roughly 7.5 miles
- Site Notes (Poor Performer):
    - Section Start: RP 171
    - Rides significantly worse than 174 section
    - Chip seal applied to surface
    - Poor base in this location—swamp to both sides
    - Significant settlement in some areas
    - Some severe longitudinal cracking
- Site Notes (Good Performer):
    - Section Start: RP 174
    - Much improved ride as compared to RP 171
    - Chip seal applied to surface
    - Also has large amount of cracking

***Trunk Highway 28 (SP 6104-11)***

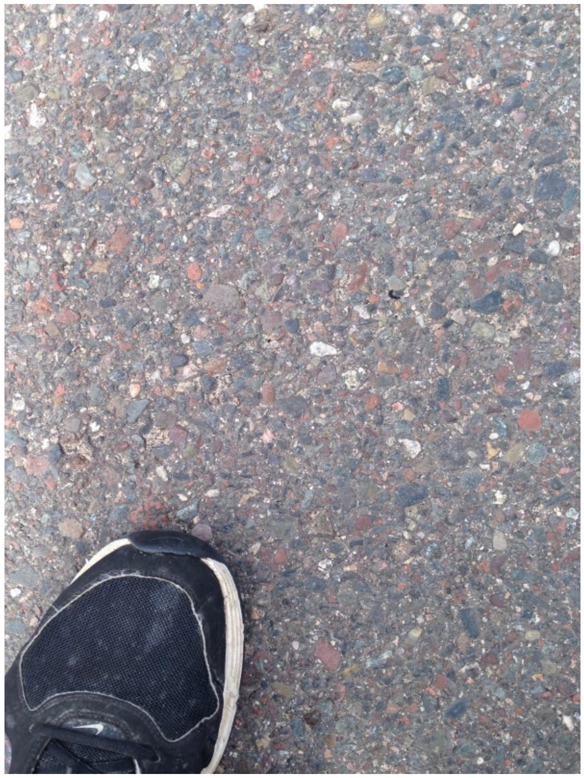
- Location: Spans from Glenwood to West Port
- Construction Year: 2012
- Construction Type(s):
    - 4-1/2 inch mill and overlay (good and poor performers)
- Section Length: Roughly 13 miles
- Site Notes (Poor Performer):
    - Section Start: RP 81
    - Rides well
    - Thermal cracking straight across
    - Centerline segregation
    - Significant shoulder cracking
    - Slightly more cracking than RP 88
- Site Notes (Good Performer):
    - Section Start: RP 88
    - Rides well
    - Thermal cracking straight across
    - Centerline segregation
    - Significant shoulder cracking

***County State Aid Highway 30 (SP 1306-44)***

- Location: In North Branch city limits
- Construction Year: 2012
- Construction Type(s):
  - 6-inch mill and overlay
- Section Length: ¼ of a mile
- Site Notes:
  - Section Start: Intersection with TH 95
  - Very short section
  - Complex geometry with large number of intersections
  - Performing well, good ride

