Improving the Foundation Layers for Pavements

TECHNICAL REPORT:
Pavement Foundation Layer Reconstruction – Iowa I-35 Field Study

May 2016

Sponsored by
Federal Highway Administration (DTFH 61-06-H-00011 (Work Plan #18))
FHWA TPF-5(183): California, Iowa (lead state), Michigan, Pennsylvania, Wisconsin

National Concrete Pavement Technology Center

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Improving the Foundation Layers for Pavements: Pavement Foundation Layer Reconstruction – Iowa I-35 Field Study

May 2016

InTrans Project 09-352

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This technical project report is one of the field project reports developed as part of the TPF-5(183) and FHWA DTFH 61-06-H-00011:WO18 studies. This report presents results and analysis from a field study conducted on interstate highway I-35 in Iowa. The project involved removal of the existing pavement and undercutting down to the new subgrade elevation, and placing 305 mm (12 in.) of special backfill on the subgrade as subgrade treatment and 152 mm (6 in.) of granular subbase. The new PCC pavement was 292 mm (11.5 in.) in thickness. The granular subbase material consisted of both virgin crushed limestone aggregate and recycled portland cement concrete material. The subbase layer construction process involved placing the material and compacting the layer with a smooth drum roller in a non-vibratory mode for a maximum of three passes followed by trimming process to trim the layer to the design grade. The main objective of this field study was to investigate the impacts of vibratory versus static mode of compaction and number of compaction passes on the granular subbase layer material properties such as material fines content, dry density, elastic modulus, California bearing ratio, modulus of subgrade reaction, and saturated hydraulic conductivity. Results from the field testing were analyzed using statistical t-tests to assess whether statistically significant differences exist between untrimmed and trimmed base layers and between low amplitude versus static compaction. The field test results indicated that the use of low amplitude vibration instead of the static mode of compaction can result in material degradation, as evidenced by increases in fines contents, but the resulting fines content were within the specified gradation limits. However, the trimming process resulted in much higher fines content, which in turn resulted in a denser and stiffer subbase layer but also decreased permeability values.

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Technical Report
May 2016

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# TABLE OF CONTENTS

ACKNOWLEDGMENTS .......................................................................................................................... ix  
LIST OF SYMBOLS .......................................................................................................................... xi  
EXECUTIVE SUMMARY .................................................................................................................. xiii  
CHAPTER 1. INTRODUCTION .........................................................................................................1  
CHAPTER 2. PROJECT INFORMATION ..........................................................................................2  
  Project Background and Construction .....................................................................................2  
  Pavement Design Input Parameter Selection and Assumptions ..............................................5  
CHAPTER 3. EXPERIMENTAL TEST METHODS ...........................................................................6  
  Laboratory Testing Methods and Data Analysis .................................................................6  
  In Situ Testing Methods ........................................................................................................6  
  Real-Time Kinematic Global Positioning System ............................................................6  
  Nuclear Gauge ..................................................................................................................6  
  Zorn Light Weight Deflectometer ......................................................................................6  
  Dynamic Cone Penetrometer .............................................................................................7  
  Rapid Gas Permeameter Test ............................................................................................8  
  Static Plate Load Test .......................................................................................................8  
  Roller-Integrated Compaction Measurements ..................................................................9  
  Statistical Analysis .........................................................................................................10  
CHAPTER 4. EXPERIMENTAL TEST RESULTS ...........................................................................12  
  Description of Test Beds and In Situ Testing ....................................................................12  
  TB1: Untrimmed Base (RPCC) .........................................................................................14  
  TB2: Trimmed base (RPCC) .............................................................................................26  
  TB3: Virgin Crushed Limestone and RPCC ......................................................................34  
  Statistical Analysis Results ..............................................................................................36  
CHAPTER 5. SUMMARY AND CONCLUSIONS ............................................................................44  
REFERENCES .................................................................................................................................45  
APPENDIX: STRESS-STRAIN CURVES FROM PLATE LOAD TESTS ........................................47
LIST OF FIGURES

Figure 1. Moisture conditioning of aggregate after placement ........................................................3
Figure 2. Self-propelled smooth drum roller used by contractor (non-vibratory) ..............................3
Figure 3. Total station for controlling leveling operations ..............................................................4
Figure 4. Open graded base layer trimming operations ...................................................................4
Figure 5. Trimble SPS-881 hand-held receiver (a), CAT CS683 smooth drum roller with CMV and MDP (b), Zorn LWD (c), gas permeability test (d), and static PLT (e) .............7
Figure 6. EV1 and EV2 determination procedure from static PLT for subgrade and base materials .................................................................9
Figure 7. Locations of the test sections and measurement points obtained from GPS ...............13
Figure 8. TB1 and TB2: Test bed layout .......................................................................................14
Figure 9. TB1: Particle size distribution after low amplitude vibratory roller passes .................15
Figure 10. TB1: \( K_{\text{sat}} \) and \( F_{200} \) after low amplitude vibratory roller passes ..................16
Figure 11. TB1: Moisture content and density after low amplitude vibratory roller passes ......17
Figure 12. TB1: \( E_{LWD-Z3} \) after low amplitude vibratory roller passes ......................................17
Figure 13. TB1: DCP-CBR profiles after low amplitude vibratory roller passes ............................18
Figure 14. TB1: MDP* compaction curves after low amplitude vibratory roller passes ..........19
Figure 15. TB1: Particle size distributions after static compaction passes ...................................20
Figure 16. TB1: \( K_{\text{sat}} \) and \( F_{200} \) after static compaction passes ...............................................21
Figure 17. TB1: Moisture content and density after static compaction passes ..............................22
Figure 18. TB1: \( E_{LWD-Z3} \) after static compaction passes ........................................................22
Figure 19. TB1: DCP-CBR profiles after static compaction passes ...............................................23
Figure 20. TB1: MDP* compaction curves after static compaction passes ..................................24
Figure 21. TB1: Comparison of in situ point measurements after low amplitude vibratory roller and static roller passes ......................................................................................25
Figure 22. TB2: \( K_{\text{sat}} \) and \( F_{200} \) after low amplitude vibratory compaction roller passes ...............26
Figure 23. TB2: Moisture content and density after low amplitude vibratory compaction roller passes ..................................................................................................................27
Figure 24. TB2: \( E_{LWD-Z3} \) after low amplitude vibratory compaction roller passes ..................27
Figure 25. TB2: DCP-CBR profiles after low amplitude vibratory compaction roller passes ........28
Figure 26. TB2: \( K_{\text{sat}} \) and \( F_{200} \) after static compaction roller passes ......................................29
Figure 27. TB2: Moisture content and density after static compaction roller passes ..................30
Figure 28. TB2: \( E_{LWD-Z3} \) after static compaction roller passes ...............................................30
Figure 29. TB2: MDP* compaction curves after static compaction roller passes ..........................31
Figure 30. TB2: DCP-CBR profiles after static compaction roller passes ..................................32
Figure 31. TB2: Comparison of average in situ point measurements after low amplitude vibratory and static compaction roller passes ...........................................................................33
Figure 32. TB3: MDP* compaction curves after low amplitude compaction roller passes ............34
Figure 33. TB3: MDP* compaction curves after static compaction roller passes .........................35
Figure 34. TB3: Comparison of MDP* after low amplitude vibratory and static compaction roller passes ..........................................................................................................................36
Figure 35. Box plots of DCP-CBR (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static) ..............................................................................37
Figure 36. Box plots of \( K_{\text{sat}} \) (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static) ..................................................................................38
Figure 37. Box plots of fines content, $F_{200}$ (0-60 mm) (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)...............................38
Figure 38. Box plots of moisture content, $w$ (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)........................................................................39
Figure 39. Box plots of density, $\gamma_d$ (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static).......................................................................39
Figure 40. Box plots of $E_{LWD-Z3}$ (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)..............................................................................40
Figure 41. Box plots of $MDP^*$ (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)..........................................................................................40
Figure 42. Box plots of $E_{v1}$ and $E_{v2}$ (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)........................................................................41
Figure 43. TB1: Stress-strain curves after low amplitude vibratory compaction (0, 1) ........47
Figure 44. TB1: Stress-strain curves after low amplitude vibratory compaction (2, 3) ........48
Figure 45. TB1: Stress-strain curves after low amplitude vibratory compaction (6, 7) ........49
Figure 46. TB1: Stress-strain curve after low amplitude vibratory compaction (8, 9) .......50
Figure 47. TB1: Stress-strain curves after static compaction (1, 2)........................................51
Figure 48. TB1: Stress-strain curves after static compaction (3, 4)...........................................52
Figure 49. TB1: Stress-strain curves after static compaction (5, 6).........................................53
Figure 50. TB1: Stress-strain curves after static compaction (7, 8)........................................54
Figure 51. TB2: Stress-strain curves after low amplitude vibratory compaction (0, 1) ........55
Figure 52. TB2: Stress-strain curves after low amplitude vibratory compaction (2, 3) ........56
Figure 53. TB2: Stress-strain curves after low amplitude vibratory compaction (4, 5) ........57
Figure 54. TB2: Stress-strain curves after low amplitude vibratory compaction (6, 7) ........58
Figure 55. TB2: Stress-strain curves after low amplitude vibratory compaction (8, 9) ........59
Figure 56. TB2: Stress-strain curves after low amplitude vibratory compaction (1, 6) ..........60
Figure 57. TB2: Stress-strain curves after low amplitude vibratory compaction (7, 8) ........61
LIST OF TABLES

