DEPARTMENT OF TRANSPORTATION

Effectiveness of Geotextiles/ Geogrids in Roadway Construction; Determine a Granular Equivalent (GE) Factor -- Appendices

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Research Project
Final Report 2021-26

LRRB
LOCAL ROAD RESEARCH BOARD

APPENDIX A
GEOGRID PROPERTIES

Tensar

Tensar International Corporation
2500 Northwinds Pkwy, Suite 500
Alpharetta, Georgia 30009
Phone: 800-TENSAR-1
www.tensarcorp.com

Product Specification - Biaxial Geogrid BX1100

Tensar International Corporation reserves the right to change its product specifications at any time. It is the responsibility of the specifier and purchaser to ensure that product specifications used for design and procurement purposes are current and consistent with the products used in each instance.

Product Type:	**Integrally Formed Biaxial Geogrid**
Polymer:	**Polypropylene**
Load Transfer Mechanism:	**Positive Mechanical Interlock**
Primary Applications:	**Spectra System (Base Reinforcement, Subgrade Improvement)**

Product Properties

Index Properties	Units	MD Values[1]	XMD Values[1]
• Aperture Dimensions[2]	mm (in)	25 (1.0)	33 (1.3)
• Minimum Rib Thickness[2]	mm (in)	0.76 (0.03)	0.76 (0.03)
• Tensile Strength @ 2% Strain[3]	kN/m (lb/ft)	4.1 (280)	6.6 (450)
• Tensile Strength @ 5% Strain[3]	kN/m (lb/ft)	8.5 (580)	13.4 (920)
• Ultimate Tensile Strength[3]	kN/m (lb/ft)	12.4 (850)	19.0 (1,300)
Structural Integrity			
• Junction Efficiency[4]	%	93	
• Flexural Stiffness[5]	mg-cm	250,000	
• Aperture Stability[6]	m-N/deg	0.32	
Durability			
• Resistance to Installation Damage[7]	%SC / %SW / %GP	95 / 93 / 90	
• Resistance to Long Term Degradation[8]	%	100	
• Resistance to UV Degradation[9]	%	100	

Dimensions and Delivery

The biaxial geogrid shall be delivered to the jobsite in roll form with each roll individually identified and nominally measuring 3.0 meters (9.8 feet) or 4.0 meters (13.1 feet) in width and 75.0 meters (246 feet) in length. A typical truckload quantity is 185 to 250 rolls.

Notes

1. Unless indicated otherwise, values shown are minimum average roll values determined in accordance with ASTM D4759-02. Brief descriptions of test procedures are given in the following notes.
2. Nominal dimensions.
3. Determined in accordance with ASTM D6637-10 Method A.
4. Load transfer capability determined in accordance with ASTM D7737-11.
5. Resistance to bending force determined in accordance with ASTM D7748-12, using specimens of width two ribs wide, with transverse ribs cut flush with exterior edges of longitudinal ribs, and of length sufficiently long to enable measurement of the overhang dimension.
6. Resistance to in-plane rotational movement measured by applying a 20 kg-cm (2 m-N) moment to the central junction of a 9 inch x 9 inch specimen restrained at its perimeter in accordance with GRI GG9.
7. Resistance to loss of load capacity or structural integrity when subjected to mechanical installation stress in clayey sand (SC), well graded sand (SW), and crushed stone classified as poorly graded gravel (GP). The geogrid shall be sampled in accordance with ASTM D5818 and load capacity shall be determined in accordance with ASTM D6637.
8. Resistance to loss of load capacity or structural integrity when subjected to chemically aggressive environments in accordance with EPA 9090 immersion testing.
9. Resistance to loss of load capacity or structural integrity when subjected to 500 hours of ultraviolet light and aggressive weathering in accordance with ASTM D4355-05.

Tensar International Corporation warrants that at the time of delivery the geogrid furnished hereunder shall conform to the specification stated herein. Any other warranty including merchantability and fitness for a particular purpose, are hereby excluded. If the geogrid does not meet the specifications on this page and Tensar is notified prior to installation, Tensar will replace the geogrid at no cost to the customer.

This product specification supersedes all prior specifications for the product described above and is not applicable to any products shipped prior to February 1, 2013.

Figure A-1 Geogrid BX1100 Product Specification

Tensar

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Phone: 800-TENSAR-1
www.tensarcorp.com

Product Specification - Biaxial Geogrid BX1200

Tensar International Corporation reserves the right to change its product specifications at any time. It is the responsibility of the specifier and purchaser to ensure that product specifications used for design and procurement purposes are current and consistent with the products used in each instance.

Product Type:	**Integrally Formed Biaxial Geogrid**
Polymer:	**Polypropylene**
Load Transfer Mechanism:	**Positive Mechanical Interlock**
Primary Applications:	**Spectra System (Base Reinforcement, Subgrade Improvement)**

Product Properties

Index Properties	**Units**	**MD Values[1]**	**XMD Values[1]**
• Aperture Dimensions[2]	mm (in)	25 (1.0)	33 (1.3)
• Minimum Rib Thickness[2]	mm (in)	1.27 (0.05)	1.27 (0.05)
• Tensile Strength @ 2% Strain[3]	kN/m (lb/ft)	6.0 (410)	9.0 (620)
• Tensile Strength @ 5% Strain[3]	kN/m (lb/ft)	11.8 (810)	19.6 (1,340)
• Ultimate Tensile Strength[3]	kN/m (lb/ft)	19.2 (1,310)	28.8 (1,970)
Structural Integrity			
• Junction Efficiency[4]	%	93	
• Flexural Stiffness[5]	mg-cm	750,000	
• Aperture Stability[6]	m-N/deg	0.65	
Durability			
• Resistance to Installation Damage[7]	%SC / %SW / %GP	95 / 93 / 90	
• Resistance to Long Term Degradation[8]	%	100	
• Resistance to UV Degradation[9]	%	100	

Dimensions and Delivery

The biaxial geogrid shall be delivered to the jobsite in roll form with each roll individually identified and nominally measuring 3.0 meters (9.8 feet) or 4.0 meters (13.1 feet) in width and 50.0 meters (164 feet) in length. A typical truckload quantity is 160 to 210 rolls.

Notes

1. Unless indicated otherwise, values shown are minimum average roll values determined in accordance with ASTM D4759-02. Brief descriptions of test procedures are given in the following notes.
2. Nominal dimensions.
3. Determined in accordance with ASTM D6637-10 Method A.
4. Load transfer capability determined in accordance with ASTM D7737-11.
5. Resistance to bending force determined in accordance with ASTM D7748-12, using specimens of width two ribs wide, with transverse ribs cut flush with exterior edges of longitudinal ribs, and of length sufficiently long to enable measurement of the overhang dimension.
6. Resistance to in-plane rotational movement measured by applying a 20 kg-cm (2 m-N) moment to the central junction of a 9 inch x 9 inch specimen restrained at its perimeter in accordance with GRI GG9.
7. Resistance to loss of load capacity or structural integrity when subjected to mechanical installation stress in clayey sand (SC), well graded sand (SW), and crushed stone classified as poorly graded gravel (GP). The geogrid shall be sampled in accordance with ASTM D5818 and load capacity shall be determined in accordance with ASTM D6637.
8. Resistance to loss of load capacity or structural integrity when subjected to chemically aggressive environments in accordance with EPA 9090 immersion testing.
9. Resistance to loss of load capacity or structural integrity when subjected to 500 hours of ultraviolet light and aggressive weathering in accordance with ASTM D4355-05.

This product specification supersedes all prior specifications for the product described above and is not applicable to any products shipped prior to February 1, 2013.

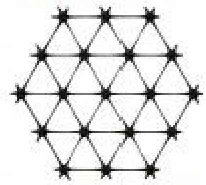
Figure A-2 Geogrid BX1200 Product Specification

Tensar. THE COMPANY YOU CAN BUILD ON®

Product Specification - TriAx® TX130S Geogrid

Tensar International Corporation reserves the right to change its product specifications at any time. It is the responsibility of the person specifying the use of this product and of the purchaser to ensure that product specifications relied upon for design or procurement purposes are current and that the product is suitable for its intended use in each instance.

Tensar TriAx® Geogrid



General

1. The geogrid is manufactured from a punched polypropylene sheet, which is then oriented in three substantially equilateral directions so that the resulting ribs shall have a high degree of molecular orientation, which continues at least in part through the mass of the integral node.
2. The properties contributing to the performance of a mechanically stabilized layer include the following:

Index Properties	Longitudinal	Diagonal	General
• Rib pitch(2), mm (in)	33 (1.30)	33 (1.30)	
• Rib shape			Rectangular
• Aperture shape			Triangular

Structural Integrity	
• Junction efficiency(3), %	93
• Isotropic Stiffness Ratio(4)	0.6
• Radial stiffness at low strain(5), kN/m @ 0.5% strain	200
(lb/ft @ 0.5% strain)	(13,708)

Durability	
• Resistance to chemical degradation(6)	100%
• Resistance to ultra-violet light and weathering(7)	70%

Dimensions and Delivery

The TX geogrid shall be delivered to the jobsite in roll form with each roll individually identified and nominally measuring 3.0 meters (9.8 feet) and/or 4.0 meters (13.1feet) in width and 75 meters (246 feet) in length and 4.87 meters (16 feet) in width by 100 meters (328 feet) in length.

Notes

1. Unless indicated otherwise, values shown are minimum average roll values determined in accordance with ASTM D4759. Brief descriptions of test procedures are given in the following notes.
2. Nominal dimensions.
3. Load transfer capability determined in accordance with ASTM D6637 and ASTM D7737 and expressed as a percentage of ultimate tensile strength.
4. The ratio between the minimum and maximum observed values of radial stiffness at 0.5% strain, measured on rib and midway between rib directions.
5. Radial stiffness is determined from tensile stiffness measured in any in-plane axis from testing in accordance with ASTM D6637.
6. Resistance to loss of load capacity or structural integrity when subjected to chemically aggressive environments in accordance with EPA 9090 immersion testing.
7. Resistance to loss of load capacity or structural integrity when subjected to 500 hours of ultraviolet light and aggressive weathering in accordance with ASTM D4355.

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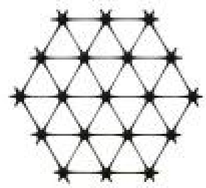
Figure A-3 Geogrid TX130s Product Specification

Tensar. THE COMPANY YOU CAN BUILD ON™

Product Specification - TriAx® TX7 Geogrid

Tensar International Corporation reserves the right to change its product specifications at any time. It is the responsibility of the person specifying the use of this product and of the purchaser to ensure that product specifications relied upon for design or procurement purposes are current and that the product is suitable for its intended use in each instance.

Tensar TriAx® Geogrid



General

1. The geogrid is manufactured from a punched polypropylene sheet, which is then oriented in three substantially equilateral directions so that the resulting ribs shall have a high degree of molecular orientation, which continues at least in part through the mass of the integral node.

2. The properties contributing to the performance of a mechanically stabilized layer include the following:

Index Properties[1]	Longitudinal/ Transverse	Diagonal	General
• Rib pitch[(2)], mm (in)	40 (1.60)	40 (1.60)	
• Mid-rib depth[(2)], mm (in)	1.6 (0.06)	2.0 (0.08)	
• Mid-rib width[(2)], mm (in)	1.3 (0.05)	1.0 (0.04)	
• Rib shape			Rectangular
• Aperture shape			Triangular

Dimensions and Delivery

The TX geogrid shall be delivered to the jobsite in roll form with each roll individually identified. Rolls are shipped with nominal measurements: Equal to 4.0 meters (13.1feet) in width by 50 meters (164 feet) in length or 4.87 meters (16 feet) in width by 100 meters (328 feet) in length.

Notes

1. Unless indicated otherwise, values shown are minimum average roll values determined in accordance with ASTM D4759-02. Brief descriptions of test procedures are given in the following notes.

2. Nominal dimensions.

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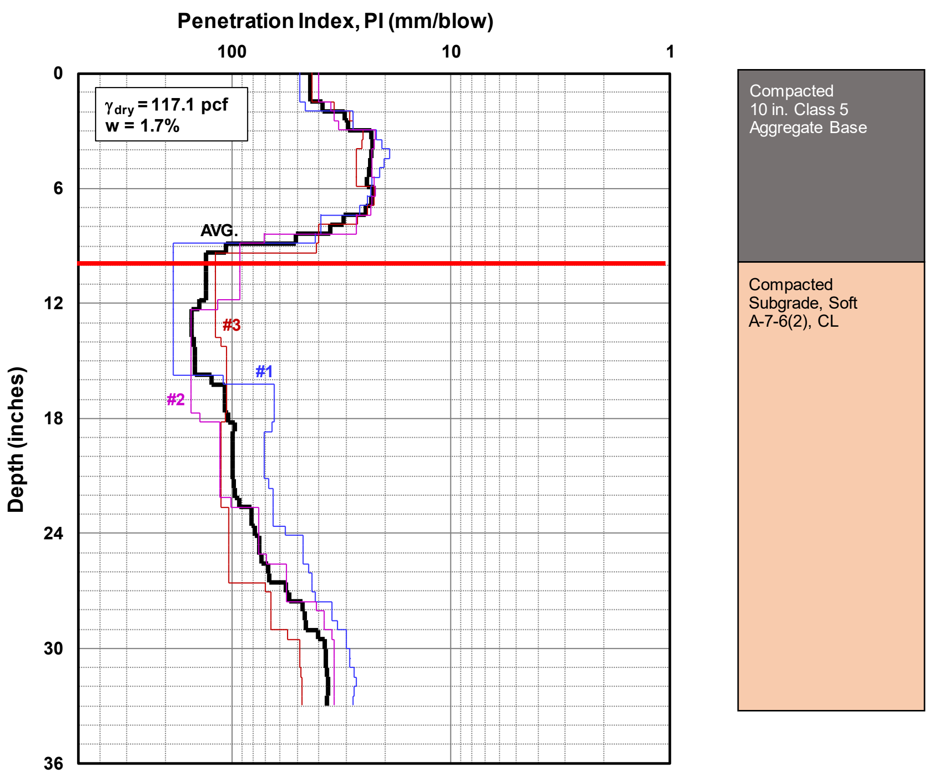
Figure A-4 Geogrid TX7 Product Specification

APPENDIX B
LABORATORY DCP TEST RESULTS

Date of Test	1/8/2020	Test ID	10" AB_Control	Operator	DW	ASTM	D6951
Latitude	NA		Longitude	NA		Elevation (ft)	NA
Location	IMAS Test Box, Northfield, MN		Station	NA			
Comments	Nominal 10 in. of aggregate base course over compacted subgrade. Three tests conducted around the plate after cyclic PLT completed with 12 inch diameter loading plate.						

DPI (mm/blow) Statistics	#1	#2	#3	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	30.7	29.8	30.8	30.4	6.4
Average: Subgrade Layer [10 to 24.0 in.]	91.7	115.1	111.0	104.9	1.6
Ratio of Average: Aggregate Base/Subgrade	0.33	0.26	0.28	0.29	4.0
Std. Dev.: Aggregate Base [0 to 10 in.]	46.9	21.6	20.5	28.0	2.5
Std. Dev.: Subgrade Layer [10 to 24.0 in.]	58.3	28.2	5.7	24.6	0.4

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

Location: Northfield, MN

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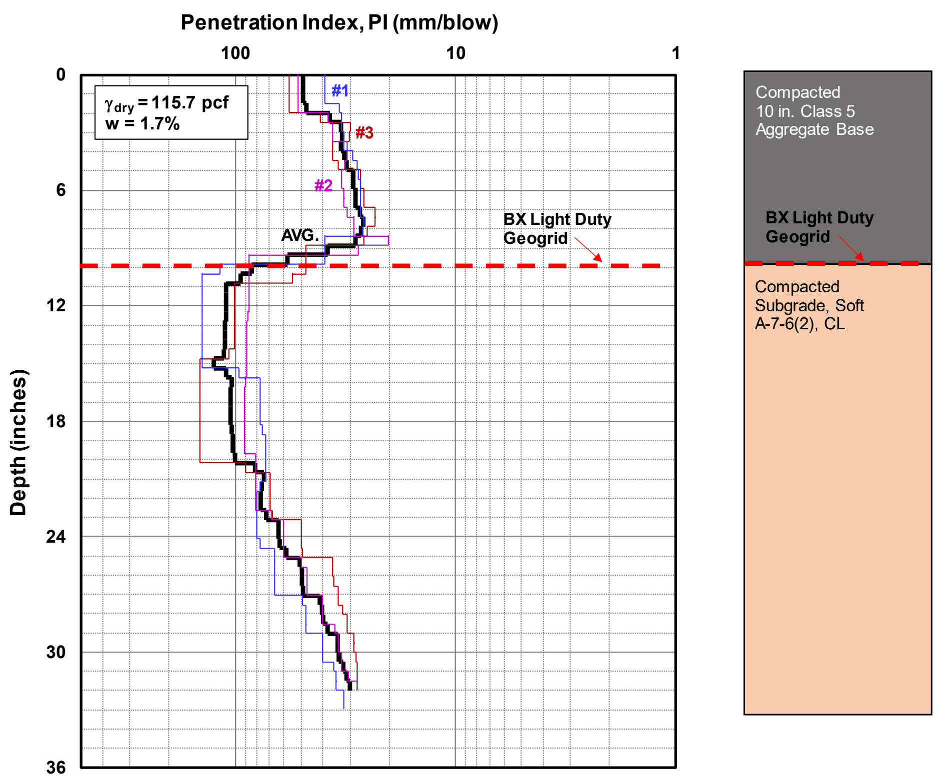
Figure B-1 DCP test results of section GE0

Date of Test	1/30/2020	Test ID	10" AB_BX Light	Operator	DW	ASTM	D6951
Latitude	NA		Longitude	NA		Elevation (ft)	NA
Location	IMAS Test Box, Northfield, MN		Station	NA			
Comments	Nominal 10 in. of aggregate base course over compacted subgrade and light duty BX geogrid placed at the sugrade/base course interface. Three tests conducted around the plate after cyclic PLT completed with 12 inch diameter loading plate.						

DPI (mm/blow) Statistics	#1	#2	#3	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	31.4	34.7	33.1	33.0	5.8
Average: Subgrade Layer [10 to 24.0 in.]	93.1	83.7	91.3	89.2	1.9
Ratio of Average: Aggregate Base/Subgrade	0.34	0.41	0.36	0.37	3.0
Std. Dev.: Aggregate Base [0 to 10 in.]	5.3	14.6	13.1	9.8	1.5
Std. Dev.: Subgrade Layer [10 to 24.0 in.]	31.2	8.5	36.0	16.8	0.4

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results	
Project Name:	ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Northfield, MN

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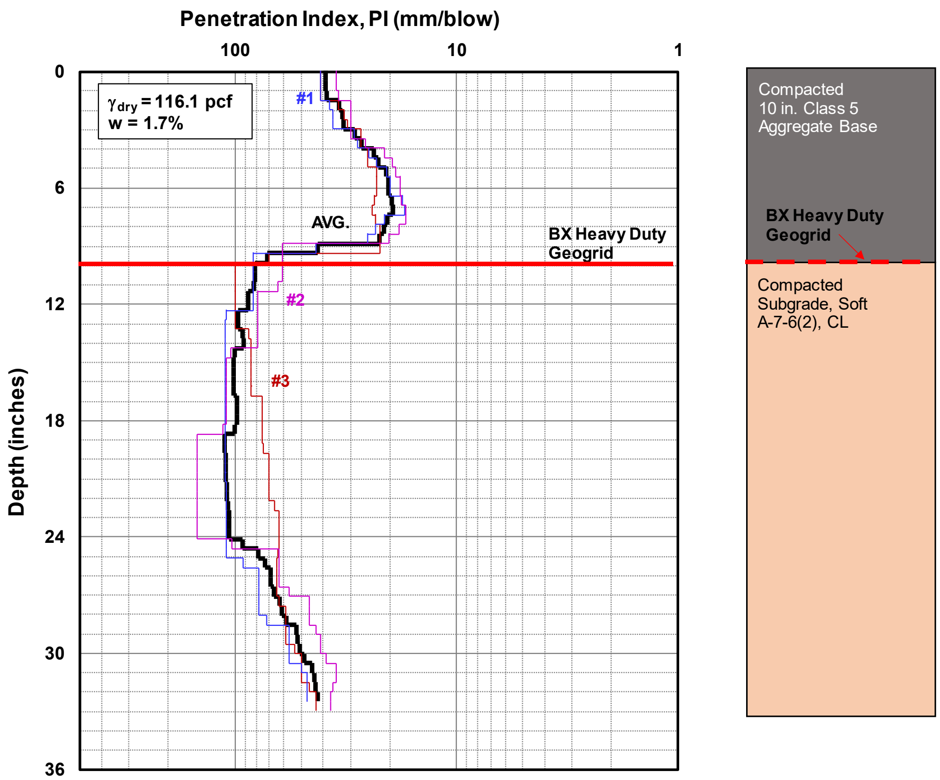
Figure B-2 DCP test results of section GE1

Date of Test	1/23/2020	Test ID	10" AB_BX Heavy	Operator	DW	ASTM	D6951
Latitude	NA	Longitude	NA			Elevation (ft)	NA
Location	IMAS Test Box, Northfield, MN	Station	NA				
Comments	Nominal 10 in. of aggregate base course over compacted subgrade and heavy duty BX geogrid placed at the sugrade/base course interface. Three tests conducted around the plate after cyclic PLT completed with 12 inch diameter loading plate.						

DPI (mm/blow) Statistics	#1	#2	#3	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	27.1	24.0	27.4	26.1	7.6
Average: Subgrade Layer [10 to 24.0 in.]	104.5	103.1	79.1	94.0	1.8
Ratio of Average: Aggregate Base/Subgrade	0.26	0.23	0.35	0.28	4.2
Std. Dev.: Aggregate Base [0 to 10 in.]	14.8	12.8	11.5	12.3	2.5
Std. Dev.: Subgrade Layer [10 to 24.0 in.]	10.6	31.9	12.9	9.2	0.2

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

Location: Northfield, MN

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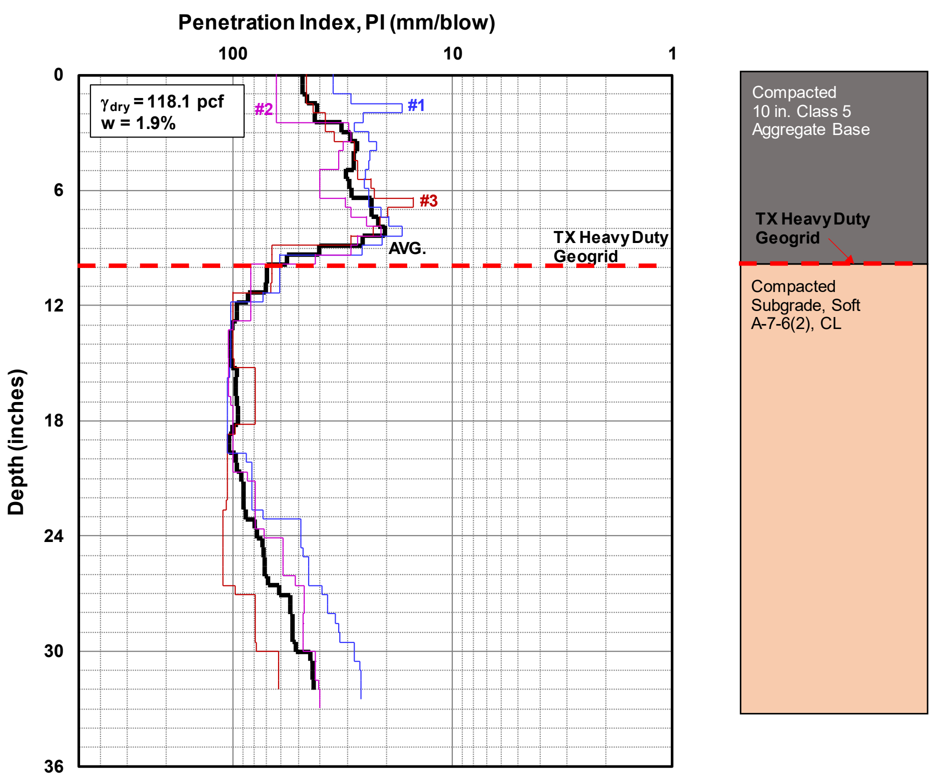
Figure B-3 DCP test results of section GE2

Date of Test	2/7/2020	Test ID	10" AB_TX Heavy	Operator	DW	ASTM	D6951
Latitude	NA	Longitude	NA			Elevation (ft)	NA
Location	IMAS Test Box, Northfield, MN	Station	NA				
Comments	Nominal 10 in. of aggregate base course over compacted subgrade and heavy duty TX geogrid placed at the sugrade/base course interface. Three tests conducted around the plate after cyclic PLT completed with 12 inch diameter loading plate.						

DPI (mm/blow) Statistics	#1	#2	#3	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	24.4	35.3	29.6	29.1	6.7
Average: Subgrade Layer [10 to 24.0 in.]	84.3	90.9	92.3	89.1	1.9
Ratio of Average: Aggregate Base/Subgrade	0.29	0.39	0.32	0.33	3.5
Std. Dev.: Aggregate Base [0 to 10 in.]	9.4	15.3	14.2	10.6	2.0
Std. Dev.: Subgrade Layer [10 to 24.0 in.]	18.9	10.8	14.6	10.1	0.3

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization
Project ID: ISP_00007
Location: Northfield, MN

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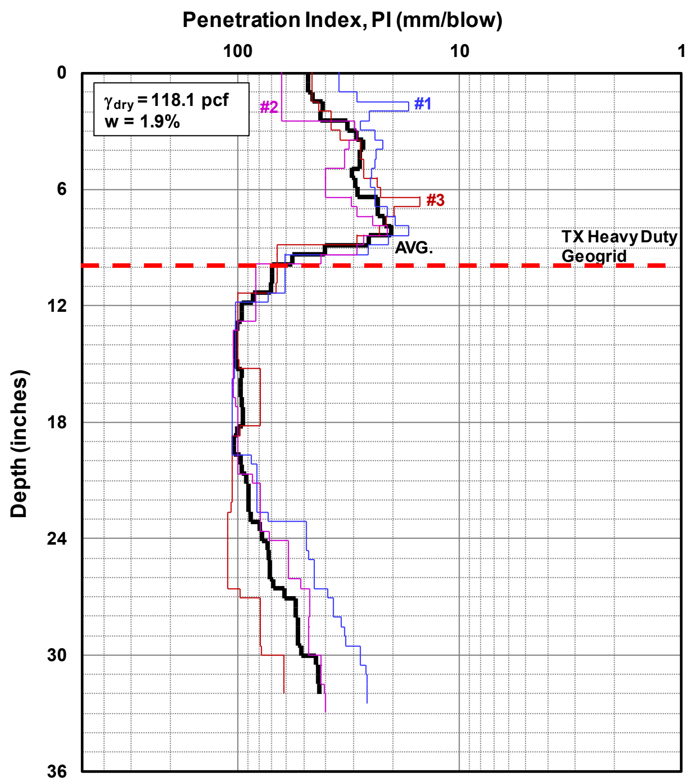
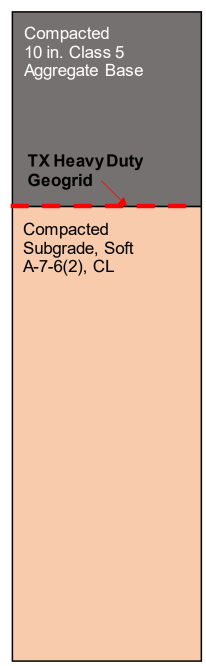
Figure B-4 DCP test results of section GE3

Date of Test	2/7/2020	Test ID	10" AB_TX Heavy	Operator	DW	ASTM	D6951
Latitude	NA	Longitude		NA		Elevation (ft)	NA
Location	IMAS Test Box, Northfield, MN	Station		NA			
Comments	Nominal 10 in. of aggregate base course over compacted subgrade and heavy duty TX geogrid placed at the sugrade/base course interface. Three tests conducted around the plate after cyclic PLT completed with 12 inch diameter loading plate.						

DPI (mm/blow) Statistics	#1	#2	#3	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	24.4	35.3	29.6	29.1	6.7
Average: Subgrade Layer [10 to 24.0 in.]	84.3	90.9	92.3	89.1	1.9
Ratio of Average: Aggregate Base/Subgrade	0.29	0.39	0.32	0.33	3.5
Std. Dev.: Aggregate Base [0 to 10 in.]	9.4	15.3	14.2	10.6	2.0
Std. Dev.: Subgrade Layer [10 to 24.0 in.]	18.9	10.8	14.6	10.1	0.3

*Note: CBR = 292/(DPI)^1.12





Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization
Project ID: ISP_00007
Location: Northfield, MN

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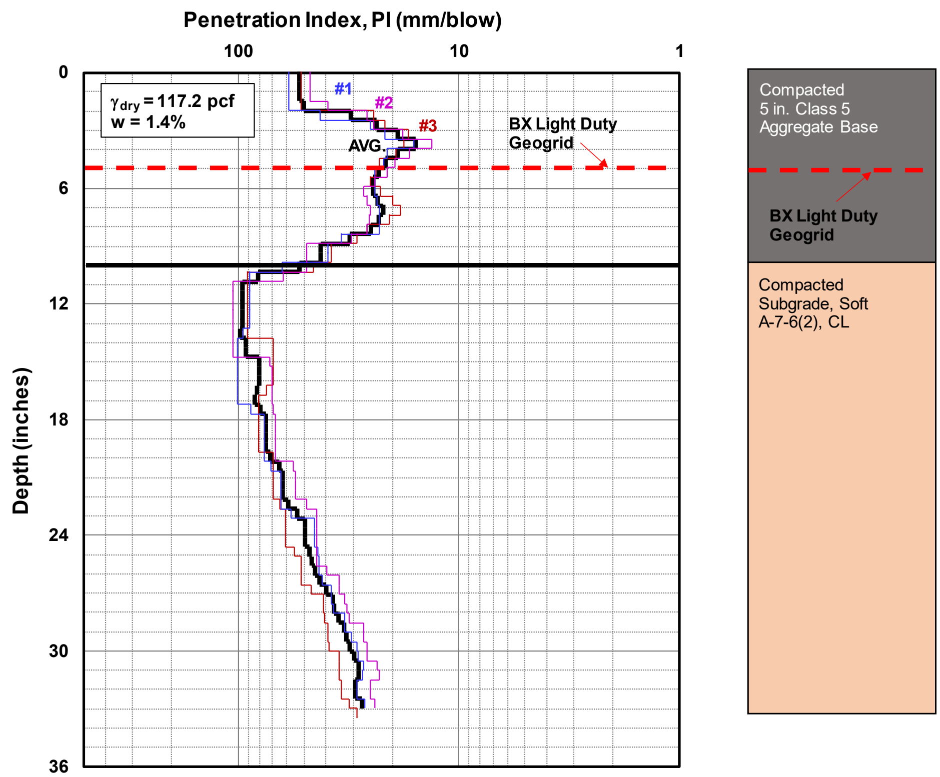
Figure B-5 DCP test results of section GE4

Date of Test	2/19/2020	Test ID	10" AB_BX Light_5	Operator	DW	ASTM	D6951
Latitude	NA		Longitude	NA		Elevation (ft)	NA
Location	IMAS Test Box, Northfield, MN		Station	NA			
Comments	Nominal 10 in. of aggregate base course over compacted subgrade and light duty BX geogrid placed at about 5 in. below surface (mid-height of base). Three tests conducted around the plate after cyclic PLT completed with 12 inch diameter loading plate.						

DPI (mm/blow) Statistics	#1	#2	#3	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	28.1	26.1	25.6	26.5	7.4
Average: Subgrade Layer [10 to 24.0 in.]	76.5	67.2	73.2	72.1	2.4
Ratio of Average: Aggregate Base/Subgrade	0.37	0.39	0.35	0.37	3.1
Std. Dev.: Aggregate Base [0 to 10 in.]	15.6	12.1	13.4	13.3	2.9
Std. Dev.: Subgrade Layer [10 to 24.0 in.]	17.2	22.3	11.9	15.1	0.6

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

Location: Northfield, MN

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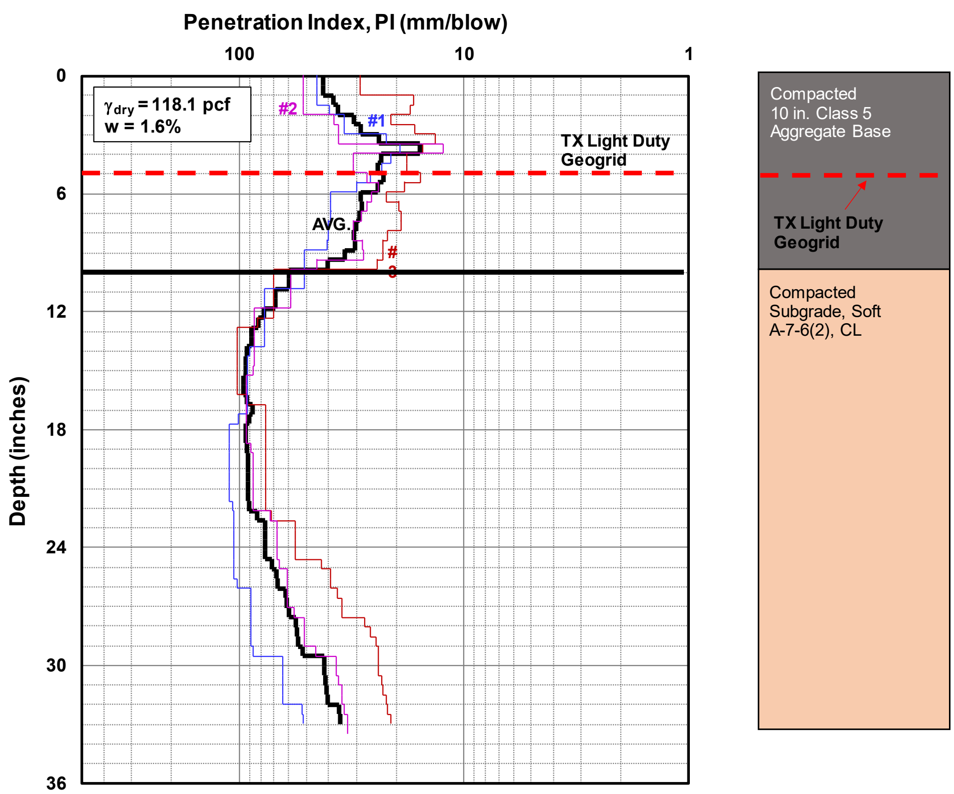
Figure B-6 DCP test results of section GE5

Date of Test	2/20/2020	Test ID	10" AB_TX Light_5	Operator	DW	ASTM	D6951
Latitude	NA	Longitude	NA			Elevation (ft)	NA
Location	IMAS Test Box, Northfield, MN	Station	NA				
Comments	Nominal 10 in. of aggregate base course over compacted subgrade and light duty TX geogrid placed at about 5 in. below surface (at mid-height of base course). Three tests conducted around the plate after cyclic PLT completed with 12 inch diameter loading plate.						

DPI (mm/blow) Statistics	#1	#2	#3	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	33.3	30.7	19.2	26.2	7.5
Average: Subgrade Layer [10 to 24.0 in.]	89.8	80.0	77.3	82.0	2.1
Ratio of Average: Aggregate Base/Subgrade	0.37	0.38	0.25	0.32	3.6
Std. Dev.: Aggregate Base [0 to 10 in.]	9.7	11.4	4.6	7.3	2.1
Std. Dev.: Subgrade Layer [10 to 24.0 in.]	17.4	11.9	14.6	10.4	0.3

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results	
Project Name:	ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Northfield, MN

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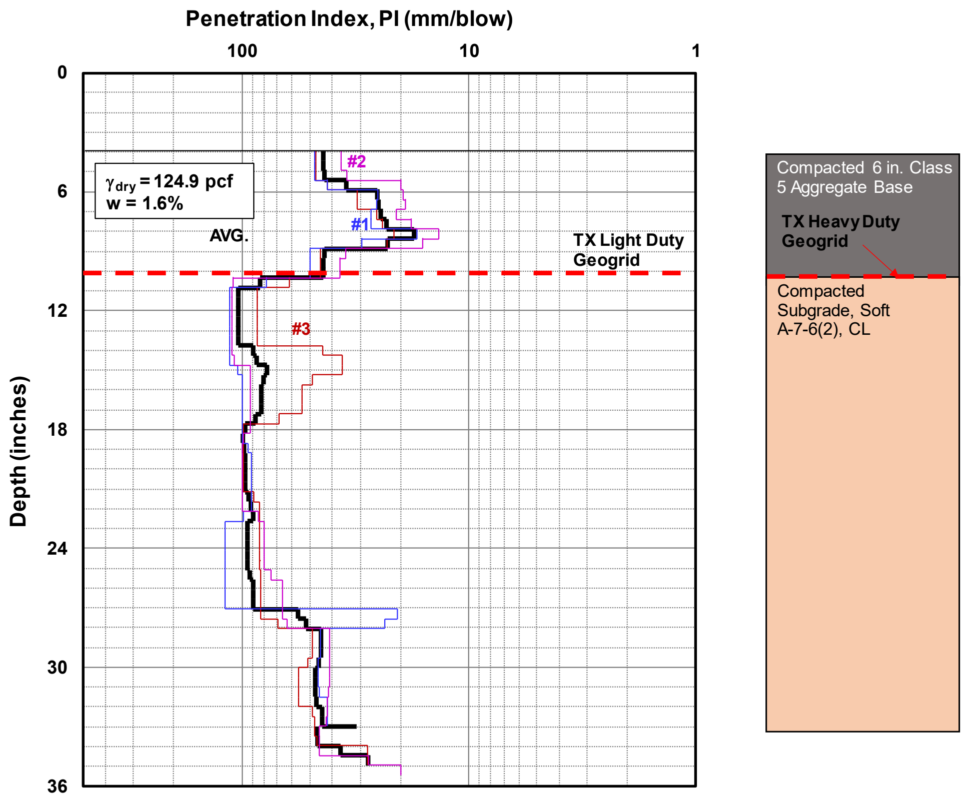
Figure B-7 DCP test results of section GE7

Date of Test	2/14/2020	Test ID	6" AB_TX Heavy	Operator	DW	ASTM	D6951
Latitude	NA	Longitude	NA			Elevation (ft)	NA
Location	IMAS Test Box, Northfield, MN	Station	NA				
Comments	Nominal 6 in. of aggregate base course over compacted subgrade and heavy duty TX geogrid placed at the sugrade/base course interface. Three tests conducted around the plate after cyclic PLT completed with 12 inch diameter loading plate.						

DPI (mm/blow) Statistics	#1	#2	#3	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	32.2	22.5	32.6	28.3	6.9
Average: Subgrade Layer [10 to 24.0 in.]	98.3	92.3	69.2	84.6	2.0
Ratio of Average: Aggregate Base/Subgrade	0.33	0.24	0.47	0.33	3.4
Std. Dev.: Aggregate Base [0 to 10 in.]	12.3	9.1	10.5	10.4	2.5
Std. Dev.: Subgrade Layer [10 to 24.0 in.]	14.6	15.3	20.8	12.0	0.5

*Note: CBR = 292/(DPI)^1.12



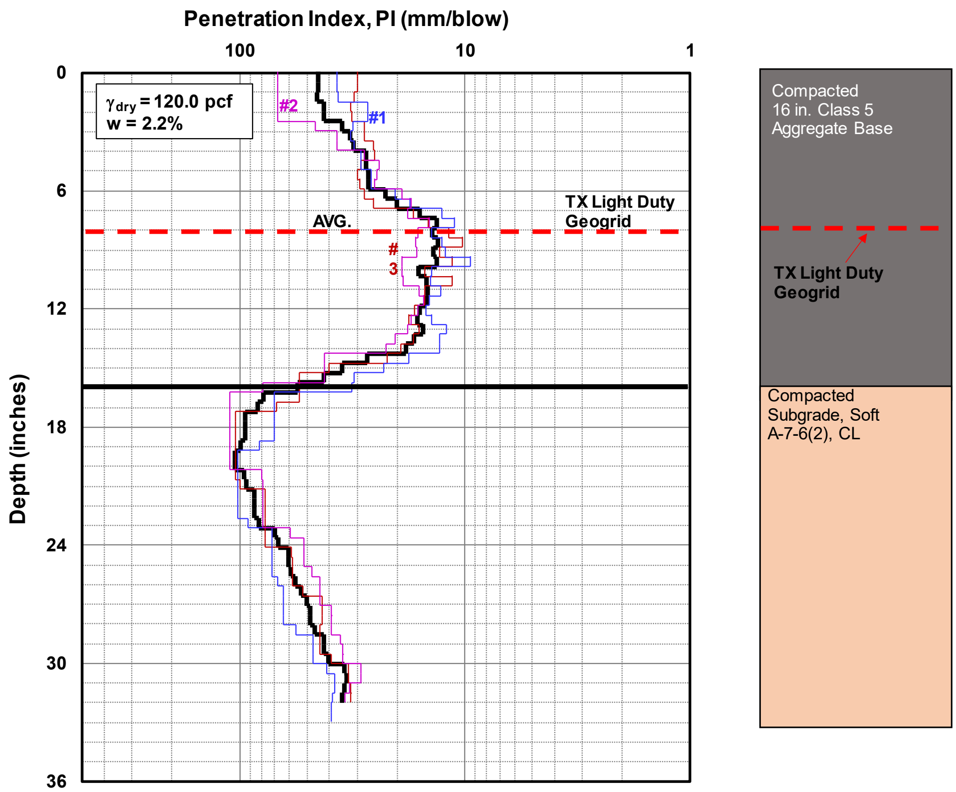
Dynamic Cone Penetrometer (DCP) Test Results		ingios GEOTECHNICS
Project Name:	ISU_MNDOT_NS555_Geogrid Stabilization	
Project ID:	ISP_00007	
Location:	Northfield, MN	

Figure B-8 DCP test results of section GE12

Date of Test	3/3/2020	Test ID	16" AB_TX Light_8	Operator	DW	ASTM	D6951
Latitude	NA	Longitude		NA		Elevation (ft)	NA
Location	IMAS Test Box, Northfield, MN	Station		NA			
Comments	Nominal 16 in. of aggregate base course over compacted subgrade and light duty TX geogrid placed at about 8 in. below surface (at mid-height of base course). Three tests conducted around the plate after cyclic PLT completed with 12 inch diameter loading plate.						