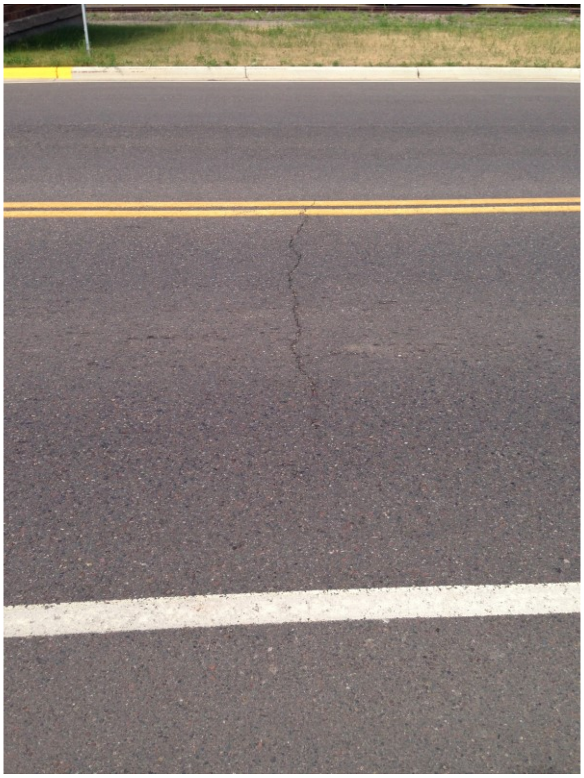

CSAH 30-section start

CSAH 30-overview



CSAH 30-surface profile

CSAH 30-typical crack configuration



CSAH 30-typical crack profile

***Trunk Highway 210 (SP 1805-72)***

- Location: Spans through Baxter
- Construction Year: 2010
- Construction Type(s):
    - 2 inch overlay on existing concrete
- Section Length: Roughly 4.5 miles
- Section Start: RP 118
- Site Notes:
    - Mix is quite coarse
    - Longitudinal joint is 100 percent cracked
    - Section exhibits transverse cracking roughly every 30 feet

- 2 inch overlay over existing concrete
- All transverse cracking is 100 percent reflective cracking
- Raveling in various areas of the section


TH 210-section start

TH 210-surface profile

TH 210-raveling

TH 210-typical crack configuration

TH 210-typical crack profile

***Trunk Highway 220 (SP 6016-37)***

- Location: Spans between Climax and East Grand Forks
- Construction Year: 2012
- Construction Type(s):
    - 3-inch mill and overlay
- Section Length: 23.5 miles
- Site Notes:
    - Section Start: RP 12
    - Good ride
    - Extremely small amount of cracking, but cracks are large where they occur
    - Open surface
    - Small amount of raveling on surface

TH 220-section start

TH 220-overview

TH 220-surface profile

TH 220-typical crack configuration

TH 220-typical crack profile

# APPENDIX D: PAVEMENT ME MECHANICAL PROPERTY INPUTS

Below is the calculated dynamic modulus data that was used as an asphalt layer input in Pavement ME Design. The table is broken down into the six field sites that were tested. The data appears exactly how it was input into Pavement ME Design.

| TH 220 - Group 1 | | | | | |
|---|---|---|---|---|---|
| T deg. C | 0.1 Hz | 0.5 Hz | 1 Hz | 5 Hz | 25 Hz |
| -10 | 2696852 | 2964844 | 3056117 | 3221361 | 3334911.5 |
| 0.4 | 1739731 | 2151832 | 2351018 | 2700511 | 2962449.5 |
| 17.1 | 450150 | 736890 | 928098 | 1357507 | 1823611.1 |
| 33.8 | 72761 | 145038 | 172982 | 361821 | 695940.67 |
| 55 | 23366 | 32876 | 39989 | 70213 | 137409.55 |

| TH 9 - Group 4 | | | | | |
|---|---|---|---|---|---|
| T deg. C | 0.1 Hz | 0.5 Hz | 1 Hz | 5 Hz | 25 Hz |
| -10 | 2240940.554 | 2686773.5 | 2858440 | 3204427.9 | 3478403 |
| 0.4 | 1490507.18 | 1926491.4 | 2141776.1 | 2617742.5 | 3130645.2 |
| 17.1 | 475918.024 | 760530.93 | 936462.02 | 1456810 | 1913244.6 |
| 33.8 | 96353.578 | 166068.51 | 209338.18 | 394213.28 | 737276.5 |
| 55 | 48650.36359 | 56560.245 | 65756.164 | 76447.214 | 102344.81 |

| TH 10 - Group 7 | | | | | |
|---|---|---|---|---|---|
| T deg. C | 0.1 Hz | 0.5 Hz | 1 Hz | 5 Hz | 25 Hz |
| -10 | 3905976.054 | 4160532.2 | 4250646.9 | 4421474.9 | 4548015.1 |
| 0.4 | 2467623.351 | 3012364.3 | 3198310.3 | 3571790.4 | 4169390.5 |
| 17.1 | 483817.7604 | 772617.43 | 906771.05 | 1421691.5 | 1724762.9 |
| 33.8 | 86814.9122 | 160632 | 175904.5 | 324764.18 | 534072.94 |
| 55 | 50039.12251 | 68445.661 | 81485.555 | 132010.24 | 229070.63 |