Table 1. Summary of pavement thickness design input parameters/assumptions using the PCA 1984 method ........................................................................................................................................................................5
Table 2. Features of the vibratory smooth drum compaction roller .................................................................10
Table 3. Summary of t-test results to compare low amplitude (LA) and static (ST) compaction on untrimmed base (UT) ...........................................................................................................................................42
Table 4. Summary of t-test results to compare low amplitude compaction (LA) on untrimmed (UT) base and trimmed (TM) base ..................................................................................................................43
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- California
- Iowa (lead state)
- Michigan
- Pennsylvania
- Wisconsin

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Caterpillar, Inc. provided the CS-563 smooth drum roller used on the project, outfitted with compaction measurement and documentation systems.

We also thank the help of Stephen Quist and Bob Steffes of Iowa State University with laboratory and field testing. Christianna White provided comments and technical editing.
LIST OF SYMBOLS AND ACRONYMS

a Plate radius
A’ Machine acceleration (m/s²)
B Machine internal loss coefficients specific to a particular machine (kJ/s)
CBR California bearing ratio
COV Coefficient of variation
D₀ Deflection measured under the plate
DCP-CBR California bearing ratio calculated from dynamic cone penetration values
DPI Dynamic penetration index
E Elastic modulus
EV₁ Initial load elastic modulus from plate load test
EV₂ Re-load elastic modulus from plate load test
E₁LWD-Z3 Elastic modulus determined from 300 mm diameter plate light weight deflectometer
F Shape factor
F₂₀₀ Percent passing No. 200 sieve
g Acceleration due to gravity
G₀ Geometric factor, a constant based on the geometry of the device and test area
GPT Rapid gas permeameter test device
k Modulus of subgrade reaction
kₑ Compress modulus of subgrade reaction
kₑ Relative permeability to gas
Kₑ Saturation hydraulic conductivity from the rapid gas permeameter test device
k₁ Modulus of subgrade reaction
LA Low-amplitude compaction
LWD Lightweight deflectometer
m Machine internal loss coefficients specific to a particular machine (kJ/m)
MDP Machine drive power (kJ/s)
MDP* Machine drive power-based measurement (manufacturer unitless scale of 1–150)
NG Humboldt nuclear gauge
n₀ and n₁ number of measurements obtained from two different conditions
Pᵃ Atmospheric pressure
P₁ Absolute gas pressure on the soil surface
Pₒ(g) Gauge pressure at the GPT orifice outlet
P₂ Atmospheric pressure
Pₑ Gross power needed to move the smooth drum roller (kJ/s)
PLT Plate load test
Q Volumetric flow rate
r Radius at the GPT outlet
s₀ and s₁ Standard deviation of the measurements obtained from two different conditions
S Water saturation
Sₑ Effective water saturation
$S_p$  Pooled standard deviation
$S_r$  Residual water saturation
ST  Static compaction
TM  Trimmed base
UT  Untrimmed base
$\nu$  Roller velocity (m/s)
w  Moisture content determined from Humboldt nuclear gauge
W  Roller weight (kN)
$\alpha$  Slope angle (roller pitch from a sensor)
$\gamma_d$  Dry unit weight determined from Humboldt nuclear gauge
$\lambda$  Brooks-Corey pore size distribution index
$\mu$  Statistical mean or average
$\mu_{water}$  Absolute viscosity of water (gm/cm-s)
$\eta$  Poisson’s ratio
$\sigma$  Statistical standard deviation
$\sigma_d$  Applied stress
$\mu_{gas}$  Kinematic viscosity of the gas
$\rho$  Density of water (g/sm$^3$)
EXECUTIVE SUMMARY

Quality foundation layers (the natural subgrade, subbase, and embankment) are essential to achieving excellent pavement performance. Unfortunately, many pavements in the United States still fail due to inadequate foundation layers. To address this problem, a research project, Improving the Foundation Layers for Pavements (FHWA DTFH 61-06-H-00011 WO #18; FHWA TPF-5(183)), was undertaken by Iowa State University (ISU) to identify, and provide guidance for implementing, best practices regarding foundation layer construction methods, material selection, in situ testing and evaluation, and performance-related designs and specifications. As part of the project, field studies were conducted in several in-service concrete pavements across the country that represented either premature failures or successful long-term pavements. A key aspect of each field study was to tie performance of the foundation layers to key engineering properties and pavement performance. In situ foundation layer performance data, as well as original construction data and maintenance/rehabilitation history data, were collected and geospatially and statistically analyzed to determine the effects of site-specific foundation layer construction methods, site evaluation, materials selection, design, treatments, and maintenance procedures on the performance of the foundation layers and of the related pavements. A technical report was prepared for each field study.