DPI (mm/blow) Statistics	#1	#2	#3	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 16.0 in.]	17.7	23.6	19.6	20.0	10.2
Average: Subgrade Layer [16 to 24.0 in.]	83.7	86.7	84.9	85.1	2.0
Ratio of Average: Aggregate Base/Subgrade	0.21	0.27	0.23	0.24	5.1
Std. Dev.: Aggregate Base [0 to 16 in.]	9.2	19.4	9.6	11.7	4.4
Std. Dev.: Subgrade Layer [16 to 24.0 in.]	19.9	20.0	18.2	13.6	0.4

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

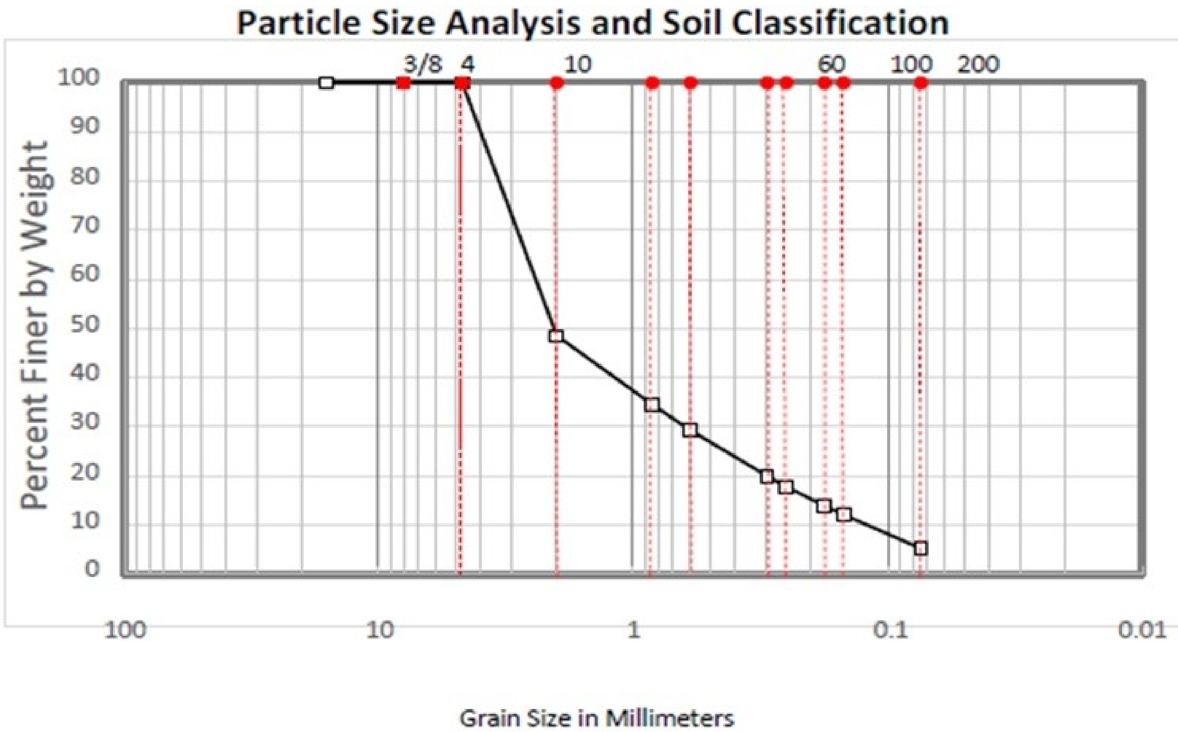
Location: Northfield, MN

Figure B-9 DCP test results of section GE15

Table B-1 Summary of laboratory DCP test results

Test No.	Test	ϒd (pcf)	ω (%)	Base AVG. CBR* (%)	Subgrade AVG. CBR* (%)	Date
GE0	**Control**	117.1	1.7	6.4	1.6	1/8/2020
GE1	**BX Light_10**	115.7	1.7	5.8	1.9	1/30/2020
GE2	**BX Heavy_10**	116.1	1.7	7.6	1.8	1/23/2020
GE4	**TX Heavy_10**	118.1	1.9	6.7	1.9	2/7/2020
GE5	**BX Light_5_5**	117.2	1.4	7.4	2.4	2/19/2020
GE7	**TX Light_5_5**	118.1	1.6	7.5	2.1	2/20/2020
GE12	**TX Heavy_6**	124.9	1.6	6.9	2.0	2/14/2020
GE15	**TX Light_8_8**	120.0	2.2	10.2	2.0	3/3/2020
AVG		118.4	1.7	7.3	2.0	

APPENDIX C
SOIL AND AGGREGATE TEST RESULTS



Materials	Classification
ID: Class 5 aggregates	AASHTO: A-1a
Sample Location: Faribault, MN	USCS: SM

Graduation Summary

% Gravel	0
% Sand	95
% Slit /Clay	5
D10(mm)	0.13
D30(mm)	0.6
D50(mm)	2.1
D60(mm)	2.5
Cu	19
Cc	1.1
D max	40.7

Atterberg Limit:

LL: 17.5

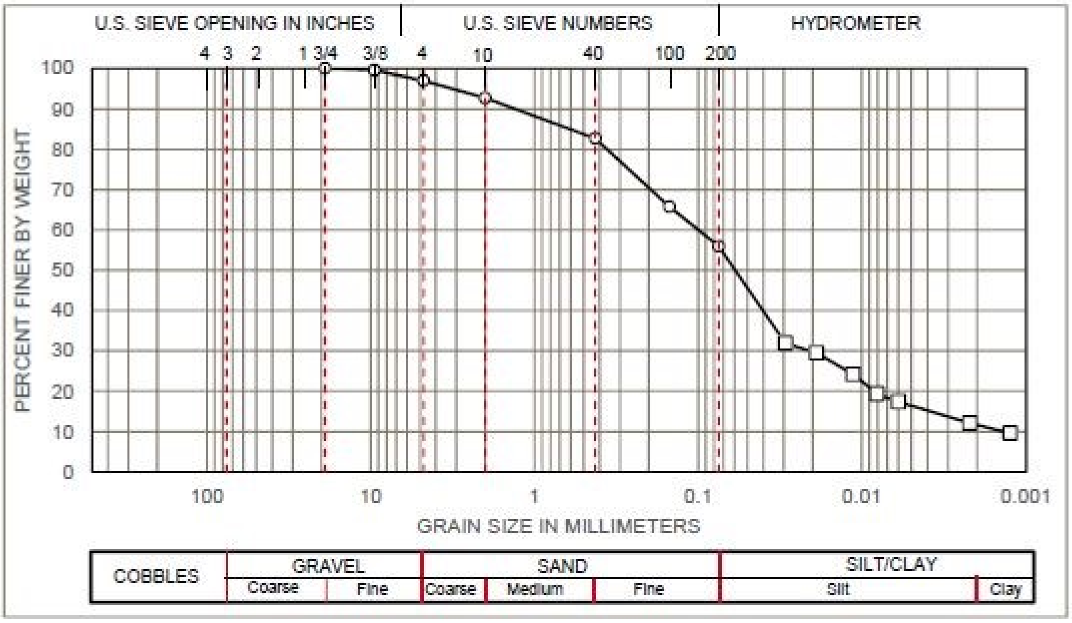
PL: N.P.

PI: -

Gradation and Soil Classification Test Results	
Project Name:	MnDOT NS555 Effectiveness of Geogrids
Project ID:	ISP-00007
Location:	142 Lab, Iowa State Univeristy

Figure C-1 Base aggregate specifications (Minnesota DOT specification range for Class 5 aggregate)

PARTICLE SIZE ANALYSIS AND SOIL CLASSIFICTAION



Material

ID: Fairbault Clay

Sample Location: Fairbault, MN

Classification

AASHTO[1]: A-7-6 (2)

USCS[2]: CL (Sandy Lean Clay)

Gradation Summary[3]

% Gravel	3.0
% Sand	41.1
% Silt	44.4
% Clay	11.6
D_{10} (mm)	0.001
D_{30} (mm)	0.021
D_{50} (mm)	0.064
D_{60} (mm)	0.106
D_{85} (mm)	0.782
C_u	76.35
C_c	3.08

Atterberg Limits[4]

LL	30
PL	22
PI	8

[1]ASTM D3282-15
[2]ASTM D2487-17
[3]ASTM D422-63
[4]ASTM D4318-17

Gradation and Soil Classification Test Results

Project Name:	MnDOT NS555 Effectiveness of Geogrids
Project ID:	ISP-00007
Location:	Ingios Lab, Northfield, MN

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Figure C-2 Subgrade soil particle size analysis and classification

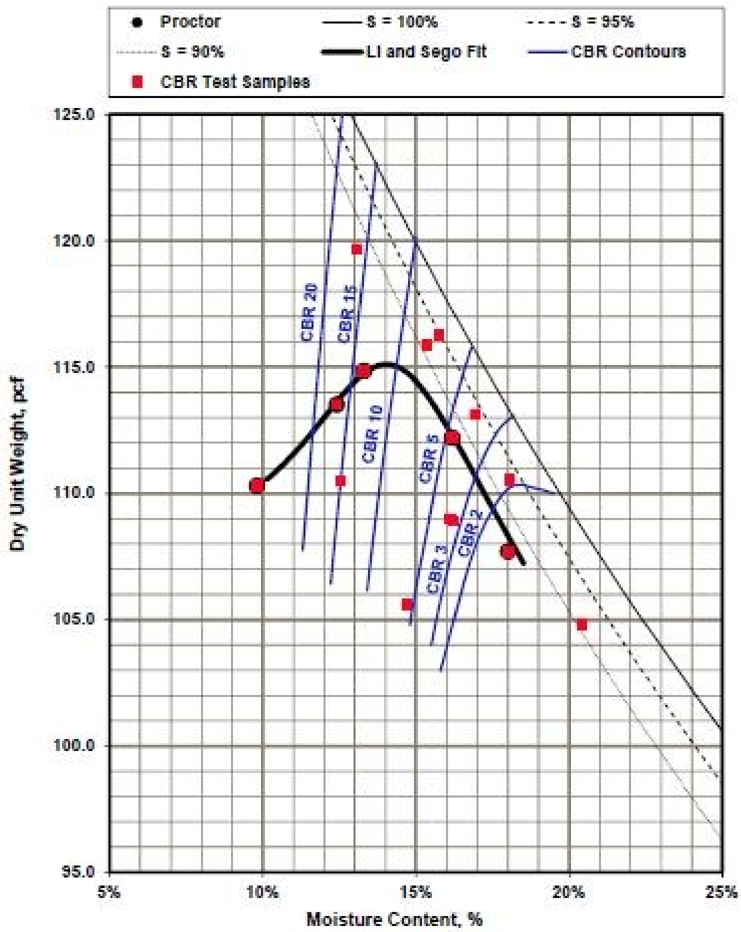
TEST ID	FB clay	TESTED BY	PV	INPUT BY	PV
MATERIAL DESCRIPTION / NOTES	Faribault Clay. CBR contours plotted based on a moisture-dry density-CBR relationship developed based on 16 samples prepared at different moisture and dry densities.				

STANDARD	ASTM D698	METHOD	A	Std. Proctor	SPECIFIC GRAVITY	2.700	Assumed

Fit Equation:

$$\gamma_d(w) = \frac{G_s \gamma_w}{1 + \dfrac{w G_s}{S_m - S_m \left[\dfrac{w_m - w}{w_m}\right]^{n+1} \left[\dfrac{w_m^n - p^n}{(w_m - w)^n + p^n}\right]}}$$

Optimum Moisture Content, %	14.0%
Maximum Dry Unit Weight, pcf	115.1



Li and Sego Fit Parameters

S_m	87.5%
w_m	18.6%
n	4.898
p	0.056
R^2	0.997

Lab w (%)	Lab γ_d (pcf)
9.8%	110.3
12.4%	113.5
13.3%	114.8
16.2%	112.2
18.0%	107.7

Equation to Predict CBR from Moisture Content and Dry Unit Weight:

CBR = 87.1 - 1349 w + 0.3603 γ_d + 3643 w^2 [Moisture content in decimals and dry unit weight in units of pcf]
N = 16, R^2 = 0.95, RMSE = 1.9

LABORATORY PROCTOR TEST RESULTS	
PROJECT NAME:	MnDOT NS555 Effectiveness of Geogrids
PROJECT ID:	ISP-00007
LOCATION:	Ingios Lab, Northfield, MN

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Figure C-3 Subgrade soil laboratory proctor test results

TEST ID	FB Clay	TESTED BY	PV	STANDARD	ASTM D1883
MATERIAL DESCRIPTION / NOTES	CBR (unsoaked) tests performed on samples compacted to different moisture contents and dry densities (see notes below).				

Sample #	Moisture Content, w (%)	Dry Unit Weight, γ_d (pcf)	CBR at 0.1 in.	CBR at 0.2 in.	CBR Mold Dia. (in.)	Relative Compaction, RC (%)	$w-w_{opt}$ (%)	Notes
1	9.8%	110.3	30	30	4.0	95.7%	-4.2%	Samples compacted in standard 4 in. diameter Proctor mold using standard Proctor compaction effort.
2	12.4%	113.5	16	15	4.0	98.5%	-1.6%	
3	13.3%	114.8	10	11	4.0	99.7%	-0.7%	
4	16.2%	112.2	4.0	4.2	4.0	97.4%	2.2%	
5	18.0%	107.7	2.1	2.3	4.0	93.5%	4.0%	
6	14.7%	105.6	3.7	3.7	4.0	91.7%	0.7%	4 in. diameter drive cylinder samples collected from compacted FB clay.
7	16.1%	109.0	5.3	5.8	4.0	94.6%	2.1%	
8	16.2%	108.9	6.5	6.6	4.0	94.5%	2.2%	
9	16.9%	113.1	2.9	3.0	6.0	98.2%	2.9%	Samples compacted to different compaction energies (50% to 100% standard Proctor) at different moisture contents in 6 in. diameter standard CBR mold.
10	16.9%	113.1	3.3	3.1	6.0	98.2%	2.9%	
11	15.8%	116.3	6.2	5.9	6.0	100.9%	1.8%	
12	15.4%	115.9	7.1	6.9	6.0	100.6%	1.4%	
13	13.1%	119.7	19.2	19.9	6.0	103.9%	-0.9%	
14	12.6%	110.5	16.4	14.6	6.0	95.9%	-1.4%	
15	20.4%	104.8	0.9	0.9	6.0	91.0%	6.4%	
16	18.1%	110.5	2.3	2.2	6.0	95.9%	4.1%	

Predicting CBR as a function of Moisture and Dry Unit Weight (4 in. diameter samples only)

N	8
Equation	$CBR\ (0.1\ in) = 118.7 - 1642\ w + 0.2328\ \gamma_d + 4792\ w^2$ (Moisture content in decimals and dry unit weight in units of pcf)
R^2	0.967
SE of fit (RMSE)	2.2

Predicting CBR as a function of Moisture and Dry Unit Weight (6 in. diameter samples only)

N	8
Equation	$CBR\ (0.1\ in) = 111.6 - 1921\ w + 0.5572\ \gamma_d + 5364\ w^2$ (Moisture content in decimals and dry unit weight in units of pcf)
R^2	0.992
SE of fit (RMSE)	0.8

Predicting CBR as a function of Moisture and Dry Unit Weight (4 in. and 6 in. diameter samples combined)

N	16
Equation	$CBR\ (0.1\ in) = 87.1 - 1349\ w + 0.3603\ \gamma_d + 3643\ w^2$ (Moisture content in decimals and dry unit weight in units of pcf)
R^2	0.953
SE of fit (RMSE)	1.9

SUMMARY OF CBR TEST RESULTS

PROJECT NAME:	MnDOT NS555 Effectiveness of Geogrids
PROJECT ID:	ISP-00007
LOCATION:	Ingios Lab, Northfield, MN

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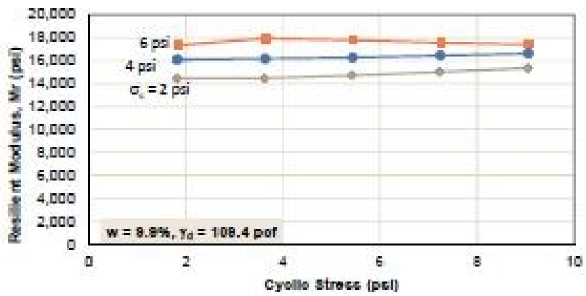
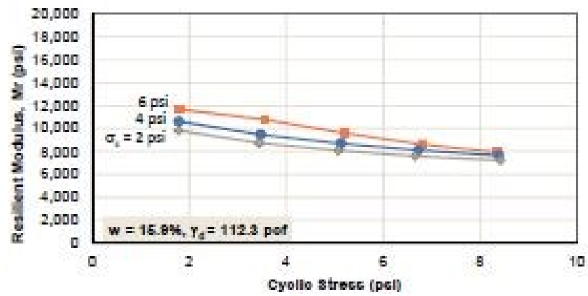
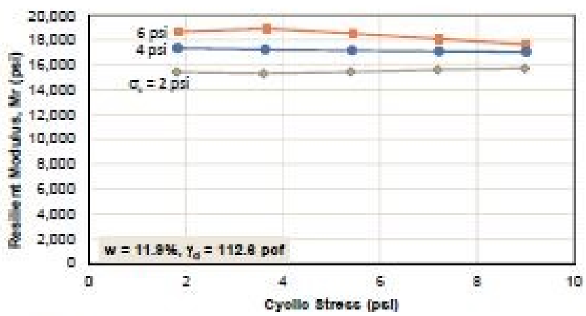
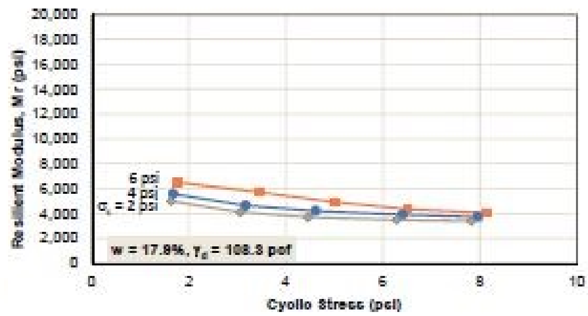
Figure C-4 Subgrade soil summary of CBR test results

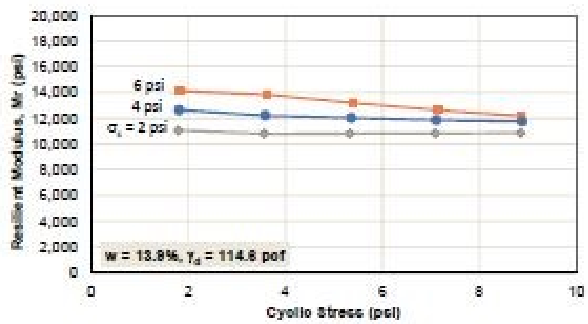
TEST ID	FB Clay	TESTED BY	Boudreau Engineering, Inc.	STANDARD	AASHTO T307-99 (Type 2 Fine Grained Soil)
MATERIAL DESCRIPTION / NOTES	Resilient modulus (M_r) tests performed at five different target moisture content and dry unit weights.				











Models to predict k_1, k_2, and k_3:

k_1 = -133,714.56 w^2 + 28,366.84 w - 328.13; R^2 = 0.95

k_2 = 24.28 w^2 - 5.35 w + 0.52; R^2 = 0.97

k_3 = -380.27 w^2 + 68.92 w - 3.45; R^2 = 0.98

Note: dry density not statistically significant.

			"Universal" Model Parameters			
Sample	w (%)	γ_d (pcf)	k_1	k_2	k_3	R^2
1	9.9%	109.4	1,141.5	0.233	-0.388	0.98
2	11.9%	112.6	1,243.3	0.230	-0.633	0.99
3	13.9%	114.6	932.5	0.261	-1.024	0.98
4	15.9%	112.3	844.3	0.277	-2.368	0.99
5	17.9%	106.3	460.4	0.350	-3.201	0.94

"Universal" Model

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2}\left(1+\frac{\tau_{oct}}{P_a}\right)^{k_3}$$

SUMMARY OF RESILIENT MODULUS TEST RESULTS

PROJECT NAME:	MnDOT NS555 Effectiveness of Geogrids
PROJECT ID:	ISP-00007
LOCATION:	Ingios Lab, Northfield, MN

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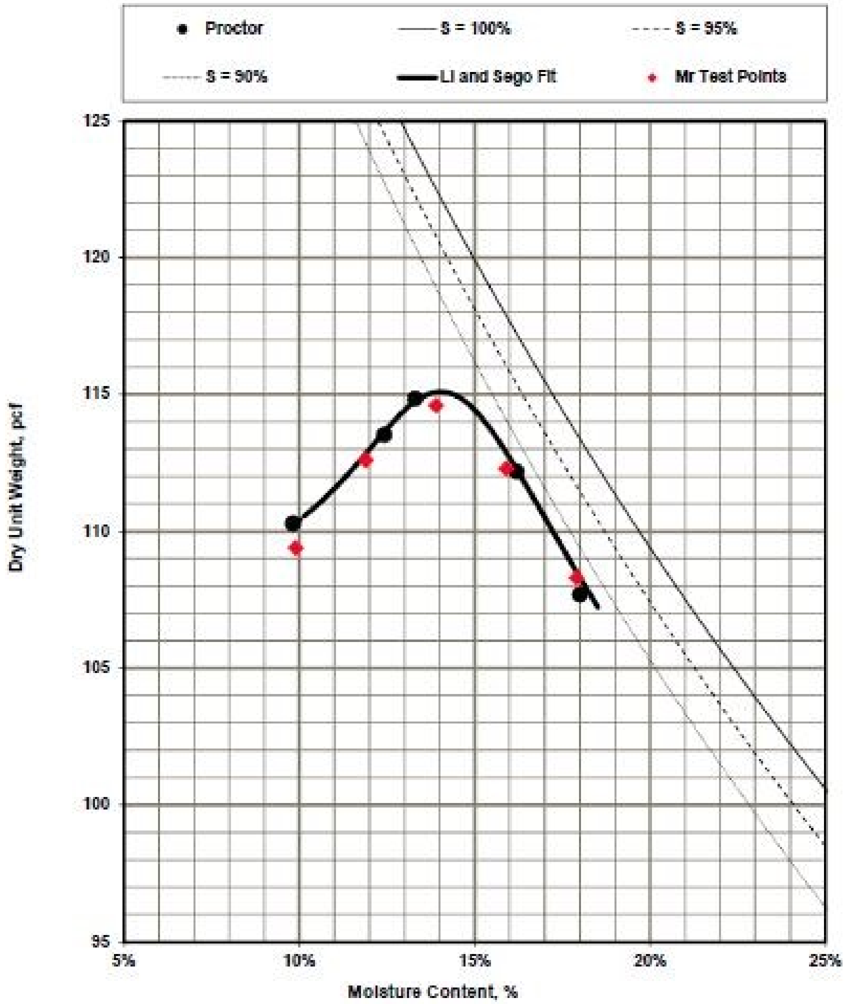
Figure C-5 Subgrade soil summary of resilient modulus test results

TEST ID	FB Clay	TESTED BY	Boudreau Engineering, Inc.	STANDARD	AASHTO T307-99 (Type 2 Fine Grained Soil)
MATERIAL DESCRIPTION / NOTES	Resilient modulus (M$_r$) tests performed at five different target moisture content and dry unit weights.				



SUMMARY OF RESILIENT MODULUS TEST RESULTS

PROJECT NAME:	MnDOT NS555 Effectiveness of Geogrids
PROJECT ID:	ISP-00007
LOCATION:	Ingios Lab, Northfield, MN

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Figure C-6 Subgrade soil summary of resilient modulus test results

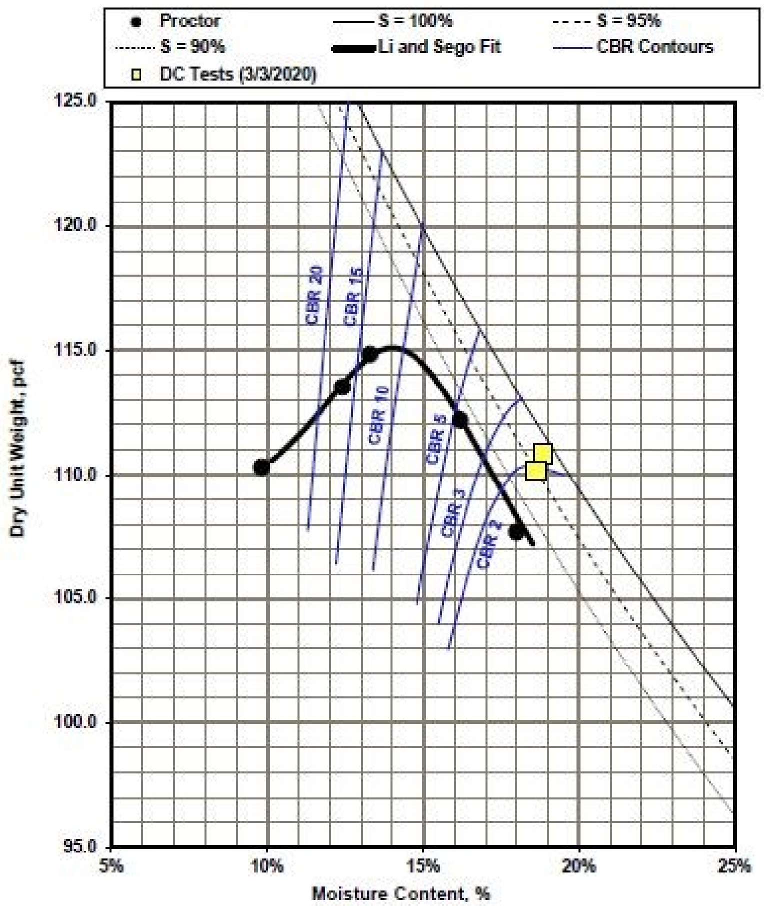
TEST ID	FB clay	TESTED BY	PV	INPUT BY	PV
SAMPLED DATE	6/7/2017	TESTED DATE	6/7/2017	DRYING TEMP, °C	110
MATERIAL DESCRIPTION / NOTES	Fairbault Clay. CBR contours plotted based on a moisture-dry density-CBR relationship developed based on 16 samples prepared at different moisture and dry densities. DC tests performed on 03/03/2020.				

ASTM	D698	pH	Not Measured	SPECIFIC GRAVITY	2.700	Assumed

Fit Equation:

$$\gamma_d(w) = \frac{G_s \gamma_w}{1 + \dfrac{w G_s}{S_m - S_m \left[\dfrac{w_m - w}{w_m}\right]^{n+1} \left[\dfrac{w_m^n - p^n}{(w_m - w)^n + p^n}\right]}}$$

Optimum Moisture Content, %	14.0%
Maximum Dry Unit Weight, pcf	115.1



Li and Sego Fit Parameters

S_m	87.5%
w_m	18.6%
n	4.898
p	0.056
R^2	0.997

Lab w (%)	Lab γ_d (pcf)
9.8%	110.3
12.4%	113.5
13.3%	114.8
16.2%	112.2
18.0%	107.7

CBR = 87.1 - 1349 w + 0.3603 γ_d (pcf) + 3643 w^2 , N = 16, R^2 = 0.95, RMSE = 1.9

LABORATORY PROCTOR TEST RESULTS

PROJECT NAME:	ISU_MNDOT_NS555_Geogrid Stabilization
PROJECT ID:	ISP_00007
LOCATION:	Northfield, MN

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Figure C-7 Subgrade soil laboratory proctor test results

APPENDIX D
LABORATORY SECTIONS PERFORMED PROCTOR TEST AND SAND CONE TEST RESULTS

Table D-1 Base aggregate Proctor test results

Test No.	Water add (gr)	Soil (gr)	Can weight (gr)	Wet + can weight (gr)	Dry + can (gr)	Dry weight (gr)	Water weight (gr)	Moisture %	Volume (CM^3)	Total Soil weight and mold (gr)	Mass of mold (gr)	Mass of soil in compaction mold (gr)	Total unit weight (gr)	Dry Density (g/cm^3)	Dry Density (lb/ft3)
1	100	2000	16	31	29.65	13.65	1.35	9.89%	944	6135	4228	1907	2.02	2.02	125.99
2	200	2000	33.5	89	83.41	49.91	5.59	11.20%	944	6175	4228	1947	2.06	2.06	128.61
3	300	2000	19	65	59.12	40.12	5.88	14.66%	944	6015	4228	1787	1.89	1.89	118.00

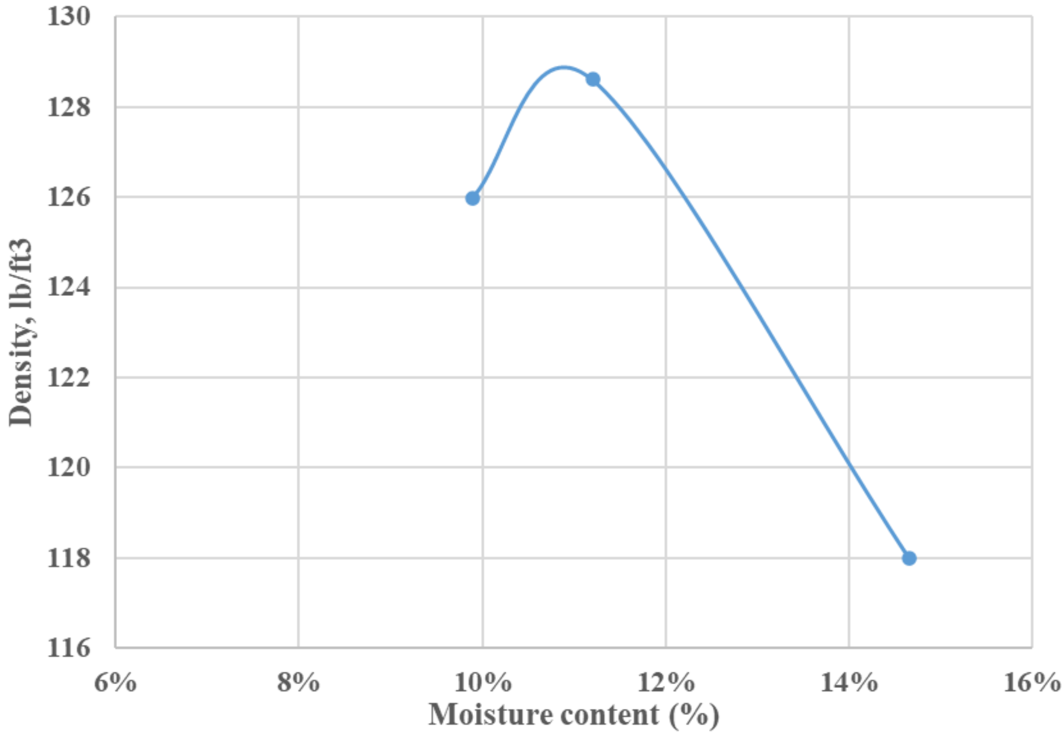
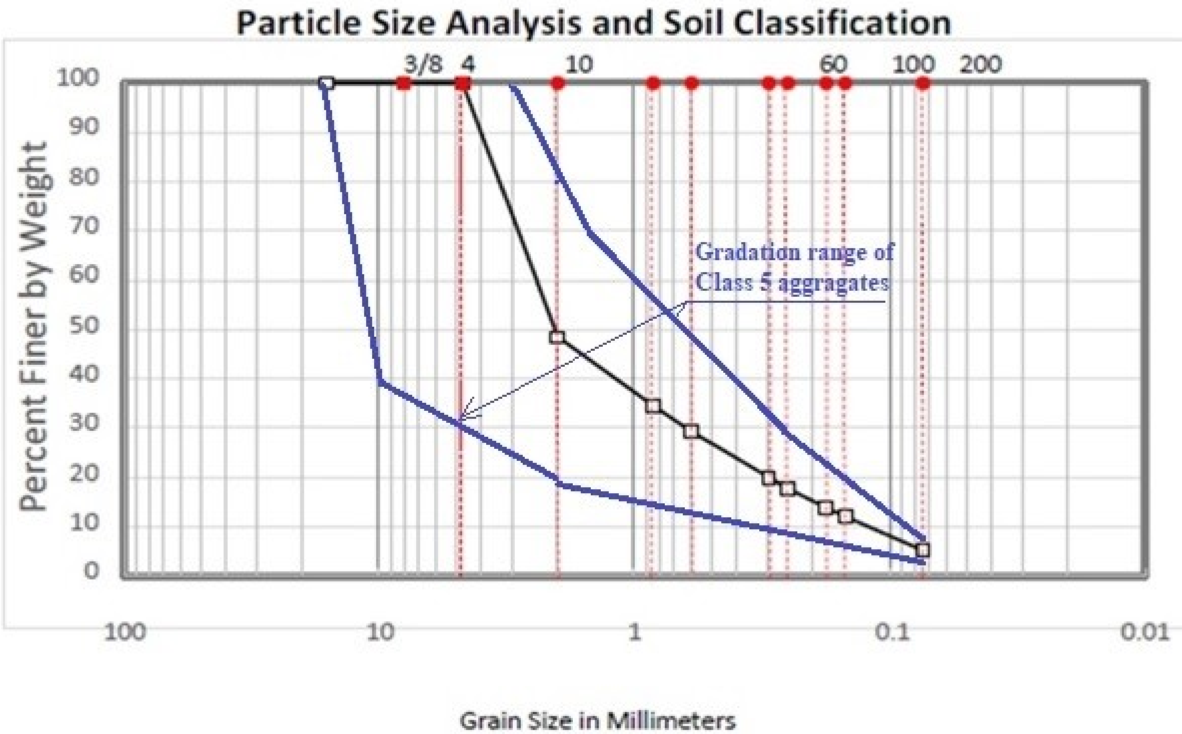


Figure D-1 Base aggregate Proctor test graph

Table D-2 Base aggregate sand cone test results

Section	Mass of sand in apparatus (before)	Mass of sand in apparatus (after)	Mass of sand in test hole + funnel + base plate (g)	Mass of sand in funnel + base plate from Calib. (g)	Bulk Density of Sand from Calib (pcf)	Vol. of Hole (ft^3)	Moist mass of material from hole (g)	Moisture Content of Material				Dry Mass of the Material (g)	Wet. Unit Weight of Material (pcf)	Dry Unit Weight of Material (pcf)	Relative compaction
			M1	M2	r	V	M3	T	T+W	T+D	w (%)	M4	r_{wet}	r_{dry}	
GE0	3732.6	1168.8	2563.8	1539.1	88.71	0.0255	1375.4	180.8	1556.2	1533.6	1.7%	1352.8	119.1	117.1	91.5
GE2	5664.1	2833.5	2830.6	1539.1	88.71	0.0321	1719.3	181.1	1900.4	1871.2	1.7%	1690.1	118.1	116.1	90.7
GE1	4609.4	827.2	3782.2	1539.1	88.71	0.0558	3182	274.5	3456.5	3404.5	1.7%	3130.0	125.8	123.8	96.7
GE1	6686.6	3961	2725.6	1539.1	88.71	0.0295	1574.1	180.4	1754.5	1728.2	1.7%	1547.8	117.7	115.7	90.4
GE4	6227.6	3216.2	3011.4	1539.1	88.71	0.0366	1996.1	277.4	2273.5	2237	1.9%	1959.6	120.3	118.1	92.2
GE12	6500.7	3242	3258.7	1539.1	88.71	0.0427	2461.2	278	2739.2	2699.3	1.6%	2421.3	127.0	124.9	97.6
GE5	6429.1	3133.2	3295.9	1539.1	88.71	0.0437	2354.1	277.9	2632	2598.7	1.4%	2320.8	118.9	117.2	91.6
GE7	5976.2	2611.9	3364.3	1539.1	88.71	0.0454	2468.5	277.5	2746	2707.7	1.6%	2430.2	120.0	118.1	92.3
GE15	6547.2	3420.7	3126.5	1539.1	88.71	0.0395	2194.4	277.4	2471.8	2424	2.2%	2146.6	122.6	120.0	93.7

APPENDIX E
FIELD SECTIONS AGGREGATE TEST RESULTS



Materials

ID: Class 5 aggregates

Sample Location: Mankato city, MN

Classification

AASHTO: A-1a

USCS: SM

Graduation Summary

% Gravel	0
% Sand	95
% Slit /Clay	5
D10(mm)	0.13
D30(mm)	0.6
D50(mm)	2.1
D60(mm)	2.5
Cu	19
Cc	1.1
D max	40.7

Atterberg Limit:

LL: 17.5

PL: N.P.

PI: -

Gradation and Soil Classification Test Results	
Project Name:	MnDOT NS555 Effectiveness of Geogrids
Project ID:	ISP-00007
Location:	142 Lab, Iowa State Univeristy

Figure E-1 Base aggregate specifications (Minnesota DOT specification range for Class 5 aggregate)

Figure E-2 Base aggregate specifications (Minnesota DOT specification range for Class 5 aggregate)

Table E-1 Base aggregate sieve analysis test (Minnesota DOT specification range for Class 5 aggregate)

Base				
Sieve No	Mass retained	Mass pass	Total Percent pass	
3	0	496.5	100%	
2	0	496.5	100%	
1.5	0	496.5	100%	
1	0	496.5	100%	25.4
(3)/(4)	0	496.5	100%	19
0.5	0	496.5	100%	12.7
(3)/(8)	0	496.5	100%	9.51
4	0	496.5	100%	4.76
10	255.5	241	49%	2
20	69.5	171.5	35%	0.841
30	26	145.5	29%	0.595
50	46	99.5	20%	0.297
60	11	88.5	18%	0.25
80	19	69.5	14%	0.177
100	9	60.5	12%	0.149
200	34	26.5	5%	0.074
Pan	26.5	0	0%	
Total	496.5			

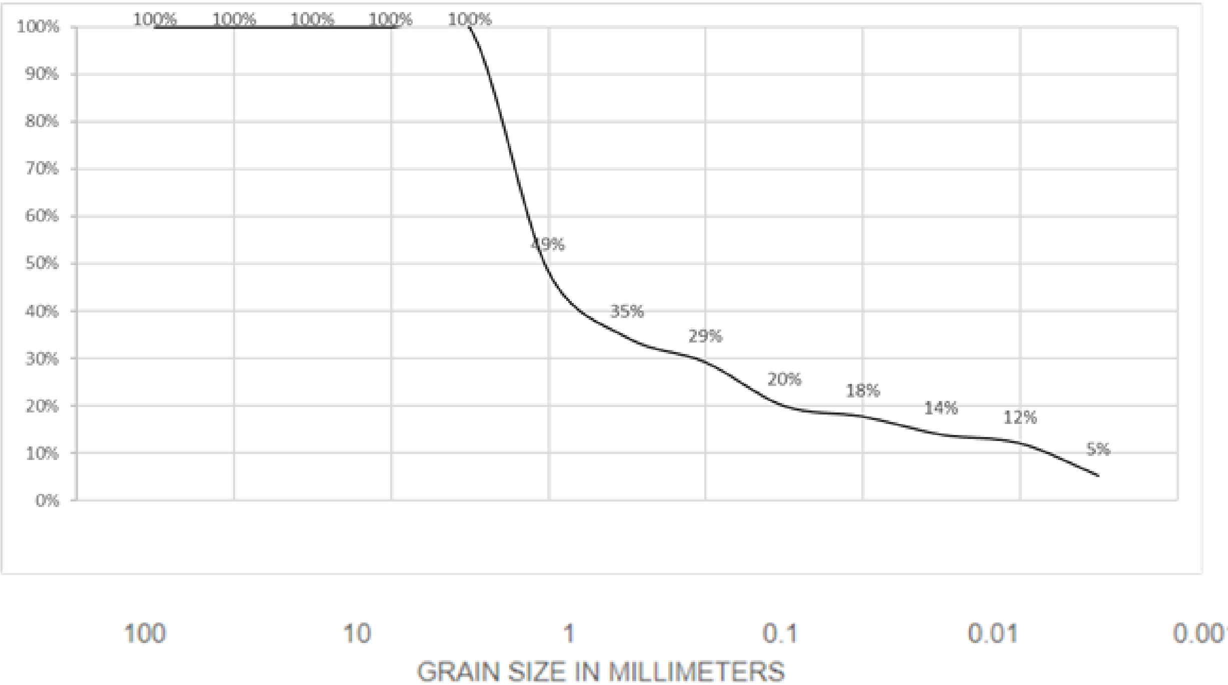


Figure E-3 Base aggregate specifications (Minnesota DOT specification range for Class 5 aggregate)

Table E-2 Liquid Limit test

Base	1	2
Mass of wet + can	36.9	62.88
Mass of dry +can	33.38	58.65
Mass of can	13.27	33.89
Dry soil	20.11	24.76
Mass of moisture	3.52	4.23
Water content	17.50%	17.08%
No. of Blows	22	30

Table E-3 Plastic Limit test (N.P.)