| TH 27 - Group 3 | | | | | |
|---|---|---|---|---|---|
| T deg. C | 0.1 Hz | 0.5 Hz | 1 Hz | 5 Hz | 25 Hz |
| -10 | 2199514.7 | 2532843.9 | 2651494 | 2873012 | 3030291.4 |
| 0.4 | 1781816 | 2133484.8 | 2308594 | 2672615.2 | 2919349 |
| 17.1 | 819803.12 | 1160110.6 | 1353156.2 | 1804079.3 | 2195488.6 |
| 33.8 | 120711.84 | 202250.37 | 262896.46 | 490101.68 | 836675.63 |
| 55 | 31805.482 | 33062.399 | 34012.404 | 37978.37 | 46544.481 |

| TH 6 - Group 6 | | | | | |
|---|---|---|---|---|---|
| T deg. C | 0.1 Hz | 0.5 Hz | 1 Hz | 5 Hz | 25 Hz |
| -10 | 2806213.9 | 3175227.3 | 3312287 | 3582068.9 | 3791090.2 |
| 0.4 | 1924025.8 | 2395350.9 | 2542612.8 | 2996291.7 | 3237780 |
| 17.1 | 568742.34 | 894497.69 | 1083675.6 | 1641008.3 | 2068773.7 |
| 33.8 | 80737.82 | 165101.59 | 220457.76 | 439223.41 | 799497.8 |
| 55 | 36828.709 | 42816.552 | 49777.936 | 57871.145 | 92350.336 |

| TH 10 - Group 9 | | | | | |
|---|---|---|---|---|---|
| T deg. C | 0.1 Hz | 0.5 Hz | 1 Hz | 5 Hz | 25 Hz |
| -10 | 2716593.5 | 3006338.8 | 3105920.3 | 3287575.5 | 3413629.6 |
| 0.4 | 1617028.7 | 2037252.1 | 2247847.3 | 2678900.2 | 3039126.3 |
| 17.1 | 311348.24 | 583004.41 | 753327.37 | 1215031.7 | 1699652 |
| 33.8 | 66330.712 | 146681.76 | 195849.65 | 351838.02 | 800077.95 |
| 55 | 30823.516 | 56330.042 | 75770.72 | 157215.33 | 322247.66 |

The next set of tables show the binder inputs that were used for each field section in Pavement ME Design. These include calculated complex shear modulus values and assumed phase angle values.

| TH 220 - Group 1 | | |
|---|---|---|
| Temperature (F) | Binder G* (Pa) | Phase Angle (δ) |
| 125.6 | 4142 | 70 |
| 136.4 | 1860 | 80 |
| 147.2 | 868 | 90 |

| TH 27 - Group 3 | | |
|---|---|---|
| Temperature (F) | Binder G* (Pa) | Phase Angle (δ) |
| 125.6 | 4896 | 70 |
| 136.4 | 2279 | 80 |
| 147.2 | 1109 | 90 |

| TH 9 - Group 4 | | |
|---|---|---|
| Temperature (F) | Binder G* (Pa) | Phase Angle (δ) |
| 136.4 | 2593 | 70 |
| 147.2 | 1286 | 80 |
| 158 | 662 | 90 |

| TH 6 - Group 6 | | |
|---|---|---|
| Temperature (F) | Binder G* (Pa) | Phase Angle (δ) |
| 136.4 | 2143 | 70 |
| 147.2 | 969 | 80 |
| 158 | 460 | 90 |

| TH 10 - Group 7 | | |
|---|---|---|
| Temperature (F) | Binder G* (Pa) | Phase Angle (δ) |
| 136.4 | 1764 | 70 |
| 147.2 | 869 | 80 |
| 158 | 445 | 90 |

| TH 10 - Group 9 | | |
|---|---|---|
| Temperature (F) | Binder G* (Pa) | Phase Angle (δ) |
| 125.6 | 2941 | 70 |
| 136.4 | 1334 | 80 |
| 147.2 | 633 | 90 |

The tables below show the calculated creep compliance data used as Pavement ME Inputs.