This report presents results and analysis from a field study conducted on interstate highway I-35 in Iowa. This project is located on I-35 in Hamilton County and involved reconstruction of the interstate highway from 1 mile north of IA 175 to 2.5 miles south of US20. The project involved removal of the existing pavement and undercutting down to the new subgrade elevation, and placing 305 mm (12 in.) of special backfill on the subgrade as subgrade treatment and 152 mm (6 in.) of granular subbase. The new PCC pavement was 292 mm (11.5 in.) in thickness. The special backfill material consisted of recycled material obtained from rubbilizing the existing pavement. The granular subbase material consisted of both virgin crushed limestone aggregate and recycled portland cement concrete material. The gradation requirements of the subbase material are from Section 4121 of the Iowa DOT standard specifications.

The Iowa State University (ISU) research team was present on site during construction of the granular subbase layer. The subbase layer construction process involved placing the material and compacting the layer with a smooth drum roller in a non-vibratory mode for a maximum of three passes followed by trimming process to trim the layer to the design grade. This placement and compaction process is in accordance with Section 2111 of the Iowa DOT standard specifications.

The main objective of this field study was to investigate the impacts of vibratory versus static mode of compaction and number of compaction passes on the granular subbase layer material properties such as material fines content, dry density, elastic modulus, California bearing ratio, modulus of subgrade reaction, and saturated hydraulic conductivity. Results from the field testing were analyzed using statistical t-tests to assess whether statistically significant differences exist between untrimmed and trimmed base layers and between low amplitude versus static compaction. Following are the key findings from analysis of the field test data:
• On the untrimmed granular subbase layer, CBR, $\gamma_d$, $F_{200}$, $E_{LWD-Z3}$, and $E_{V1}$ showed statistically significant differences in the measurement values between low amplitude and static mode of compaction. The lane compacted with low amplitude mode resulted in higher values. There was no statistically significant difference in the $k$, $K_{sat}$, $E_{v2}$, and $w$ measurements.

• On trimmed granular subbase layer, only $K_{sat}$, $E_{v2}$, and $w$ measurements showed statistically significant differences between low amplitude and static compaction lanes. The lane compacted in static mode showed higher $K_{sat}$ values. $E_{v2}$ was higher in low amplitude compaction lane. There were no statistically significant differences in the remaining measurements between the static and low amplitude compaction lanes.

• For lanes compacted using low amplitude vibration, all measurements except CBR showed statistically significant differences between UT and TM base. $\gamma_d$, $F_{200}$, $E_{LWD-Z3}$, $k$, $E_{v1}$ and $E_{v2}$ were higher in TM base, while $K_{sat}$ was lower in TM base.

• For lanes compacted in static mode, the t-test results show similar conclusions as the above case with low amplitude compaction. All measurements except CBR showed statistically significant differences between UT and TM base. $\gamma_d$, $F_{200}$, $E_{LWD-Z3}$, $k$, $E_{v1}$ and $E_{v2}$ were higher in TM base, while $K_{sat}$ was lower in TM base.

These results indicate that the use of low amplitude vibration instead of the static mode of compaction can result in material degradation, as evidenced by increases in fines contents, but the resulting fines content were within the specified gradation limits. However, the trimming process resulted in much higher fines content, which in turn resulted in a denser and stiffer subbase layer but also decreased permeability values.
CHAPTER 1. INTRODUCTION

This report presents results and analysis from a field study conducted on interstate highway I-35 in Iowa. This project is located on I-35 in Hamilton County and involved reconstruction of the interstate highway from 1 mile north of IA 175 to 2.5 miles south of US20.

The project involved removal of the existing pavement and undercutting down to the new subgrade elevation, and placing 305 mm (12 in.) of special backfill on the subgrade as subgrade treatment and 152 mm (6 in.) of granular subbase. The new PCC pavement was 292 mm (11.5 in.) in thickness. The special backfill material consisted of recycled material obtained from rubblizing the existing pavement. The granular subbase material consisted of both virgin crushed limestone aggregate and recycled portland cement concrete material. The gradation requirements of the subbase material was per Section 4121 of the Iowa DOT standard specifications.

The Iowa State University (ISU) research team was present on site during construction of the granular subbase layer. The subbase layer construction process involved placing the material and compacting the layer with a smooth drum roller in a non-vibratory mode for a maximum of three passes followed by trimming process to trim the layer to the design grade. This placement and compaction process is in accordance with Section 2111 of the Iowa DOT standard specifications.

The main objective of this field study was to investigate the assess the impacts of vibratory versus static mode of compaction and number of compaction passes on the granular subbase layer material properties such as material fines content, dry density, elastic modulus, California bearing ratio (CBR), modulus of subgrade reaction, and saturated hydraulic conductivity.

The ISU research team conducted field testing in three test beds (TB) that consisted of granular subbase layers before and after trimming. In each test bed, 1 to 9 roller passes were made in static and low amplitude vibration mode and followed by in situ point testing. A Caterpillar CS56 smooth drum vibratory roller equipped with machine drive power (MDP*) based roller integrated compaction monitoring system was used for compaction passes. In situ point testing involved nuclear gauge (NG) testing to determine material moisture content and dry density, dynamic cone penetrometer (DCP) to determine CBR, light weight deflectometer (LWD) to determine elastic modulus, static plate load test to determine modulus of subgrade reaction \( k \) value and elastic and re-load modulus, and air permeameter test (APT) to determine saturated hydraulic conductivity. The results are analyzed using statistical t-test analysis to assess if statistically significant differences exist between untrimmed and trimmed base layers, and low amplitude versus static compaction.

The findings from this report should be of significant interest to researchers, practitioners, and agencies who deal with design, construction, and maintenance aspects of PCC pavements. Results from this project provide one of several field project reports being developed as part of the TPF-5(183) and FHWA DTFH 61-06-H-00011:WO18 studies.
CHAPTER 2. PROJECT INFORMATION

This chapter presents brief background information on the project based on the project plans, design input parameters based on information obtained from the Iowa DOT pavement design engineer, and pictures taken during construction.