Base	1
Mass of wet + can	35.39
Mass of dry +can	33.82
Mass of can	25.05
Dry soil	8.77
Mass of moisture	1.57
Water content	17.90%

APPENDIX F

FIELD TEST SECTIONS PERFORMED PROCTOR TEST, LFWD TEST, AND SAND CONE TEST RESULTS

Table F-1 Base aggregate Proctor test results

Test No.	Water add (gr)	Soil (gr)	Can weight (gr)	Wet + can weight (gr)	Dry + can (gr)	Dry weight (gr)	Water weight (gr)	Moisture %	Volume (CM^3)	Total Soil weight and mold (gr)	Mass of mold (gr)	Mass of soil in compaction mold (gr)	Total unit weight (g/cm^3)	Dry Density (g/cm^3)	Dry Density (lb/ft3)
1	100	2000	16	31	29.65	13.65	1.35	9.89%	944	6135	4228	1907	2.02	2.02	125.99
2	200	2000	33.5	89	83.41	49.91	5.59	11.20%	944	6175	4228	1947	2.06	2.06	128.61
3	300	2000	19	65	59.12	40.12	5.88	14.66%	944	6015	4228	1787	1.89	1.89	118.00

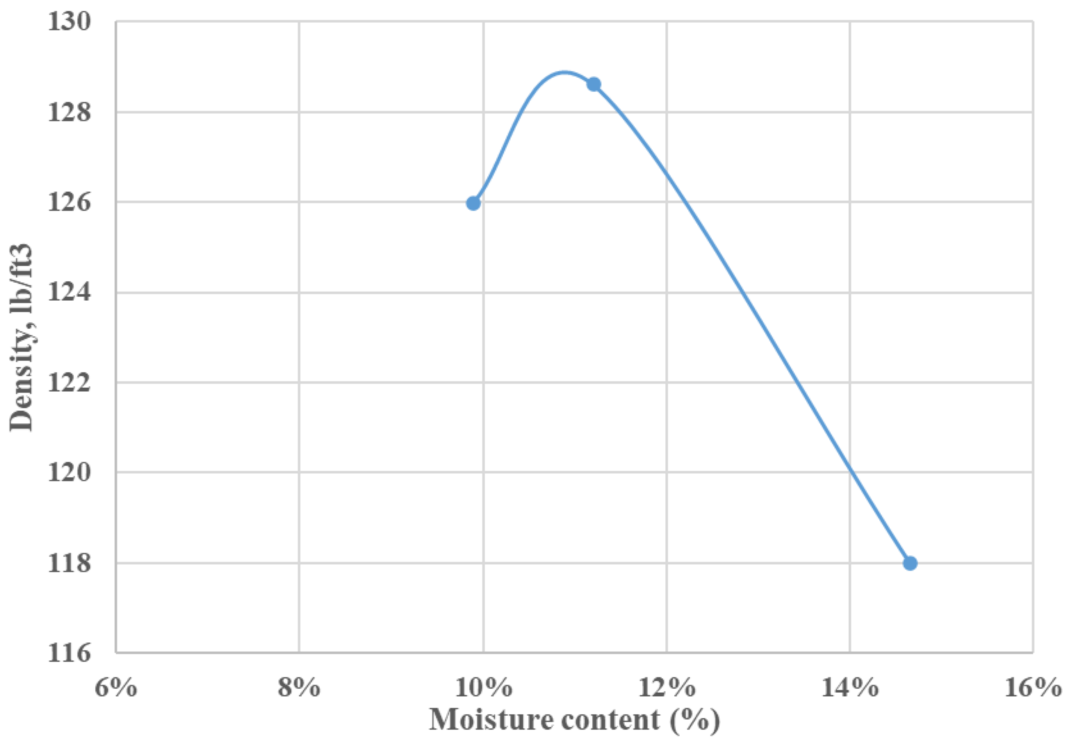


Figure F-1 Base aggregate Proctor test graph

Table F-2 LFWD test results and details

Subgrade Light Falling Weight Deflectometer test results, S Frontriver Dr., Mankato City, Mn

Test Section	Control (1)			T 1			T2		
Section No	Left	Centre	Right	Left	Centre	Right	Left	Centre	Right
Distance (ft)	12.5	25	37.5	62.5	75	87.5	112.5	125	137.5
Average δ (mm)	0.397	0.451	0.423	0.521	0.551	0.259	0.281	0.35	0.352
Evd (Mn/m2)	56.7	49.9	53.2	43.2	40.8	86.9	80.1	64.3	63.9
Date of the test	7/29/2020	7/30/2020	7/31/2020	8/1/2020	8/2/2020	8/3/2020	8/4/2020	8/5/2020	8/6/2020
Temp	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny

Test Section	T4			T5			T7		
Section No	Left	Centre	Right	Left	Centre	Right	Left	Centre	Right
Distance (ft)	162.5	175	187.5	212.5	225	237.5	262.5	275	287.5
Average δ (mm)	0.793	0.703	0.482	0.42	1.426	2.115	0.501	0.393	0.481
Evd (Mn/m2)	28.4	32	46.7	53.6	15.8	10.6	44.9	57.3	46.8
Date of the test	8/7/2020	8/8/2020	8/9/2020	8/10/2020	8/11/2020	8/12/2020	8/13/2020	8/14/2020	8/15/2020
Temp	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny

Test Section	Control (2)			T12		
Section No	Left	Centre	Right	Left	Centre	Right
Distance (ft)	312.5	325	337.5	362.5	375	387.5
Average δ (mm)	0.511	0.484	0.469	0.43	0.437	0.456
Evd (Mn/m2)	44	46.5	48	52.3	51.5	49.3
Date of the test	8/16/2020	8/17/2020	8/18/2020	8/19/2020	8/20/2020	8/21/2020
Temp	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny

Table F-3 LFWD test results

Test Section	East Lane	T5	Control (2)
Section No	-	Centre	Centre
Distance (ft)	-	225	325
Average δ (mm)	3.028	3.935	0.49
Evd (Mn/m2)	7.4	5.7	45.9
Date of the test	7/29/2020	7/29/2020	7/29/2020
Temp	82˚F, Sunny	82˚F, Sunny	82˚F, Sunny

Table F-4 LFWD test results

Test Section	T2			T5		
Section No	Left	Centre	Right	Left	Centre	Right
Distance (ft)	112.5	125	137.5	212.5	225	237.5
Average δ (mm)	0.269	0.399	0.242	0.568	5.041	3.223
Evd (Mn/m2)	83.6	56.4	93	39.6	4.5	7
Date of the test	7/30/2020	7/30/2020	7/30/2020	7/30/2020	7/30/2020	7/30/2020
Temp	74°F, Sunny	74°F, Sunny	74°F, Sunny	74°F, Sunny	74°F, Sunny	74°F, Sunny

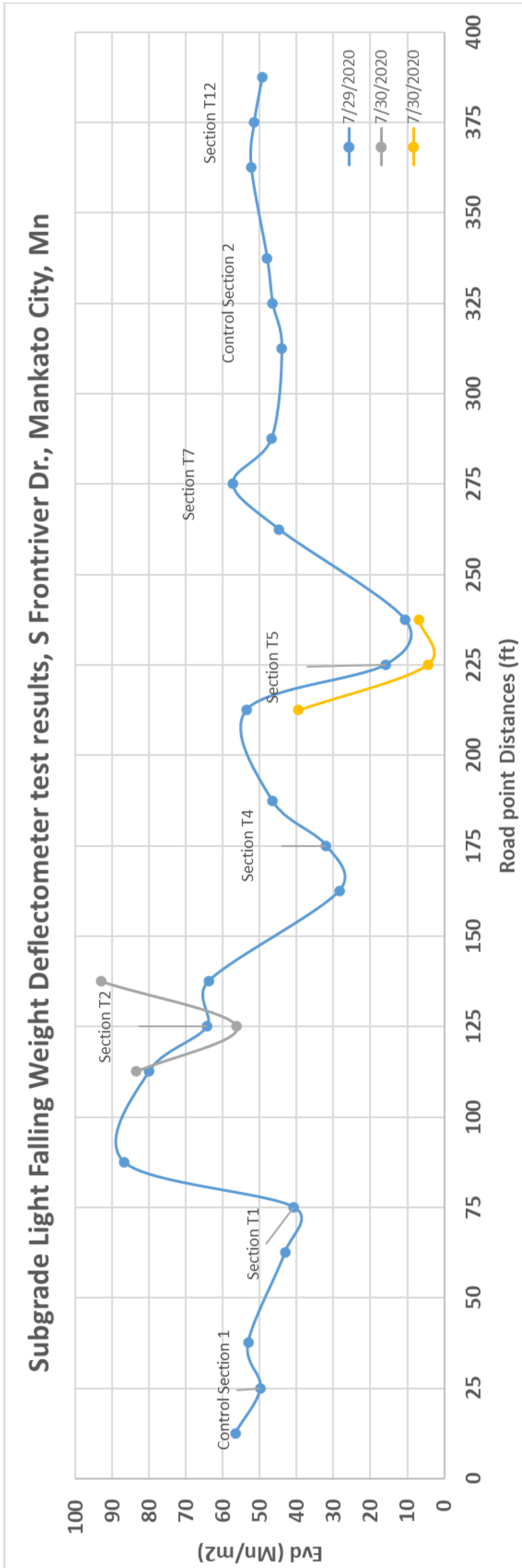


Figure F-2 LFWD test results graph

Table F-5 Sand cone test

Date	Section	Weight of wet soil from the hole (Ww) gr	Weight of sand (before puring W1) gr	Weight of sand (after puring W4) gr	Weight of sand in funel (W2) gr	Weight of sand in the hole (Wb= W1-W4-W2) gr	Bulk density of sand Ys	Bulk density Yb = (Ww/Wb)*Ys	Water content			Dry Density Yd= ((100Yb)/(100+w))		Dry Unit Weight of Material from Proctor test (pcf)	Relative compaction
									Mass of water in soil gr	Dry mass of soil gr	Water content (W%)			ρ_{dry}	
8/1/2020	T1	1766.8	4829.8	1829	565	2435.8	1884	1366.55	139.1	1627.7	8.55	**1259.0**		1500.36	83.9
							kg/m3	kg/m3				kg/m3		kg/m3	

APPENDIX G
FIELD PERFORMED DCP TEST RESULTS

Date of Test	7/31/2020	Test ID	PT1_CTRL	Operator	HG/CV	ASTM	D6951
Latitude	44.1578980		Longitude	-94.0266420		Elevation (ft)	208
Location	Control Section # 1		Station	NA			
Comments	10 in. (nominal) Class 5 Aggregate Base over subgrade. Base layer compacted with pneumatic rubber wheeled roller passes, followed by 2 passes with a vibratory smooth drum roller.						

Parameter	DPI (mm/blow)	CBR (%)	E_{CBR}, Elastic Modulus (ksi) (non stress-dependent)	S_{u-CBR}, Bearing Capacity (psf)
Avg. Top Layer	6.0	38.9	26.6	6,215
Avg. Bottom Layer	4.2	58.5	34.5	8,148
Ratio of Avg. Top/Bottom Layer	1.4	0.7	0.8	0.8
Std.Dev. Top Layer	0.8	6.1	8.2	1,822
Std. Dev. Bottom Layer	1.4	18.8	16.7	3,833

NOTE: *Top layer thickness assumed (nominal)*

NOTES:

Subgrade is classified as CL

[1] $CBR = 292/DPI^{1.12}$

[2] $CBR = 1/(0.017019 DPI)^2$

for CL soils with CBR < 10

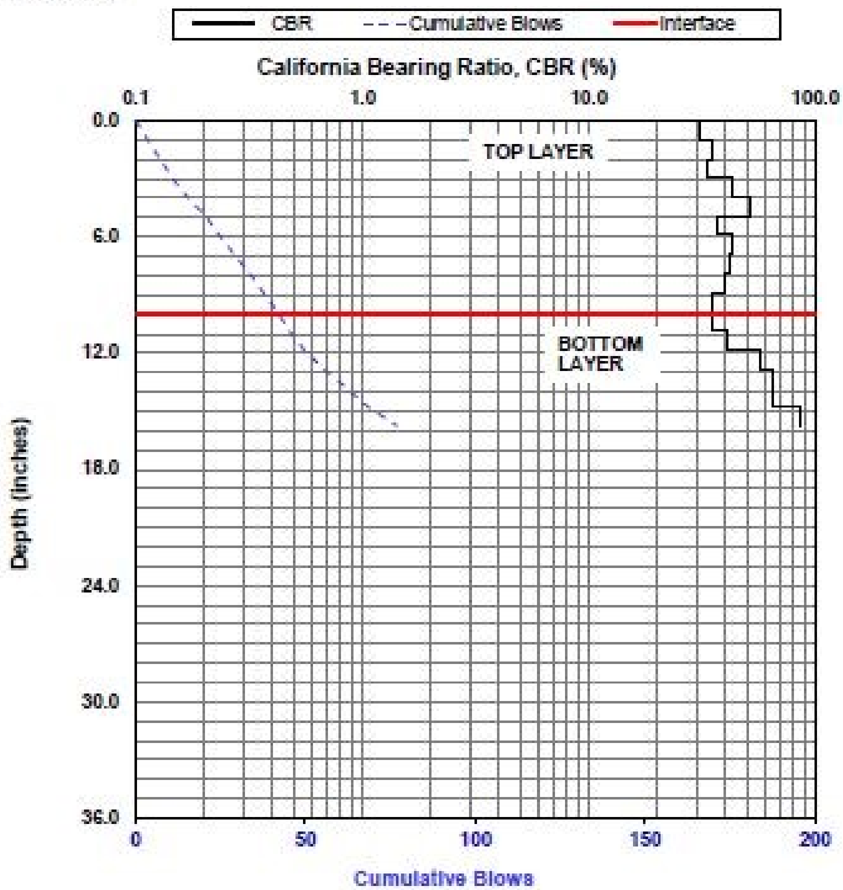
[2] $E\ (ksi) = (17.6\ CBR^{0.64}) \times 0.1450377$

[3] $S_u\ (psf) = (3.794 \times CBR^{0.664}) \times 144$

[1] ASTM D6951-03

[2] Powell et al. (1984)

[3] Portland Cement Assoc. (1966)



Dynamic Cone Penetrometer (DCP) Test Results

Project Name:	ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Riverfront Drive between Carney St and Woodland Ave, Mankato, MN

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Figure G-1 DCP test results of control section 1, Ingios Geotechnics Inc. test results

Date of Test	7/31/2020	Test ID	PT2_BIAXLT	Operator	HG/CV	ASTM	D6951
Latitude	44.1578325		Longitude	-94.0268077		Elevation (ft)	208
Location	Section # 1		Station	NA			
Comments	10 in. (nominal) Class 5 Aggregate Base over subgrade with light duty biaxial (BIAXLT) geogrid at the base/subgrade interface. Base layer compacted with pneumatic rubber wheeled roller passes, followed by 2 passes with a vibratory smooth drum roller						

Parameter	DPI (mm/blow)	CBR (%)	E_{CBR}, Elastic Modulus (ksi) (non stress-dependent)	S_{u-CBR}, Bearing Capacity (psf)
Avg. Top Layer	6.7	34.8	24.8	5,770
Avg. Bottom Layer	10.8	20.3	17.5	4,028
Ratio of Avg. Top/Bottom Layer	0.6	1.7	1.4	1.4
Std.Dev. Top Layer	1.5	6.9	8.8	1,976
Std. Dev. Bottom Layer	18.4	20.1	17.4	4,001

NOTE: *Top layer thickness assumed (nominal)*

NOTES:

Subgrade is classified as CL

[1]CBR = 292/DPI$^{1.12}$

[1]CBR = 1/(0.017019DPI)^2

for CL soils with CBR < 10

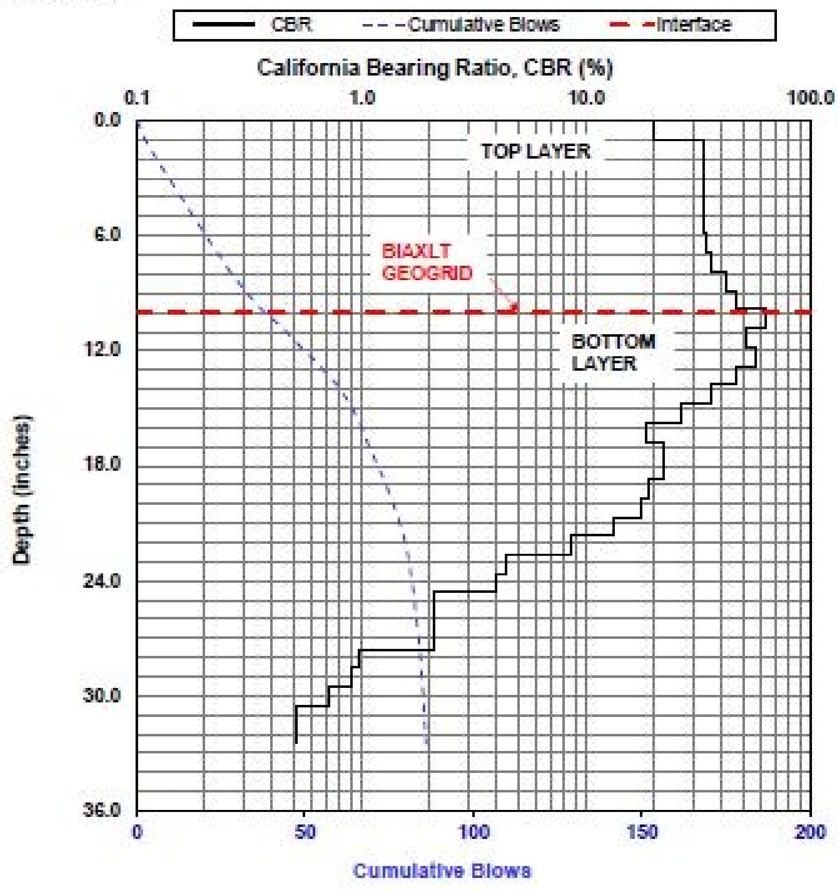
[2]E (ksi) = (17.6 CBR$^{0.64}$) x 0.1450377

[3]S_u (psf) =(3.794 x CBR$^{0.664}$) x 144

[1] ASTM D6951-03

[2]Powell et al. (1986)

[3]Portland Cement Assoc. (1955)



Dynamic Cone Penetrometer (DCP) Test Results

Project Name:	ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Riverfront Drive between Carney St and Woodland Ave, Mankato, MN

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Figure G-2 DCP test results of control section 1, Ingios Geotechnics Inc. test results

Date of Test	7/31/2020	Test ID	PT3_BIAXHV	Operator	HG/CV	ASTM	D6951
Latitude	44.1577652		Longitude	-94.0269745		Elevation (ft)	208
Location	Section # 2		Station	NA			
Comments	10 in. (nominal) Class 5 Aggregate Base over subgrade, with heavy duty biaxial geogrid (BIAXHV) at the subgrade/base interface. Base layer compacted with pneumatic rubber wheeled roller passes, followed by 2 passes with a vibratory smooth drum roller.						

Parameter	DPI (mm/blow)	CBR (%)	E_{CBR}, Elastic Modulus (ksi) (non stress-dependent)	S_{u-CBR}, Bearing Capacity (psf)
Avg. Top Layer	7.9	28.7	21.9	5,072
Avg. Bottom Layer	10.7	20.5	17.7	4,063
Ratio of Avg. Top/Bottom Layer	0.7	1.4	1.2	1.2
Std.Dev. Top Layer	1.0	4.1	6.3	1,393
Std. Dev. Bottom Layer	12.1	19.0	16.8	3,856

NOTE: *Top layer thickness assumed (nominal)*

NOTES:

Subgrade is classified as CL

[1] $CBR = 292/DPI^{1.12}$

[1] $CBR = 1/(0.017019 DPI)^2$

for CL soils with CBR < 10

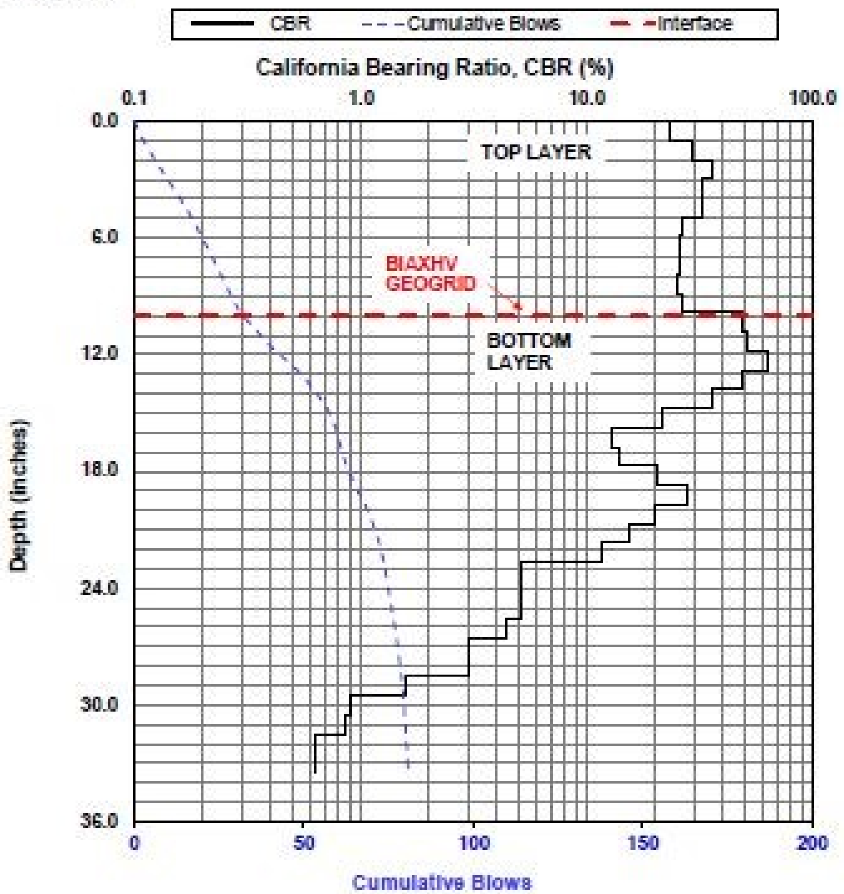
[2] $E\ (ksi) = (17.6\ CBR^{0.64}) \times 0.1450377$

[3] $S_u\ (psf) = (3.794 \times CBR^{0.664}) \times 144$

[1] ASTM D6951-03

[2] Powell et al. (1986)

[3] Portland Cement Assoc. (1955)



Dynamic Cone Penetrometer (DCP) Test Results	
Project Name:	ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Riverfront Drive between Carney St and Woodland Ave, Mankato, MN

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Figure G-3 DCP test results of section 2, Ingios Geotechnics Inc. test results

Date of Test	7/31/2020	Test ID	PT4_TRIAXHV	Operator	HG/CV	ASTM	D6951
Latitude	44.1576983	Longitude		-94.0271387		Elevation (ft)	208
Location	Section # 4	Station		NA			
Comments	10 in. (nominal) Class 5 Aggregate Base over subgrade, with heavy duty triaxial geogrid (TRIAXHV) at the subgrade/base interface. Base layer compacted with pneumatic rubber wheeled roller passes, followed by 2 passes with a vibratory smooth drum roller.						

Parameter	DPI (mm/blow)	CBR (%)	E_{CBR}, Elastic Modulus (ksi) (non stress-dependent)	S_{u-CBR}, Bearing Capacity (psf)
Avg. Top Layer	7.8	29.2	22.1	5,140
Avg. Bottom Layer	15.8	13.3	13.4	3,043
Ratio of Avg. Top/Bottom Layer	0.5	2.2	1.7	1.7
Std.Dev. Top Layer	2.5	7.4	9.2	2,056
Std. Dev. Bottom Layer	17.1	12.8	13.0	2,967

NOTE: *Top layer thickness assumed (nominal)*

NOTES:

Subgrade is classified as CL

[1] $CBR = 292/DPI^{1.12}$

[2] $CBR = 1/(0.017019 DPI)^2$

for CL soils with CBR < 10

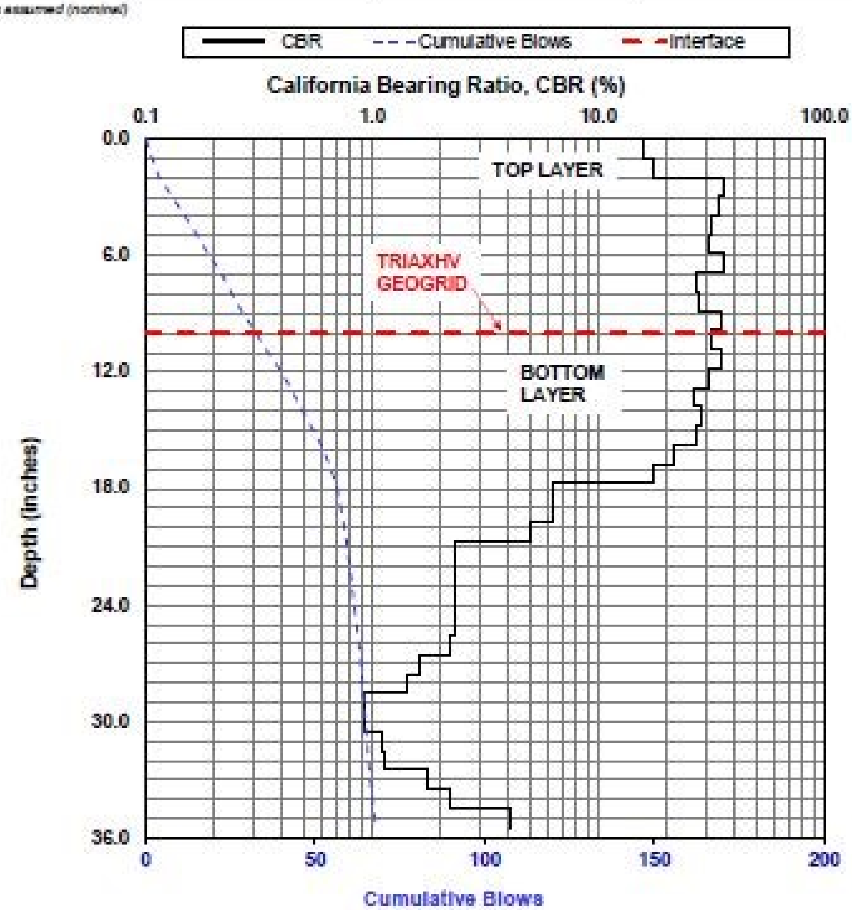
[2] $E\ (ksi) = (17.6\ CBR^{0.64}) \times 0.1450377$

[3] $S_u\ (psf) = (3.794 \times CBR^{0.664}) \times 144$

[1] ASTM D6951-03

[2] Powell et al. (1986)

[3] Portland Cement Assoc. (1955)



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

Location: Riverfront Drive between Carney St and Woodland Ave, Mankato, MN

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Figure G-4 DCP test results of section 4, Ingios Geotechnics Inc. test results

Date of Test	7/31/2020	Test ID	PT5_BIAXLT	Operator	HG/CV	ASTM	D6951
Latitude	44.1576320		Longitude	-94.0273067		Elevation (ft)	208
Location	Section # 5		Station	NA			
Comments	10 in. (nominal) Class 5 Aggregate Base over subgrade, with light duty biaxial geogrid (BIAXLT) placed within the base layer at about mid-depth. Base layer compacted with pneumatic rubber wheeled roller passes, followed by 2 passes with a vibratory smooth drum roller.						

Parameter	DPI (mm/blow)	CBR (%)	E_{CBR}, Elastic Modulus (ksi) (non stress-dependent)	$S_{u\text{-}CBR}$, Bearing Capacity (psf)
Avg. Top Layer	5.7	41.4	27.7	6,471
Avg. Bottom Layer	4.8	50.5	31.4	7,390
Ratio of Avg. Top/Bottom Layer	1.2	0.8	0.9	0.9
Std.Dev. Top Layer	1.5	9.0	10.4	2,347
Std. Dev. Bottom Layer	3.1	15.2	14.5	3,321

NOTE: *Top layer thickness assumed (nominal)*

NOTES:

Subgrade is classified as CL

[1] $CBR = 292/DPI^{1.12}$

[1] $CBR = 1/(0.017019DPI)^2$

for CL soils with CBR < 10

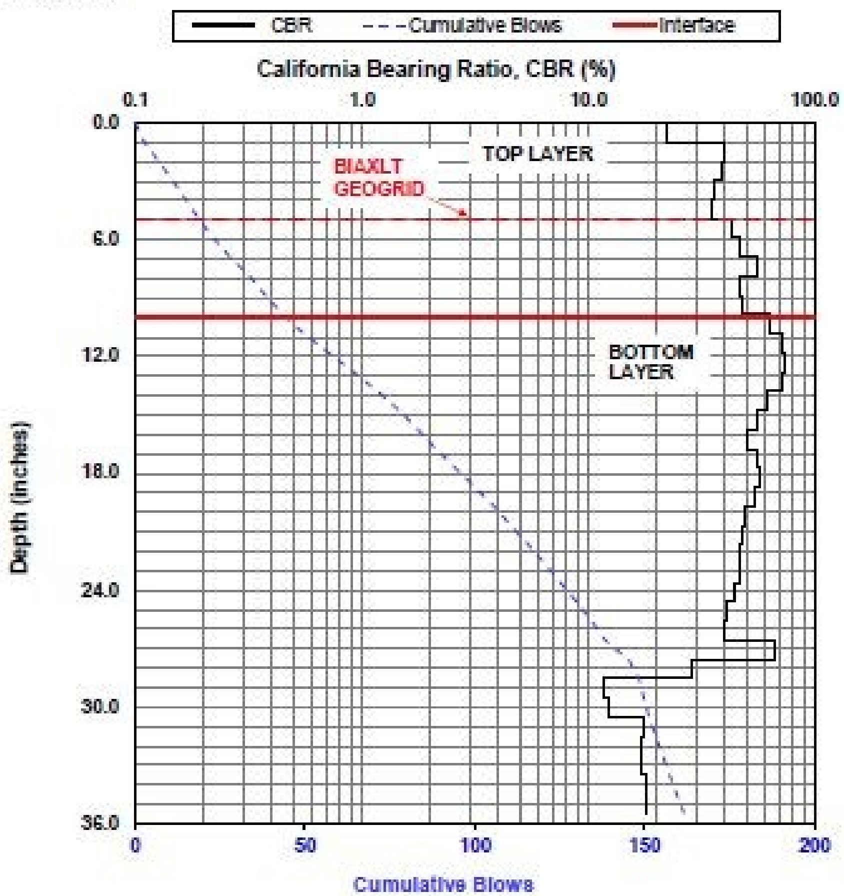
[2] $E\ (ksi) = (17.6\ CBR^{0.64}) \times 0.1450377$

[3] $S_u\ (psf) = (3.794 \times CBR^{0.664}) \times 144$

[1] ASTM D6951-03

[2] Powell et al. (1984)

[3] Portland Cement Assoc. (1955)



Dynamic Cone Penetrometer (DCP) Test Results

Project Name:	ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Riverfront Drive between Carney St and Woodland Ave, Mankato, MN

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Figure G-5 DCP test results of section 5, Ingios Geotechnics Inc. test results

Date of Test	7/31/2020	Test ID	PT6_TRIAXLT	Operator	HG/CV	ASTM	D6951
Latitude	44.1575727		Longitude	-94.0274807		Elevation (ft)	208
Location	Section # 7		Station	NA			
Comments	10 in. (nominal) Class 5 Aggregate Base over subgrade, with light duty triaxial geogrid (TRIAXLT) placed within the base layer at about mid-depth. Base layer compacted with pneumatic rubber wheeled roller passes, followed by 2 passes with a vibratory smooth drum roller.						

Parameter	DPI (mm/blow)	CBR (%)	E_{CBR}, Elastic Modulus (ksi) (non stress-dependent)	S_{u-CBR}, Bearing Capacity (psf)
Avg. Top Layer	6.4	36.5	25.5	5,956
Avg. Bottom Layer	5.5	43.3	28.5	6,674
Ratio of Avg. Top/Bottom Layer	1.2	0.8	0.9	0.9
Std.Dev. Top Layer	2.4	8.5	10.0	2,255
Std. Dev. Bottom Layer	2.2	15.2	14.5	3,323

NOTE: *Top layer thickness assumed (nominal)*

NOTES:

Subgrade is classified as CL

[1] $CBR = 292/DPI^{1.12}$

[1] $CBR = 1/(0.017019DPI)^2$

for CL soils with CBR < 10

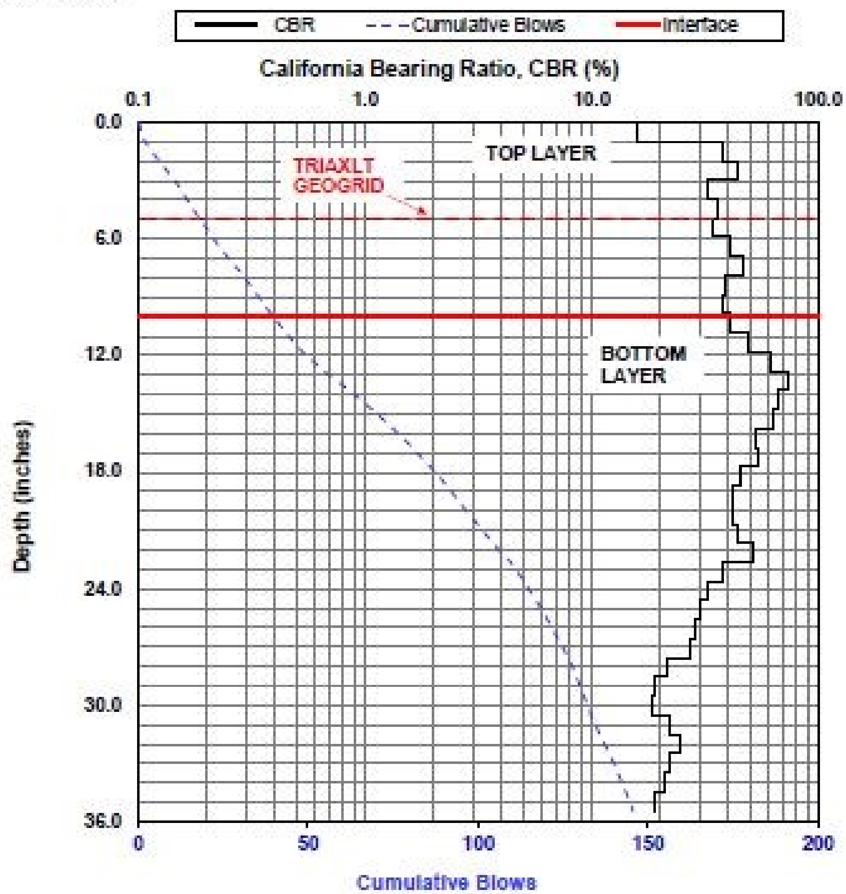
[2] $E\ (ksi) = (17.6\ CBR^{0.64}) \times 0.1450377$

[3] $S_u\ (psf) = (3.794 \times CBR^{0.664}) \times 144$

[1] ASTM D6951-03

[2] Powell et al. (1986)

[3] Portland Cement Assoc. (1955)



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

Location: Riverfront Drive between Carney St and Woodland Ave

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Figure G-6 DCP test results of section 7, Ingios Geotechnics Inc. test results

Date of Test	7/31/2020	Test ID	PT7_CTRL	Operator	HG/CV	ASTM	D6951
Latitude	44.1575193		Longitude	-94.0276545		Elevation (ft)	208
Location	Control Section # 2		Station	NA			
Comments	6 in. (nominal) Class 5 Aggregate Base over subgrade. Base layer compacted with pneumatic rubber wheeled roller passes, followed by 2 passes with a vibratory smooth drum roller.						

Parameter	DPI (mm/blow)	CBR (%)	E_{CBR}, Elastic Modulus (ksi) (non stress-dependent)	S_{u-CBR}, Bearing Capacity (psf)
Avg. Top Layer	7.4	31.1	23.0	5,354
Avg. Bottom Layer	4.3	57.3	34.0	8,029
Ratio of Avg. Top/Bottom Layer	1.7	0.5	0.7	0.7
Std.Dev. Top Layer	0.7	3.1	5.2	1,146
Std. Dev. Bottom Layer	2.8	25.6	20.4	4,709

NOTE: *Top layer thickness interpreted based on CBR profile*

NOTES:

Subgrade is classified as CL

[1]CBR = 292/DPI$^{1.12}$

[2]CBR = 1/(0.017019DPI)^2

for CL soils with CBR < 10

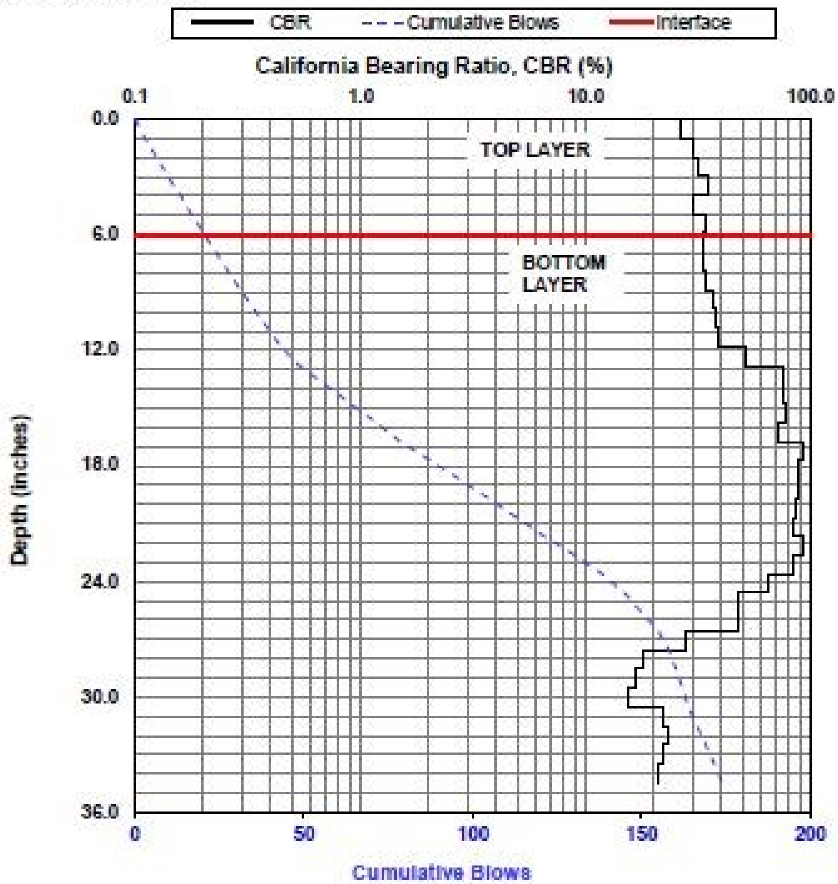
[3]E (ksi) = (17.6 CBR$^{0.64}$) x 0.1450377

[3]S_u (psf) =(3.794 x CBR$^{0.664}$) x 144

[1] ASTM D6951-03

[2]Powell et al. (1984)

[3]Portland Cement Assoc. (1955)



Dynamic Cone Penetrometer (DCP) Test Results	
Project Name:	ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Riverfront Drive between Carney St and Woodland Ave

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Figure G-7 DCP test results of control section 2, Ingios Geotechnics Inc. test results

Date of Test	7/31/2020	Test ID	PT8_TRIAXHV	Operator	HG/CV	ASTM	D6951
Latitude	44.1574783		Longitude	-94.0277983		Elevation (ft)	207
Location	Section # 12		Station	NA			
Comments	6 in. (nominal) Class 5 Aggregate Base over subgrade, with heavy duty triaxial geogrid (TRIAXHV) at the subgrade/base interface. Base layer compacted with pneumatic rubber wheeled roller passes, followed by 2 passes with a vibratory smooth drum roller.						