| TH 220 - Group 1 | | | |
|---|---|---|---|
| | Low Temperature | Medium Temperature | High Temperature |
| Loading Time (s) | -20 | -10 | 0 |
| 1 | 2.84665E-07 | 4.09678E-07 | 6.63425E-07 |
| 2 | 3.08804E-07 | 4.59882E-07 | 7.76636E-07 |
| 5 | 3.53968E-07 | 5.44231E-07 | 9.80519E-07 |
| 10 | 3.93251E-07 | 6.26603E-07 | 1.20583E-06 |
| 20 | 4.39282E-07 | 7.2992E-07 | 1.5401E-06 |
| 50 | 5.17451E-07 | 9.13528E-07 | 2.16561E-06 |
| 100 | 5.92768E-07 | 1.10884E-06 | 2.79038E-06 |

| TH 9 - Group 4 | | | |
|---|---|---|---|
| | Low Temperature | Medium Temperature | High Temperature |
| Loading Time (s) | -20 | -10 | 0 |
| 1 | 3.13514E-07 | 4.66268E-07 | 7.70561E-07 |
| 2 | 3.54681E-07 | 5.41178E-07 | 9.30662E-07 |
| 5 | 4.15471E-07 | 6.6407E-07 | 1.22523E-06 |
| 10 | 4.77273E-07 | 7.93696E-07 | 1.572E-06 |
| 20 | 5.54226E-07 | 9.5966E-07 | 2.03244E-06 |
| 50 | 6.82158E-07 | 1.27209E-06 | 2.82835E-06 |
| 100 | 8.17721E-07 | 1.63837E-06 | 3.694E-06 |

| TH 10 - Group 7 | | | |
|---|---|---|---|
| | Low Temperature | Medium Temperature | High Temperature |
| Loading Time (s) | -20 | -10 | 0 |
| 1 | 2.31909E-07 | 3.42256E-07 | 5.73517E-07 |
| 2 | 2.51285E-07 | 3.85078E-07 | 6.7272E-07 |
| 5 | 2.87683E-07 | 4.56843E-07 | 8.5028E-07 |
| 10 | 3.21186E-07 | 5.25905E-07 | 1.04409E-06 |
| 20 | 3.59096E-07 | 6.12278E-07 | 1.33256E-06 |
| 50 | 4.23244E-07 | 7.64939E-07 | 1.86164E-06 |
| 100 | 4.84013E-07 | 9.22831E-07 | 2.37756E-06 |

| TH 27 - Group 3 | | | |
|---|---|---|---|
| | Low Temperature | Medium Temperature | High Temperature |
| Loading Time (s) | -20 | -10 | 0 |
| 1 | 3.30954E-07 | 3.81059E-07 | 5.0201E-07 |
| 2 | 3.38778E-07 | 3.99621E-07 | 5.49382E-07 |
| 5 | 3.51804E-07 | 4.30194E-07 | 6.29483E-07 |
| 10 | 3.63952E-07 | 4.60011E-07 | 7.10293E-07 |
| 20 | 3.7864E-07 | 4.96059E-07 | 8.1216E-07 |
| 50 | 4.03237E-07 | 5.58879E-07 | 9.94484E-07 |
| 100 | 4.26367E-07 | 6.19453E-07 | 1.1804E-06 |

| TH 6 - Group 6 | | | |
|---|---|---|---|
| | Low Temperature | Medium Temperature | High Temperature |
| Loading Time (s) | -20 | -10 | 0 |
| 1 | 2.32321E-07 | 3.16496E-07 | 4.96601E-07 |
| 2 | 2.40983E-07 | 3.45583E-07 | 5.62467E-07 |
| 5 | 2.60929E-07 | 3.93069E-07 | 6.74007E-07 |
| 10 | 2.84801E-07 | 4.37388E-07 | 7.84707E-07 |
| 20 | 3.13167E-07 | 4.89784E-07 | 9.2838E-07 |
| 50 | 3.52039E-07 | 5.77739E-07 | 1.20237E-06 |
| 100 | 3.88336E-07 | 6.63E-07 | 1.49204E-06 |

| TH 10 - Group 9 | | | |
|---|---|---|---|
| | Low Temperature | Medium Temperature | High Temperature |
| Loading Time (s) | -20 | -10 | 0 |
| 1 | 2.17701E-07 | 3.11151E-07 | 4.9436E-07 |
| 2 | 2.3118E-07 | 3.3558E-07 | 5.54256E-07 |
| 5 | 2.5669E-07 | 3.71244E-07 | 6.60328E-07 |
| 10 | 2.75952E-07 | 4.06262E-07 | 7.52587E-07 |
| 20 | 2.92658E-07 | 4.49735E-07 | 8.69589E-07 |
| 50 | 3.20413E-07 | 5.15829E-07 | 1.08163E-06 |
| 100 | 3.45745E-07 | 5.83231E-07 | 1.2772E-06 |