Project Background and Construction

This project is located on I-35 in Hamilton County and involved reconstruction of the interstate highway from 1 mile north of IA 175 to 2.5 miles south of US20. All ISU testing was performed on I-35 north bound lanes just north and south of the 270th St. overpass bridge near mile marker 139.

The project involved removal of the existing pavement and undercutting down to the new subgrade elevation, and placing 305 mm (12 in.) of special backfill on the subgrade as subgrade treatment and 152 mm (6 in.) of granular subbase. The new PCC pavement was 292 mm (11.5 in.) in thickness. The subbase layer construction process involved placing the material and compacting the layer with a smooth drum roller in a non-vibratory mode for a maximum of three passes followed by trimming process to trim the layer to the design grade. This placement and compaction process is in accordance with Section 2111 of the Iowa DOT standard specifications.

The ISU research team was present on site during construction of the granular subbase layer, and photographs are shown in Figure 1 to Figure 4. The subbase layer process involved placing the granular subbase layer and compacting the layer with a smooth drum roller in a non-vibratory mode for a maximum of three passes followed by trimming process to trim the layer to the design grade. This placement and compaction process is in accordance with Section 2111 of the Iowa DOT standard specifications.
Figure 1. Moisture conditioning of aggregate after placement

Figure 2. Self-propelled smooth drum roller used by contractor (non-vibratory)
Figure 3. Total station for controlling leveling operations

Figure 4. Open graded base layer trimming operations
Pavement Design Input Parameter Selection and Assumptions

A summary of pavement thickness design input parameters is provided in Table 1. A composite modulus of subgrade reaction, $k_{\text{comp}} = 43 \text{ kPa/mm (160 pci)}$, was determined by the Iowa DOT engineer following design guidelines in PCA (1984) as summarized in Table 1. The minimum design thickness was about 279 mm (11 in.) for the new pavement.

### Table 1. Summary of pavement thickness design input parameters/assumptions using the PCA 1984 method

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface Layer Design Assumptions</strong></td>
<td></td>
</tr>
<tr>
<td>Design period</td>
<td>40</td>
</tr>
<tr>
<td>Average daily traffic (ADT) volume</td>
<td>25,670 (2009) 76,669 (2049)</td>
</tr>
<tr>
<td>Average daily truck traffic (ADTT) volume</td>
<td>14,733 (2049)</td>
</tr>
<tr>
<td>ADT annual growth</td>
<td>~3%</td>
</tr>
<tr>
<td>Doweled joints (yes/no)</td>
<td>Yes</td>
</tr>
<tr>
<td>Concrete shoulder (yes/no)</td>
<td>No</td>
</tr>
<tr>
<td>Concrete modulus of rupture</td>
<td>575</td>
</tr>
<tr>
<td>Load safety factor</td>
<td>1.2</td>
</tr>
<tr>
<td>Equivalent stresses (for single and tandem axles)</td>
<td>161 single, 154 tandem</td>
</tr>
<tr>
<td>Stress ratio factors (for single and tandem axles)</td>
<td>.280/.268</td>
</tr>
<tr>
<td>Erosion factors (for single and tandem axles)</td>
<td>2.40/2.62</td>
</tr>
<tr>
<td>Allowable load repetitions</td>
<td>Variable for each axle category</td>
</tr>
<tr>
<td>Lane distribution factor, $L$</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Foundation Layer Design Assumptions</strong></td>
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<tr>
<td>Subgrade layer stiffness, $k$ (pci)</td>
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</tr>
<tr>
<td>Type of subbase (treated/untreated)</td>
<td>untreated</td>
</tr>
<tr>
<td>Subbase layer thickness</td>
<td>Variable (6 in. min, 8 in. avg)</td>
</tr>
<tr>
<td>Composite stiffness, $k_{\text{comp}}$ (pci)</td>
<td>160</td>
</tr>
<tr>
<td><strong>Pavement Thickness Design</strong></td>
<td></td>
</tr>
<tr>
<td>Calculated design thickness</td>
<td>11 in.</td>
</tr>
</tbody>
</table>
CHAPTER 3. EXPERIMENTAL TEST METHODS

This chapter summarizes the laboratory and in situ testing methods used in this study.

Laboratory Testing Methods and Data Analysis

Samples from the new open graded base layer were collected from the field and were carefully sealed and transported to the laboratory for testing. Particle-size analysis tests were performed in accordance with ASTM C136-06 Standard test method for sieve analysis of fine and coarse aggregates.

In Situ Testing Methods

The following in situ testing methods and procedures were used in this study: real-time kinematic (RTK) global positioning system (GPS); dynamic cone penetrometer (DCP); calibrated Humboldt nuclear gauge (NG); rapid gas permeameter device (GPT); static plate load test (PLT) setup with 300 mm diameter plate; and roller-integrated compaction monitoring measurements. Pictures of these test devices are shown in Figure 5.

Real-Time Kinematic Global Positioning System

A real-time kinematic GPS system (RTK-GPS) was used to obtain spatial coordinates (x, y, and z) of in situ test locations and tested pavement slabs. A Trimble SPS 881 receiver was used with base station correction provided from a Trimble SPS851 established on site Figure 3. According to the manufacturer, this survey system is capable of horizontal accuracies of < 10 mm and vertical accuracies of < 20 mm.

Nuclear Gauge

A calibrated Humboldt nuclear moisture-density gauge (NG) device was used to provide rapid measurements of soil dry unit weight ($\gamma_d$) and moisture content ($w$) in the base materials. Tests were performed following ASTM D6938-10 Standard Test Method for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth). Measurements of $w$ and $\gamma_d$ were obtained at each test location and average values are reported.

Zorn Light Weight Deflectometer

Zorn LWD tests were performed on base and subbase layers to determine elastic modulus. The LWD was set up with a 300 mm diameter plate and a 71 cm drop height. The tests were performed following manufacturer recommendations (Zorn 2003), and the elastic modulus values were determined using Equation 1:
\[ E = \frac{(1 - \eta^2)\sigma_0 a}{D_0} \times F \]  

where \( E \) = elastic modulus (MPa), \( D_0 \) = measured deflection under the plate (mm), \( \eta \) = Poisson’s ratio (0.4), \( \sigma_0 \) = applied stress (MPa), \( r \) = radius of the plate (mm), \( F \) = shape factor depending on stress distribution (assumed as 8/3) (see Vennapusa and White 2009). The results are reported as \( E_{\text{LWD-Z3}} \) where \( Z \) represents Zorn LWD and 3 represents 300 mm diameter plate.

