Proctor Compaction Testing

Nebraska Department of Roads
Research Project SG-10

By

Construction Management Program
University of Nebraska
Lincoln, NE 68588-0050

Joshua Connelly
Wayne Jensen, Ph.D., P.E.
Paul Harmon, P.E.

Technical Report Documentation Page

1. Report No	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Proctor Compaction Testing		5. Report Date May 2008 6. Performing Organization Code	
7. Author/s Joshua Connelly, Wayne Jensen, and Paul Harmon		8. Performing Organization Report No.	
9. Performing Organization Name and Address University of Nebraska- Lincoln W-145 Nebraska Hall Lincoln, NE 68588-0500		10. Work Unit No. (TRAIS) 11. Contract or Grant No. SG-10	
12. Sponsoring Organization Name and Address The Nebraska Department of Roads 1500 Highway 2 Lincoln, NE 68509-4659		13. Type of Report and Period Covered 14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract			
17. Key Words Proctor, Modified, Standard, Compaction	18. Distribution Statement		
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. Of Pages	22. Price

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 Proctors 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.

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized

Table of Contents

List of Tables

List of Figures

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

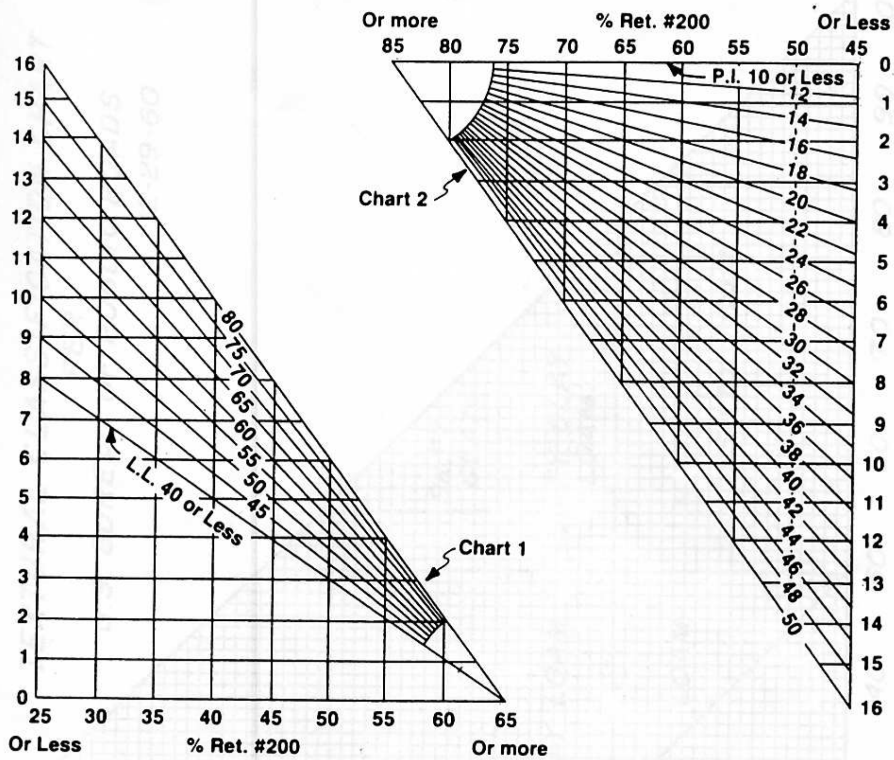
Testing procedures for the standard and modified Proctor test procedures are the American Association of State Highway and Transportation Officials (AASHTO) T99 and T180 respectively. The corresponding American Society for Testing and Materials (ASTM) testing procedures are D 698 and D 1557 respectively.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

Table 1. Differences Between AASHTO T99 and T180

	AASHTO T99 (Standard Proctor)	**AASHTO T180 (Modified Proctor)**
Hammer Weight	5.5 lbf	10 lbf
Drop Distance	12 inches	18 inches
Energy	12,400 ft-lbf/ft^3	56,000 ft-lbf/ft^3
Number of Layers	3	5

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.

NEBRASKA REVISED GROUP INDEX CHARTS



Group Index { Positive Values - Sum of Readings on Vertical Scale of Charts 1 & 2.
Negative Values - Use Chart 3.

	Well Graded Gravel Base	Clean Coarse Sand	Clean Fine Sand	Loamy Coarse Sand	Loamy Fine Sand	Loamy Very Fine Sand
Group Index	- 4	- 3	- 2		- 1	0
% Ret. #10	40 Min.					
% Ret. #40	60 Min.	35 Min.	34 Max.	35 Min.	34 Max. 10 Min.	9 Max.
% Ret. #200	85 Min.	85 Min.	85 Min.	84 Max. 65 Min.	84 Max. 65 Min.	84 Max. 65 Min.
P.I.	4 Max.	4 Max.	4 Max.	10 Max.	10 Max.	10 Max.

The first group from the left into which the test data will fit is the correct classification.

Figure 1. Nebraska Group Index Chart

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.