Parameter	DPI (mm/blow)	CBR (%)	E_{CBR}, Elastic Modulus (ksi) (non stress-dependent)	S_{u-CBR}, Bearing Capacity (psf)
Avg. Top Layer	7.7	29.6	22.3	5,185
Avg. Bottom Layer	4.5	53.6	32.6	7,683
Ratio of Avg. Top/Bottom Layer	1.7	0.6	0.7	0.7
Std.Dev. Top Layer	1.5	4.9	7.1	1,575
Std. Dev. Bottom Layer	1.3	12.3	12.7	2,897

NOTE: *Top layer thickness assumed (nominal)*

NOTES:

Subgrade is classified as CL

[1] $CBR = 292/DPI^{1.12}$

[2] $CBR = 1/(0.017019 DPI)^2$

for CL soils with CBR < 10

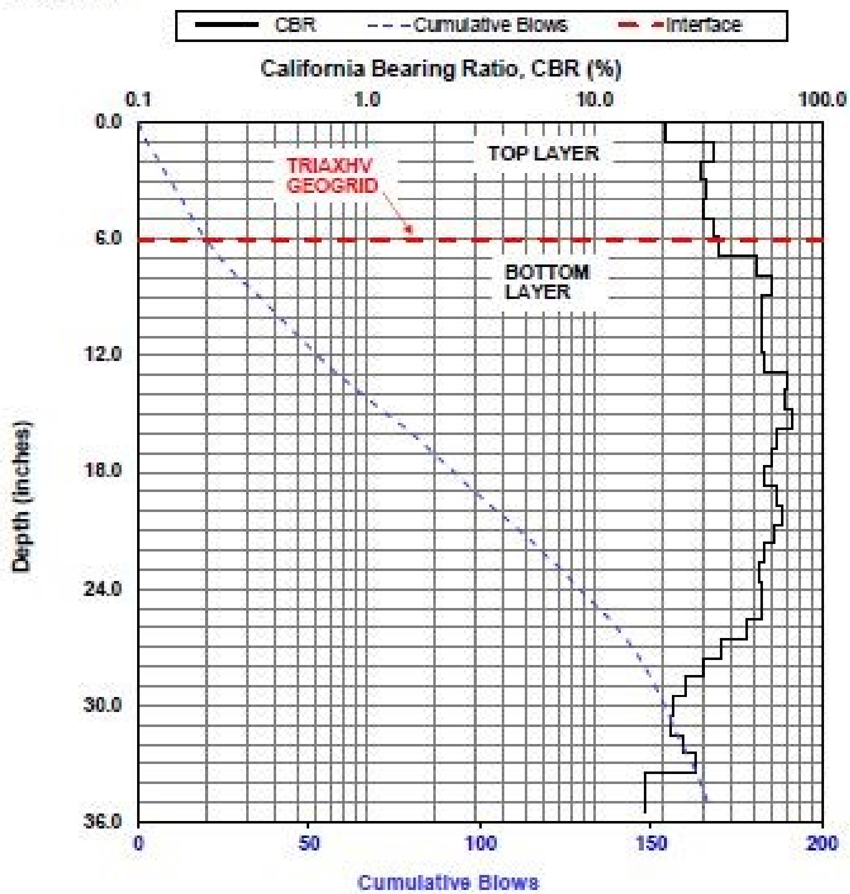
[2] $E\ (ksi) = (17.6\ CBR^{0.64}) \times 0.1450377$

[3] $S_u\ (psf) = (3.794 \times CBR^{0.664}) \times 144$

[1] ASTM D6951-03

[2] Powell et al. (1986)

[3] Portland Cement Assoc. (1955)



Dynamic Cone Penetrometer (DCP) Test Results	
Project Name:	ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Riverfront Drive between Carney St and Woodland Ave, Mankato, MN

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Figure G-8 DCP test results of section 12, Ingios Geotechnics Inc. test results

Date of Test	8/1/2020	Test ID	PT9_BIAXLT_MANHOLE	Operator	HG/CV	ASTM	D6951
Latitude	44.1576232		Longitude	-94.0272675		Elevation (ft)	209
Location	Section # 5		Station	NA			
Comments	Test performed near manhole. 10 in. (nominal) Class 5 Aggregate Base over subgrade, with light duty biaxial geogrid (BIAXLT) placed within the base layer at about mid-depth. Base layer compacted with pneumatic rubber wheeled roller passes, followed by 2 passes with a vibratory smooth drum roller. Test performed next to a utility manhole.						

Parameter	DPI (mm/blow)	CBR (%)	E_{CBR}, Elastic Modulus (ksi) (non stress-dependent)	S_{u-CBR}, Bearing Capacity (psf)
Avg. Top Layer	8.3	27.2	21.2	4,903
Avg. Bottom Layer	12.3	17.5	16.0	3,660
Ratio of Avg. Top/Bottom Layer	0.7	1.6	1.3	1.3
Std.Dev. Top Layer	3.1	7.4	9.2	2,068
Std. Dev. Bottom Layer	6.1	11.1	11.9	2,703

NOTE: *Top layer thickness assumed (nominal)*

NOTES:

Subgrade is classified as CL

[1]$CBR = 292/DPI^{1.12}$

[1]$CBR = 1/(0.017019 DPI)^2$

for CL soils with CBR < 10

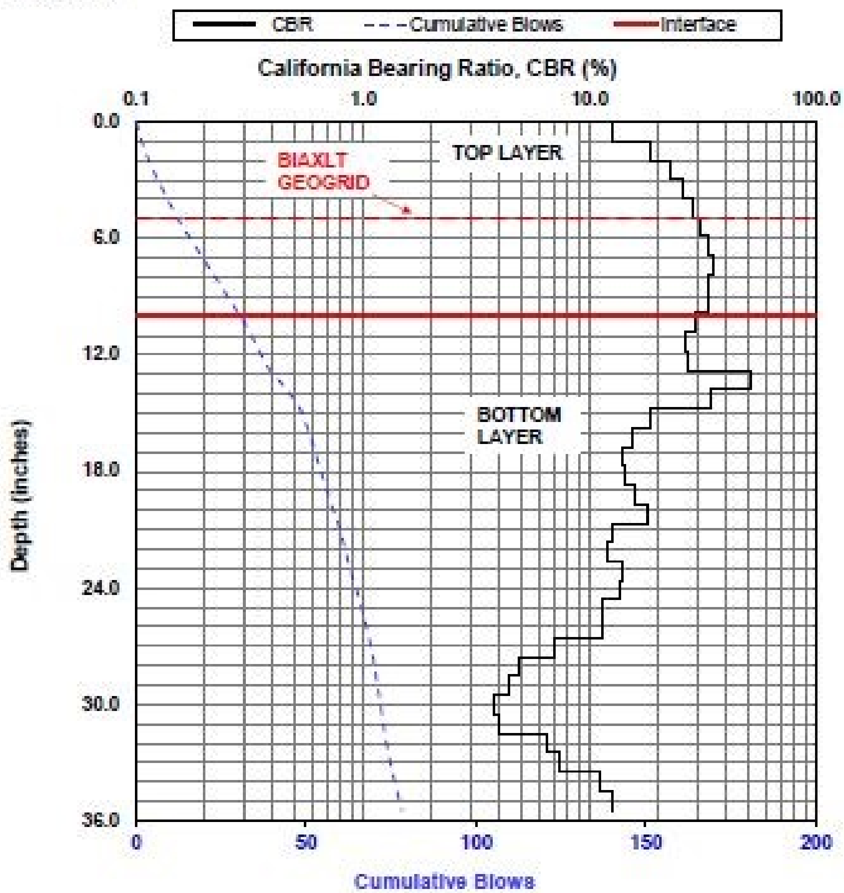
[2]$E\ (ksi) = (17.6\ CBR^{0.64}) \times 0.1450377$

[3]$S_u\ (psf) = (3.794 \times CBR^{0.664}) \times 144$

[1] ASTM D6951-03

[2]Powell et al. (1986)

[3]Portland Cement Assoc. (1965)



Dynamic Cone Penetrometer (DCP) Test Results

Project Name:	ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Riverfront Drive between Carney St and Woodland Ave, Mankato, MN

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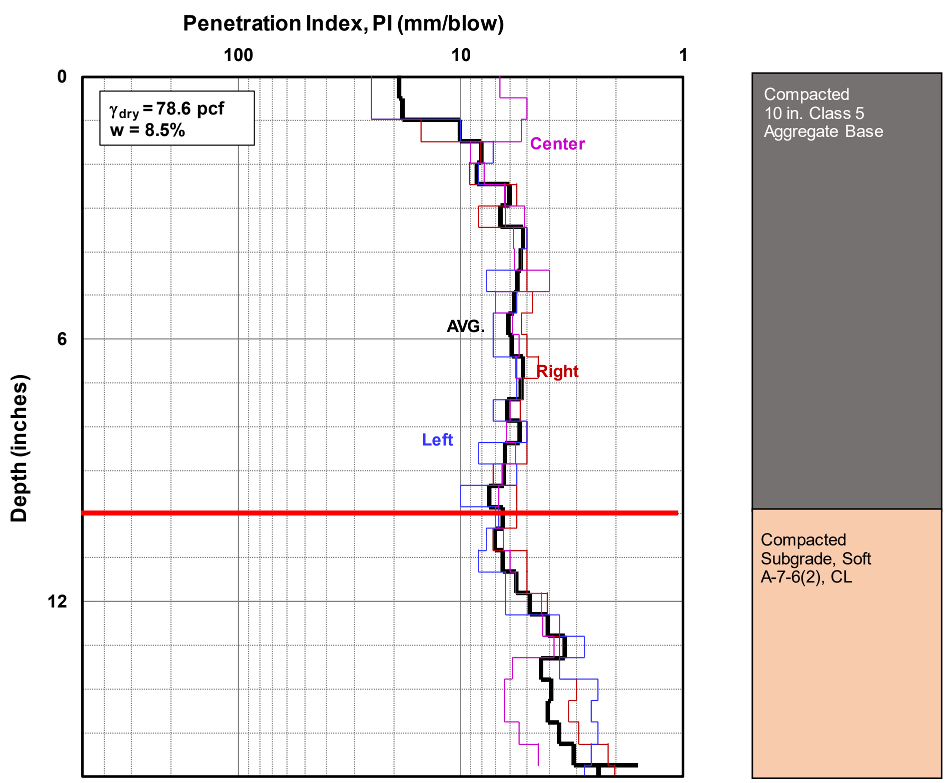
Figure G-9 DCP test results of section 5, Ingios Geotechnics Inc. test results

Date of Test	7/31/2020	Test ID	10" Control 1	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA	Longitude		NA		Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN	Station		NA			
Comments	Nominal 10 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	7.0	5.9	6.3	6.4	36.8
Average: Subgrade Layer [10 to 16.0 in.]	3.5	5.3	3.5	3.8	64.9
Ratio of Average: Aggregate Base/Subgrade	1.99	1.11	1.78	1.66	0.6
Std. Dev.: Aggregate Base [0 to 10 in.]	6.7	1.1	7.1	4.6	11.6
Std. Dev.: Subgrade Layer [10 to 16.0 in.]	2.2	1.0	1.4	1.5	22.5

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

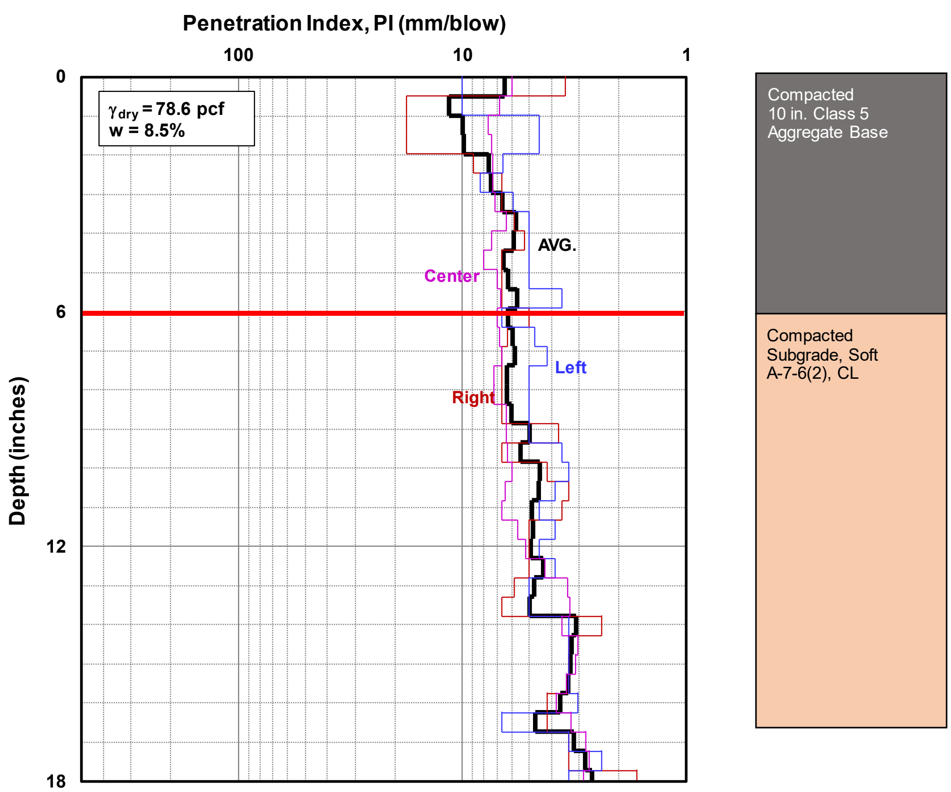
Project Name:	ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Mankato city, MN

Figure G-10 Average DCP test results of control section 1

Date of Test	8/1/2020	Test ID	6" Control 2	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA	Longitude	NA			Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN	Station	NA				
Comments	Thin 6 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 6.0 in.]	5.6	7.0	7.1	6.5	35.9
Average: Subgrade Layer [6 to 18.0 in.]	3.9	4.0	3.9	4.1	59.7
Ratio of Average: Aggregate Base/Subgrade	1.41	1.74	1.82	1.57	0.6
Std. Dev.: Aggregate Base [0 to 10 in.]	2.3	0.6	5.3	1.9	7.6
Std. Dev.: Subgrade Layer [10 to 16.0 in.]	1.1	1.7	1.6	1.2	20.1

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

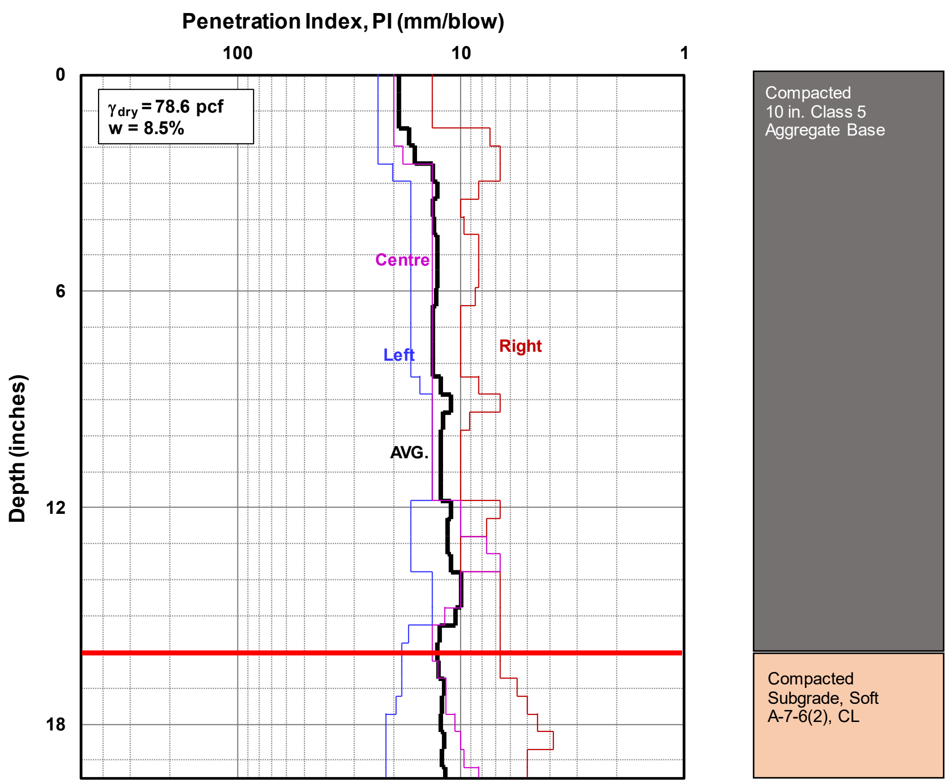
Project Name: ISU_MNDOT_NS555_Geogrid Stabilization
Project ID: ISP_00007
Location: Mankato city, MN

Figure G-11 Average DCP test results of control section 2

Date of Test	8/7/2020	Test ID	16" control section 3	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA	Longitude	NA			Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN	Station	NA				
Comments	Thick 16 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 16.0 in.]	16.3	12.7	8.6	11.7	18.6
Average: Subgrade Layer [16 to 24.0 in.]	15.5	8.6	5.0	68.9	2.6
Ratio of Average: Aggregate Base/Subgrade	1.05	1.48	1.73	0.17	7.3
Std. Dev.: Aggregate Base [0 to 16 in.]	3.4	3.4	2.1	2.5	3.0
Std. Dev.: Subgrade Layer [16 to 24.0 in.]	4.1	2.4	1.0	1.3	2.4

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

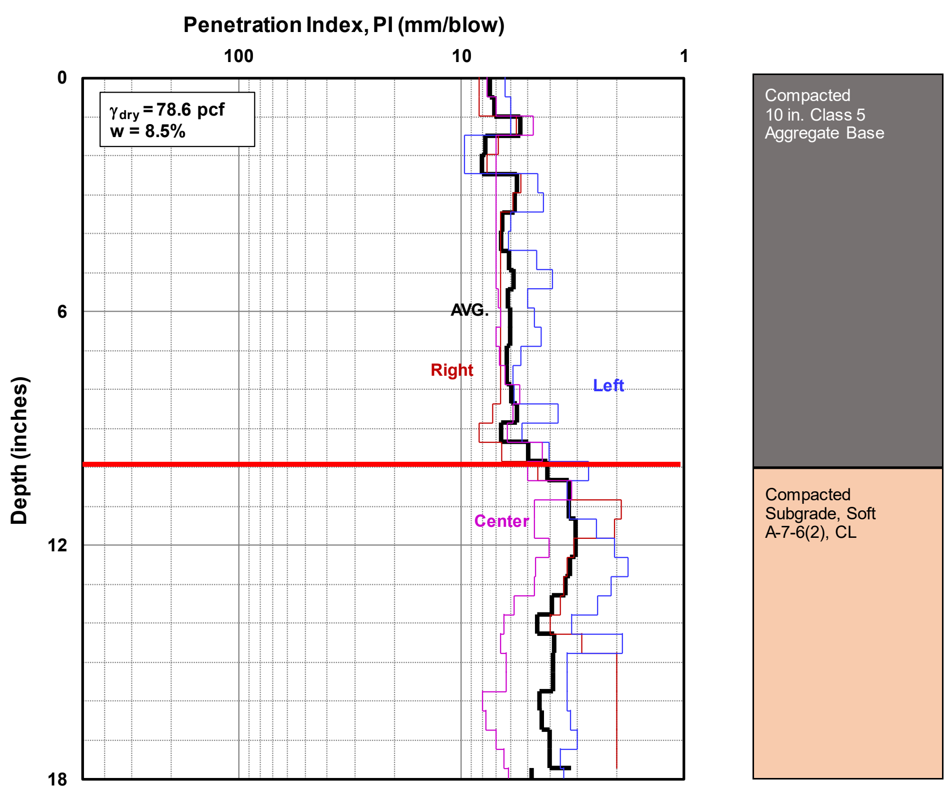
Project Name: ISU_MNDOT_NS555_Geogrid Stabilization
Project ID: ISP_00007
Location: Mankato city, MN

Figure G-12 Average DCP test results of control section 3

Date of Test	7/31/2020	Test ID	10" T1 (Light Duty Biaxial)	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA	Longitude		NA		Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN	Station		NA			
Comments	Nominal 10 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	5.2	6.4	6.8	6.0	38.9
Average: Subgrade Layer [10 to 16.0 in.]	2.9	8.9	2.5	9.3	24.1
Ratio of Average: Aggregate Base/Subgrade	1.79	0.72	2.67	0.65	1.6
Std. Dev.: Aggregate Base [0 to 10 in.]	1.6	0.9	0.9	0.8	5.1
Std. Dev.: Subgrade Layer [10 to 16.0 in.]	0.8	8.2	0.9	9.0	27.8

*Note: CBR = 292/(DPI)^1.12



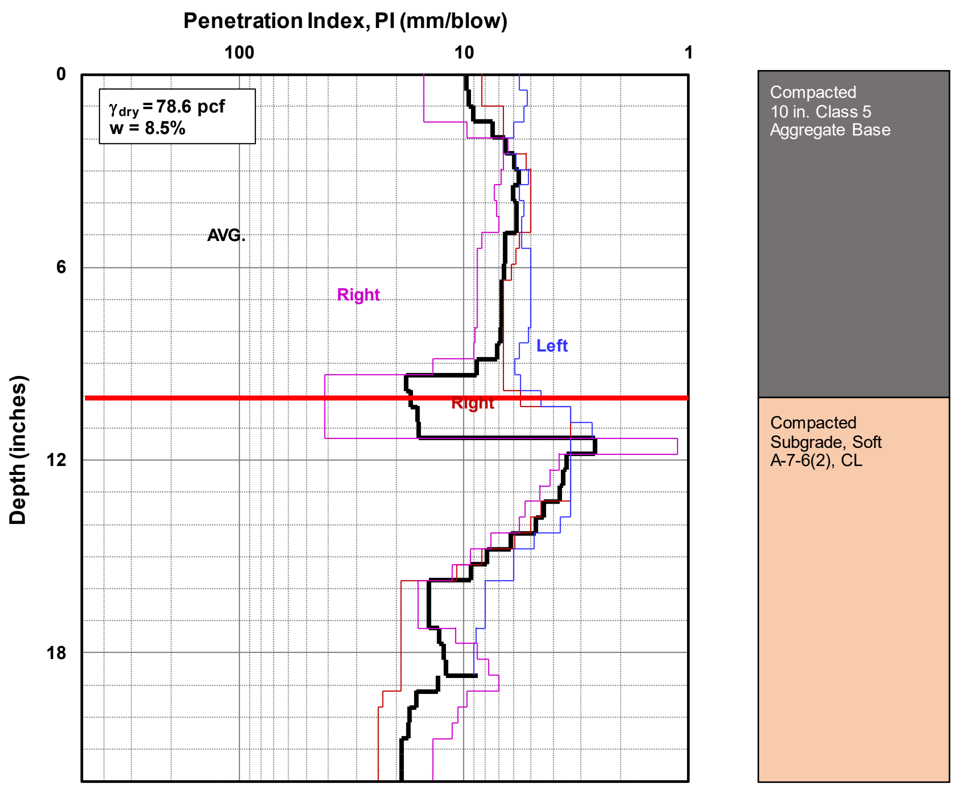
Dynamic Cone Penetrometer (DCP) Test Results	
Project Name:	ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Mankato city, MN

Figure G-13 Average DCP test results of section 1

Date of Test	7/31/2020	Test ID	10" T2 (High Duty Biaxial)	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA		Longitude	NA		Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN		Station	NA			
Comments	Nominal 10 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	5.4	8.2	6.2	6.4	36.4
Average: Subgrade Layer [10 to 16.0 in.]	4.6	8.5	7.9	10.4	21.3
Ratio of Average: Aggregate Base/Subgrade	1.18	0.96	0.78	0.62	1.7
Std. Dev.: Aggregate Base [0 to 10 in.]	0.4	7.6	1.0	2.7	7.7
Std. Dev.: Subgrade Layer [10 to 16.0 in.]	2.4	11.3	8.8	7.7	23.6

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

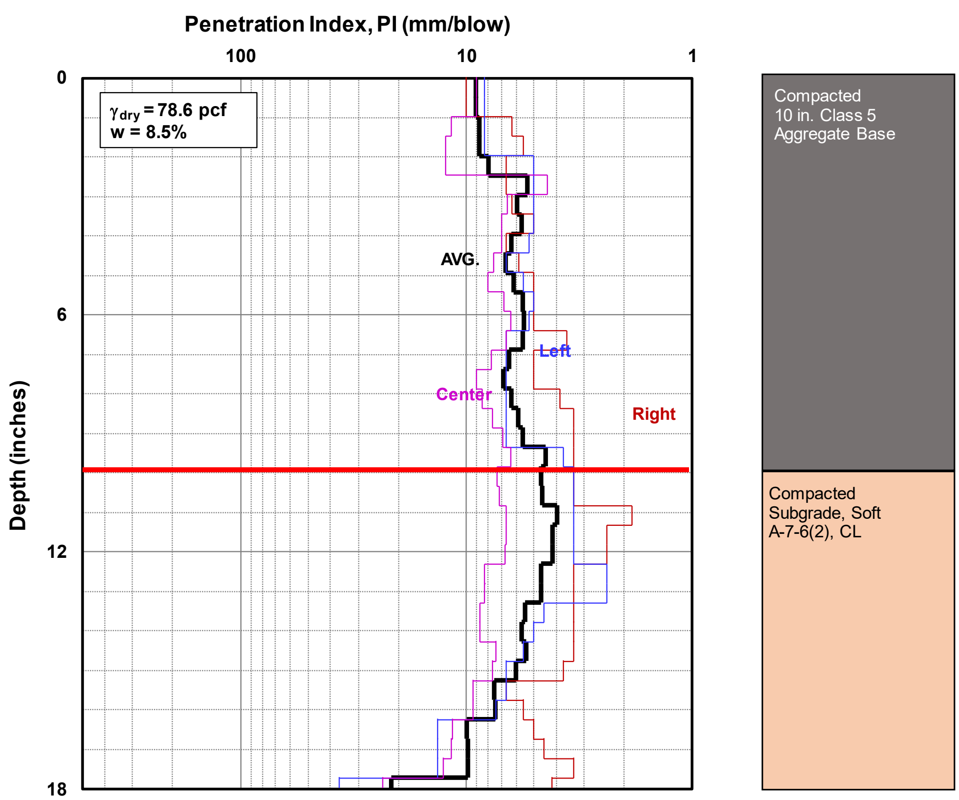
Location: Mankato city, MN

Figure G-14 Average DCP test results of section 2

Date of Test	7/31/2020	Test ID	10" T4 (Heavy Duty Triaxial)	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA	Longitude		NA		Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN	Station		NA			
Comments	Nominal 10 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	6.0	7.6	5.1	6.0	39.1
Average: Subgrade Layer [10 to 16.0 in.]	6.3	18.1	3.4	23.7	8.4
Ratio of Average: Aggregate Base/Subgrade	0.94	0.42	1.47	0.25	4.6
Std. Dev.: Aggregate Base [0 to 10 in.]	1.4	2.0	2.1	1.4	8.1
Std. Dev.: Subgrade Layer [10 to 16.0 in.]	11.6	18.1	1.2	19.0	19.2

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

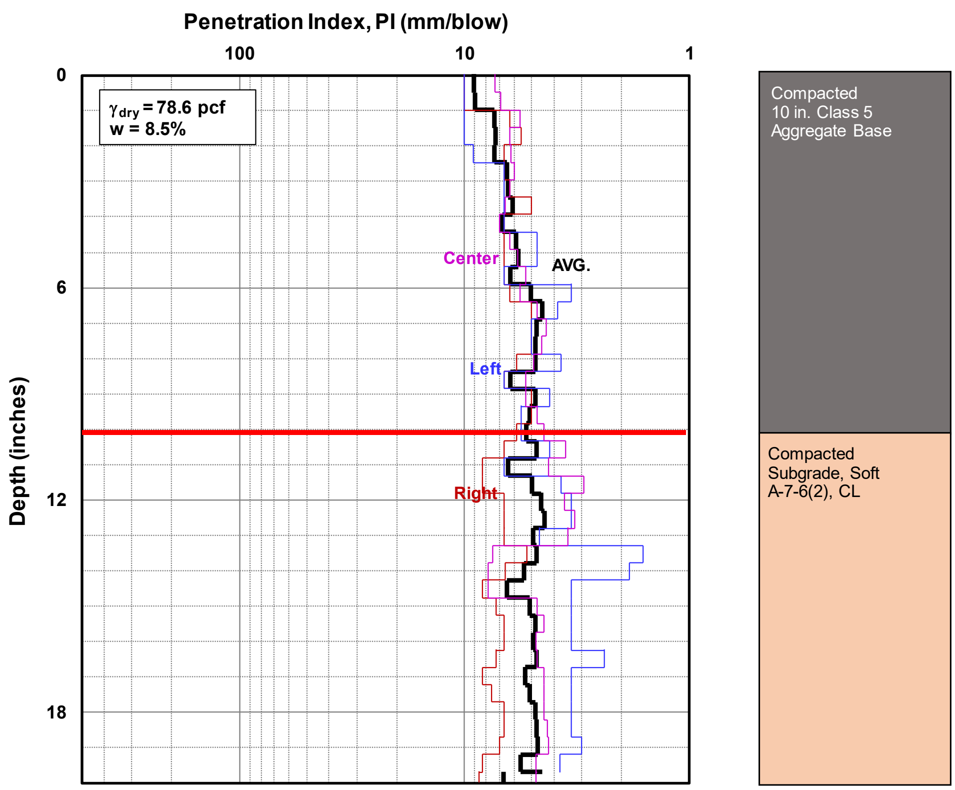
Project Name: ISU_MNDOT_NS555_Geogrid Stabilization
Project ID: ISP_00007
Location: Mankato city, MN

Figure G-15 Average DCP test results of section 4

Date of Test	7/31/2020	Test ID	10" T5 (Biaxial Ligh Duty-Center base position)	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA		Longitude	NA		Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN		Station	NA			
Comments	Nominal 10 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	5.7	5.6	6.1	5.8	40.6
Average: Subgrade Layer [10 to 16.0 in.]	3.2	4.9	7.2	4.9	49.5
Ratio of Average: Aggregate Base/Subgrade	1.79	1.14	0.84	1.19	0.8
Std. Dev.: Aggregate Base [0 to 10 in.]	2.3	0.9	1.6	1.4	9.1
Std. Dev.: Subgrade Layer [10 to 16.0 in.]	1.1	1.9	1.2	1.7	13.1

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

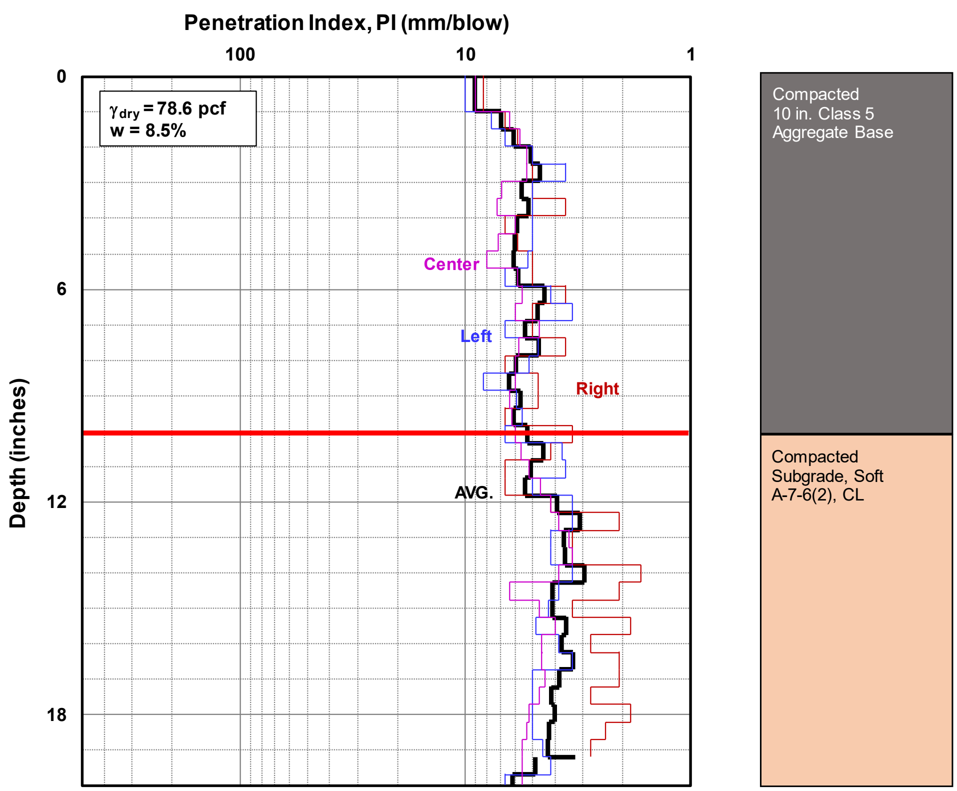
Location: Mankato city, MN

Figure G-16 Average DCP test results of section 5

Date of Test	7/31/2020	Test ID	10" T7 (Triaxial Light Duty - Center position)	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA		Longitude	NA		Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN		Station	NA			
Comments	Nominal 10 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 10.0 in.]	5.5	6.3	5.2	5.6	42.3
Average: Subgrade Layer [10 to 16.0 in.]	4.2	5.1	2.7	5.3	45.3
Ratio of Average: Aggregate Base/Subgrade	1.29	1.23	1.94	1.06	0.9
Std. Dev.: Aggregate Base [0 to 10 in.]	2.0	1.3	1.5	1.4	8.6
Std. Dev.: Subgrade Layer [10 to 16.0 in.]	1.0	0.9	1.5	1.1	13.4

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

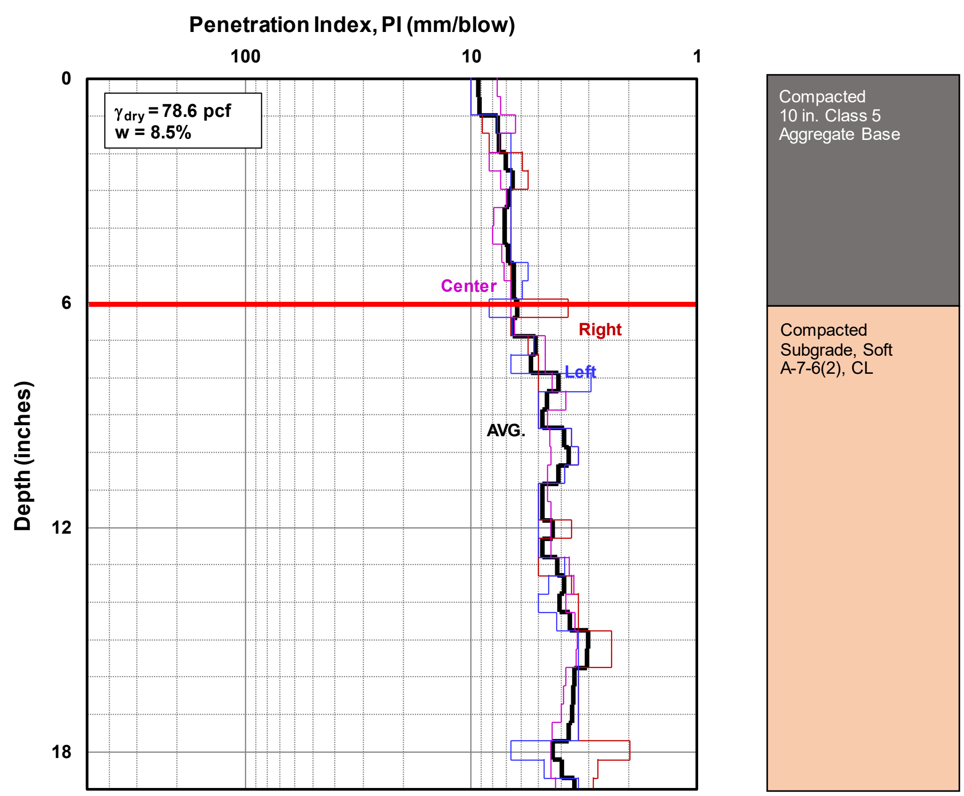
Location: Mankato city, MN

Figure G-17 Average DCP test results of section 7

Date of Test	8/7/2020	Test ID	6" T12 (Triaxial Heavy Duty)	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA		Longitude	NA		Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN		Station	NA			
Comments	Thick 16 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 6.0 in.]	6.9	7.4	7.1	7.1	32.3
Average: Subgrade Layer [6 to 19.0 in.]	4.2	4.2	3.6	4.2	58.9
Ratio of Average: Aggregate Base/Subgrade	1.67	1.77	1.99	1.71	0.5
Std. Dev.: Aggregate Base [0 to 10 in.]	1.6	0.5	1.6	1.1	4.4
Std. Dev.: Subgrade Layer [10 to 16.0 in.]	1.3	0.7	1.1	0.8	11.8

*Note: CBR = 292/(DPI)^1.12



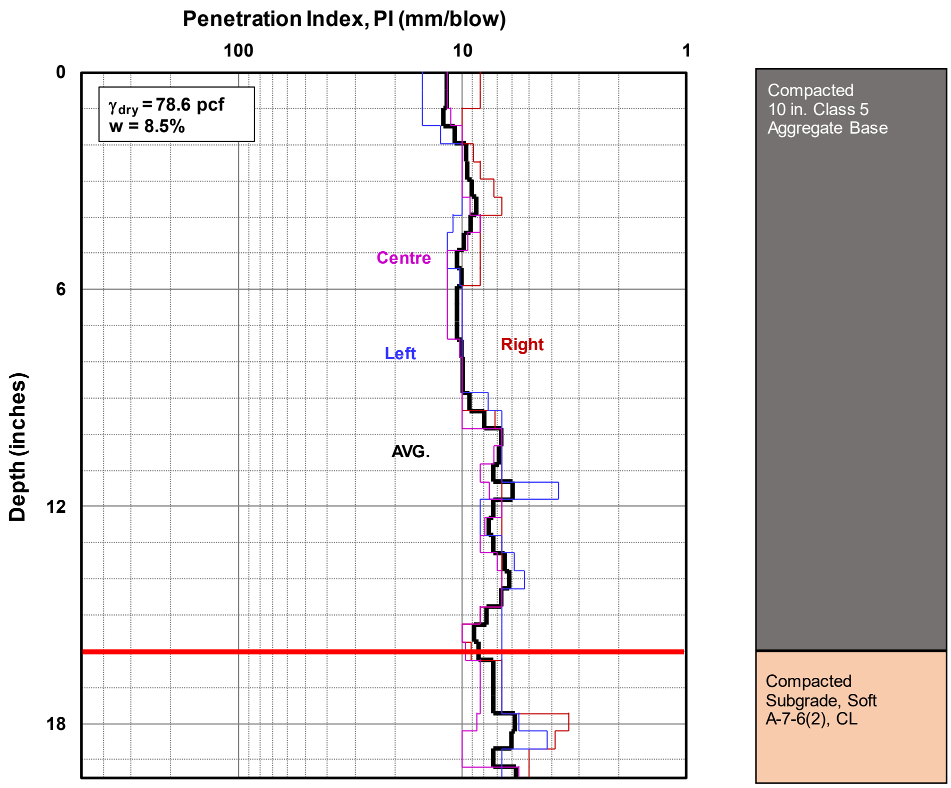
Dynamic Cone Penetrometer (DCP) Test Results	
Project Name:	ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Mankato city, MN

Figure G-18 Average DCP test results of section 12

Date of Test	8/7/2020	Test ID	16" T15	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA		Longitude	NA		Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN		Station	NA			
Comments	Thick 16 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 16.0 in.]	8.3	9.1	8.0	8.5	26.7
Average: Subgrade Layer [16 to 20.0 in.]	5.9	7.6	4.7	5.8	40.5
Ratio of Average: Aggregate Base/Subgrade	1.41	1.20	1.71	1.45	0.7
Std. Dev.: Aggregate Base [0 to 16 in.]	3.0	1.8	1.4	1.8	6.2
Std. Dev.: Subgrade Layer [16 to 20.0 in.]	0.9	1.8	1.9	1.1	7.8

