Proctor Compaction Testing

Nebraska Department of Roads
Research Project SG-10

By

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The Nebraska Department of Roads specifies the standard Proctor test (ASTM D 698/AASHTO T 99) as the method of estimating maximum dry density and optimum moisture content for subgrades and compacted fill sections. The standard Proctor test approximates maximum soil density capable of being produced by early generations of construction equipment.

Laboratory procedures known as the modified Proctor test (ASTM D 1557/AASHTO T 180) have been developed that accurately estimate the greater densities available from the compaction efforts of modern construction equipment. For the same soil, the optimum moisture content (OMC) for a modified Proctor test is usually less than OMC for a standard Proctor test while maximum dry density is higher.

This research consisted of performing both standard and modified Proctor tests on representative groups of Nebraska soils and then evaluating and comparing the test results. A table with formula to convert standard Proctor dry densities and moisture contents to modified Proctor specifications and vice versa was produced. Sample calculations estimating the cost savings from compacting to modified versus standard Proctor specifications were included as was a chart showing the compaction standards currently used by state transportation agencies.
Table of Contents

CHAPTER 1 Introduction ...................................................................................................................................... 1

CHAPTER 2 Literature Review & Procedures .................................................................................................. 2

CHAPTER 3 Procedures & Methods ................................................................................................................ 5

  3.1 Nebraska Group Index ............................................................................................................................ 5

  3.2 Preparation ........................................................................................................................................... 5

  3.3.1 Standard Proctor ............................................................................................................................... 7

  3.3.2 Modified Proctor ............................................................................................................................... 8

  3.3.3 Specific Gravity ................................................................................................................................ 8

CHAPTER 4 Results ............................................................................................................................................. 9

  4.1 Shale .................................................................................................................................................. 9

  4.2 Till ................................................................................................................................................ 10

  4.3 Loess-Till ........................................................................................................................................... 10

  4.4 Loess .............................................................................................................................................. 11

  4.5 Sandy Silt ......................................................................................................................................... 11

  4.6 Fine Sand ........................................................................................................................................ 12

  4.7 Gravel ............................................................................................................................................. 12

CHAPTER 5 Summary & Conclusions ............................................................................................................. 13

  5.1 Conversion Formulas ............................................................................................................................ 13

  5.2 Compaction Specifications Used by State Departments of Transportation ........................................... 14

  5.3 Cost Analysis .................................................................................................................................... 15
List of Tables

Table 1. Differences Between AASHTO T99 and T180........................................2
Table 2. Soil Types and Correlating Nebraska Group Indices..........................5
Table 3. Sieve Analysis Of Soils.......................................................................6
Table 4. Limits of Nebraska Group Indexes......................................................7
Table 5. Conversion Formulas..........................................................................13
**List of Figures**

Figure 1. Nebraska Group Index Chart.................................................................3

Figure 2. Particle Size Distribution for NGI Soil Types........................................6

Figure 3. Shale Compaction Curves..................................................................9

Figure 4. Till Compaction Curves...................................................................10

Figure 5. Loess-Till Compaction Curves..........................................................10

Figure 6. Loess Compaction Curves.................................................................11

Figure 7. Sandy Silt Compaction Curves.........................................................11

Figure 8. Fine Sand Compaction Curves..........................................................12

Figure 9. Gravel Compaction Curves...............................................................12

Figure 10. Map of Compaction Specifications by State......................................15
CHAPTER ONE
INTRODUCTION

The Nebraska Department of Roads (NDOR) specifies use of standard Proctor (AASHTO T99/ASTM D 698) testing procedures to determine the moisture-density relationship of soil for highway construction projects. The standard Proctor approximates the compaction effort achieved by earlier generations of compaction equipment. Newer compaction equipment is heavier and capable of achieving 100+% of standard Proctor compaction specifications after a minimal number of passes. Modified Proctor (AASHTO T180/ASTM D1557) testing procedures more closely approximate the compaction effort of modern equipment. For the same type of soil, the modified Proctor yields a higher maximum dry density and lower optimum moisture content. This research investigated the use of the modified Proctor as an alternative to the standard Proctor within the NDOR compaction specifications. A secondary objective was to develop formulas to convert soil densities and moisture contents from standard to modified Proctor specifications and vice versa.