**Figure 5.** Trimble SPS-881 hand-held receiver (a), CAT CS683 smooth drum roller with CMV and MDP (b), Zorn LWD (c), gas permeability test (d), and static PLT (e)

**Dynamic Cone Penetrometer**

DCP tests were performed in accordance with ASTM D6951-03 *Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications* to determine dynamic penetration index (DPI) and calculate California bearing ratio (CBR) using Equation 2.

\[ \text{CBR} = \frac{292}{\text{DPI}^{1.12}} \]  

(2)
The DCP test results are presented in this report as CBR with depth profiles at a test location and as point values of average CBR of the subbase layer. The point data values represent the weighted average CBR within the granular subbase layer.

**Rapid Gas Permeameter Test**

The rapid gas permeameter test device (GPT) was used to determine saturated hydraulic conductivity of OGDC base and the existing subbase layers. GPT is a recently developed rapid permeability testing device that uses gas as a permeating fluid to determine the saturated hydraulic conductivity (K\(_{\text{sat}}\)) at a test location in situ (White et al. 2010a). Air was used as the permeating gas in this field study. The GPT consists of a self-contained pressurized gas system with a self-sealing base plate and a theoretical algorithm to rapidly determine the K\(_{\text{sat}}\). The gas flow is controlled using a regulator and a precision orifice. The inlet pressure and flow rate values are recorded in the device and are used in K\(_{\text{sat}}\) calculations using Equation 3.

\[
K_{\text{sat}} = \frac{2\mu_{\text{gas}} Q P_1}{r G \sqrt{P_1^2 - P_2^2}} \times \frac{\rho g}{\mu_{\text{water}} (1-S_e)^3 (1-S_e^{(2+\lambda)})}
\]

(3)

where K\(_{\text{sat}}\) = saturated hydraulic conductivity (cm/s); K\(_{\text{gas}}\) = gas permeability; K\(_{\text{rg}}\) = relative permeability to gas; \(\mu_{\text{gas}}\) = kinematic viscosity of the gas (PaS); Q = volumetric flow rate (cm\(^3\)/s); P\(_1\) = absolute gas pressure on the soil surface (Pa) \(P_{\text{o(g)}}\) x 9.81 + 101325; \(P_{\text{o(g)}}\) = gauge pressure at the orifice outlet (mm of H\(_2\)O); P\(_2\) = atmospheric pressure (Pa); r = radius at the outlet (4.45 cm); Go = Geometric factor (constant based on geometry of the device and test area; White et al. 2007), S\(_e\) = effective water saturation \(S_e = (S - S_r)/(1-S_r)\); \(\lambda\) = Brooks-Corey pore size distribution index; S\(_r\) = residual water saturation; S = water saturation; \(\rho\) = density of water (g/sm\(^3\)); g = acceleration due to gravity (cm/s\(^2\)); \(\mu_{\text{water}}\) = absolute viscosity of water (gm/cm-s).

More details on the test device and K\(_{\text{sat}}\) calculation procedure are provided in White et al. (2007, 2010a). The degree of saturation (S) values were obtained from in situ dry unit weight and moisture content measurements. The S\(_r\) and \(\lambda\) parameters can be obtained by determining the soil-water retention properties (also known as soil water characteristic curves (SWCC) of the materials). Tests to determine the SWCC parameters can be time-consuming and require precise calibration of test equipment. As an alternative, empirical relationships from material gradation properties can be used (Zapata and Houston 2008). A summary of these relationships and the procedure to estimate S\(_r\) and \(\lambda\) parameters are summarized in White et al. (2010a). For the results presented in this report, \(\lambda\) = 0.98 and S\(_r\) = 12% were used for granular base material.

**Static Plate Load Test**

Static PLTs were conducted on the test sections by applying a static load on a 300 mm diameter plate against a 6.2 kN capacity reaction force. The applied load was measured using a 90-kN load cell and deformations were measured using three 50-mm LVDTs. The load and deformation readings were continuously recorded during the test using a data logger. The E\(_{V1}\) and E\(_{V2}\) values
were determined from Equation 1 using corresponding deflection values at 0.2 and 0.4 MPa contact stresses, respectively, as illustrated in Figure 6.

![Figure 6. EV1 and EV2 determination procedure from static PLT for subgrade and base materials](image)

**Figure 6. EV1 and EV2 determination procedure from static PLT for subgrade and base materials**

Modulus of subgrade reaction was also determined from the PLT results by using Equation 4, where \( k_1 \) = modulus of subgrade reaction (kPa/mm), \( D_0 \) = measured deflection under the plate (mm) for 0.2 to 0.4 MPa applied stress range, and \( \sigma_0 \) = applied stress (kPa).

\[
k_1 = \frac{\sigma_0}{D_0}
\]  

(4)

The PLT was performed using a 300 mm (12 in.) diameter plate, but the \( k_{comp} \) used in the AASHTO (1993) design guide is based on a 720 mm (30 in.) diameter plate. Therefore, the measured \( k_{comp} \) values were corrected for plate size using theoretical relationship (Equation 5) proposed by Terzaghi (Terzaghi and Peck 1967) for granular materials.

\[
k_{comp} = k_1 \left[ \frac{B+B_1}{2B} \right]^2
\]

(5)

where \( k_{comp} \) = modulus of subgrade reaction using a 762 mm (30 in.) diameter plate, \( k_1 \) = modulus of subgrade reaction using a 300 mm (12 in.) diameter plate, \( B_1 = 300 \text{ mm} \); and \( B = 762 \text{ mm} \).

**Roller-Integrated Compaction Measurements**

The Caterpillar CS563 vibratory smooth drum roller used on the project was equipped with machine drive power (MDP) compaction monitoring technology. Brief descriptions of these
measurement values are provided below, and some key features of the roller are summarized in Table 2.

**Table 2. Features of the vibratory smooth drum compaction roller**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum Geometry</td>
<td>2.13 m width and 1.52 m diameter</td>
</tr>
<tr>
<td>Frequency ( (f) )</td>
<td>30 Hz</td>
</tr>
<tr>
<td>Amplitude ( (a) )</td>
<td>Static, 0.90 mm (low amplitude), and 1.80 mm (high amplitude)</td>
</tr>
<tr>
<td>Settings</td>
<td>Machine drive power based measurement value (shown as CCV in the output)</td>
</tr>
<tr>
<td>Compaction</td>
<td>Output</td>
</tr>
<tr>
<td>Measurement Value</td>
<td>Machine drive power based measurement value (shown as CCV in the output)</td>
</tr>
<tr>
<td>Display Software</td>
<td>AccuGrade</td>
</tr>
<tr>
<td>GPS coordinates</td>
<td>UTM Zone 15N (NAD83)</td>
</tr>
<tr>
<td>Output</td>
<td>Date/Time, Location (Northing/Easting/Elevation of left and right ends of the roller drum), Speed, CCV, CMV, Frequency, Amplitude, Direction (forward/backward), Vibration (On/Off)</td>
</tr>
</tbody>
</table>

MDP technology relates mechanical performance of the roller during compaction to the properties of the compacted soil. Detailed background information on the MDP system is provided in White et al. (2005). Controlled field studies documented by White and Thompson (2008), Thompson and White (2008), and Vennapusa et al. (2009) verified that MDP values are empirically related to soil compaction characteristics (i.e., density, stiffness, and strength). MDP is calculated using Equation 6.

\[
MDP = P_g - Wv \left( \sin \alpha + \frac{A'}{g} \right) - (mv + b)
\]

where MDP = machine drive power (kJ/s); \( P_g \) = gross power needed to move the machine (kJ/s); \( W \) = roller weight (kN); \( A' \) = machine acceleration (m/s²); \( g \) = acceleration of gravity (m/s²); \( \alpha \) = slope angle (roller pitch from a sensor); \( v \) = roller velocity (m/s); and \( m \) (kJ/m) and \( b \) (kJ/s) = machine internal loss coefficients specific to a particular machine (White et al. 2005).