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

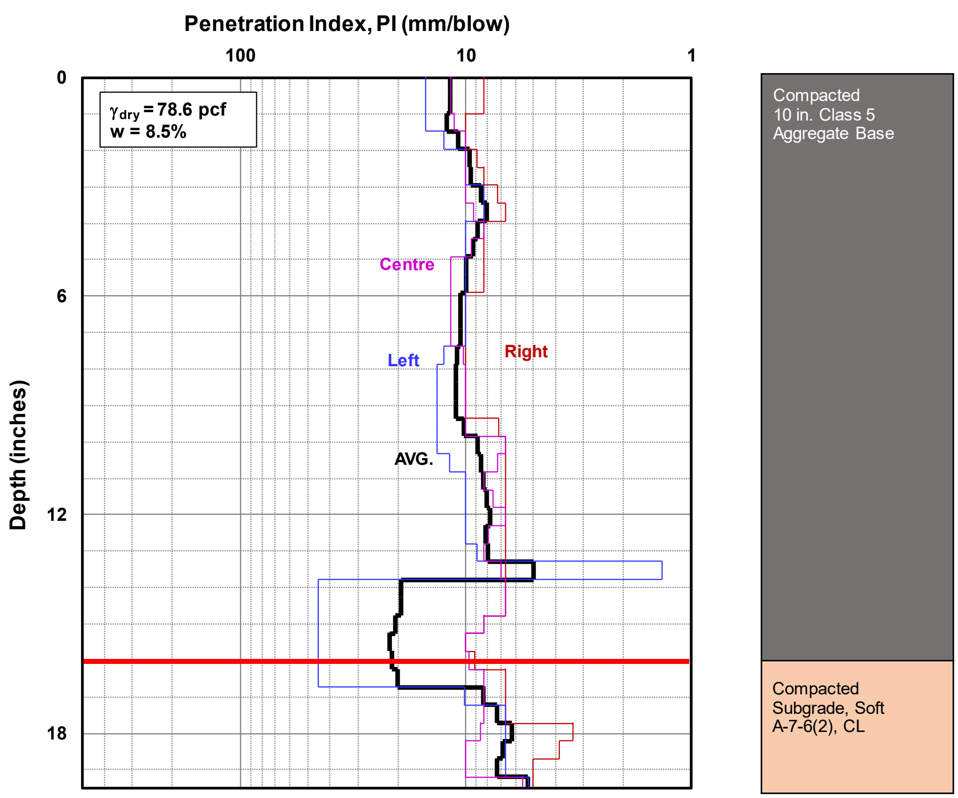
Location: Mankato city, MN

Figure G-19 Average DCP test results of section 15

Date of Test	8/7/2020	Test ID	16" T15 and control 3 intersection test	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA	Longitude	NA			Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN	Station	NA				
Comments	Thick 16 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 16.0 in.]	9.7	9.1	8.0	8.9	25.3
Average: Subgrade Layer [16 to 20.0 in.]	7.2	7.6	4.7	6.2	37.9
Ratio of Average: Aggregate Base/Subgrade	1.34	1.20	1.71	1.43	0.7
Std. Dev.: Aggregate Base [0 to 16 in.]	11.6	1.8	1.4	3.8	7.2
Std. Dev.: Subgrade Layer [16 to 20.0 in.]	16.9	1.8	1.9	6.3	14.8

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

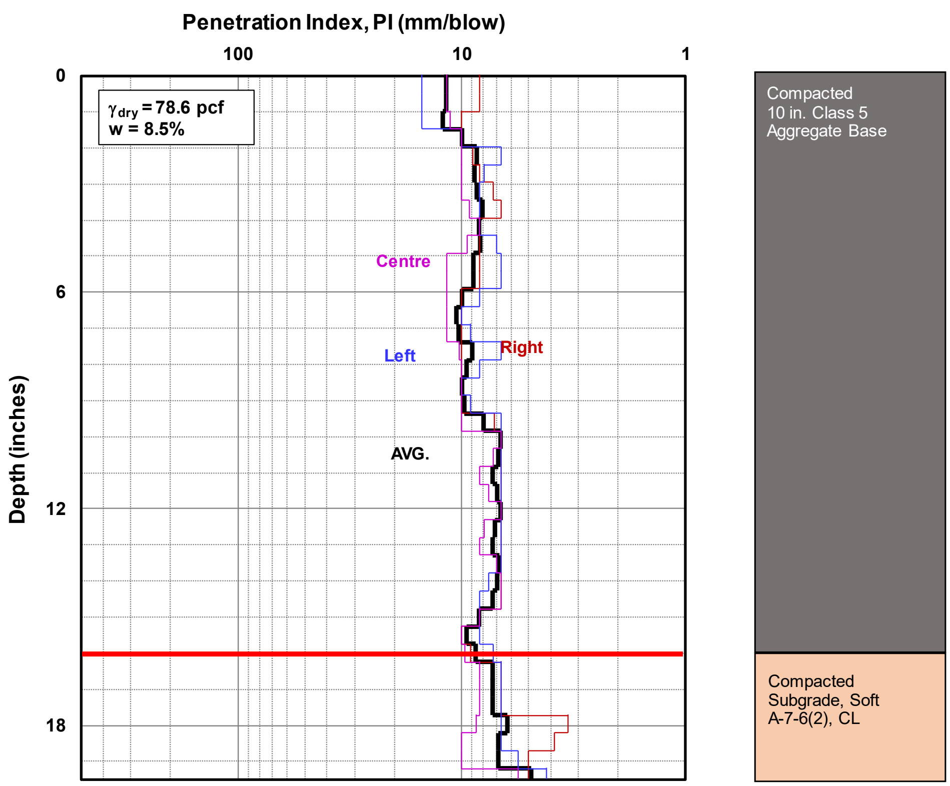
Location: Mankato city, MN

Figure G-20 DCP test results of section 15 and control section 3

Date of Test	8/7/2020	Test ID	16" T15 end lane point	Operator	V. S. & H. A.	ASTM	D6951
Latitude	NA		Longitude	NA		Elevation (ft)	NA
Location	S Riverdrive, Mankato city, MN		Station	NA			
Comments	Thick 16 in. of aggregate base course Class 5 over compacted subgrade. Three tests conducted in each test sections						

DPI (mm/blow) Statistics	Left	Centre	Right	AVG. DPI (mm/blow)	AVG. CBR* (%)
Average: Aggregate Base [0 to 16.0 in.]	7.9	9.1	8.0	8.3	27.3
Average: Subgrade Layer [16 to 20.0 in.]	6.1	7.6	4.7	5.9	40.2
Ratio of Average: Aggregate Base/Subgrade	1.31	1.20	1.71	1.41	0.7
Std. Dev.: Aggregate Base [0 to 16 in.]	2.6	1.8	1.4	1.6	5.3
Std. Dev.: Subgrade Layer [16 to 20.0 in.]	0.9	1.8	1.9	1.2	7.8

*Note: CBR = 292/(DPI)^1.12



Dynamic Cone Penetrometer (DCP) Test Results

Project Name: ISU_MNDOT_NS555_Geogrid Stabilization

Project ID: ISP_00007

Location: Mankato city, MN

Figure G-21 DCP test results of the end of section 15

APPENDIX H
FIELD TEST PICTURES AND LOCATION

Project Location and Test Locations

Test Locations	
Project Name:	ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Riverfront Drive between Carney St and Woodland Ave, Mankato, MN

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Figure H-1 condition of sites and procedure of construction of base and subgrade and setting the geogrids in the construction process

Site Conditions and Pictures

Pictures

Project Name:	ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Riverfront Drive between Carney St and Woodland Ave, Mankato, MN

Figure H-2 condition of sites and procedure of construction of base and subgrade and setting the geogrids in the construction process

Site Conditions and Pictures

Pictures	
Project Name:	ISP_00007 ISU_MNDOT_NS555_Geogrid Stabilization
Project ID:	ISP_00007
Location:	Riverfront Drive between Carney St and Woodland Ave, Mankato, MN

ingios

Figure H-3 condition of sites and procedure of construction of base and subgrade and setting the geogrids in the construction process

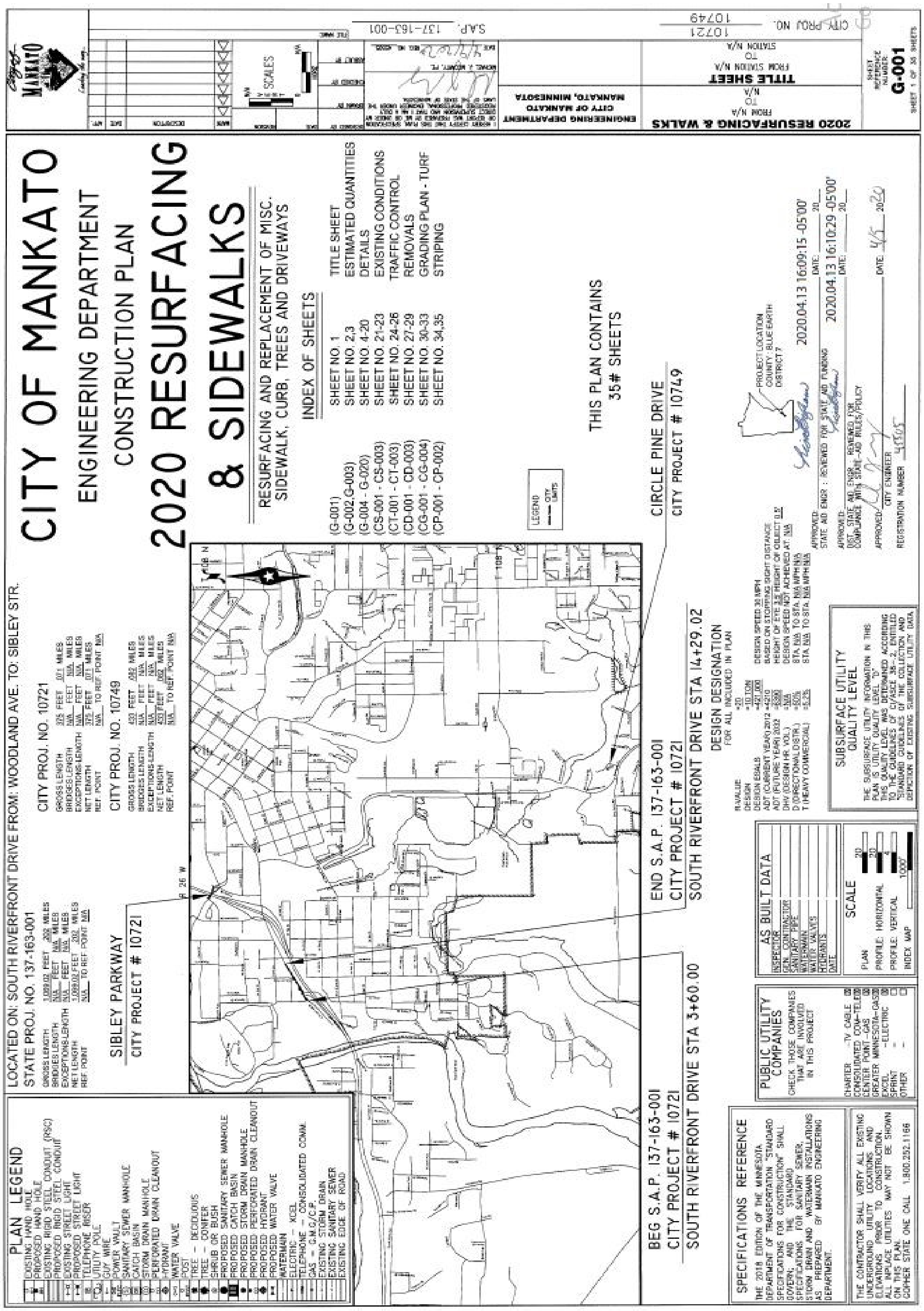


Figure H-4 Project location and the field location in the city of Mankato and test arrangements

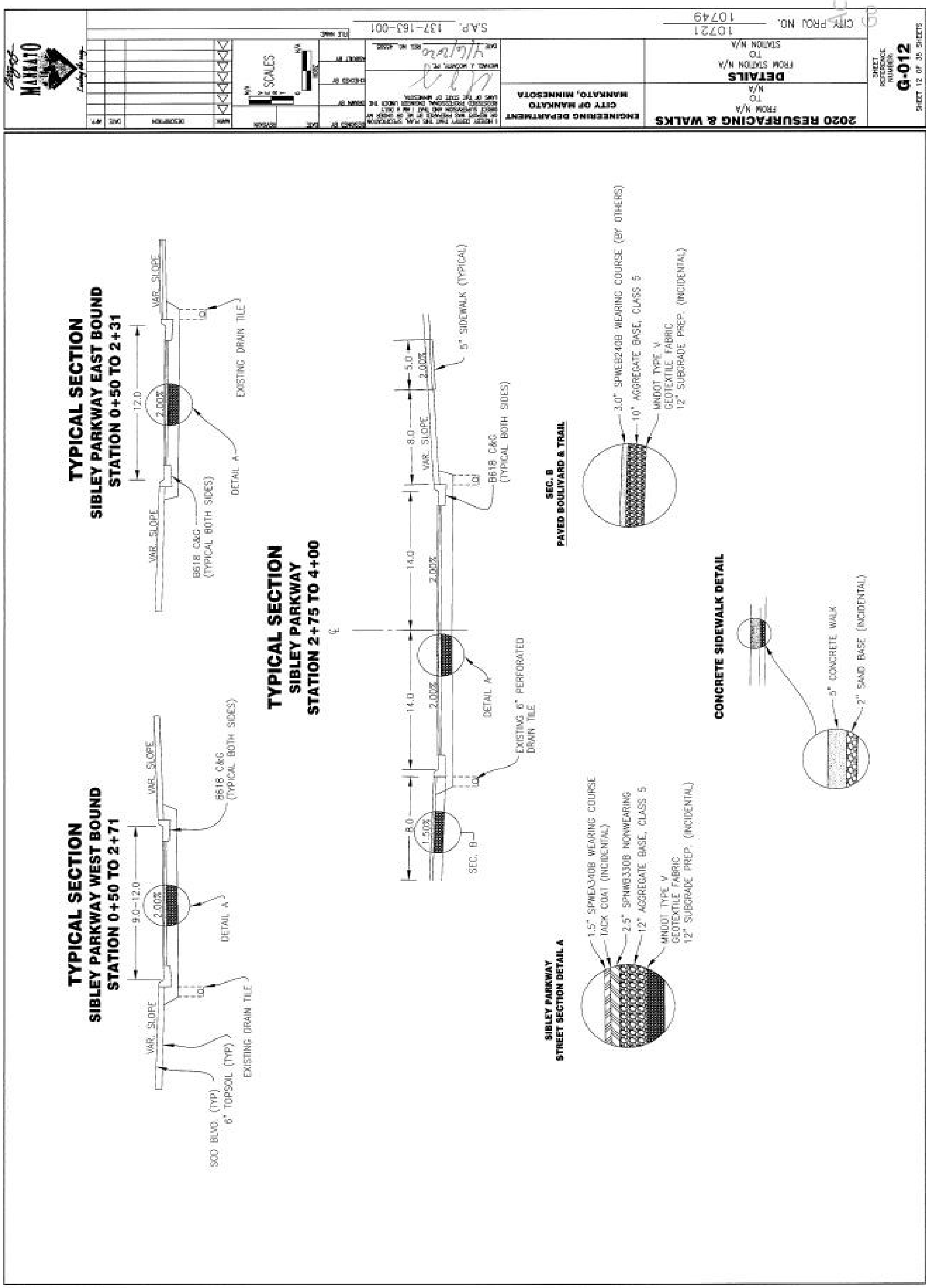


Figure H-5 Project location and the field location in the city of Mankato and test arrangements

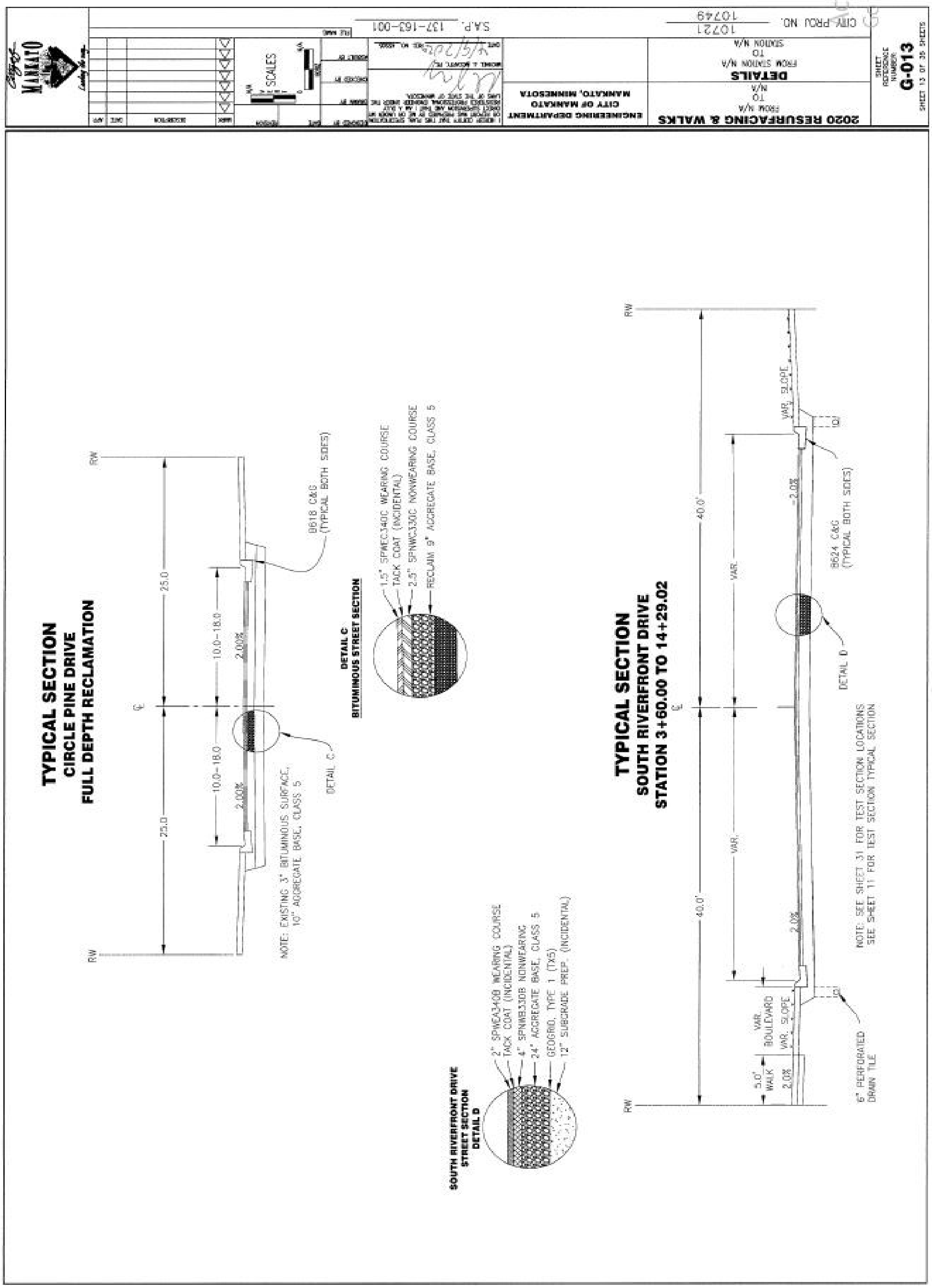


Figure H-6 Project location and the field location in the city of Mankato and test arrangements

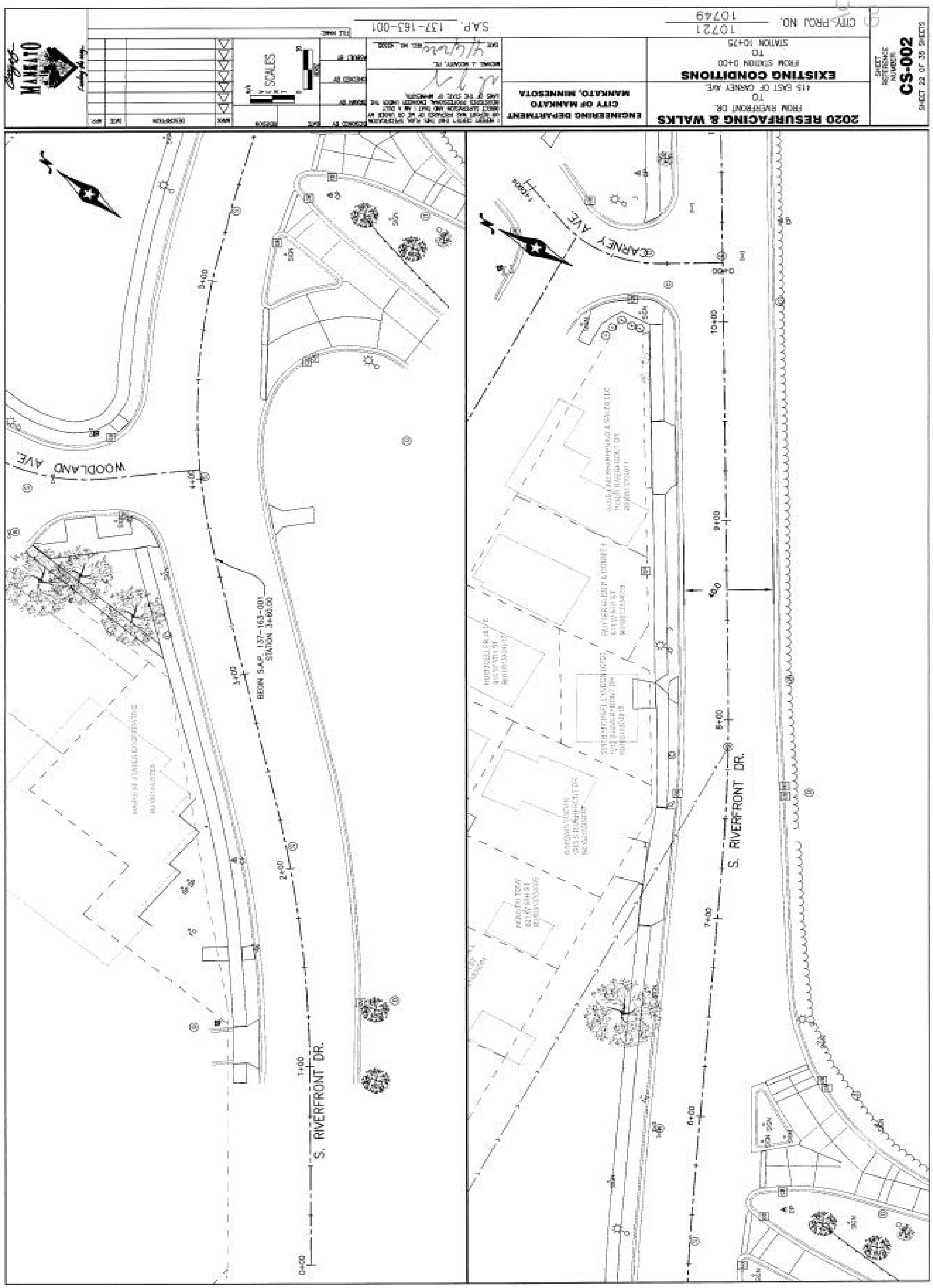


Figure H-7 Project location and the field location in the city of Mankato and test arrangements

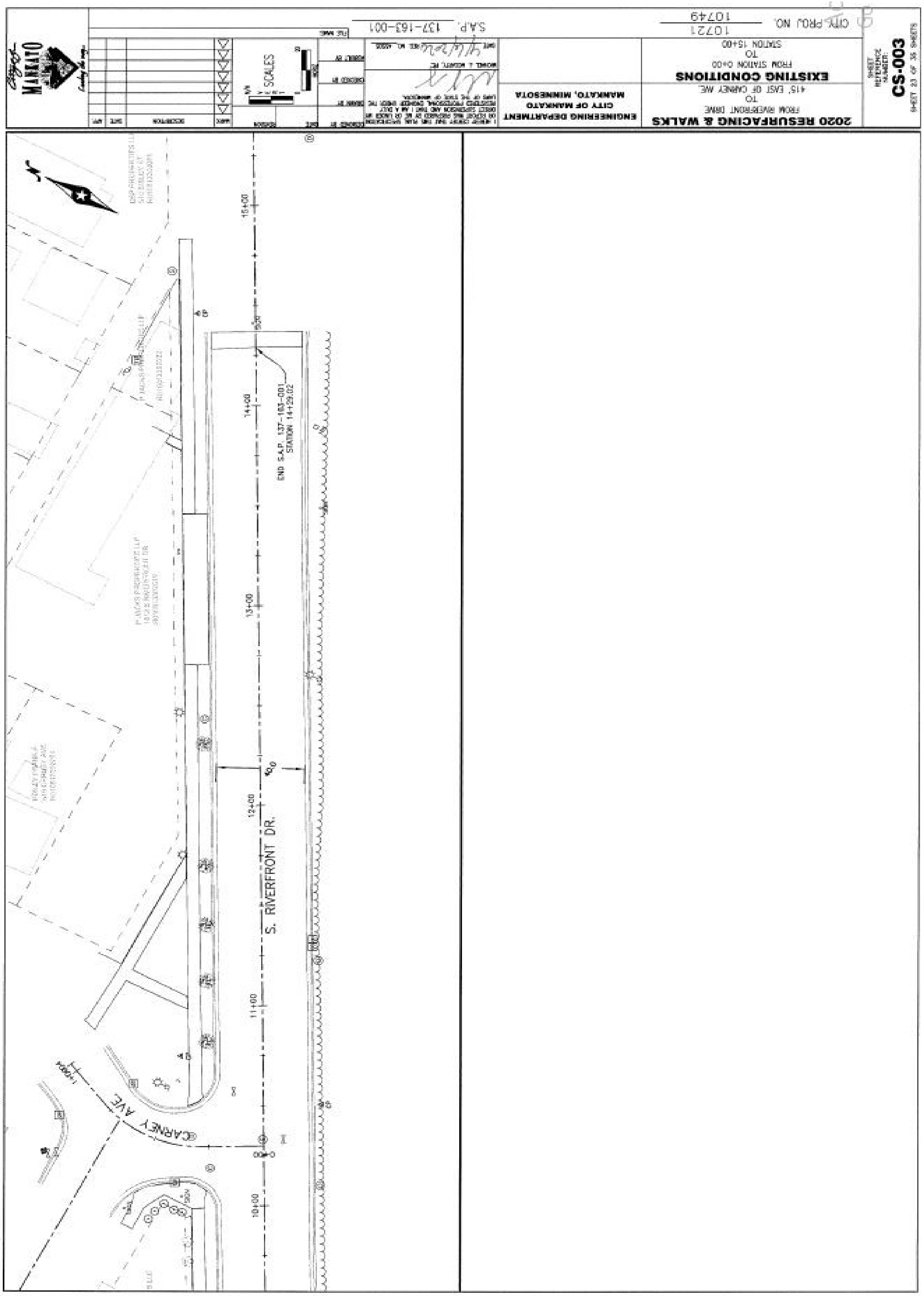


Figure H-8 Project location and the field location in the city of Mankato and test arrangements

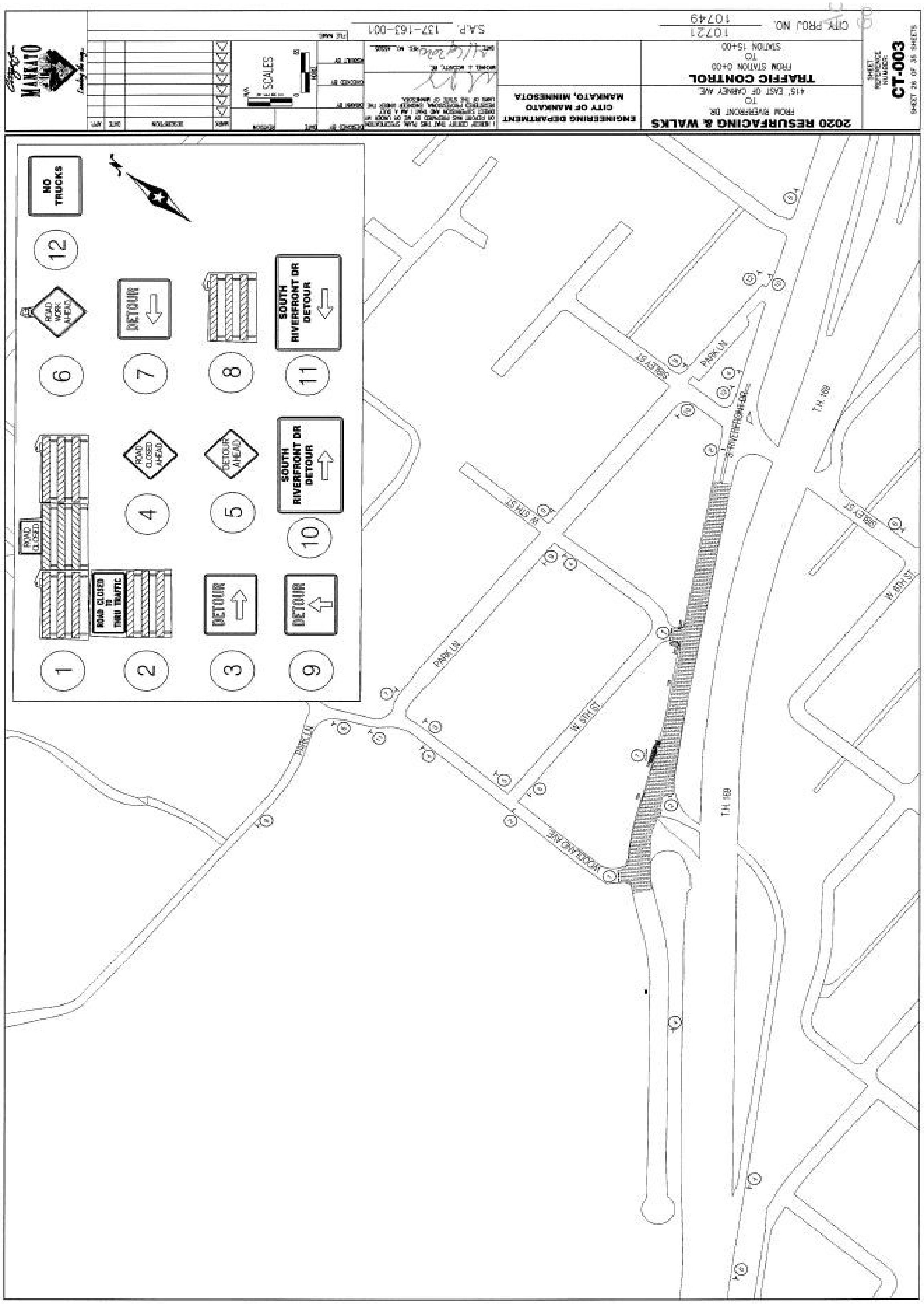


Figure H-9 Project location and the field location in the city of Mankato and test arrangements

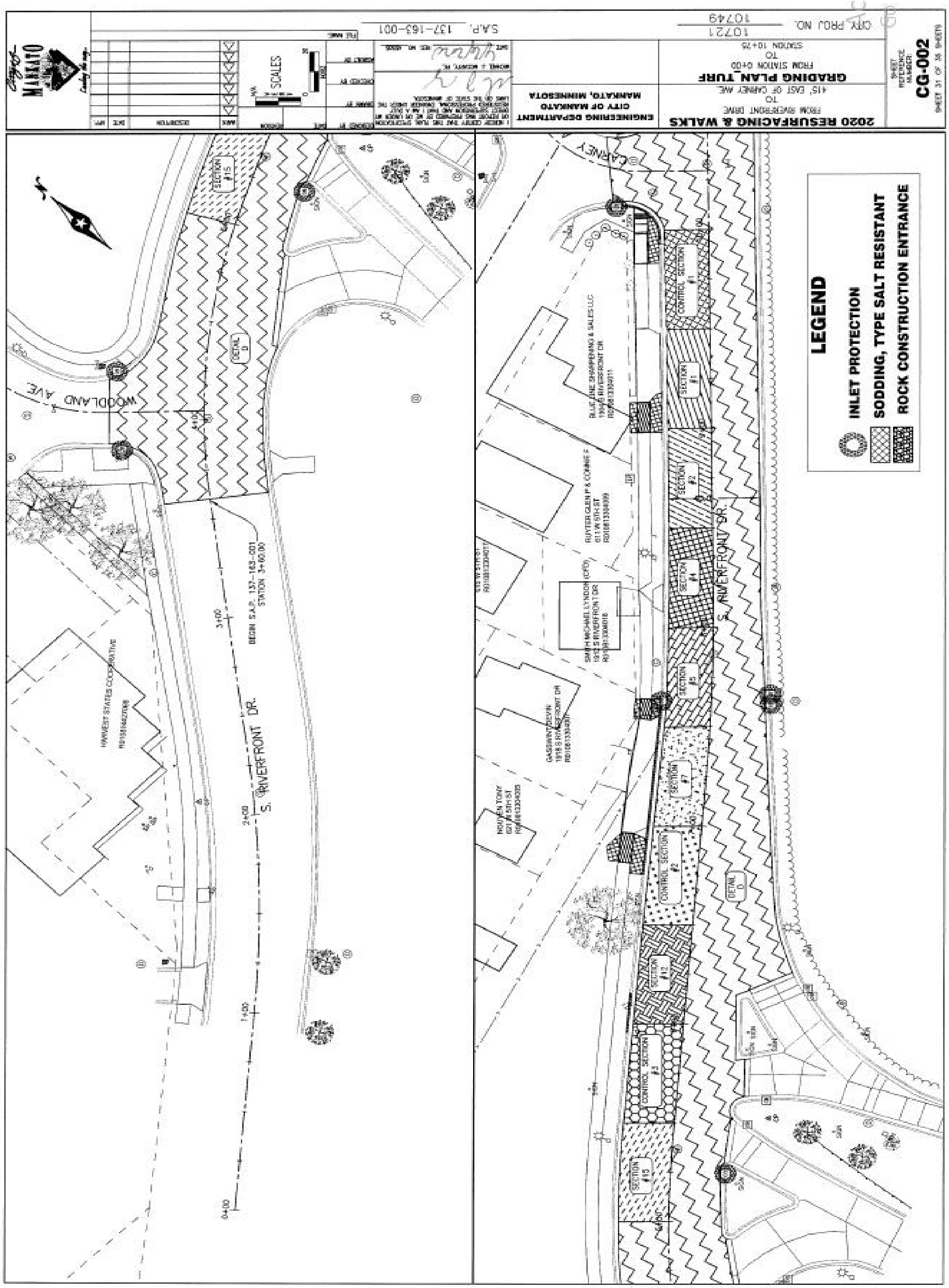


Figure H-10 Project location and the field location in the city of Mankato and test arrangements

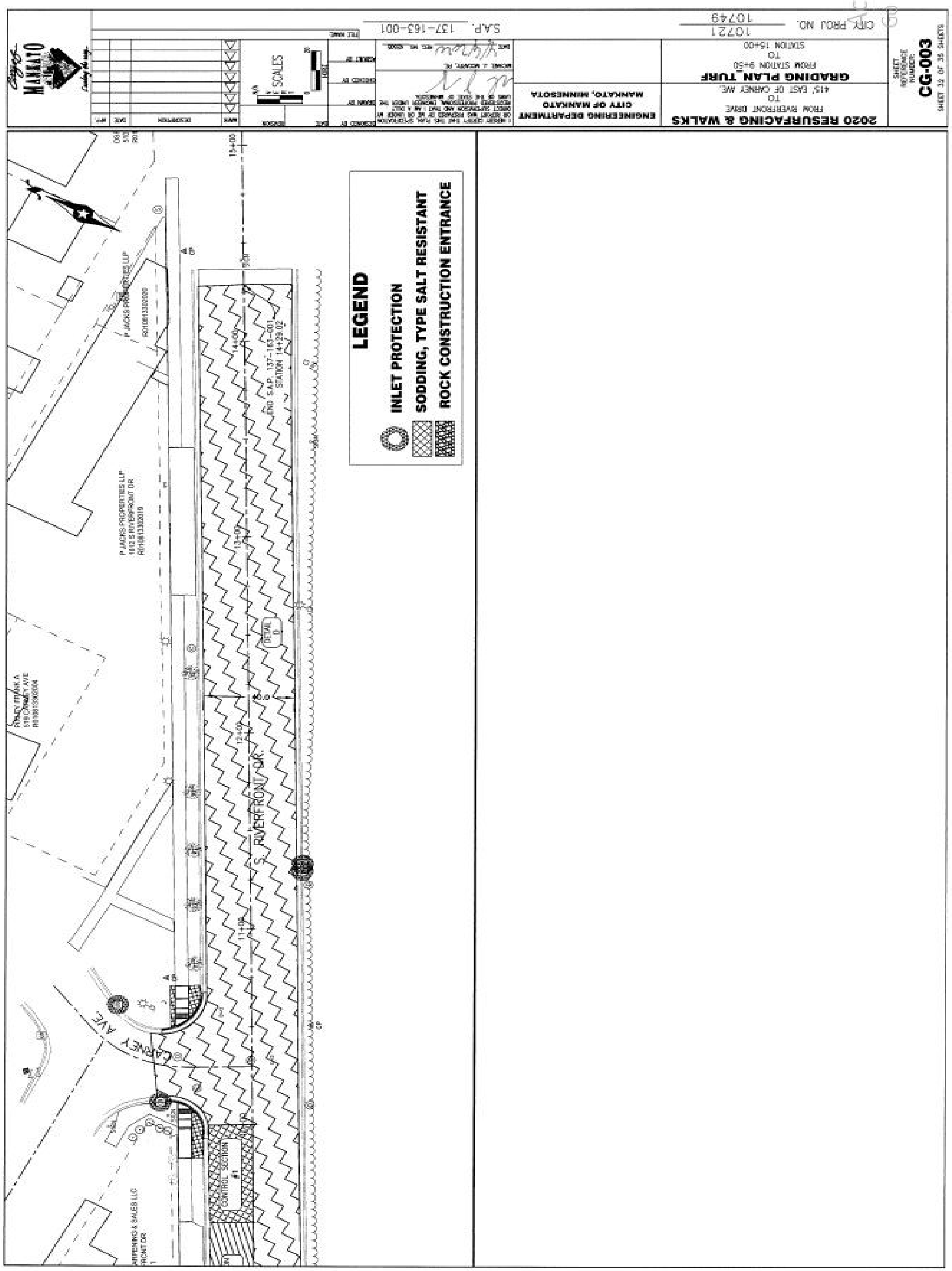


Figure H-11 Project location and the field location in the city of Mankato and test arrangements

APPENDIX I

TENSAR SOFTWARE SIMULATIONS INPUT PARAMETERS AND STEPS

Input information for the roads in the spectra software was as below:
For unreinforced section and section 1:

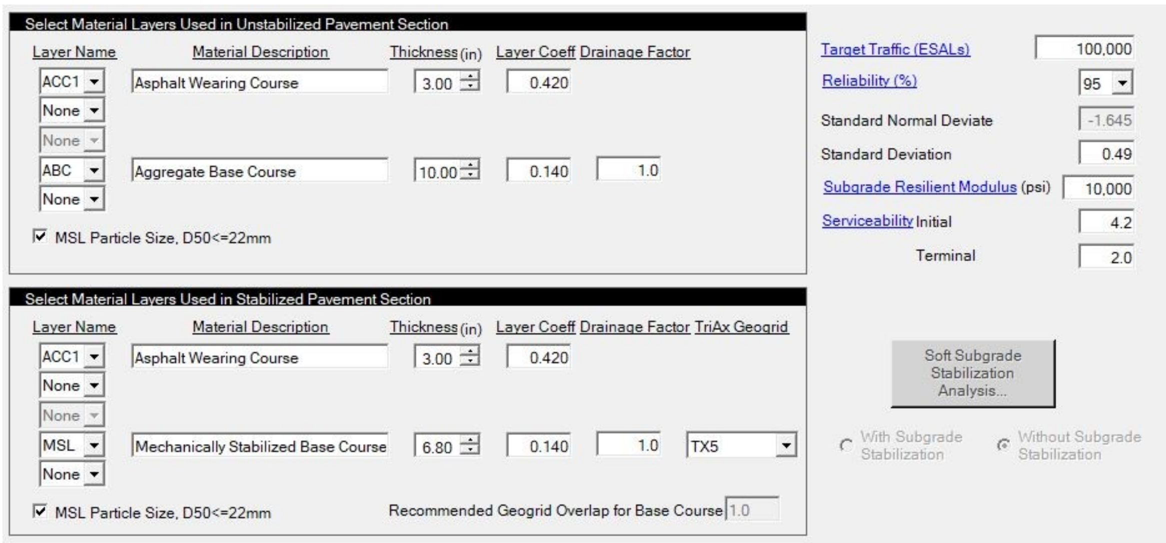


Figure I-1 Input information for the roads in the spectra software

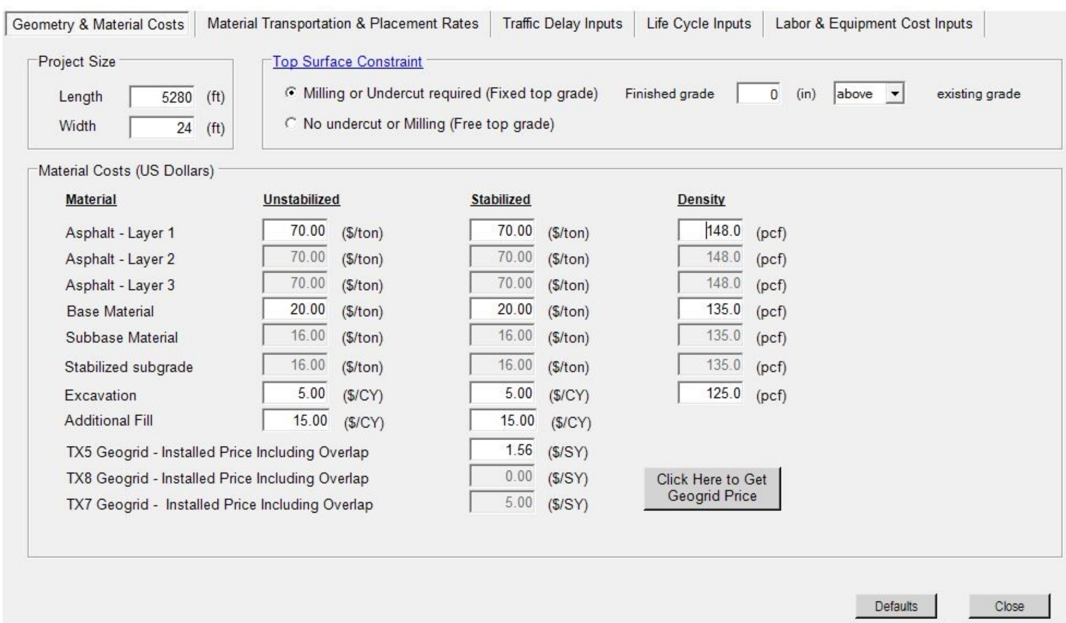
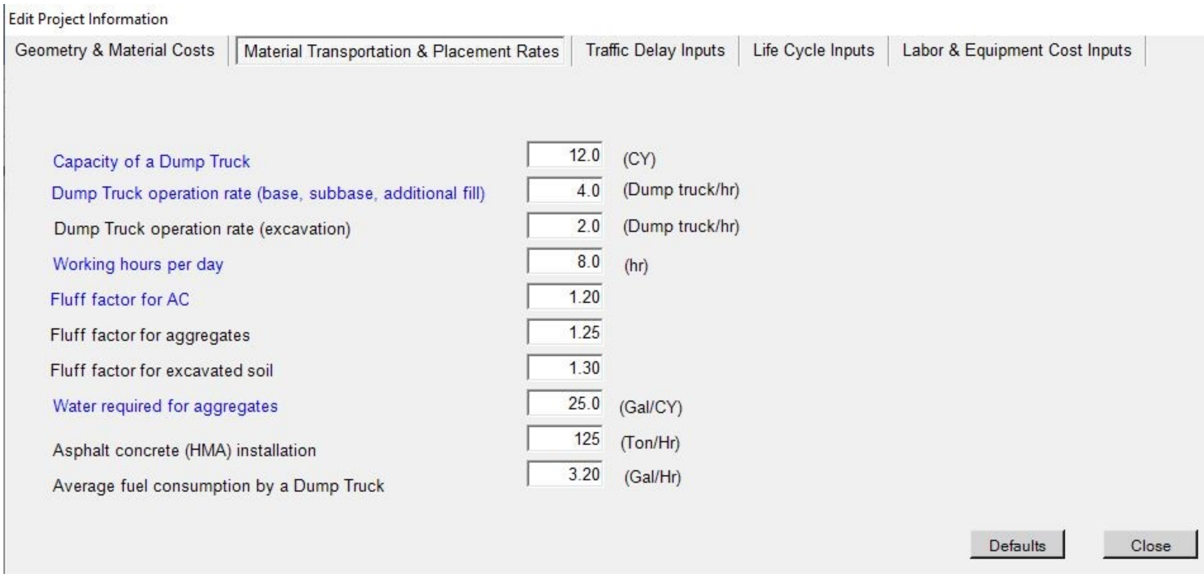


Figure I-2 Input information for the roads in the spectra software



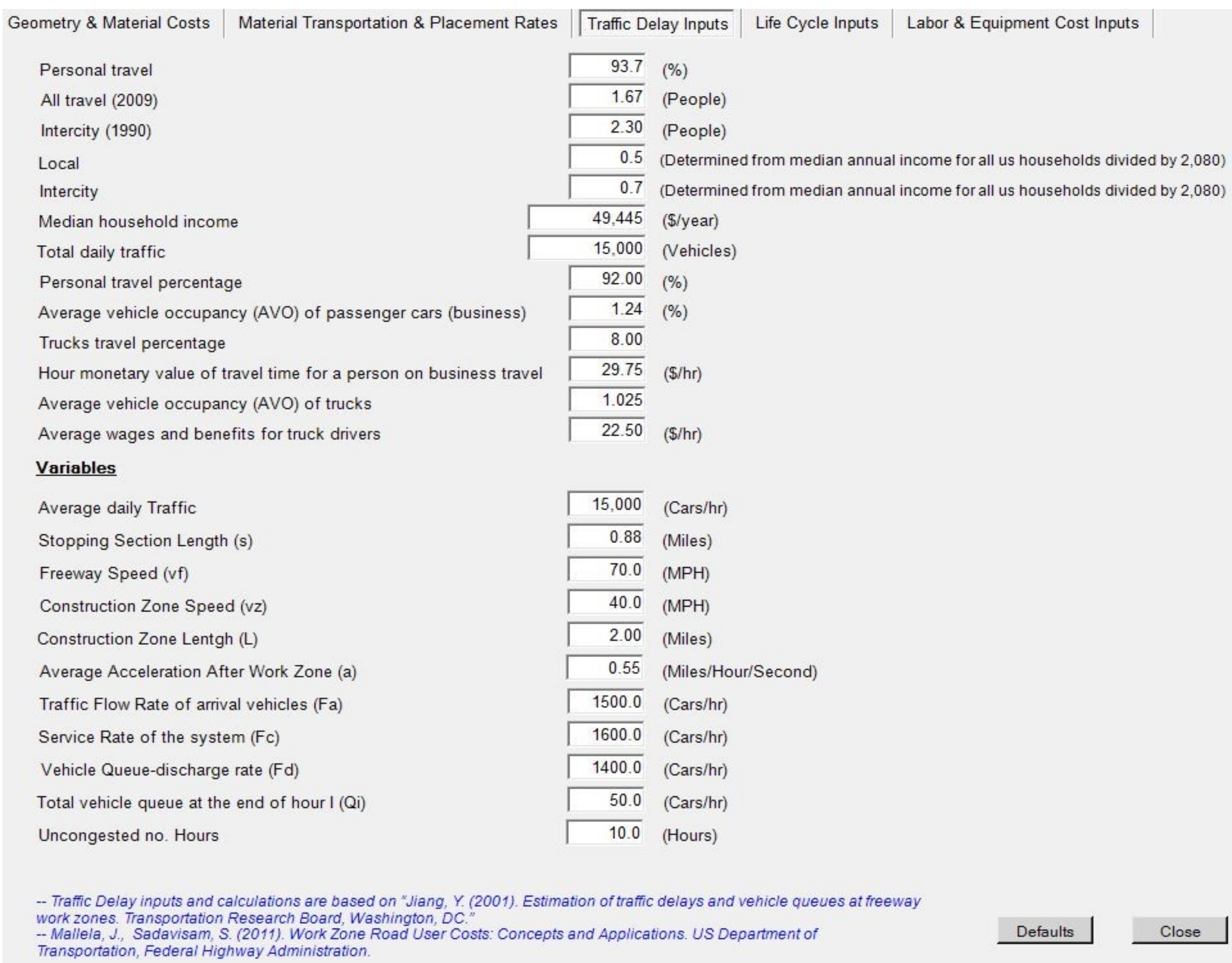
Edit Project Information

Geometry & Material Costs | Material Transportation & Placement Rates | Traffic Delay Inputs | Life Cycle Inputs | Labor & Equipment Cost Inputs

Capacity of a Dump Truck	12.0	(CY)
Dump Truck operation rate (base, subbase, additional fill)	4.0	(Dump truck/hr)
Dump Truck operation rate (excavation)	2.0	(Dump truck/hr)
Working hours per day	8.0	(hr)
Fluff factor for AC	1.20	
Fluff factor for aggregates	1.25	
Fluff factor for excavated soil	1.30	
Water required for aggregates	25.0	(Gal/CY)
Asphalt concrete (HMA) installation	125	(Ton/Hr)
Average fuel consumption by a Dump Truck	3.20	(Gal/Hr)

Defaults | Close

Figure I-3 Input information for the roads in the spectra software



Geometry & Material Costs | Material Transportation & Placement Rates | Traffic Delay Inputs | Life Cycle Inputs | Labor & Equipment Cost Inputs

Personal travel	93.7	(%)
All travel (2009)	1.67	(People)
Intercity (1990)	2.30	(People)
Local	0.5	(Determined from median annual income for all us households divided by 2,080)
Intercity	0.7	(Determined from median annual income for all us households divided by 2,080)
Median household income	49,445	($/year)
Total daily traffic	15,000	(Vehicles)
Personal travel percentage	92.00	(%)
Average vehicle occupancy (AVO) of passenger cars (business)	1.24	(%)
Trucks travel percentage	8.00	
Hour monetary value of travel time for a person on business travel	29.75	($/hr)
Average vehicle occupancy (AVO) of trucks	1.025	
Average wages and benefits for truck drivers	22.50	($/hr)

Variables

Average daily Traffic	15,000	(Cars/hr)
Stopping Section Length (s)	0.88	(Miles)
Freeway Speed (vf)	70.0	(MPH)
Construction Zone Speed (vz)	40.0	(MPH)
Construction Zone Lentgh (L)	2.00	(Miles)
Average Acceleration After Work Zone (a)	0.55	(Miles/Hour/Second)
Traffic Flow Rate of arrival vehicles (Fa)	1500.0	(Cars/hr)
Service Rate of the system (Fc)	1600.0	(Cars/hr)
Vehicle Queue-discharge rate (Fd)	1400.0	(Cars/hr)
Total vehicle queue at the end of hour I (Qi)	50.0	(Cars/hr)
Uncongested no. Hours	10.0	(Hours)

-- Traffic Delay inputs and calculations are based on "Jiang, Y. (2001). Estimation of traffic delays and vehicle queues at freeway work zones. Transportation Research Board, Washington, DC."
-- Mallela, J., Sadavisam, S. (2011). Work Zone Road User Costs: Concepts and Applications. US Department of Transportation, Federal Highway Administration.

Defaults | Close

Figure I-4 Input information for the roads in the spectra software

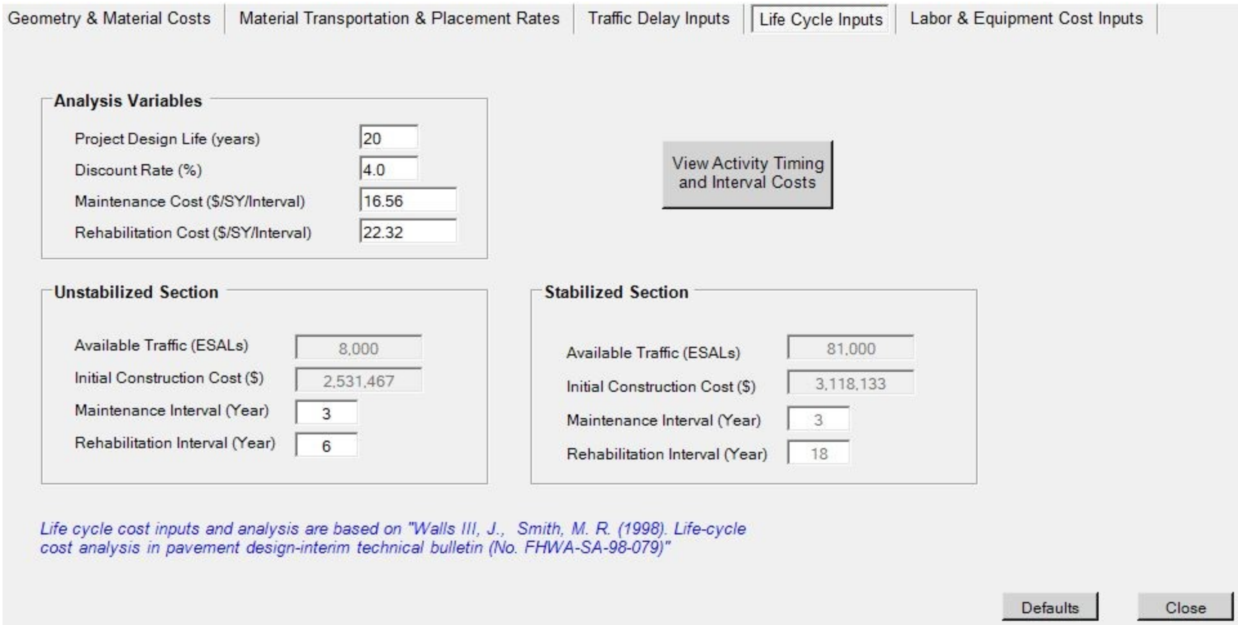


Figure I-5 Input information for the roads in the spectra software

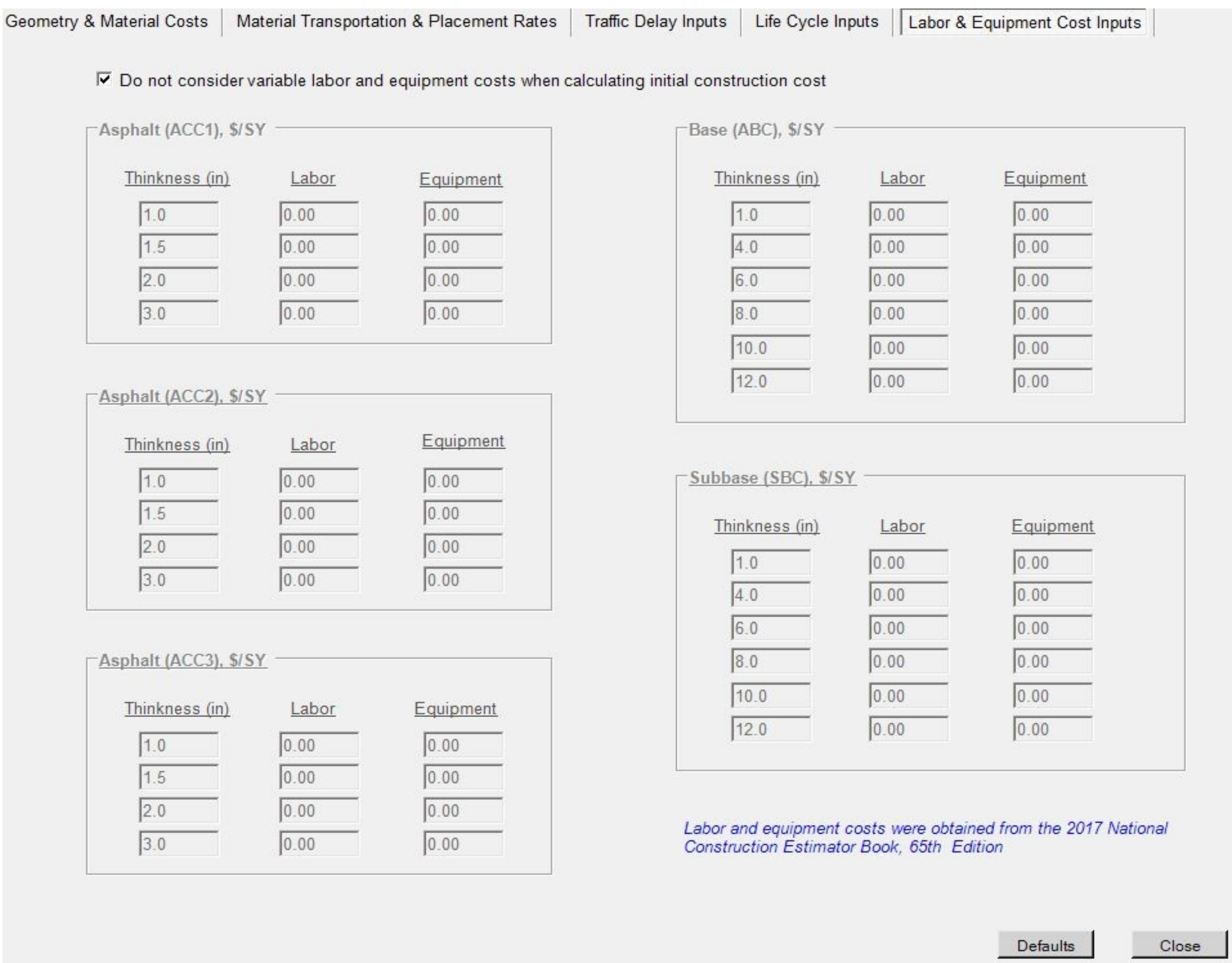


Figure I-6 Input information for the roads in the spectra software

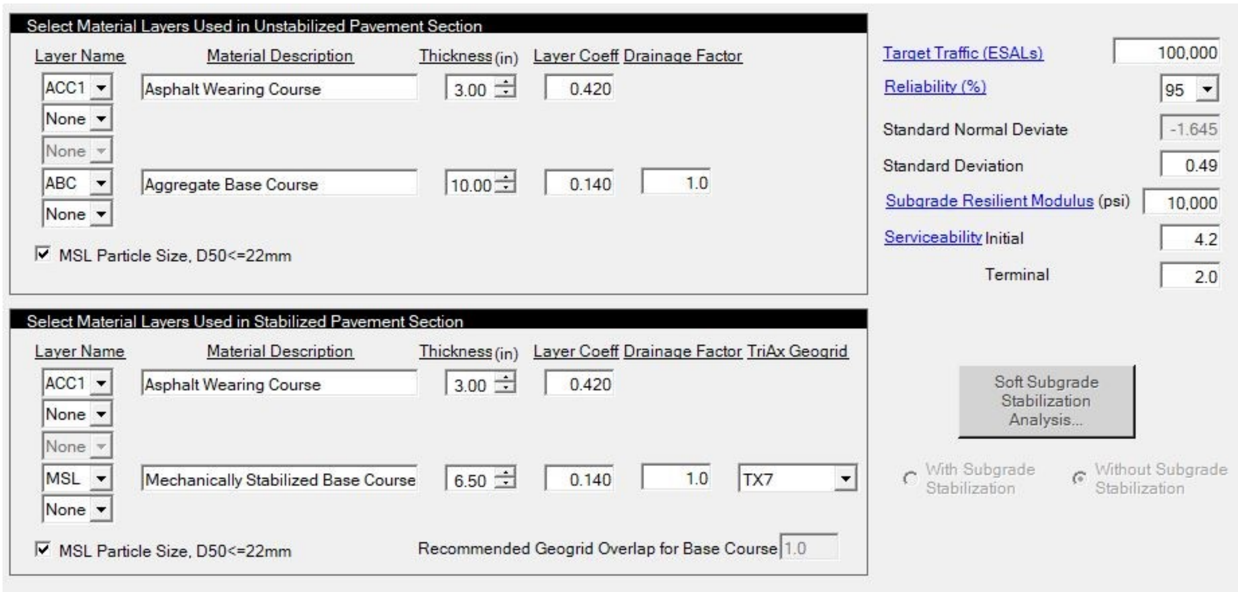


Figure I-7 Input information for the roads in the spectra software

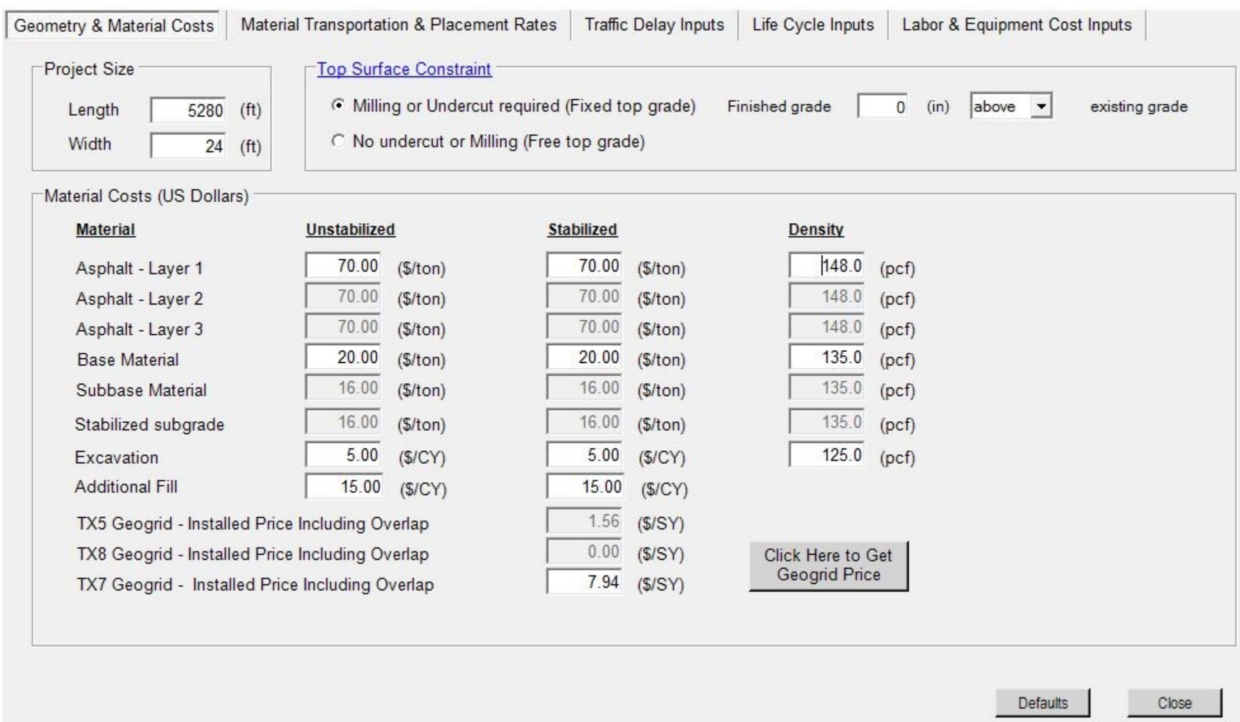


Figure I-8 Input information for the roads in the spectra software

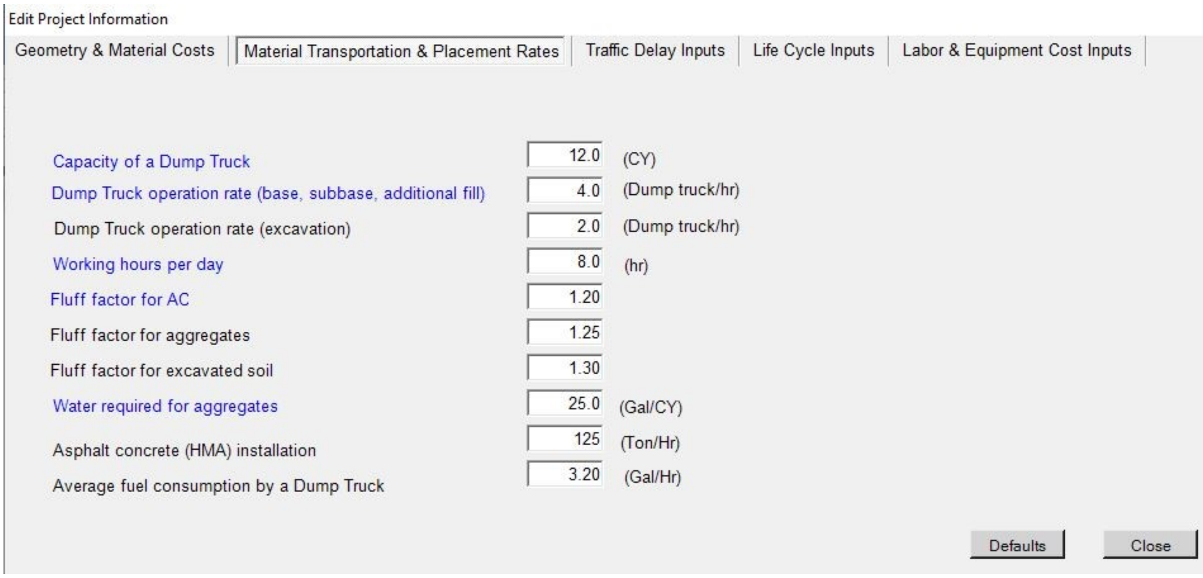


Figure I-9 Input information for the roads in the spectra software

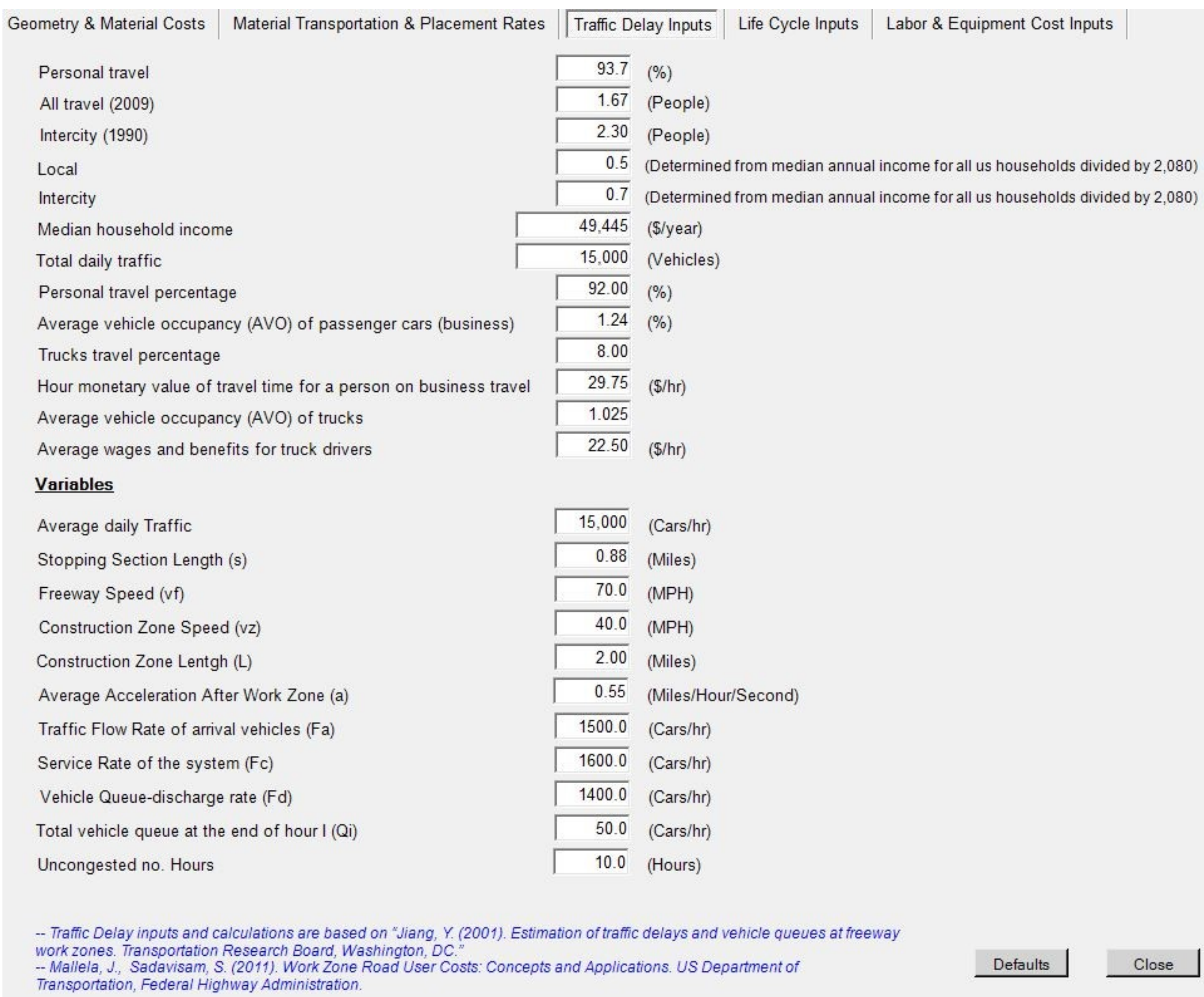


Figure I-10 Input information for the roads in the spectra software

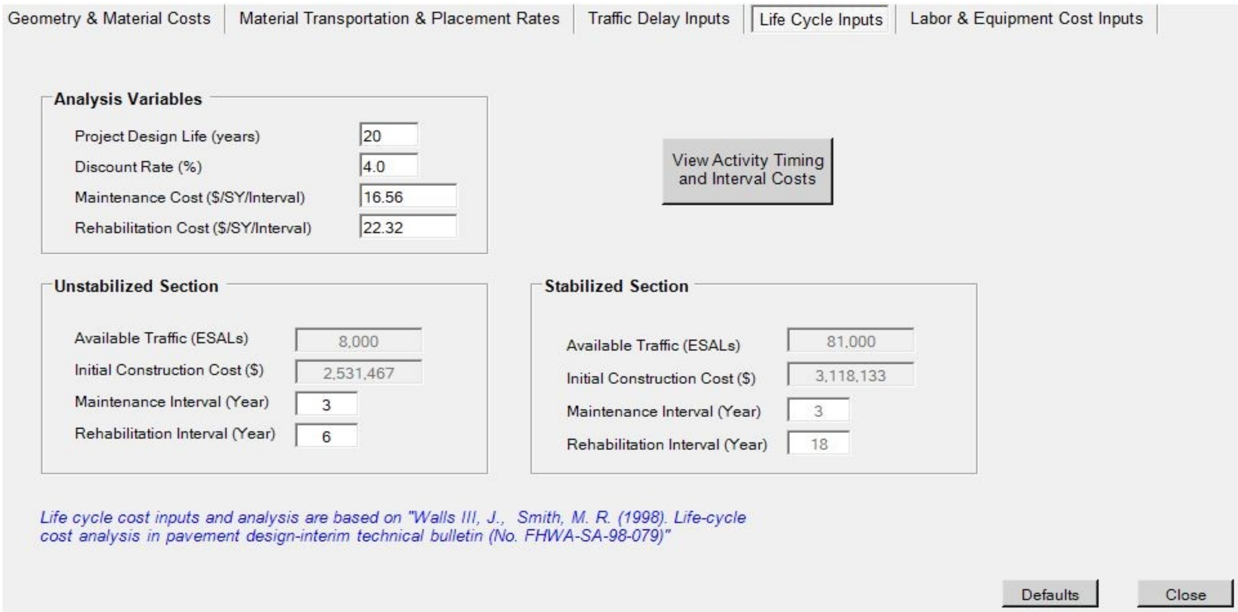


Figure I-11 Input information for the roads in the spectra software

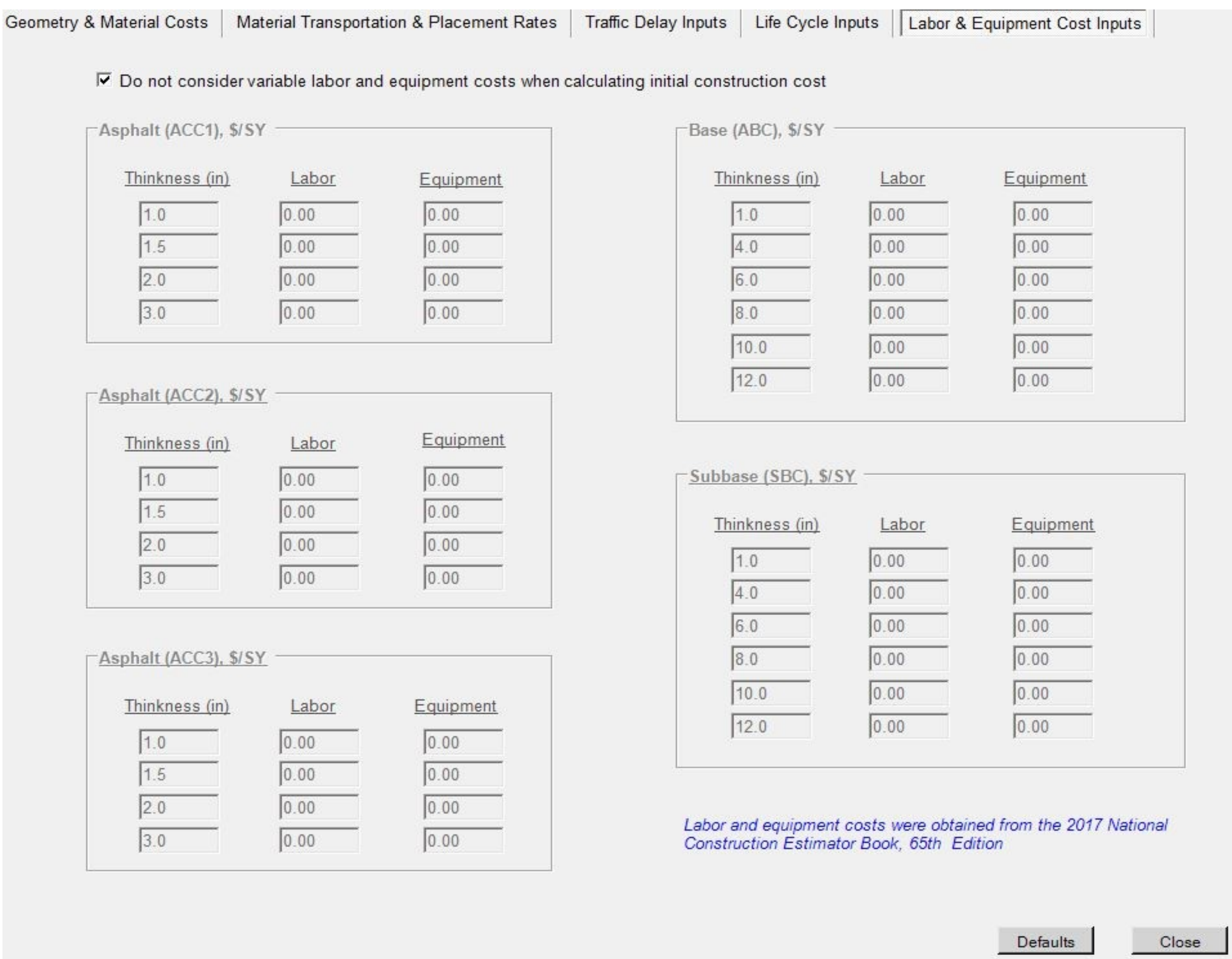


Figure I-12 Input information for the roads in the spectra software

APPENDIX J
MNPAVE USER'S GUIDE

Introduction

MnPAVE is a computer program that combines known empirical relationships with a representation of the physics and mechanics behind flexible pavement behavior. The mechanistic portions of the program rely on finding the tensile strain at the bottom of the asphalt layer, the compressive strain at the top of the subgrade, and the maximum principal stress in the middle of the aggregate base layer.

MnPAVE consists of three input modules: Climate, Traffic, and Structure; and three design levels: Basic, Intermediate, and Advanced. The level is selected based on the amount and quality of information known about the material properties and traffic data. In the basic mode, only a general knowledge of the materials and traffic data are required. The intermediate level corresponds to the amount of data currently required for Mn/DOT projects. The advanced level requires the determination of modulus values for all materials over the expected operating range of moisture and temperature.

MnPAVE simulates traffic loads on a pavement using a Layered Elastic Analysis (LEA) called WESLEA. It is a five-layer isotropic system program written in 1987 by Frans Van Cauwelaert at the Catholic Superior Industrial Institute Department of Civil Engineering in Belgium and modified in 1989 by Don R. Alexander at the U.S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi. All layers are assumed to be isotropic in all directions and infinite in the horizontal direction. The fifth layer is assumed to be semi-infinite in the vertical direction. Material inputs include layer thickness, modulus, Poisson’s ratio, and an index indicating the degree of slip between layers. MnPAVE assumes zero slip at all layer interfaces. Other inputs include load and evaluation locations. Loads are characterized by pressure and radius. The LEA program calculates normal and shear stress, normal strain, and displacement at specified locations.

MnPAVE output includes the expected life of the pavement, which is calculated using a damage factor based on Miner's Hypothesis. Reliability is estimated using Monte Carlo simulation. There is also a batch section for testing a range of layer thicknesses. In Research Mode (accessible from the "View" menu in the main MnPAVE window), output includes various pavement responses for each season.

Units

The default system of engineering units is English, however the system of units can be changed in any of the main modules. System International (SI) or English units may be selected.

English		SI
Length		
1 in	=	25.4 mm
1 ft	=	0.3048 m
1 mi	=	1.609344 km
Weight		
1 lb	=	4.448222 N
1 kip	=	1000 lbs
1 kip	=	4.448222 kN
Pressure (Modulus)		
1 psi	=	6.894757 kPa
(pounds per square inch)		

1 ksi = 1000 psi = 6.894757 Mpa

Starting MnPAVE

The program can be started by double-clicking on the MnPAVE icon on the desktop or selecting MnPAVE from the Windows Start menu under the folder name specified in Step 6 of **Installing MnPAVE**.

At this point, the Main Control Panel is visibile:

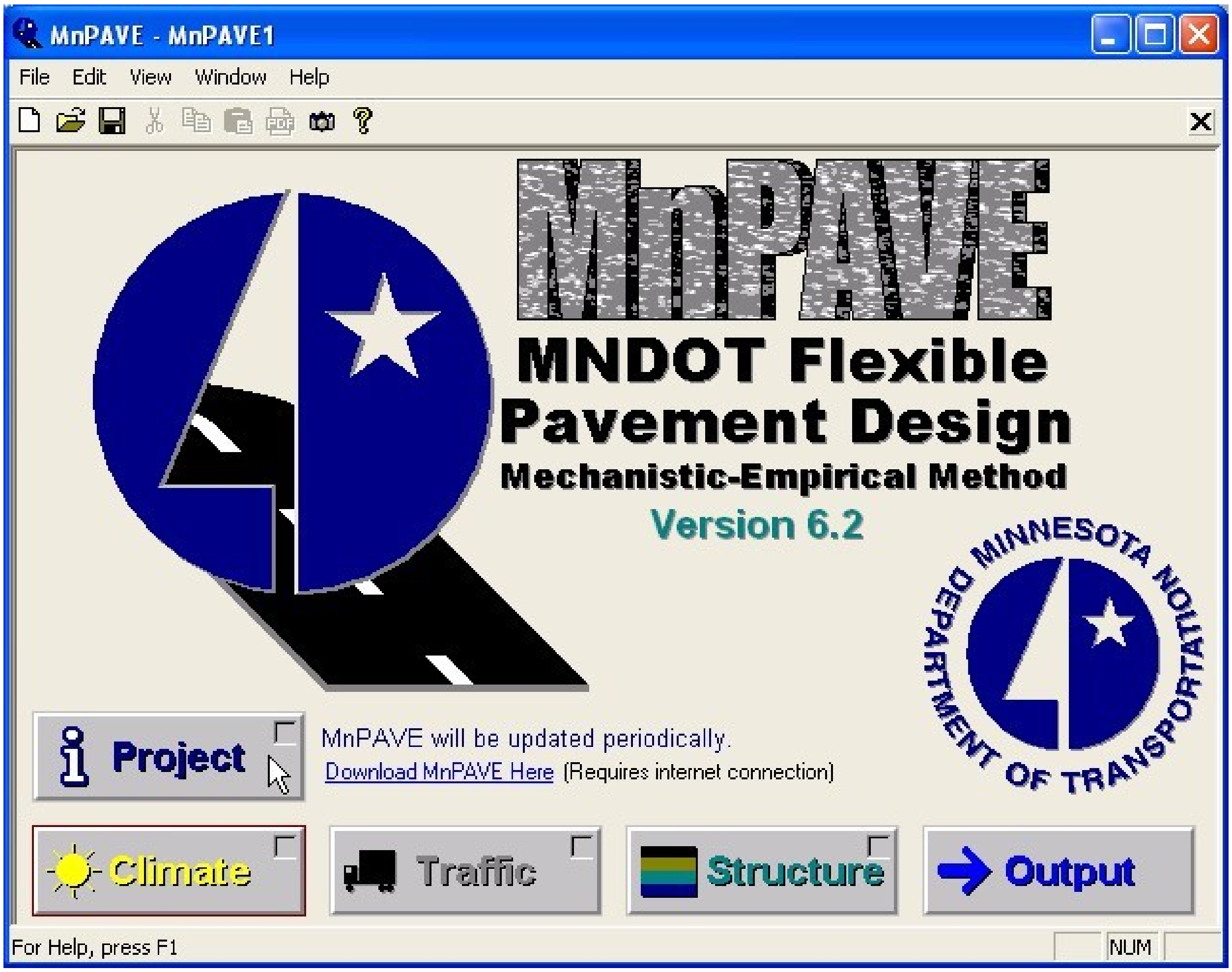


Figure J-1 MnPAVE Software

A new MnPAVE file can be opened by clicking on the icon or by selecting "New" from the "File" menu.