Seven specific native Nebraskan soils distributed across the range of Nebraska Group Index values were tested, each using both the standard and the modified Proctor testing procedures. Two compaction curves were developed for each soil type as the standard and modified Proctor test results were plotted. Algorithms were subsequently developed to compare the difference between standard and modified Proctors, as well as to create conversion formulas between the two Proctors for each soil type.
CHAPTER TWO
LITERATURE REVIEW & PROCEDURES

Testing procedures for the standard and modified Proctor test procedures are the American Association of State Highway and Transportation Officials (AASHTO) T99 and T180 respectively. The corresponding American Society for Testing and Materials (ASTM) testing procedures are D 698 and D 1557 respectively. The differences between AASHTO T99 and T180 are shown in Table 1.

Table 1. Differences Between AASHTO T99 and T180

<table>
<thead>
<tr>
<th></th>
<th>AASHTO T99 (Standard Proctor)</th>
<th>AASHTO T180 (Modified Proctor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer Weight</td>
<td>5.5 lbf</td>
<td>10 lbf</td>
</tr>
<tr>
<td>Drop Distance</td>
<td>12 inches</td>
<td>18 inches</td>
</tr>
<tr>
<td>Energy</td>
<td>12,400 ft-lbf/ft³</td>
<td>56,000 ft-lbf/ft³</td>
</tr>
<tr>
<td>Number of Layers</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

Dry preparation of soil samples was completed using AASHTO T87 (ASTM D 421). The liquid limit, plastic limit, and plasticity index of soils were determined using AASHTO T89 (ASTM D 4318) procedures. Particle size of the solids was determined using AASHTO T88 (ASTM D 422) procedures. Soils were classified using the Nebraska Group Index (NGI) based upon the results of sieve analysis and Atterberg Limit testing using the Nebraska Group Index Chart shown in Figure 1. The specific gravity was determined using AASHTO T84 (ASTM C128). Specific gravity measurements were subsequently used to plot a zero air void curve on the moisture density diagrams for each soil type.
A soil with 23% retained on the #10 sieve, 34% retained on the #40 sieve, and 46% retained on the #200 sieve, a liquid limit of 50 and a plastic limit of 22 would be classified using the Nebraska Group Index Chart (Figure 1) according to the following procedures. First using Chart 1, the 46% retained on the #200 sieve would
be aligned with a Liquid Limit (LL) of 50, producing a reference number of about 4.9. Then using Chart 2, the 46% retained for the number 200 sieve is aligned with the Plastic Index (PI) of 28, producing a reference number of about 7.1. The Nebraska Group Index is the sum of the reference values from Chart 1 and Chart 2. The sum of 4.9 and 7.1 is 12, which can be used for soil classification using Table 2. A NGI of 12 falls within the range of a loess soil type.
3.1 Nebraska Group Index

Seven native Nebraskan Soils were initially collected for testing. Each soil was analyzed to determine particle size and Atterberg limits and subsequently classified into a specific Nebraska Group Index. Additional samples were collected until one sample was available for each of the soil types shown in Table 2.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>NGI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>-4 to -2</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>-1 to 1</td>
</tr>
<tr>
<td>Sandy Silt</td>
<td>2 to 7</td>
</tr>
<tr>
<td>Loess</td>
<td>8 to 12</td>
</tr>
<tr>
<td>Loess/ Till</td>
<td>13 to 14</td>
</tr>
<tr>
<td>Till</td>
<td>15 to 21</td>
</tr>
<tr>
<td>Shale</td>
<td>22 to 24</td>
</tr>
</tbody>
</table>

3.2 Preparation

Soil samples were collected from various parts of Nebraska. After each soil was transported to the laboratory, a sieve analysis was performed in accordance to AASHTO T87 (ASTM D 421). The results of the sieve analysis are shown in Table 3 and the particle size distributions for the soils are plotted in Figure 2.
### Table 3. Sieve Analysis Of Soils