MDP is a relative value referencing the material properties of the calibration surface, which is generally a hard compacted surface (MDP = 0 kJ/s). Positive MDP values therefore indicate material that is less compact than the calibration surface, while negative MDP values indicate material that is more compacted than the calibration surface (i.e., less roller drum sinkage). The MDP values obtained from the machine were recalculated to range between 1 and 150 according to the manufacturer (referred to as MDP* in this report).

**Statistical Analysis**

Student \( t \)-test analysis (Ott and Longnecker 2008) was conducted to assess differences between results obtained from sections with trimmed (TM) or untrimmed (UT) base material and results
obtained from sections with low amplitude compaction (LA) or static compaction (ST) using the following equations:

\[
t = \frac{\mu_0 - \mu_1}{s_p \sqrt{\frac{1}{n_0} + \frac{1}{n_1}}}
\]

where

\[
s_p = \sqrt{\frac{(n_0-1)s_0^2 + (n_1-1)s_1^2}{n_0 + n_1 - 2}}
\]

\(n_0\) and \(n_1\) = number of measurements obtained from the two sections being compared, respectively; \(S_p\) = pooled standard deviation; and \(s_0\) and \(s_1\) = standard deviation of measurements obtained the two sections being compared.

The observed \(t\)-values were compared with the minimum \(t\)-value for a one-tailed test with degree of freedom (df) = \(n_0 + n_1 - 2\), for 95% confidence level (i.e., \(\alpha = 0.05\)). When comparing measurements from cracked or uncracked sections, if the \(t\)-values were greater than the minimum \(t\)-value, then it was concluded that there is sufficient evidence that the measurements were statistically different.
CHAPTER 4. EXPERIMENTAL TEST RESULTS

Description of Test Beds and In Situ Testing

A total of three test beds were tested in this field study. Test beds 1 and 2 (TB1 and TB2) consisted of RPCC material in the granular subbase and TB3 consisted of a mixture of RPCC and virgin crushed limestone material. The material was placed 1 to 2 days before testing. In TB1 and TB3, the material was not trimmed to grade (referred to as untrimmed base), while in TB2 it was trimmed to grade (referred to as trimmed base).

Each test bed was approximately 4.6 m (15 ft) wide x 122 to 214 m (400 to 700 ft) long. The test beds were divided into two side-by-side roller lanes that are about 2.3 m (7.5 ft) wide. Each lane was compacted either in static mode or in low amplitude vibratory mode using Caterpillar CS563 smooth drum roller. Each lane was then divided into 8 or 9 segments, in which each segment was compacted using roller passes ranging from 1 to 9. In situ tests were conducted in each segment after the compaction passes. The test bed layout along with test locations from GPS measurements are shown in Figure 7. A closer view of the test bed layout and test points from TB1 and TB2 is shown in Figure 8.

In situ testing in TB1 and TB2 involved LWD, GPT, MnDOT permeameter, PLT, NG, and DCP testing in each segment. In addition, bag samples of the subbase material were obtained from each test location from depths 0 to 60 mm and 60 to 100 mm below surface to perform gradation tests. Percent passing No. 200 sieve (F200) were determined from each test location and a full gradation test was performed from one location in each segment. LWD and GPT tests, and F200 tests were performed at 3 locations from each segment, and all other tests MDP* values were obtained during the compaction passes from the roller. TB3 was also compacted and MDP* values were obtained but in situ testing was not performed after compaction due to rain at the time of testing.

In the following sections of the report, results from each test bed are presented separately for each measurement and is followed by results of statistical analysis assessing differences in the measurement values between trimmed vs. untrimmed base and static vs. low amplitude compaction test lanes.
Figure 7. Locations of the test sections and measurement points obtained from GPS
TB1: Untrimmed Base (RPCC)

TB1 consisted of two lanes, one compacted in static mode and one in low amplitude vibration mode. Results of the two lanes are presented separately in the following.

Particle size distribution curves from one sample obtained in each segment compacted to passes 1 to 8 are shown in Figure 9. K_{sat} and F_{200} from 0 to 60 and 60 to 100 mm depths for each segment are shown in Figure 10. Moisture and dry density measurements from NG are presented in Figure 11. Elastic modulus measurements from LWD test are presented in Figure 12. DCP-CBR profiles are shown in Figure 13. MDP* measurements are presented in Figure 14. The results from the static compaction lane are presented in Figure 15 to Figure 20.

All the measurements are compared in plots showing each measurement value versus compaction passes in Figure 21. The results indicated that the moduli values from PLT and LWD, dry density values and CBR values were all slightly higher in the lane compacted in vibratory mode. F_{200} values were generally higher in the low amplitude lane, although all were within the maximum allowed F_{200} of 6% for the granular subbase material. MDP* values were higher in the static lane although it must be noted that MDP* values are influenced by the compaction mode.
Figure 9. TB1: Particle size distribution after low amplitude vibratory roller passes
Figure 10. TB1: $K_{sat}$ and $F_{200}$ after low amplitude vibratory roller passes
Figure 11. TB1: Moisture content and density after low amplitude vibratory roller passes

Figure 12. TB1: $E_{LWD-Z3}$ after low amplitude vibratory roller passes
Figure 13. TB1: DCP-CBR profiles after low amplitude vibratory roller passes
Figure 14. TB1: MDP* compaction curves after low amplitude vibratory roller passes
Figure 15. TB1: Particle size distributions after static compaction passes
Figure 16. TB1: $K_{\text{SAT}}$ and $F_{200}$ after static compaction passes
Figure 17. TB1: Moisture content and density after static compaction passes

Figure 18. TB1: $E_{LWD-Z3}$ after static compaction passes
Figure 19. TB1: DCP-CBR profiles after static compaction passes
Figure 20. TB1: MDP* compaction curves after static compaction passes
Figure 21. TB1: Comparison of in situ point measurements after low amplitude vibratory roller and static roller passes
TB2: Trimmed base (RPCC)

TB2 consisted of two lanes, one compacted in static mode and one in low amplitude vibration mode. Testing was conducted after compaction and trimming operations were performed by the contractor. Results of the two lanes are presented separately in the following.