An existing MnPAVE file can be opened by clicking on the icon or by selecting "Open" from the file menu. A recently saved file can also be selected from the list at the bottom of the "File" menu.

Changes to the current file can by saved by clicking on the or by selecting "Save" from the "File" menu. Changes can be saved as a new file name by selecting "Save As" from the "File" menu.

Project Information

Project information is a form for entering information necessary to identify a MnPAVE project. Mn/DOT District, county, city, highway, construction type, design engineer and project notes are entered in this module.

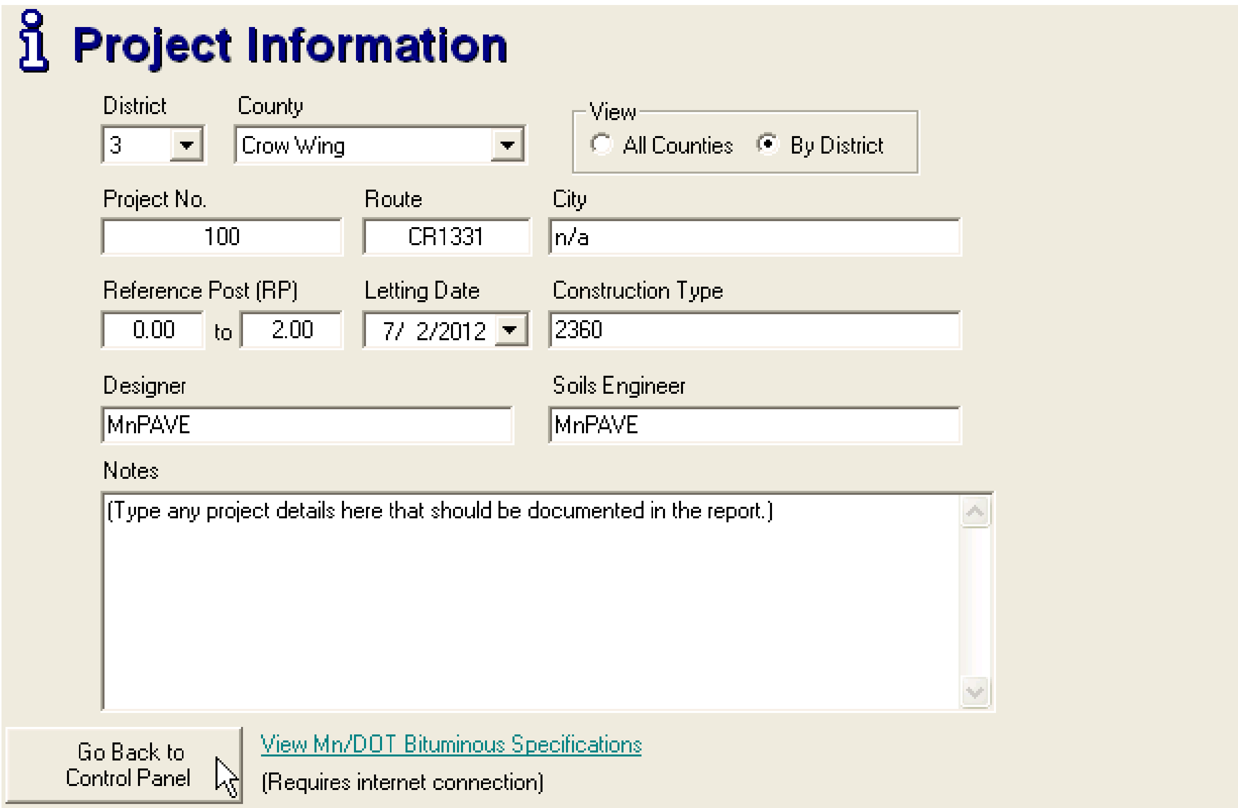


Figure J-2 project information input part in MnPAVE software

Climate

Climate contains a map of Minnesota where more specific location data can be entered. MnPAVE calculates season lengths and temperatures for each location using data from surrounding weather stations.

MnPAVE has five default seasons based on material properties measured at the Mn/ROAD research site throughout the year. Spring is divided into two seasons because of the drastic changes in aggregate base and subgrade soil properties during the Spring thaw period.

MnPAVE calculates the average pavement temperature for each season based on data from surrounding weather stations. Details of this calculation can be viewed in the Details window.

The county and district can be selected from menus in the Project Information window. Clicking on the map will also select them. The season lengths and average seasonal temperatures are shown in the left portion of the Climate window.

As the pointer moves over the map, the current district, county, and coordinates under the pointer are displayed to the left under Pointer Location. Click the left mouse button to select this location. The district and county can also be selected in Project Information.

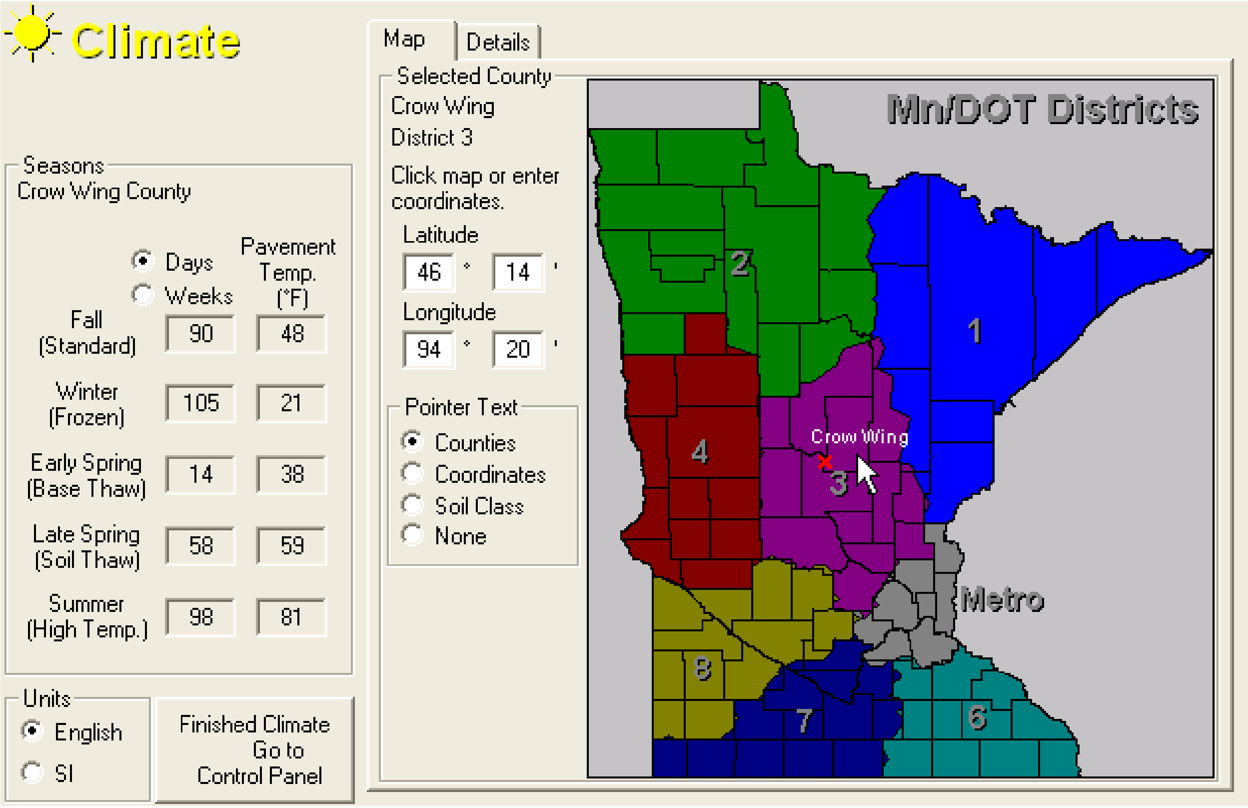


Figure J-3 climate district zones map in MnPAVE software

Climate Details

Seasonal air and pavement temperatures can be viewed in this window.

The air temperature at the selected location is based on a weighted average of data from weather stations in a 75 mile (120 km) radius. Each seasonal air temperature value represents the average daily temperature for that season. The equation used to convert air temperature to pavement temperature can be seen by clicking the 

button.

Early Spring Thaw Depth is the assumed depth of the thawed/frozen interface during Early Spring. The thawed portion of the base and/or soil is assumed to have a high moisture content and low modulus. Seasonal modulus multipliers for the selected pavement materials can be viewed in Advanced Structure. If the thaw depth extends into a soil layer, then the Late Spring multiplier is used for the thawed portion of the soil.

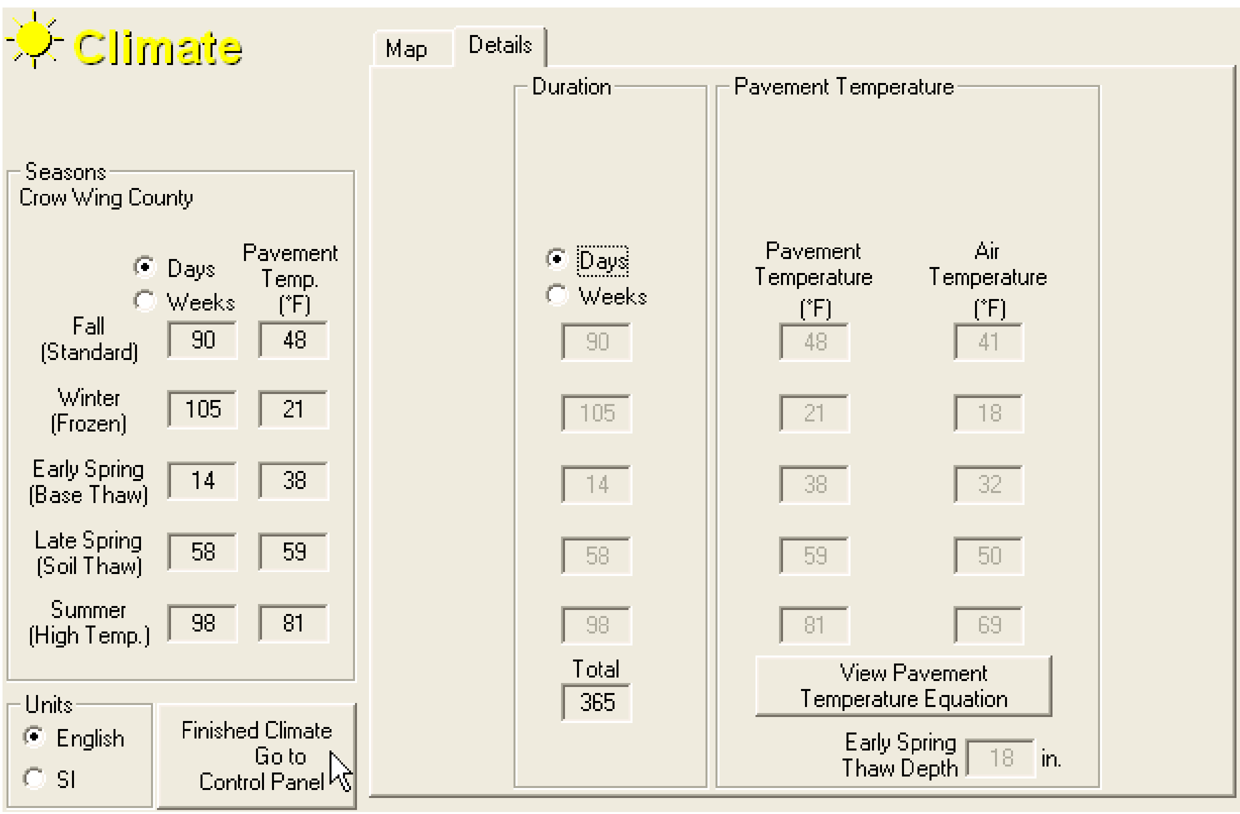


Figure j-4 climate district zone details tab in MnPAVE software

Traffic

ESAL (Equivalent Single Axle Load) is a simplified measure of traffic for pavement design. An ESAL is defined as an 18 kip (80 kN) dual tire axle with a tire pressure of 80 psi (552 kPa). Other axle loads and configurations can be converted to ESALs by using Load Equivalency Factors (LEF) as defined in Appendix D of the 1993 AASHTO Guide for Design of Pavement Structures.

Lifetime ESALs are the number of ESALs expected during the number of years specified in Design Period Length.
The First-Year value is calculated based on the Design Period Length and Growth Rate. If only First Year ESALs are known, it can be entered here and Lifetime ESALs will be calculated based on the Design Period Length and Growth Rate. The Design Period Length is typically 20 years. The Annual Growth Rate determines the amount that traffic increases during each year of the Design Period. Traffic analysis conducted by Mn/DOT has indicated that a simple growth model is appropriate for most Minnesota routes (traffic increases by a fixed amount each year).

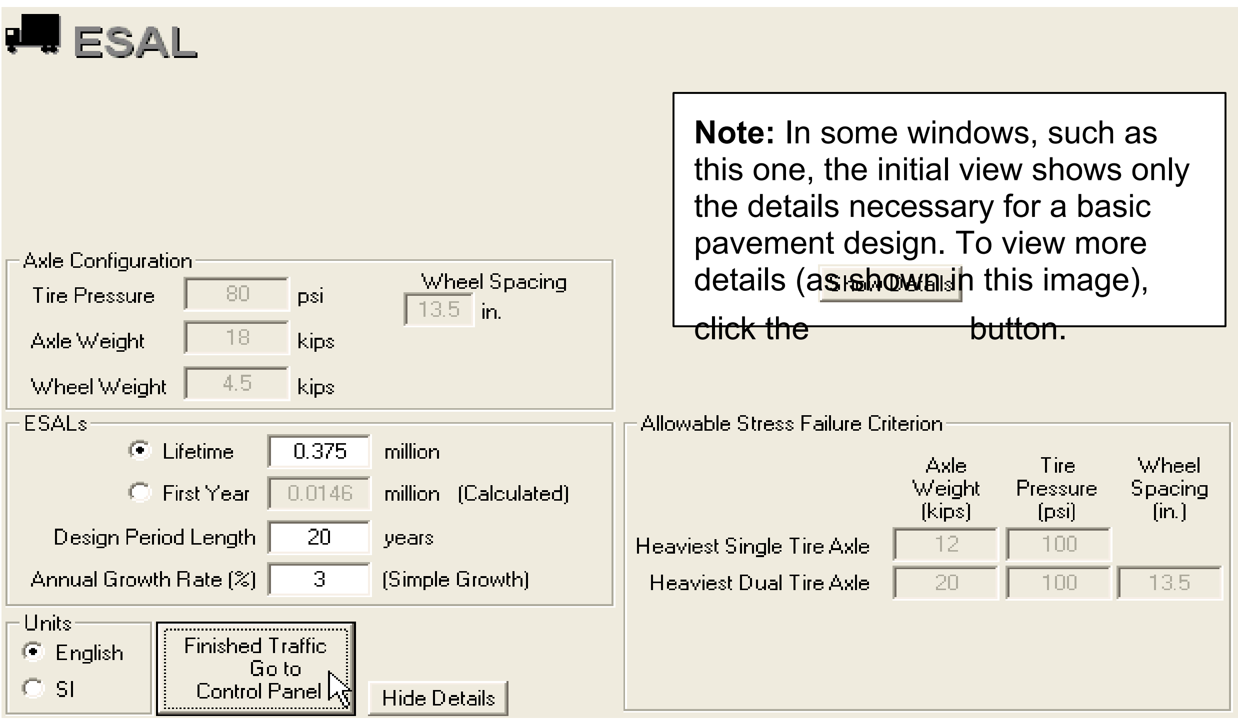


Figure J-5 ESAL input section in MnPave software

Allowable Stress is used to protect against failure in the aggregate base layer due to a single heavy load event. For this reason, the axle weights in this window represent the heaviest axles expected. The default values for low-volume roads (less than 1,000,000 ESALs) are legal axle weights in Minnesota. Values used for higher traffic volumes are consistent with data from around the state.

Structure

When Structure is opened for the first time in a project, the **HMA Mix Properties** Window opens to make sure all mix design information is entered correctly. Mix design information such as asphalt binder content and gradation are required to estimate the HMA dynamic modulus. Currently, the selection of a binder grade serves only to document the binders used in the design. Only PG 58-28 data was available for the current MnPAVE calibration, so all HMA layers will have PG 58-28 properties regardless of the binder type selected.

Up to three HMA types can be defined for layer 1. Since the LEA procedure only allows five layers, multiple HMA layers are combined into a single layer using the equivalent thickness method.

Click on the colored bar to select a default gradation based on a Mn/DOT specification. A custom gradation can be defined by entering numbers in the “Percent Passing” edit boxes.

To view more details about how HMA modulus is calculated, click on the “Show Details” button and then the Advanced button next to each lift.

The Structural Number (SN) is calculated using the method described in Section 2.3.5 of the 1993 AASHTO Guide for Design of Pavement Structures.

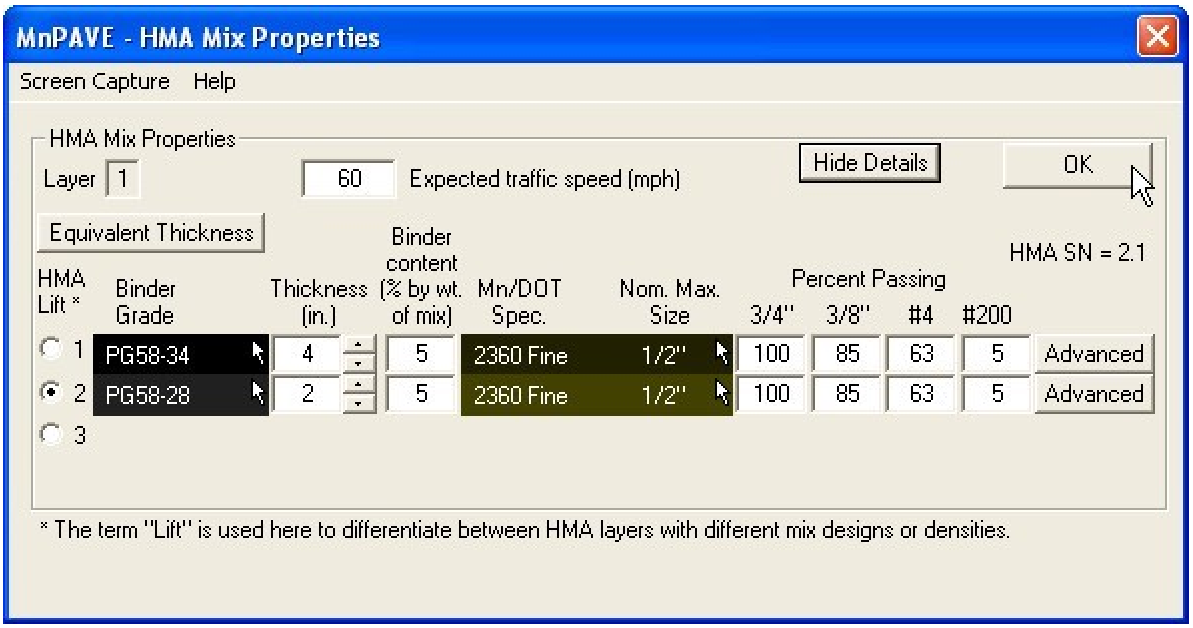


Figure J-6 HMA mix properties tab in MnPAVE software

Basic Structure

Basic Structure is intended for low-volume roads or designs that don't require a high degree of reliability. MnPAVE uses default design modulus values. These modulus values are adjusted for seasonal variations in moisture and temperature.

Click on a layer button to select the number of layers in the pavement structure. The bottom layer is always semi-infinite. A MnPAVE pavement structure must have between two and five layers. Due to limitations in the LEA procedure, layer 5 cannot be analyzed for rutting. Therefore layers 2 through 4 must contain at least one engineered soil[1] or undisturbed soil[2] layer.

The **Default Structures** area provides shortcuts for several common pavement structures. Select the desired pavement structure, then adjust the layer thicknesses and material subtypes.

Material Types for each layer are selected on the left side of the Structure window under **Edit Structure**. Layers with a white pointer arrow can be clicked to select a different subtype. R-Value Design can be clicked to view the traditional MNDOT design results for this structure.

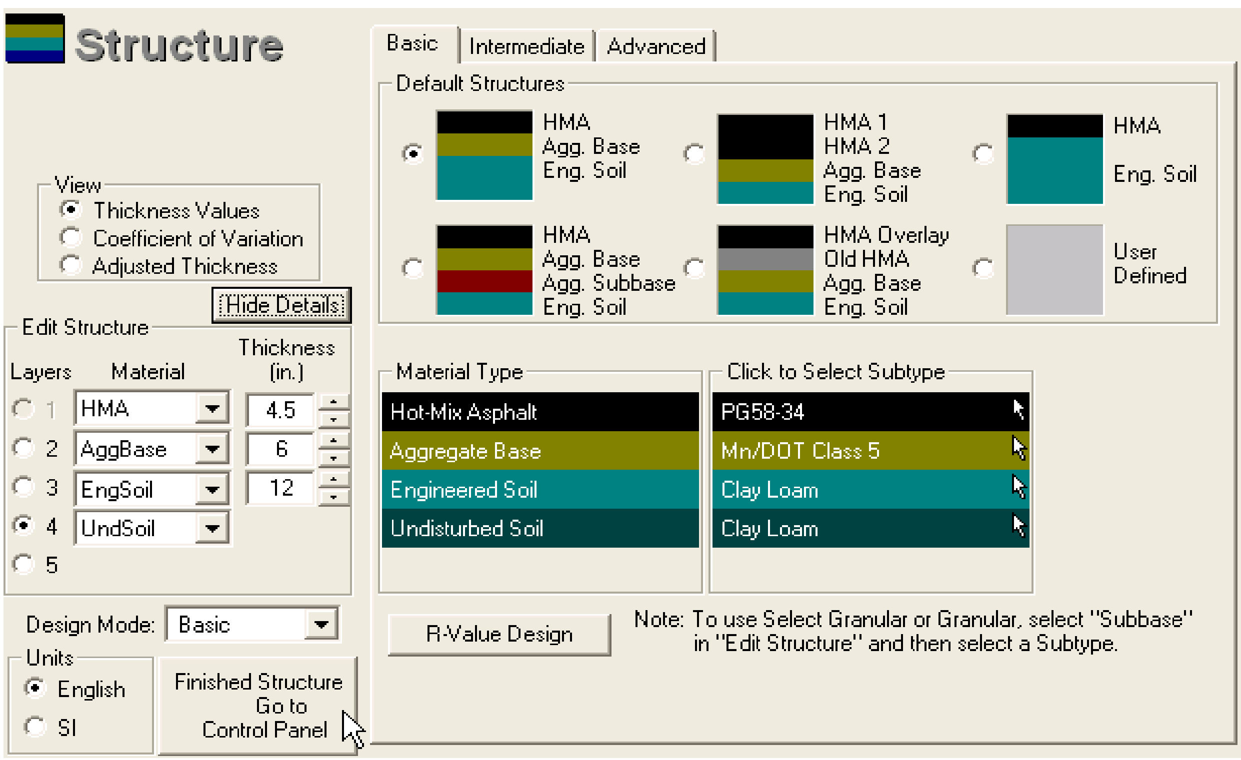


Figure J-7 Basic structure sublayers information in MnPAVE software

[1] ~~Soil that has been blended and~~ compacted prior to construction.

[2] Existing soil that has not been reworked. Because of uncertainty in the quality and uniformity of the material, the default undisturbed soil modulus is equal to half of the corresponding engineered soil modulus.

Confidence Level

This value is used to adjust layer thickness and modulus values to assure that a proportion of the pavement area meets or exceeds the desired values, based on the coefficient of variation (COV). The higher the confidence level and COV the more the value is reduced. A confidence level of 50% results in no reduction (the mean value is used in the simulation). The Confidence Level differs from the reliability value calculated in the Output Monte Carlo simulation. The Confidence Level reduces the values for all layers and acts as a factor of safety to account for variability and uncertainty. A Monte Carlo simulation should be run on the final design to determine reliability. In Design Mode, the Confidence Level is set at a default value of 70%. It is adjustable in Research Mode.

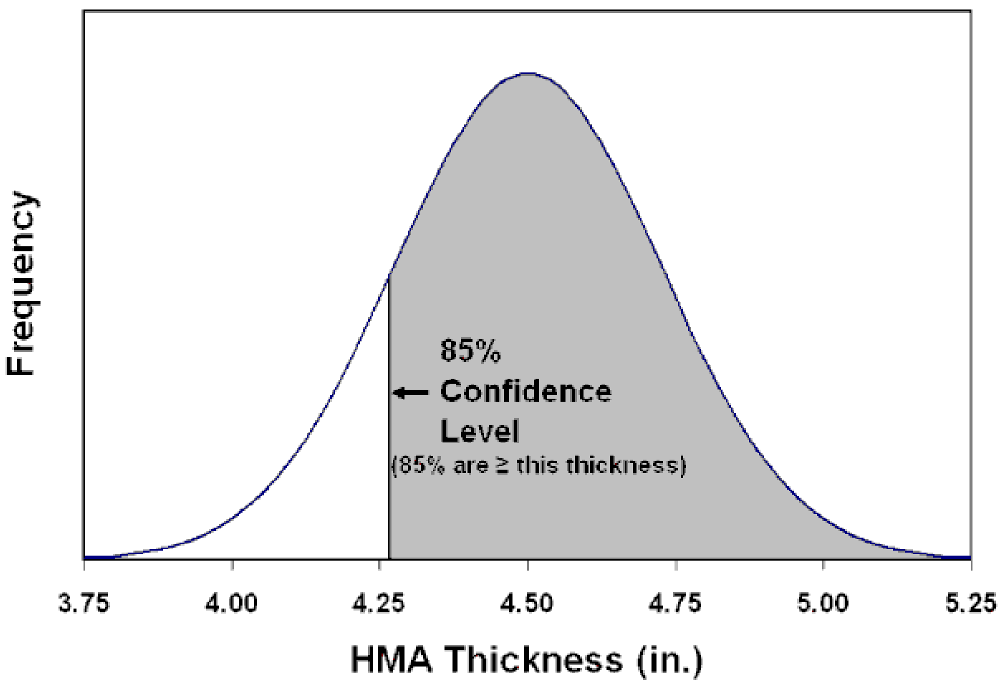


Figure J-8 Confidence Level cure concept

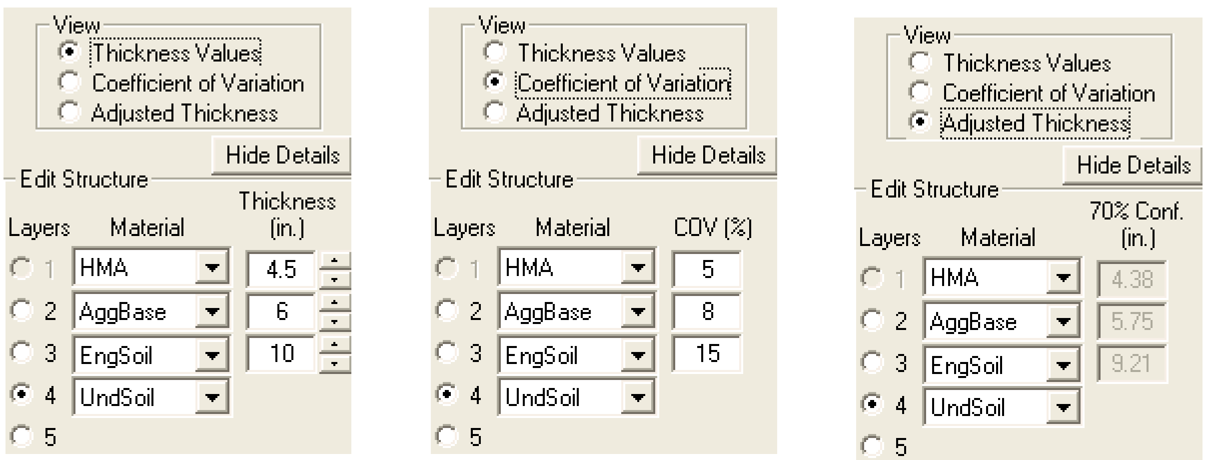
Thickness Views

Thickness Values Displays the design thickness. These values are adjusted based on the Thickness Coefficient of Variation (COV) for the simulation.

Thickness Coefficient of Variation indicates the variability of the thickness value of each layer.

$$\text{COV}\ (\%) = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100$$

Adjusted Thickness Displays the reduced thickness used in the pavement simulation.



a) b) c)

Figure J-9 thickness values in MnPave including a) thickness value tab, b) Coefficient of Variation (COV), c) adjusted thickness tab

Intermediate Structure

Intermediate Structure has a form for entering test data for aggregate base and subgrade soils. These values are converted to design modulus and adjusted for seasonal variations If no test has been performed on a given material, it's box can be left unchecked to use default Basic material properties. Basic HMA data is used in this mode. A material subtype need not be selected if test data is entered. If the material subtype is known, it can be selected by clicking on the pointer arrow to the right of the edit box. If the material subtype is not known, select **Unknown** from the list. To view the calculated moduli, click on the **Advanced** tab.

If **Other** is selected in the **Edit Structure** area, material properties are edited in **Intermediate** or **Advanced Structure**.

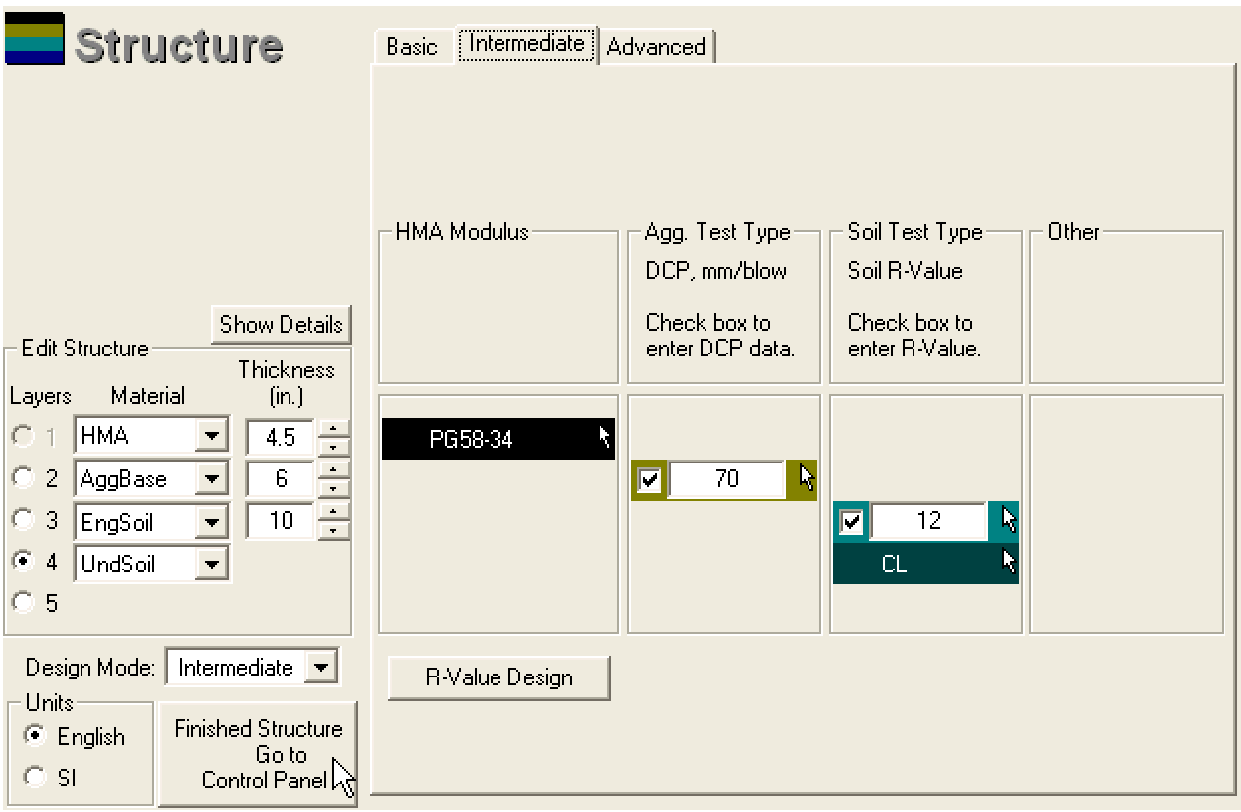


Figure J-10 Intermediate structure input tab in MnPave software

Advanced Structure

Advanced Structure requires the input of design modulus values for every layer and every layer.

Design Mode: Click on Basic, Intermediate, or Advanced to view the corresponding material properties below. Selecting Basic or Intermediate displays values calculated based on data from those modules. In Advanced mode, all material properties must be entered manually.

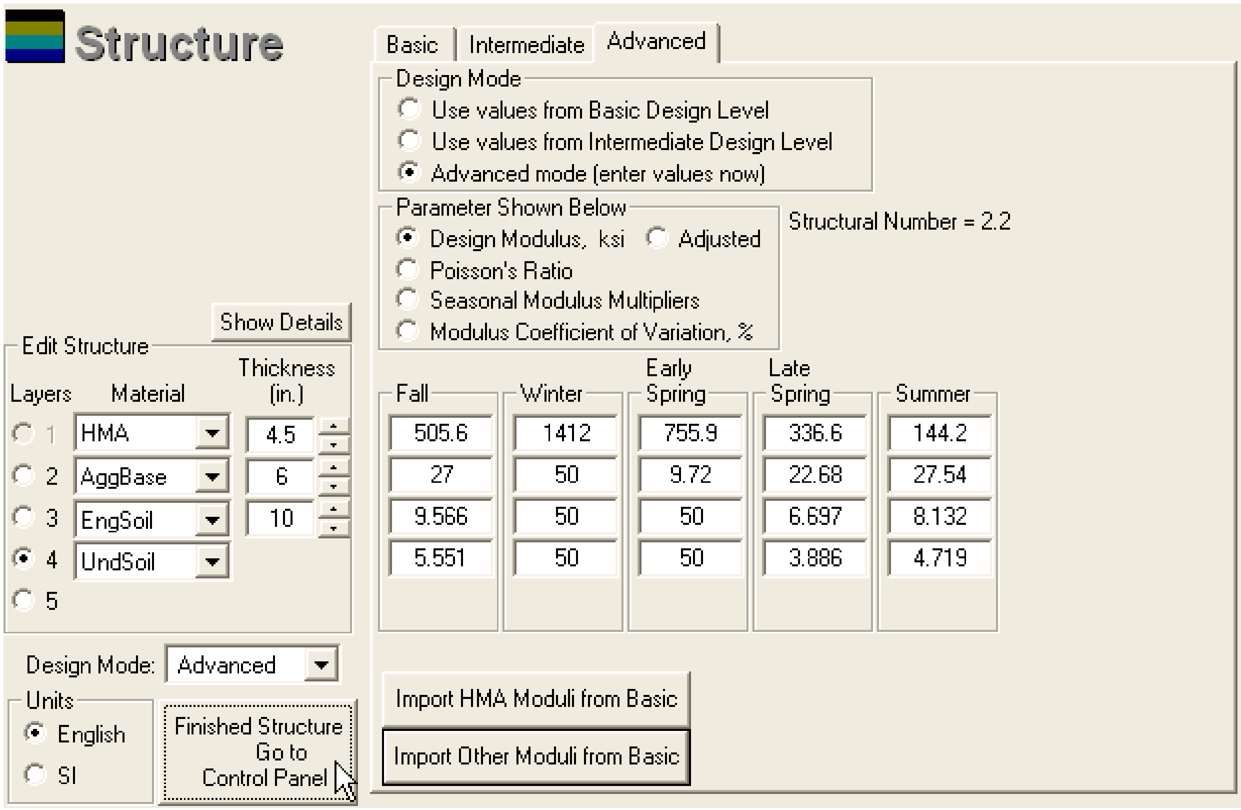


Figure J-11 advanced structure input tab in MnPave software

The design mode is displayed above the "Finished" button to confirm that the correct mode is selected. Any editing that is done in the Basic, Intermediate, or Advanced windows will change the mode. If any editing causes the wrong mode to be selected, this can be corrected prior to clicking on the "Finished" button.

Import Moduli

These buttons appear in the **Advanced Structure** window when **Advanced Mode** is selected. Basic default modulus values can be imported into Advanced Mode when custom values are not available for all layers and seasons.

Structure Views

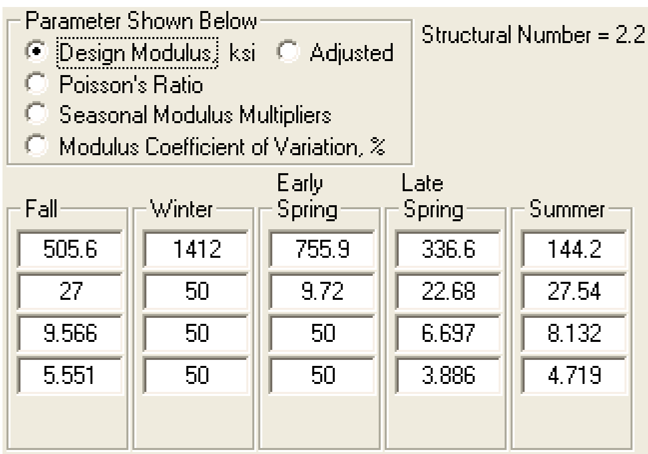
Structure views for all design levels can be viewed by clicking the **Advanced** tab.

Design Modulus displays design modulus values. For pavement simulations these values are adjusted according to the Confidence Level.

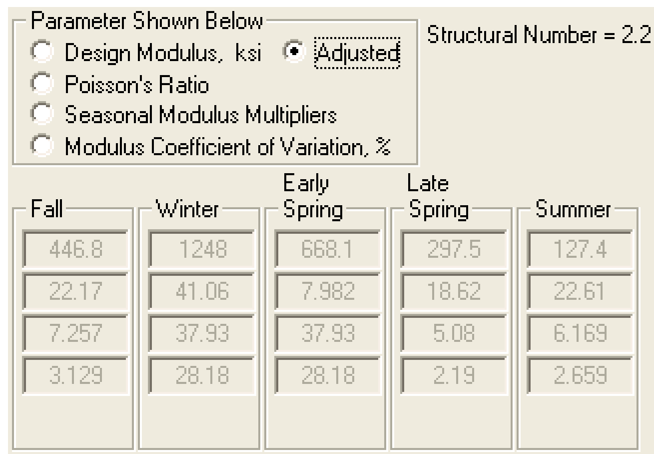
Adjusted Modulus indicates how values used in the pavement simulation are adjusted according to the Confidence Level.

Poisson's Ratio is a measure of a material's tendency to expand in the horizontal direction when it is compressed in the vertical direction. Poisson's Ratio is used in Layered Elastic Analysis (LEA) simulations.

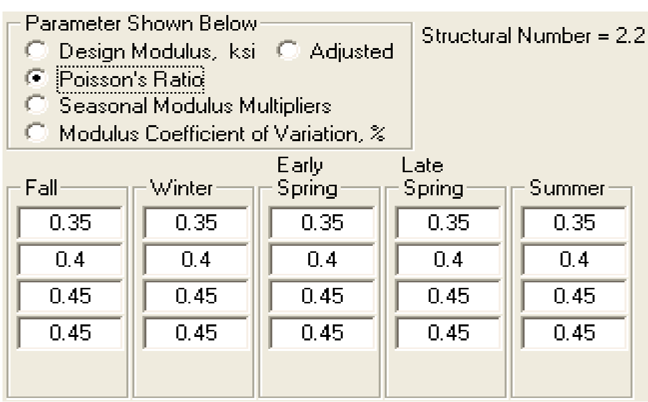
Seasonal Modulus Multipliers displays seasonal multipliers for each aggregate base, subbase, and soil material (HMA moduli are calculated for each season). Multipliers indicate moisture susceptibility and the state of the material (frozen or thawed).