<table>
<thead>
<tr>
<th>Sieve Size (mm)</th>
<th>Part Diam (mm)</th>
<th>Gravel</th>
<th>Fine Sand</th>
<th>Sandy Silt</th>
<th>Loess</th>
<th>Loess/Till</th>
<th>Till</th>
<th>Shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.76</td>
<td>79.5</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>2.00</td>
<td>56.8</td>
<td>98</td>
<td>99.8</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>16</td>
<td>0.84</td>
<td>34.4</td>
<td>91.4</td>
<td>97.5</td>
<td>98.9</td>
<td>98.2</td>
<td>98.6</td>
<td>100</td>
</tr>
<tr>
<td>40</td>
<td>0.42</td>
<td>17.5</td>
<td>66.4</td>
<td>76.7</td>
<td>93.3</td>
<td>88.2</td>
<td>84.4</td>
<td>96.6</td>
</tr>
<tr>
<td>100</td>
<td>0.149</td>
<td>2.3</td>
<td>25.1</td>
<td>50.3</td>
<td>82.6</td>
<td>70.9</td>
<td>61.4</td>
<td>87.9</td>
</tr>
<tr>
<td>200</td>
<td>0.074</td>
<td>0.3</td>
<td>16.3</td>
<td>44.4</td>
<td>78.2</td>
<td>61.4</td>
<td>52.8</td>
<td>82.5</td>
</tr>
</tbody>
</table>

**Figure 2. Particle Size Distribution for NGI Soil Types**
The Atterberg Limits were then measured for each soil in accordance with AASHTO T89 (ASTM D 4318), which yielded the Liquid Limit (LL), Plastic Limit (PL), and the Plasticity Index (PI). The results of Atterberg Limits testing are shown in Table 4. Additional samples were collected until a soil was available that fell within each range of the Nebraska Group Indices shown in Table 2.

### Table 4. Limits of Nebraska Group Indexes

<table>
<thead>
<tr>
<th>NDOR NGI Limits</th>
<th>-4 to -2</th>
<th>-1 to 1</th>
<th>2 to 7</th>
<th>8 to 12</th>
<th>13 to 14</th>
<th>15 to 21</th>
<th>22 to 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Type</td>
<td>Gravel</td>
<td>Fine Sand</td>
<td>Sandy Silt</td>
<td>Loess</td>
<td>Loess/Till</td>
<td>Till</td>
<td>Shale</td>
</tr>
<tr>
<td>Actual NGI</td>
<td>-4</td>
<td>-1</td>
<td>2</td>
<td>8</td>
<td>13</td>
<td>16.5</td>
<td>25</td>
</tr>
<tr>
<td>LL</td>
<td>NP</td>
<td>NP</td>
<td>NP</td>
<td>33.5</td>
<td>49.4</td>
<td>68.2</td>
<td>67</td>
</tr>
<tr>
<td>PI</td>
<td>NP</td>
<td>NP</td>
<td>NP</td>
<td>9.8</td>
<td>27</td>
<td>42.6</td>
<td>41.4</td>
</tr>
<tr>
<td>% Pass #200</td>
<td>0.3</td>
<td>16.3</td>
<td>44.4</td>
<td>78.2</td>
<td>61.4</td>
<td>52.8</td>
<td>82.5</td>
</tr>
</tbody>
</table>

#### 3.3.1 Standard Proctor Testing

For each soil type, water was added to the soil to bring it to a predetermined moisture content percentage. Three layers of the soils then were compacted in a standard four-inch mold using an automatic standard Proctor hammer in accordance with AASHTO T99 (ASHTO D 698). The T99 procedure specifies a hammer weighing 5.5 pounds and a drop distance of 12 inches, which creates 12,400 ft-lbf/ft³ of force.
3.3.2 Modified Proctor

The modified proctor is similar to the standard proctor; water was added to each soil sample to bring it to the desired moisture content. Five layers of the soil then were compacted in a standard four-inch mold using an automatic modified Proctor hammer in accordance to AASHTO T180 (ASTM D 1557). The T180 procedure specifies a hammer weighing 10 pounds and a drop distance of 18 inches, which creates 56,000 ft-lbf/ft³ of force. The heavier hammer and lengthened drop distance significantly increase the compactive effort.