Results from the lane compacted using low amplitude vibration are presented in Figure 22 to Figure 25 and the results from the static compaction lane are presented in Figure 26 to Figure 30. No significant differences were observed between measurements from the two lanes. Statistical analysis is performed on this data to assess statistically significance and is presented in the following sections of the report.

Figure 22. TB2: $K_{\text{SAT}}$ and $F_{200}$ after low amplitude vibratory compaction roller passes
Figure 23. TB2: Moisture content and density after low amplitude vibratory compaction roller passes

Figure 24. TB2: $E_{LWD-Z3}$ after low amplitude vibratory compaction roller passes
Figure 25. TB2: DCP-CBR profiles after low amplitude vibratory compaction roller passes
Figure 26. TB2: $K_{\text{SAT}}$ and $F_{200}$ after static compaction roller passes
Figure 27. TB2: Moisture content and density after static compaction roller passes

Figure 28. TB2: $E_{\text{LWD-Z3}}$ after static compaction roller passes
Figure 29. TB2: MDP* compaction curves after static compaction roller passes
Figure 30. TB2: DCP-CBR profiles after static compaction roller passes
Figure 31. TB2: Comparison of average in situ point measurements after low amplitude vibratory and static compaction roller passes
TB3: Virgin Crushed Limestone and RPCC

MDP* results obtained from TB3 from the two lanes are presented in Figure 32 and Figure 33. Average MDP* values per pass are shown in Figure 34 for the two lanes. Results indicated that the MDP* values obtained in static mode were higher than in vibratory mode, which was also observed in TB1. As noted earlier, MDP* measurements are influenced by vibration mode.

Figure 32. TB3: MDP* compaction curves after low amplitude compaction roller passes

Figure 33. TB3: MDP* compaction curves after low amplitude compaction roller passes
Figure 33. TB3: MDP* compaction curves after static compaction roller passes
Figure 34. TB3: Comparison of MDP*after low amplitude vibratory and static compaction roller passes

Statistical Analysis Results

In this section, results obtained from TB1 and TB2 are presented as box plots that show the raw data and identify the mean, median, and 5th, 25th, 75th, and 95th percentiles. Box plots are presented for each measurement value separately in Figure 35 to Figure 42.

The results are analyzed using t-tests to assess if statistically significant differences exist between the different test lanes. Comparisons are made between untrimmed (UT) and trimmed (TM) base layers, and low amplitude (LA) versus static (ST) compaction lanes. Results of statistical t-test analysis are shown in Table 3 and Table 4 for these two comparison cases. These tables also summarize the mean and coefficient of variation (COV) of the measurement values.

Following are the key findings from the statistical analysis:

- On UT base, CBR, $\gamma_d$, $F_{200}$, $E_{LWD-Z3}$, and $E_{V1}$ showed statistically significant differences in the measurement values between low amplitude and static mode of compaction. The lane compacted with low amplitude mode resulted in higher values. There was no statistically significant difference in the $k$, $K_{sat}$, $E_{v2}$, and $w$ measurements.

- On TM base, only $K_{sat}$, $E_{v2}$, and $w$ measurements showed statistically significant differences between low amplitude and static compaction lanes. The lane compacted in static mode showed higher $K_{sat}$ values. $E_{v2}$ was higher in low amplitude compaction lane.
There was no statistically significant difference between the static and low amplitude compaction lanes in the remaining measurements.

- For lanes compacted using low amplitude vibration, all measurements except CBR showed statistically significant differences between UT and TM base. $\gamma_d$, $F_{200}$, $E_{LWD-Z3}$, $k$, $E_{V1}$ and $E_{V2}$ were higher in TM base, while $K_{sat}$ was lower in TM base. These results indicate that trimming process resulted in higher fines content, and a denser and stiffer base layer but decreased the permeability values.

- For lanes compacted in static mode, the t-test results show similar conclusions as the above case with low amplitude compaction. All measurements except CBR showed statistically significant differences between UT and TM base. $\gamma_d$, $F_{200}$, $E_{LWD-Z3}$, $k$, $E_{V1}$ and $E_{V2}$ were higher in TM base, while $K_{sat}$ was lower in TM base.

Figure 35. Box plots of DCP-CBR (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)
Figure 36. Box plots of $K_{sat}$ (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)

Figure 37. Box plots of fines content, $F_{200}$ (0-60 mm) (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)
Figure 38. Box plots of moisture content, $w$ (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)

Figure 39. Box plots of density, $\gamma_d$ (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)
Figure 40. Box plots of $E_{LWD-Z3}$ (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)

Figure 41. Box plots of $\text{MDP}^*$ (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)
Figure 42. Box plots of $E_{v1}$ and $E_{v2}$ (UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static)
Table 3. Summary of t-test results to compare low amplitude (LA) and static (ST) compaction on untrimmed base (UT)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Mean</th>
<th>COV (%)</th>
<th>t</th>
<th>P</th>
<th>Condition</th>
<th>Mean</th>
<th>COV (%)</th>
<th>t</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UT/LA</td>
<td>11.7</td>
<td>45</td>
<td>3.01</td>
<td>0.007</td>
<td>TM/LA</td>
<td>9.4</td>
<td>38</td>
<td>1.80</td>
<td>0.048</td>
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<td>UT/ST</td>
<td>5.5</td>
<td>43</td>
<td></td>
<td></td>
<td>TM/ST</td>
<td>7.2</td>
<td>18</td>
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<tr>
<td></td>
<td>UT/LA</td>
<td>15.85</td>
<td>3</td>
<td>2.97</td>
<td>0.005</td>
<td>TM/LA</td>
<td>17.78</td>
<td>4</td>
<td>1.05</td>
<td>0.16</td>
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<tr>
<td></td>
<td>UT/ST</td>
<td>15.18</td>
<td>3</td>
<td></td>
<td></td>
<td>TM/ST</td>
<td>17.47</td>
<td>3</td>
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<tr>
<td></td>
<td>UT/LA</td>
<td>2.7</td>
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<td>2.13</td>
<td>0.019</td>
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<td>TM/ST</td>
<td>9.5</td>
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<td>1.02</td>
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<tr>
<td></td>
<td>UT/LA</td>
<td>54.6</td>
<td>25</td>
<td>1.62</td>
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<td>90.8</td>
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<td></td>
<td>UT/ST</td>
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<td>UT/LA</td>
<td>40.4</td>
<td>87</td>
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<td>0.482</td>
<td>TM/LA</td>
<td>3.1</td>
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<td>124</td>
<td>0.05</td>
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<td>TM/ST</td>
<td>9.0</td>
<td>67</td>
<td>4.14</td>
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<tr>
<td></td>
<td>UT/LA</td>
<td>50.7</td>
<td>15</td>
<td>4.26</td>
<td>0.001</td>
<td>TM/LA</td>
<td>61.1</td>
<td>7</td>
<td>1.11</td>
<td>0.141</td>
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<td>UT/ST</td>
<td>38.3</td>
<td>11</td>
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<td>TM/ST</td>
<td>59.2</td>
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<td>UT/LA</td>
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<td>&lt;0.001</td>
<td>TM/LA</td>
<td>140.4</td>
<td>1</td>
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<td>&lt;0.001</td>
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<td>UT/ST</td>
<td>141.4</td>
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<td>6.33</td>
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<td>TM/ST</td>
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Notes: UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static. Cells highlighted indicate statistical significance at the 95% confidence level.
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Notes: UT indicates untrimmed; LA indicates low amplitude; TM indicates trimmed; ST indicates static. Cells highlighted indicate statistical significance at the 95% confidence level.
CHAPTER 5. SUMMARY AND CONCLUSIONS