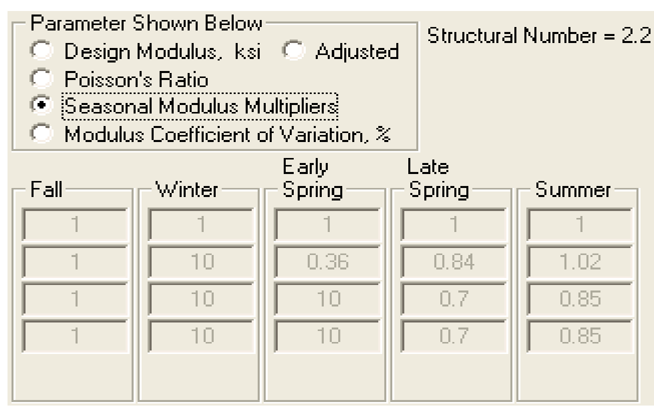
a)



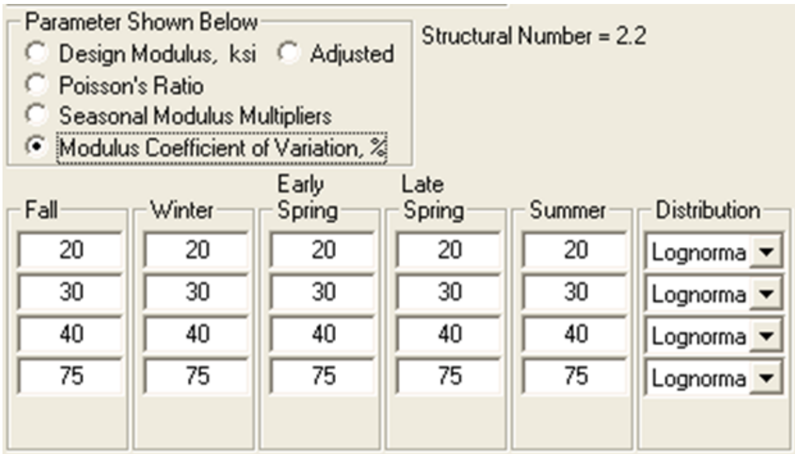
b)



c)



d)



e)

Figure J-12 Structure views in the Advanced tab in MnPave software including a) Design Modulus, b) Adjusted Modulus, c) Poisson's Ratio, d) Seasonal Modulus Multipliers, e) Modulus Coefficient of Variation

Modulus Coefficient of Variation (COV) shows the expected variability in modulus for each layer along with the assumed distribution shape. This data is used to determine the adjusted modulus values used in the simulation and the data set used for the Monte Carlo simulation in Output.

The default modulus data used in MnPAVE fits a lognormal distribution (log-transformed data fits a normal distribution). The COV of this data is calculated as follows:

$$COV = \sqrt{e^{\sigma}\ } - 1 \times 100$$

Overlay Design

While a complete Mechanistic-Empirical overlay design method has not yet been developed for MnPAVE, overlays can be designed using the conventional fatigue and rutting criteria to check for structural capacity. In addition, FWD[3] deflections and the TONN method can be used to determine the necessary overlay thickness to avoid the need for Spring load restrictions.

Basic Overlay Design Procedure

While MnPAVE can check for fatigue, rutting, and shear failure in the aggregate base, these are often not the primary factors in determining overlay thickness. When designing overlays in Basic mode, the designer must also rely on other overlay design methods and guidelines. Do Project Information and Climate, and then go to Structure.

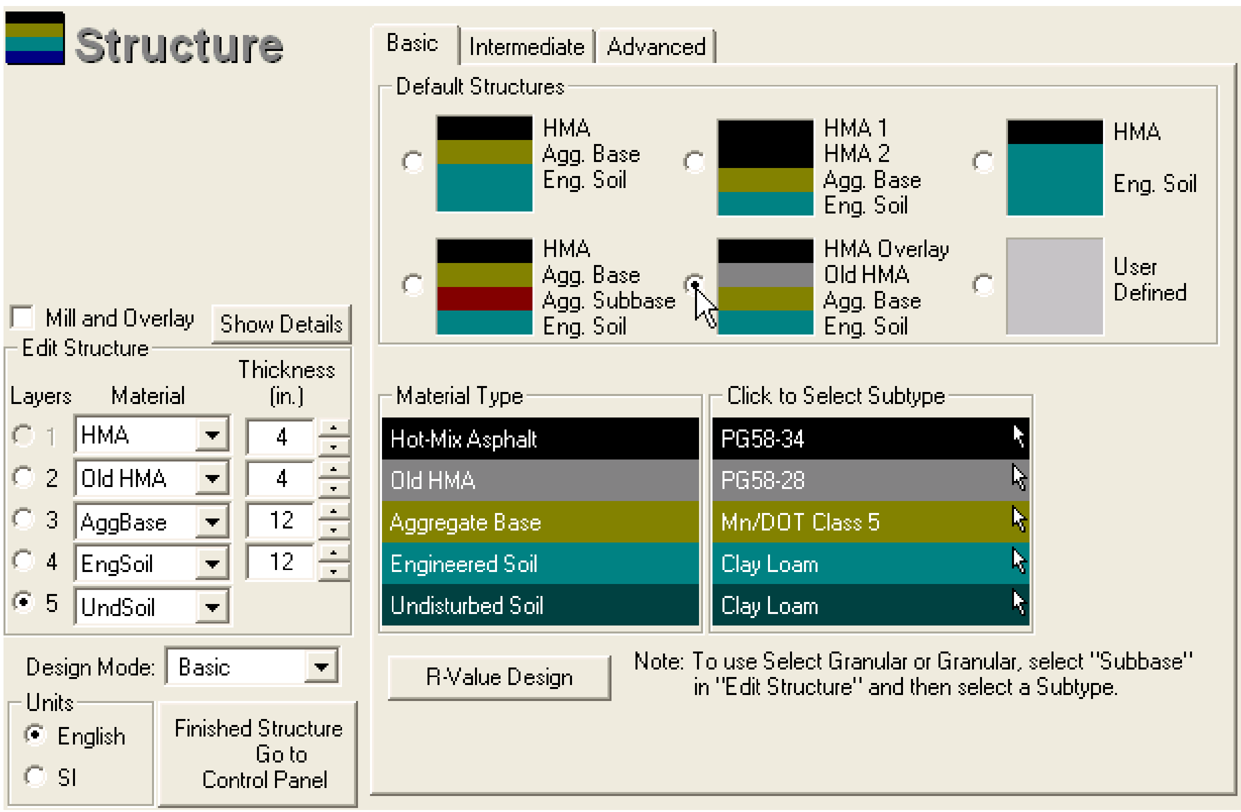


Figure J-13 Basic overlay structure sublayers information in MnPAVE software

Select the default overlay structure. If the old HMA properties for this layer have not yet been defined, the HMA Mix Properties window will open up.

[3] Falling-Weight Deflectometer: A device that measures deflections that result from a weight dropped onto the pavement. These deflections can be used to determine the modulus of the pavement layers.

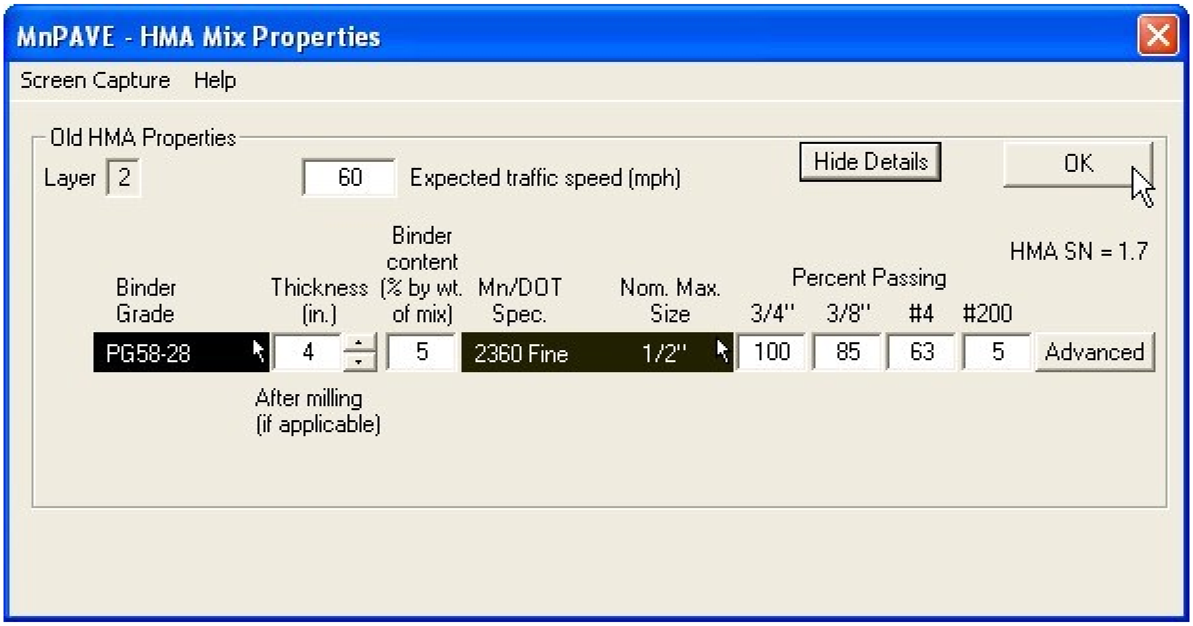


Figure J-14 HMA mix properties tab in MnPAVE software

If the HMA Mix Properties window did not open, click on the gray Old HMA subtype bar.

Select the binder grade of the old HMA and any other mix properties that are known and click OK.

Check the Mill and Overlay checkbox if applicable (the old HMA thickness should be the thickness after milling).

Define the HMA properties for the new (overlay) HMA.

Define the other pavement layers to the extent that their material types and thicknesses are known.

Continue to Traffic and Output.

If this is a Mill and Overlay project, HMA fatigue and subgrade rutting results will be displayed. If it is not a Mill and Overlay project and rutting has been observed in the old HMA, check the Rutting is present in old HMA box. If rutting is not present in the existing HMA, it is not necessary to check for subgrade rutting.

Intermediate Overlay Design Procedure

Select material types and subtypes for the layers, with HMA overlay in layer 1 and Old HMA in layer 2.

Click on the Intermediate tab and select FWD Deflections.

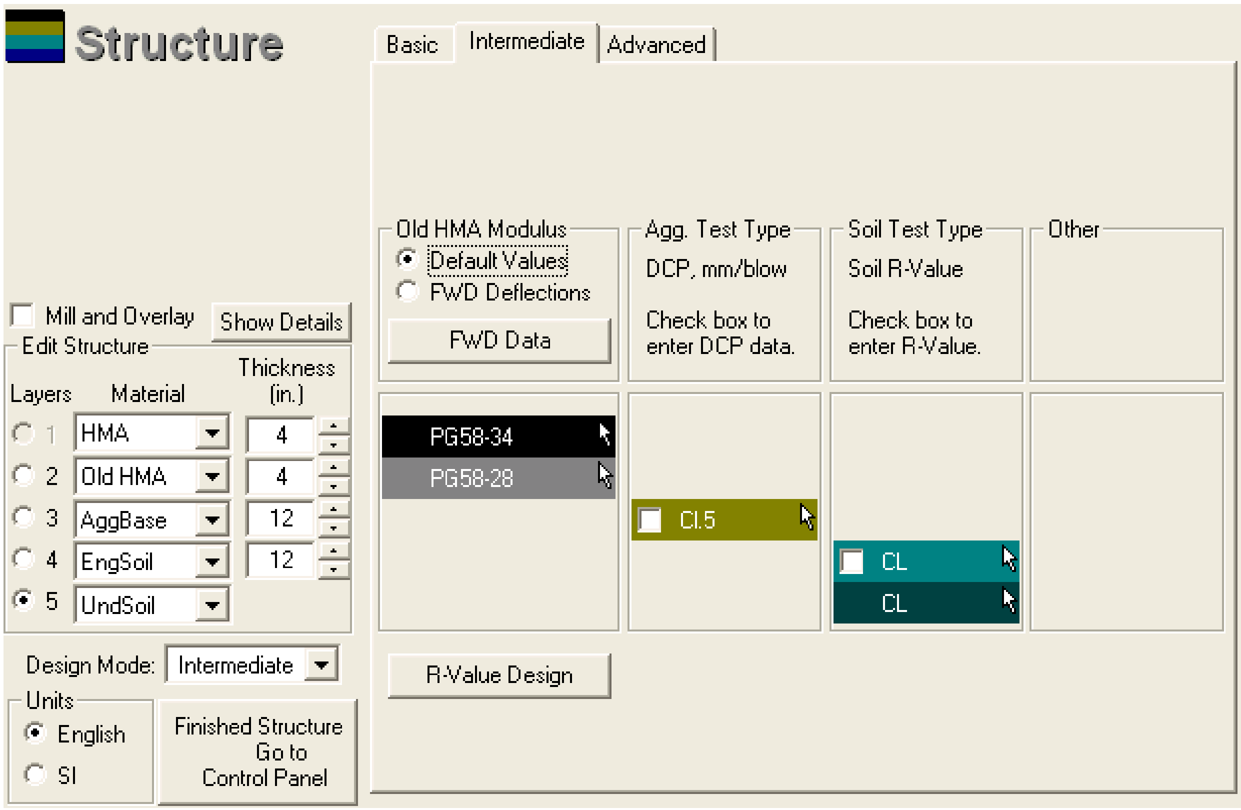


Figure J-15 Intermediate overly structure input tab in MnPave software

The FWD Data window will open. FWD loads and deflections must be entered in the spreadsheet. Data entry is greatly simplified by opening the FWD deflection file in a spreadsheet such as Excel, cutting and pasting to put the data in the appropriate columns, and then pasting the data into MnPAVE.

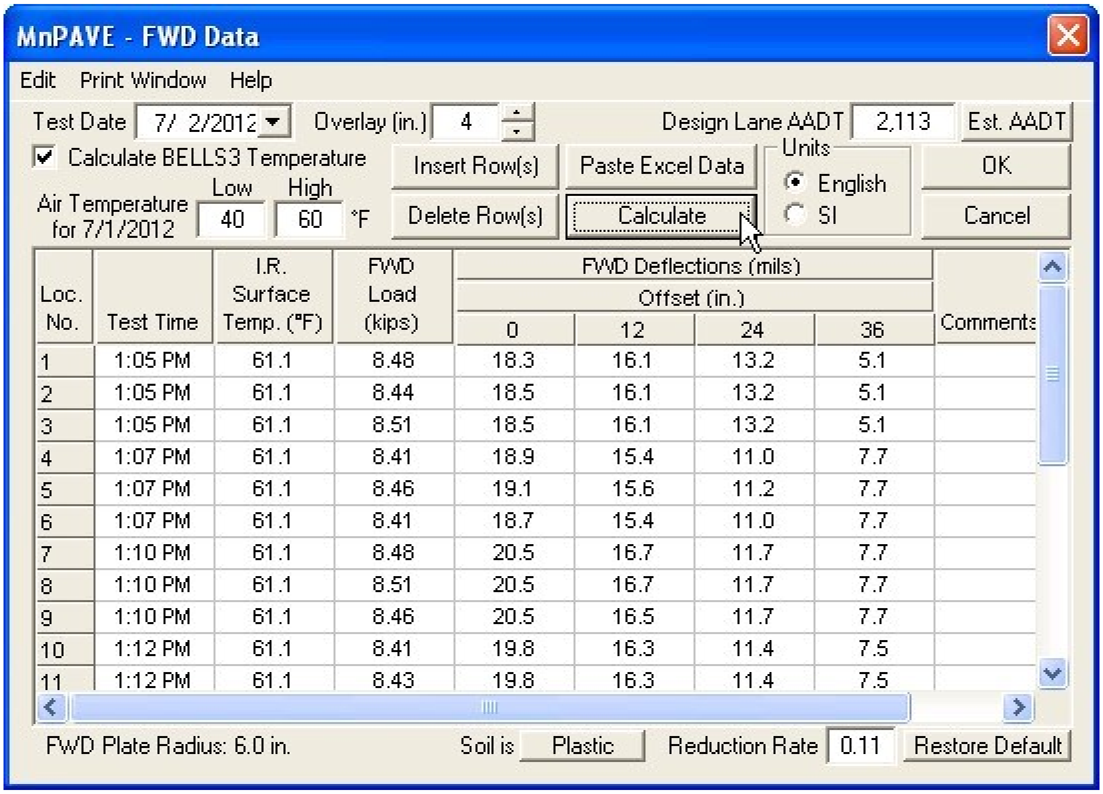


Figure J-16 FWD input data tab in MnPave software

Pavement temperature can be entered by two methods. If the pavement temperature is known, uncheck the ☑ Calculate BELLS3 Temperature checkbox and enter the known pavement temperature values in column 2. If the pavement temperature is not known, it can be estimated using the BELLS 3 method. Enter the previous day's high and low air temperatures in the appropriate boxes and the infrared surface temperatures in column 2. Air Temperature for 7/1/2012 Low 40 High 60 °F

If Mill and Overlay was checked, the Old HMA button must be clicked to define the old HMA thickness at the time of the FWD testing and after milling.

Annual Average Daily Traffic (AADT) must also be entered. If this value is not known, it can be estimated from the design ESALs and the road type by clicking on the Est. AADT button.

Select the soil plasticity at the bottom by clicking on the Soil is Plastic button. Clicking on the button toggles through three levels: Plastic, Semi-Plastic, and Non-Plastic. If this property is unknown, assume the soil is plastic.

The Reduction Rate 0.11 value is used in the TONN procedure. This value is typically 0.11 and ordinarily does not need to be changed.

Once all data has been entered, click on the Calculate button.

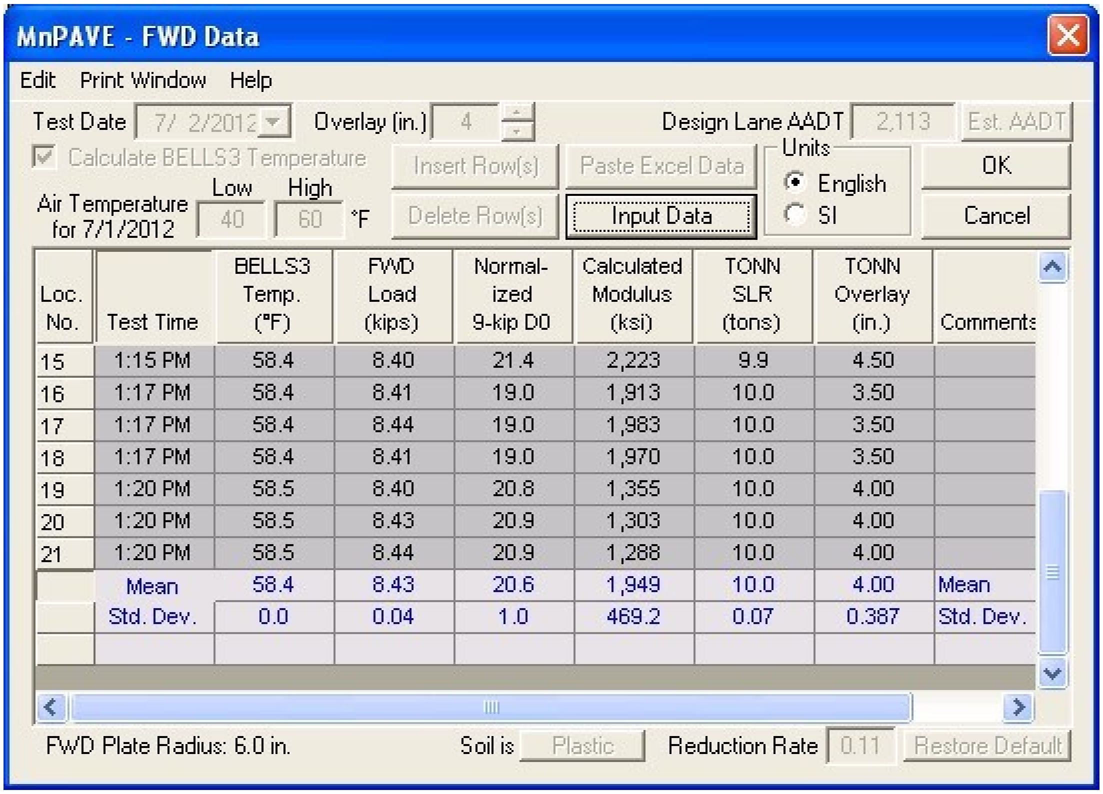


Figure J-17 FWD input data tab in MnPave software

If BELLS3 was used, column 2 displays the estimated pavement temperatures at 1/3 of the pavement depth. Column 3 displays the fwd load, and column 4 displays the center deflection normalized to a 9 kip (40 kN) load (all deflections are normalized for the calculations). Column 5 displays the calculated HMA modulus and column 6 displays the Spring Load Restriction recommended by the TONN procedure for the selected overlay thickness. Column 7 displays the overlay thickness recommended by the TONN procedure. The mean and standard deviation for these values is displayed at the bottom of the table.

Output

Output displays the expected life based on fatigue and rutting damage. Optimum layer thickness can be determined automatically in ESAL mode.

Fatigue and Rutting Models

The expected life of a pavement is calculated by simulating the strains due to traffic loads and using an empirical transfer function to determine the Allowed Repetitions[4] for each load. If the applied load repetitions exceeds the allowed repetitions, the pavement is assumed to have failed.

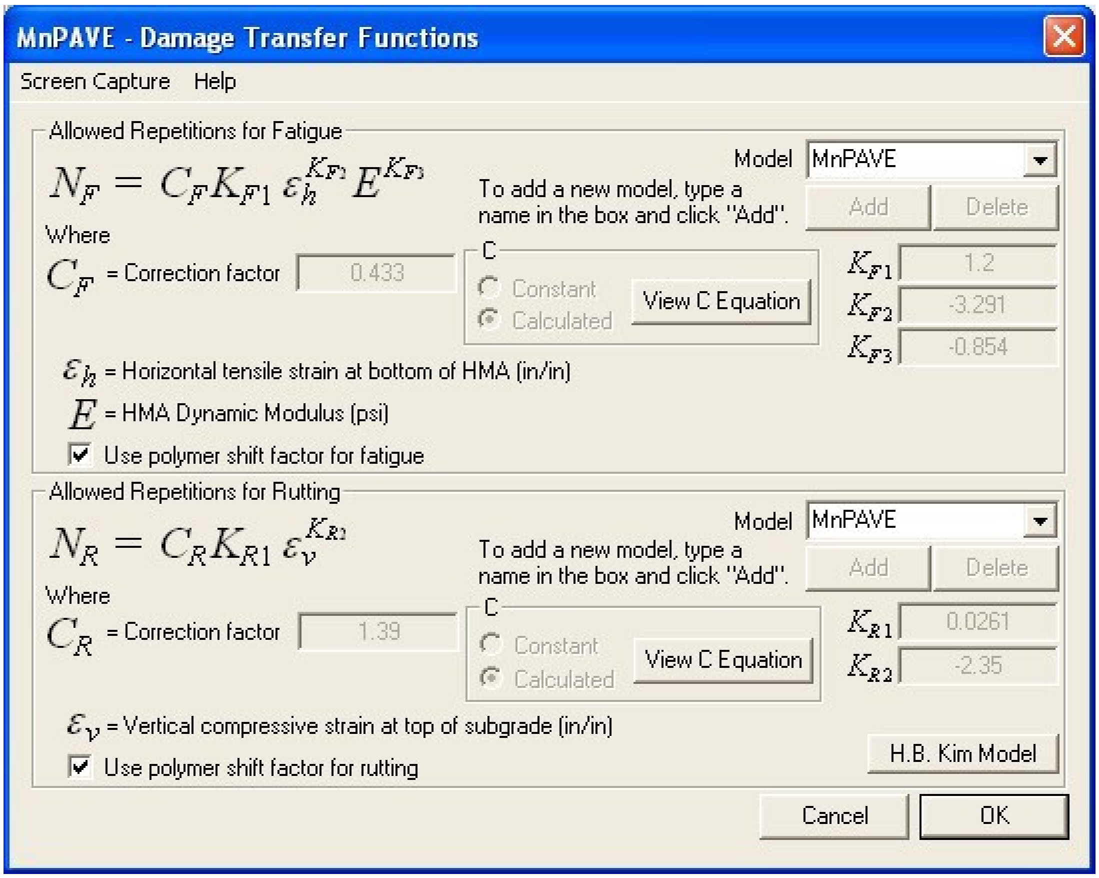


Figure J-18 Fatigue damage function and details tab in MnPave software

[4] The number of repetitions of a given axle load that are assumed to cause pavement failure by fatigue cracking or rutting

Initial Output

Basic Output displays the expected years of pavement life based on calculated fatigue and rutting damage. The pavement damage is also expressed as a percent contribution by each season.

If fatigue or rutting values are too low or too high, Material subtypes and layer thicknesses can be adjusted. After each change "Recalculate" must be clicked to view the new results. For Basic designs, HMA and aggregate subtypes can be adjusted in Output. For Intermediate designs, only HMA can be adjusted in Output (other materials must be changed in Structure). In Advanced mode, all material types must be changed in Structure.

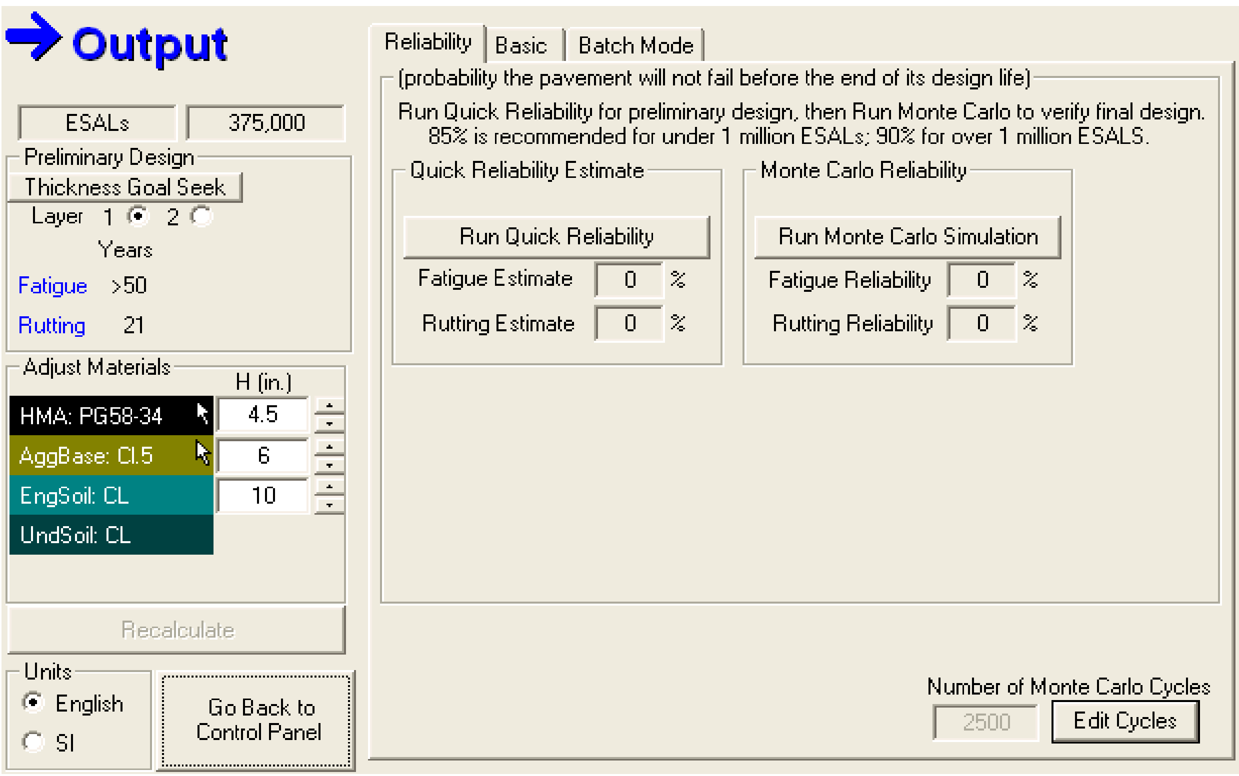


Figure J-19 Reliability input tab in MnPave software

Thickness Goal Seek is a tool for determining design layer thicknesses in ESAL mode. To adjust the HMA layer only, select "Layer 1" and click on Thickness Goal Seek. A number of cycles will be executed until the pavement fails in neither fatigue nor rutting.

When Thickness Goal Seek is done for non-HMA layers, the HMA layer will be adjusted for fatigue first (if necessary), and then the selected layer will be adjusted. This is because adjusting underlying layers has a relatively small effect on fatigue life and may result in a large number of cycles and very thick layers.

After running Thickness Goal Seek, layer thicknesses can be adjusted manually to obtain the desired structure.

Reliability

Output reliability considers the variability of the thickness and modulus values for each layer to determine a reliability value for the pavement design.

The reliability will not necessarily agree with the confidence level selected in Structure because the confidence level selects the "worst case" thickness and modulus value for each layer while the reliability analysis considers a random combination of thickness and modulus values.

The number of Monte Carlo cycles can be adjusted by clicking the Edit Cycles button. A sensitivity analysis was conducted to determine the optimum value of 2500 cycles.

Run Quick Reliability uses equations derived from running a range of full Monte Carlo simulations to estimate the Monte Carlo reliability for a given structure. This is a time-saving feature that allows quick adjustments in the structure. Once the desired quick reliability value is reached a full Monte Carlo reliability should be run for verification.

The Run Monte Carlo Simulation button runs the selected number of Monte Carlo cycles. The time for this process ranges from less than one minute to a few minutes for an ESAL design (depending on the computer's processor speed) and up to several hours for a load spectrum design.

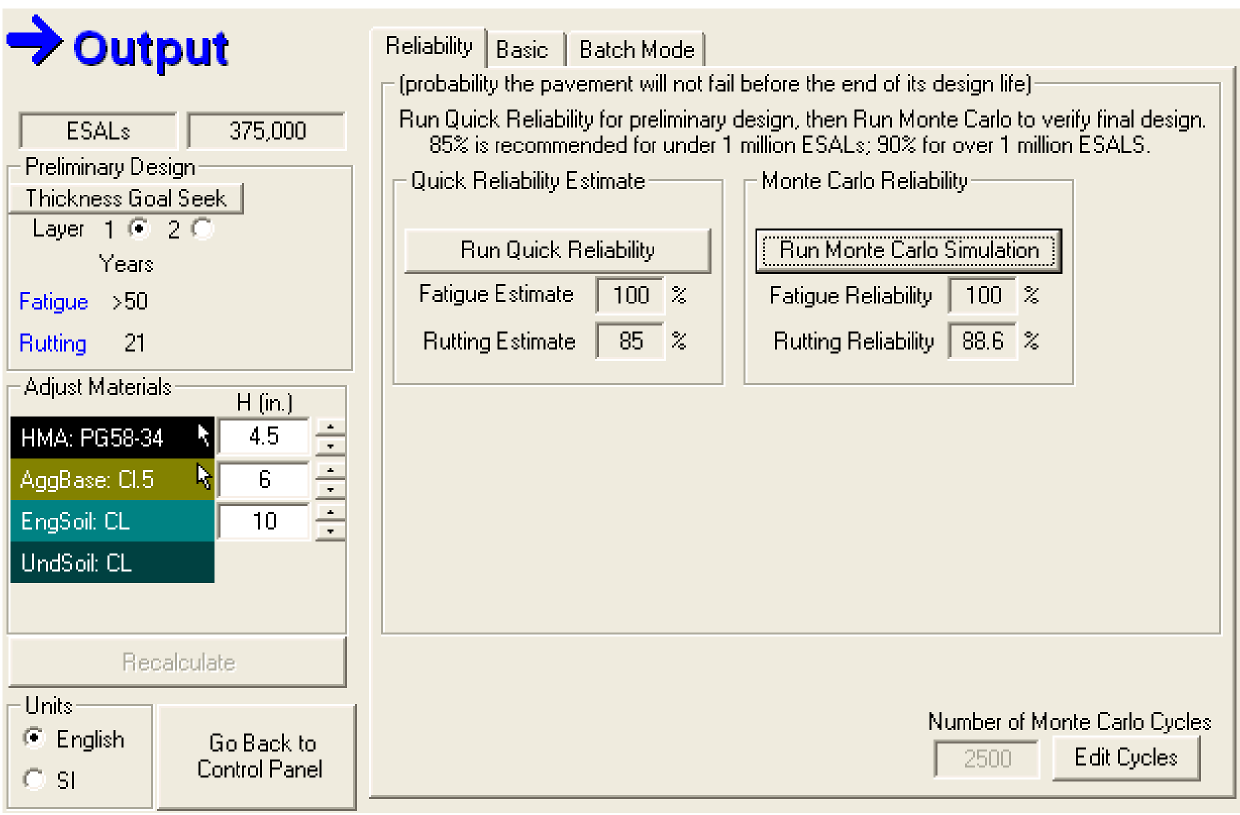


Figure J-20 Reliability input tab in MnPave software

Reports

A summary report can be saved as PDF file by clicking on the PDF icon or by selecting "PDF Design Summary" from the "File" menu

A screen shot of the output window can be printed by clicking on the camera icon . Most other windows have a camera icon that can be clicked to print a screen shot.

Basic Output

Basic Output displays the expected years of pavement life based on calculated fatigue and rutting damage. The pavement damage is also expressed as a percent contribution by each season.

The relative damage effect from each season is displayed on the right side of the window. These values are affected by both the magnitude of strain that occurs during each season as well as the season length.

Results can be exported to a text file (comma or tab delimited) or to an “Excel” file. The Excel file is actually a tab delimited text file with an “xls” file extension. Double-clicking on this file opens it in Excel, but it must be “Saved As” Excel to convert it to true Excel format.

The Design Summary contains expected life and damage, project information, and limited structural and traffic information.

Damage Details includes more seasonal and traffic information.

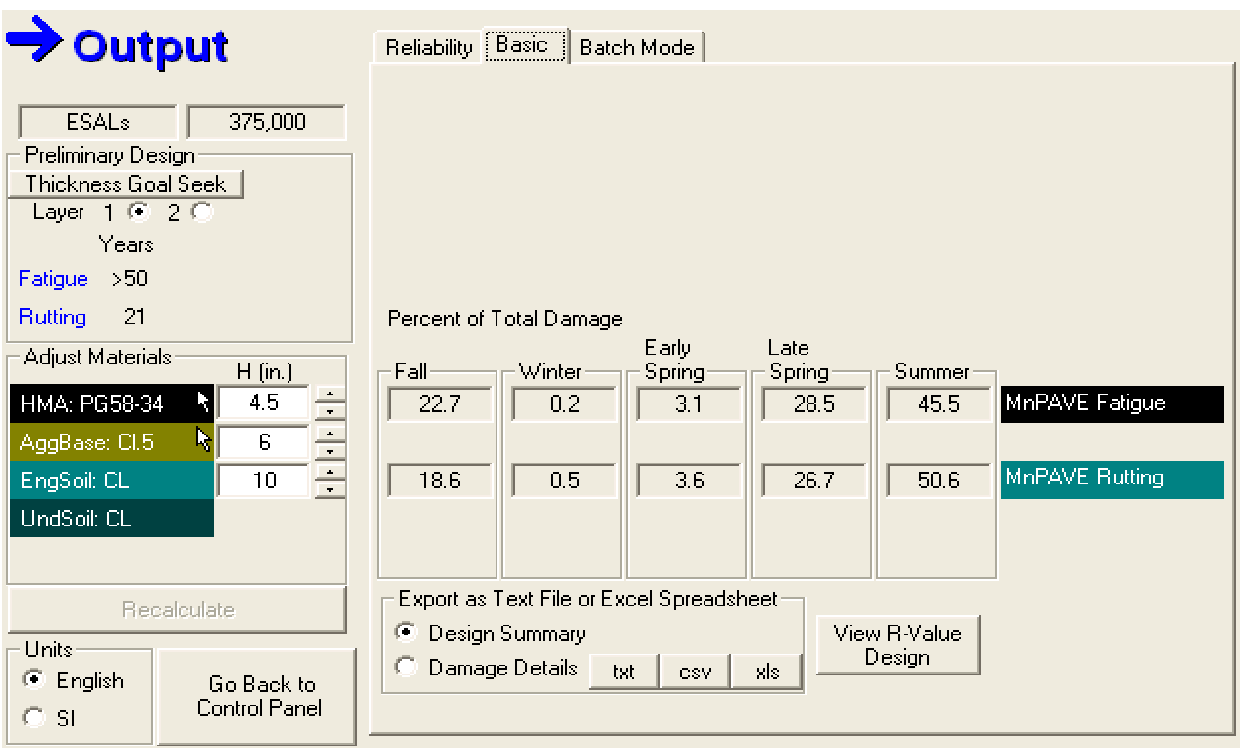


Figure J-21 Basic Fatigue and rutting damage input tab in MnPave software

Batch Mode

The batch mode allows the user to specify a range of layer thickness values and have all results tabulated in a text file or spreadsheet.

Check the box for each layer for which the thickness will be varied. Type the thinnest value in the "Begin" box, the thickest value in the "End" box, and the amount to increase the thickness in the "Incr." box. Damage Limits are used to exclude extremely over- or under-designed structures from the output file. When Set Frost-Free Depth is selected, each simulated structure will be adjusted so that the specified thickness of granular or better material is placed above the subgrade soil.

Selecting one of the output format buttons 

will prompt the user for a file name and then run the batch process.

The value under **Batch Cycles** is the number of structures that will be simulated. If **Set Damage Limits** is checked, the number of lines in the output file may be fewer than this value.

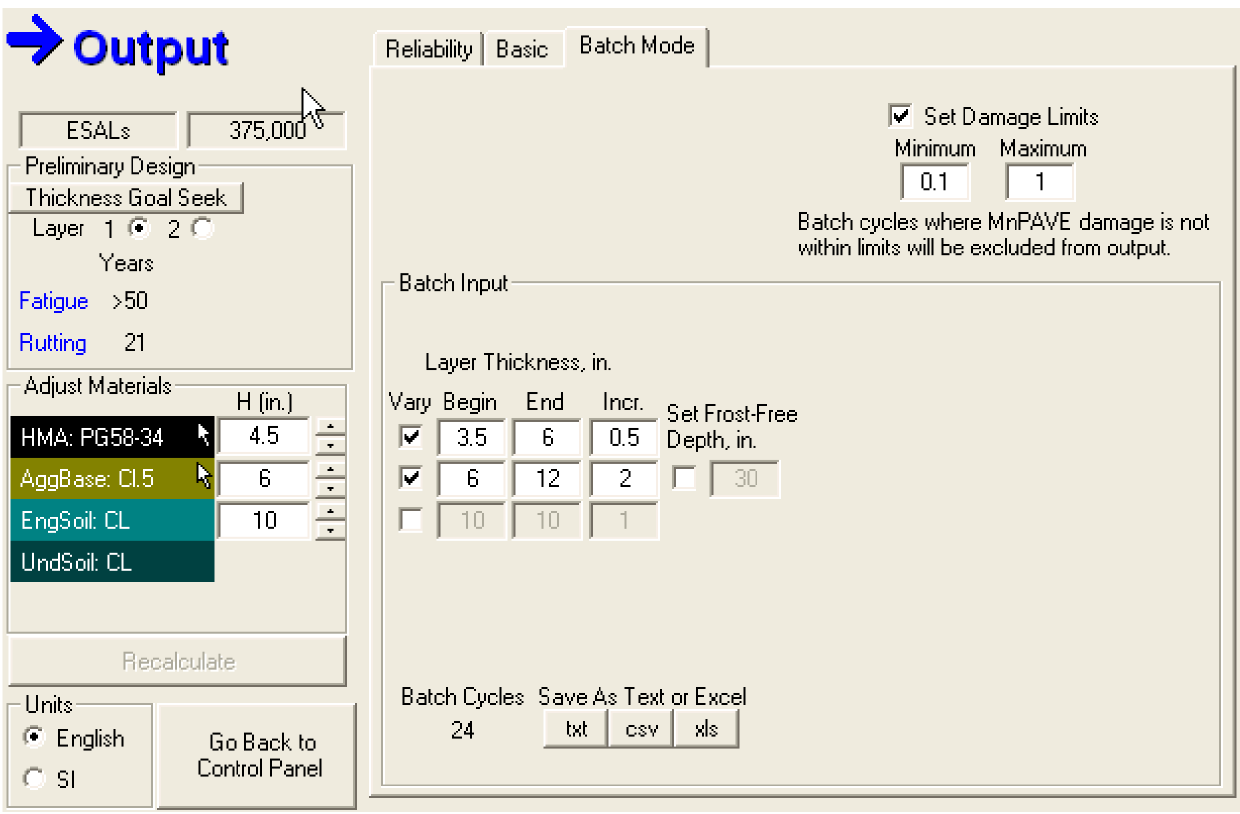


Figure J-22 Batch mode input damage limits tab in MnPave software

Research Mode

The standard design mode in MnPAVE provides the features necessary to complete a pavement design. Research Mode can be selected from the Main Control Panel from the View menu.

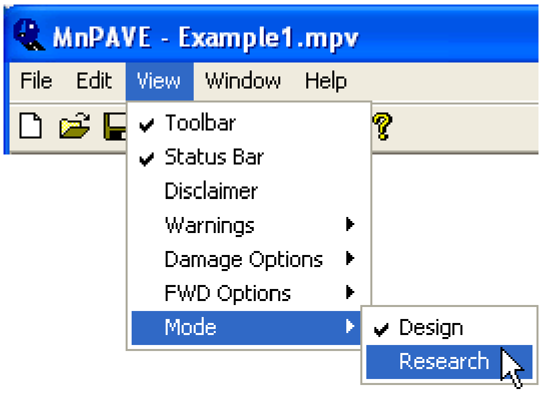


Figure J-23 Research mode selection in MnPave software

In Research Mode there are more features and more flexibility in entering data. However, since data entered in Research Mode may fall outside the range of date used to calibrate MnPAVE, Research Mode is not recommended for pavement design