3.3.3 Specific Gravity

A small sample for each of the soils was taken to perform AASHTO T84 (ASTM C 128) procedures. Once the specific gravity was determined, it was used to plot a zero air voids (ZAV) curve as a reference for each soil’s two compaction curves.
CHAPTER FOUR
RESULTS

The actual results were similar to expectations. Higher maximum dry density resulted when more compaction effort was applied. Optimum moisture content was lower when more compaction effort was applied, reflecting the reduced volume of void space between soil particles. Actual test results for each NGI soil type are shown in Figures 3 though 9 below.

4.1 Shale

![Shale Compaction Curves](image)

**Figure 3. Shale Compaction Curves**
4.2 Till

Figure 4. Till Compaction Curves

4.3 Loess-Till

Figure 5. Loess-Till Compaction Curves
4.4 Loess

Fig. 6. Loess Compaction Curves

4.5 Sandy Silt

Fig. 7. Sandy Silt Compaction Curves
4.6 Fine Sand

![Figure 8. Fine Sand Compaction Curves](image)

4.7 Gravel

![Figure 9. Gravel Compaction Curves](image)
CHAPTER FIVE
CONCLUSION & SUMMARY

5.1 Conversion Formulas

Procedures for converting from specifications expressed in the standard Proctor system to equivalents in the modified Proctor system for various NGIs was one of the objectives of this research. Based upon the data points shown in Figures 3–9, the formulas shown in Table 5 were developed to convert one type of compaction specifications to the other.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>NGI Range</th>
<th>Standard To Modified</th>
<th>Modified To Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>-4 to -2</td>
<td>$\gamma_d + 0$</td>
<td>$\gamma_d - 0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OMC -2</td>
<td>OMC +2</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>-1 to 1</td>
<td>$\gamma_d + 1$</td>
<td>$\gamma_d - 1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OMC -1</td>
<td>OMC +1</td>
</tr>
<tr>
<td>Sandy Silt</td>
<td>2 to 7</td>
<td>$\gamma_d +10$</td>
<td>$\gamma_d -10$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OMC -3</td>
<td>OMC +3</td>
</tr>
<tr>
<td>Loess</td>
<td>8 to 12</td>
<td>$\gamma_d +10$</td>
<td>$\gamma_d -10$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OMC -4</td>
<td>OMC +4</td>
</tr>
<tr>
<td>Loess-Till</td>
<td>13 to 14</td>
<td>$\gamma_d +12$</td>
<td>$\gamma_d -12$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OMC -6.5</td>
<td>OMC +6.5</td>
</tr>
<tr>
<td>Till</td>
<td>15 to 21</td>
<td>$\gamma_d +15$</td>
<td>$\gamma_d -15$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OMC -6.5</td>
<td>OMC +6.5</td>
</tr>
<tr>
<td>Shale</td>
<td>22 to 24</td>
<td>$\gamma_d +13$</td>
<td>$\gamma_d -13$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OMC -7</td>
<td>OMC +7</td>
</tr>
</tbody>
</table>

where $\gamma_d$ is the Dry Unit Weight and OMC is the Optimum Moisture Content

The formulas allow easy and quick conversion of specifications based upon standard Proctor testing to modified Proctor and vice versa. Use of modified versus standard Proctor specifications has the potential to result in cost savings on projects.
where water must be transported to the site to increase the moisture content of the soil to near optimum for standard Proctor specifications.

5.2 Compaction Specifications Used by State Departments of Transportation

The Department of Transportation (DOT) within each state defines specifications for compaction of soil on highway projects within that state. Figure 10 illustrates current practice with regard to compaction specifications employed by each state agency. Hawaii, Idaho, Nevada, and Vermont use localized procedures which do not correspond directly with either standard or modified Proctor. The

Figure 10. Map of Compaction Specifications by State

Legend
Standard
Modified
Combination
Neither
twenty-seven states shown in red currently base subgrade compaction effort on standard Proctor specifications, while the fourteen states in orange specify either standard or modified Proctor for different situations. The five states in yellow use strictly modified Proctor specifications.