The main objective of this field study was to investigate the impacts of vibratory versus static mode of compaction and number of compaction passes on the granular subbase layer material properties such as material fines content, dry density, elastic modulus, California bearing ratio, modulus of subgrade reaction, and saturated hydraulic conductivity. Results from the field testing are presented above and are analyzed using statistical t-test analysis to assess if statistically significant differences exist between untrimmed and trimmed base layers, and low amplitude versus static compaction. Following are the key findings from the field testing analysis:

- On untrimmed granular subbase layer, CBR, $\gamma_d$, $F_{200}$, $E_{LWD-Z3}$, and $E_{V1}$ showed statistically significant differences in the measurement values between low amplitude and static mode of compaction. The lane compacted with low amplitude mode resulted in higher values. There was no statistically significant difference in the $k$, $K_{sat}$, $E_{v2}$, and $w$ measurements.
- On trimmed granular subbase layer, only $K_{sat}$, $E_{v2}$, and $w$ measurements showed statistically significant differences between low amplitude and static compaction lanes. The lane compacted in static mode showed higher $K_{sat}$ values. $E_{v2}$ was higher in low amplitude compaction lane. There were no statistically significant differences in the remaining measurements between the static and low amplitude compaction lanes.
- For lanes compacted using low amplitude vibration, all measurements except CBR showed statistically significant differences between UT and TM base. $\gamma_d$, $F_{200}$, $E_{LWD-Z3}$, $k$, $E_{v1}$ and $E_{v2}$ were higher in TM base, while $K_{sat}$ was lower in TM base.
- For lanes compacted in static mode, the t-test results show similar conclusions as the above case with low amplitude compaction. All measurements except CBR showed statistically significant differences between UT and TM base. $\gamma_d$, $F_{200}$, $E_{LWD-Z3}$, $k$, $E_{v1}$ and $E_{v2}$ were higher in TM base, while $K_{sat}$ was lower in TM base.

These results indicate that the use of low amplitude vibration instead of the static mode of compaction can result in material degradation, as evidenced by increases in fines contents, but the resulting fines content were within the specified gradation limits. However, the trimming process resulted in much higher fines content, which in turn resulted in a denser and stiffer subbase layer but also decreased permeability values.
REFERENCES


APPENDIX: STRESS-STRAIN CURVES FROM PLATE LOAD TESTS

Figure 43. TB1: Stress-strain curves after low amplitude vibratory compaction (0, 1)

EV1 = 28 MPa
EV2 = 130 MPa

EV1 = 25 MPa
EV2 = 134 MPa

EV1 = 25 MPa
EV2 = 137 MPa

EV1 = 23 MPa
EV2 = 113 MPa

EV1 = 26 MPa
EV2 = 75 MPa
Figure 44. TB1: Stress-strain curves after low amplitude vibratory compaction (2, 3)
Figure 45. TB1: Stress-strain curves after low amplitude vibratory compaction (6, 7)
Figure 46. TB1: Stress-strain curve after low amplitude vibratory compaction (8, 9)
Figure 47. TB1: Stress-strain curves after static compaction (1, 2)
Figure 48. TB1: Stress-strain curves after static compaction (3, 4)
Figure 49. TB1: Stress-strain curves after static compaction (5, 6)

- **S5-1**:  
  - Applied Stress (MPa): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5  
  - Deflection (mm): 0, 2, 4, 6, 8, 10  
  - \( E_{v1} = 27 \text{ MPa} \)  
  - \( E_{v2} = 97 \text{ MPa} \)  

- **S5-2**:  
  - Applied Stress (MPa): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5  
  - Deflection (mm): 0, 2, 4, 6, 8, 10  
  - \( E_{v1} = 59 \text{ MPa} \)  
  - \( E_{v2} = 120 \text{ MPa} \)  

- **S5-3**:  
  - Applied Stress (MPa): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5  
  - Deflection (mm): 0, 2, 4, 6, 8, 10  
  - \( E_{v1} = 30 \text{ MPa} \)  
  - \( E_{v2} = 120 \text{ MPa} \)  

- **S6-1**:  
  - Applied Stress (MPa): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5  
  - Deflection (mm): 0, 2, 4, 6, 8, 10  
  - \( E_{v1} = 24 \text{ MPa} \)  
  - \( E_{v2} = 95 \text{ MPa} \)  

- **S6-2**:  
  - Applied Stress (MPa): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5  
  - Deflection (mm): 0, 2, 4, 6, 8, 10  
  - \( E_{v1} = 37 \text{ MPa} \)  
  - \( E_{v2} = 162 \text{ MPa} \)  

- **S6-3**:  
  - Applied Stress (MPa): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5  
  - Deflection (mm): 0, 2, 4, 6, 8  
  - \( E_{v1} = 33 \text{ MPa} \)  
  - \( E_{v2} = 88 \text{ MPa} \)
Figure 50. TB1: Stress-strain curves after static compaction (7, 8)
Figure 51. TB2: Stress-strain curves after low amplitude vibratory compaction (0, 1)
Figure 52. TB2: Stress-strain curves after low amplitude vibratory compaction (2, 3)
Figure 53. TB2: Stress-strain curves after low amplitude vibratory compaction (4, 5)
Figure 54. TB2: Stress-strain curves after low amplitude vibratory compaction (6, 7)
Figure 55. TB2: Stress-strain curves after low amplitude vibratory compaction (8, 9)
Figure 56. TB2: Stress-strain curves after low amplitude vibratory compaction (1, 6)
Figure 57. TB2: Stress-strain curves after low amplitude vibratory compaction (7, 8)