5.3 Cost Analysis

A soil’s optimum moisture content is usually lower when compacted to modified Proctor versus standard Proctor specifications. The heavier hammer weight and longer drop distance involved in modified Proctor procedures result in more compaction energy, creating higher unit weight. Higher unit weight corresponds to less void space, so maximum unit weight can be achieved using less water. The difference in quantity of water needed for compaction to OMC when comparing standard to modified procedures depends primarily on the soil type and the percent void space remaining after each compaction procedure.

For loess, research indicated about four percent difference in OMC between modified and standard Proctor tests, with the standard Proctor having an OMC of 18.75% and the modified Proctor having an OMC of 14.75%. The wet unit weight, $\gamma_w$, of this soil was approximately 120 lbs/ft³ at 14.75% moisture content. The dry unit weight, $\gamma_d$, can be calculated by dividing the wet unit weight by one plus the water content.

$$\gamma_d = \frac{\gamma_w}{1 + \omega} = \frac{120 \text{ lbs/ft}^3}{1 + 0.1475} = 104.6 \text{ lbs/ft}^3$$

The difference in quantity of water needed for compaction of one cubic yard of loess can then be calculated by multiplying the dry unit weight by the difference in moisture content at OMC (4%).
The amount of water saved is 112.9 lbs/cy. Since water weighs 8.34 pounds per gallon, 13.5 gallons less water are needed at OMC when loess is compacted using modified versus standard specifications.

\[
\frac{112.9 \text{ lbs/cy}}{8.34 \text{ lbs/gal}} = 13.5 \text{ gal/cy}
\]

If the subgrade for a paving project is 30 feet wide, 8 inches thick, and 5 miles long, slightly more than 19,565 cubic yards of material will be compacted.

\[
30 \text{ ft} \times \frac{8''}{12''} \times 5 \text{ miles} \times \frac{5,280 \text{ ft/mile}}{12''} = 528,264 \text{ ft}^3
\]

\[
\frac{528,264 \text{ ft}^3}{27 \text{ ft}^3/\text{cy}} = 19,565.33 \text{ cy}
\]

The total amount of water saved on a five miles of subgrade would be 13.5 gal/cy multiplied by 19,565.33 cy or 264,132 gallons. As of April 2008, the NDOR’s average unit cost for water was about $11 per 1,000 gallons. Multiplying 264,132 gallons by $11/1,000 gallons results in saving $2,905.45.

\[
13.5 \text{ gal/cy} \times 19,565.33 \text{ cy} = 264,132 \text{ gal}
\]
\[
264,132 \text{ gal} \times \frac{11}{1,000} \text{ gal} = $2,905.45
\]

Note that the savings shown result from the cost of water only and do not include the cost of transporting water to the site. Soils such as loess-till, till, and shale, with greater differences in optimum moisture content between standard to modified optimum moisture contents will produce additional savings. Soils such as gravel, fine sand, and sandy silt, with lower differences in optimum moisture content will produce less savings.
ACKNOWLEDGEMENTS

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REFERENCES

AASHTO T84, Specific Gravity and Absorption of Fine Aggregate.
AASHTO T87, Dry Preparation of Disturbed Soil & Soil Aggregate Samples for Test.
AASHTO T88, Particle Size Analysis of Soils.
AASHTO T89, Determining the Liquid Limit of Soils.
AASHTO T99, Standard Method of Test for the Moisture-Density Relations of Soils.
AASHTO T180, Modified Method of Test for the Moisture-Density Relations of Soils.

The above standards were published by:
American Association of State Highway & Transportation Officials
444 North Capitol Street N.W., Suite 249
Washington, DC 20001

ASTM C 128, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate.
ASTM D 421, Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants.

The above standards were published by:
ASTM International
100 Barr Harbor Drive
PO Box C700
West Conshohocken, PA 19428-2959

1500 Highway 2, Lincoln, NE 68509-4759.