CHAPTER THREE
PROCEDURES & METHODS

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 2. Soil Types and Correlating Nebraska Group Indices

Soil Type	NGI
Gravel	-4 to -2
Fine Sand	-1 to 1
Sandy Silt	2 to 7
Loess	8 to 12
Loess/ Till	13 to 14
Till	15 to 21
Shale	22 to 24

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

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

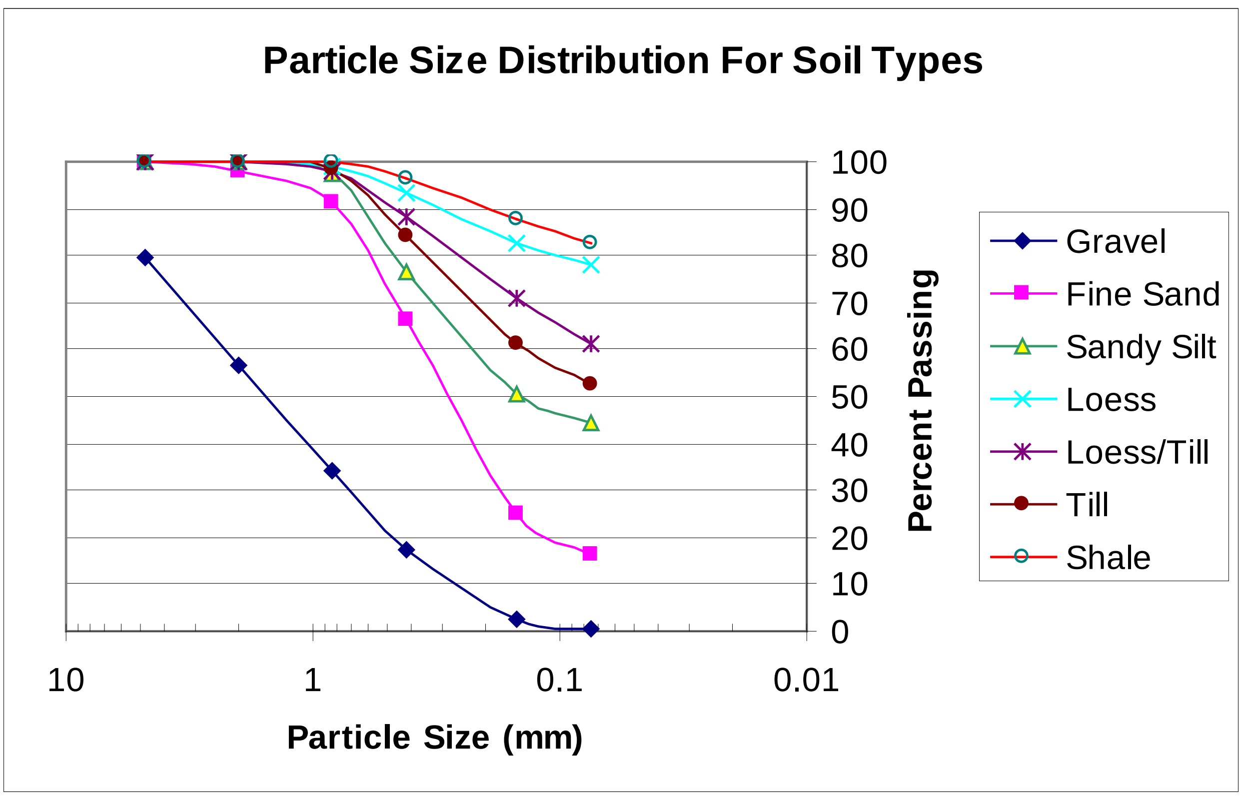


Figure 2. Particle Size Distribution for NGI Soil Types

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

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

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/ft^3 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/ft^3 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

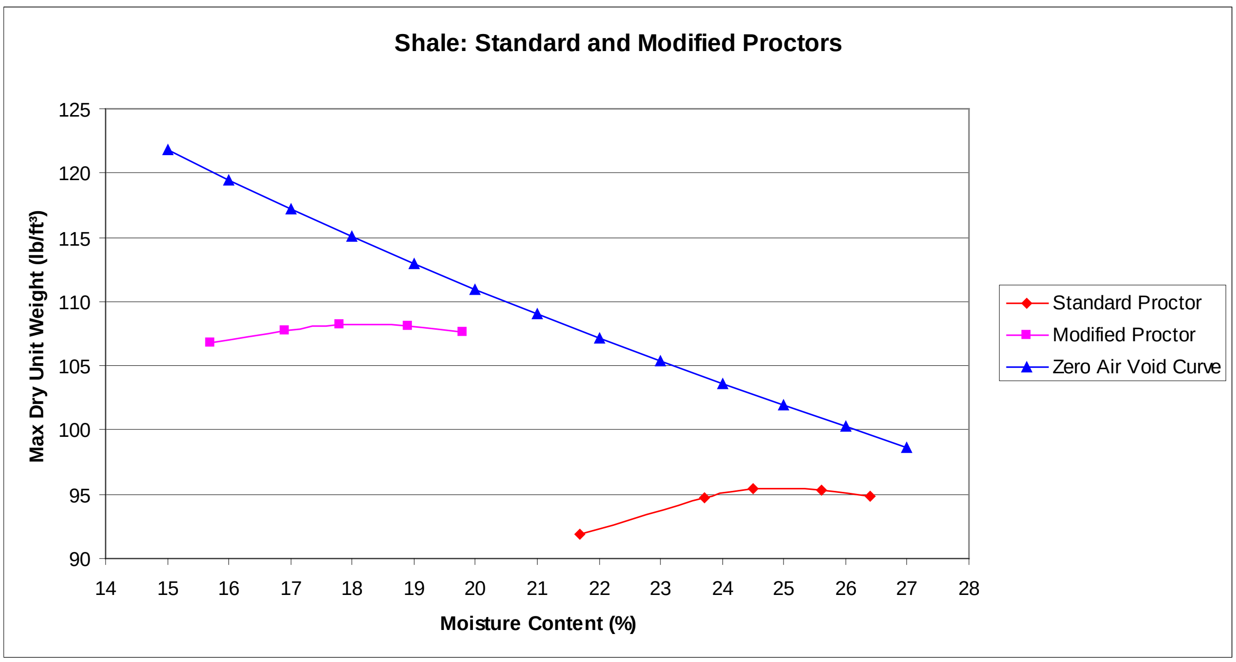


Figure 3. Shale Compaction Curves

4.2 Till

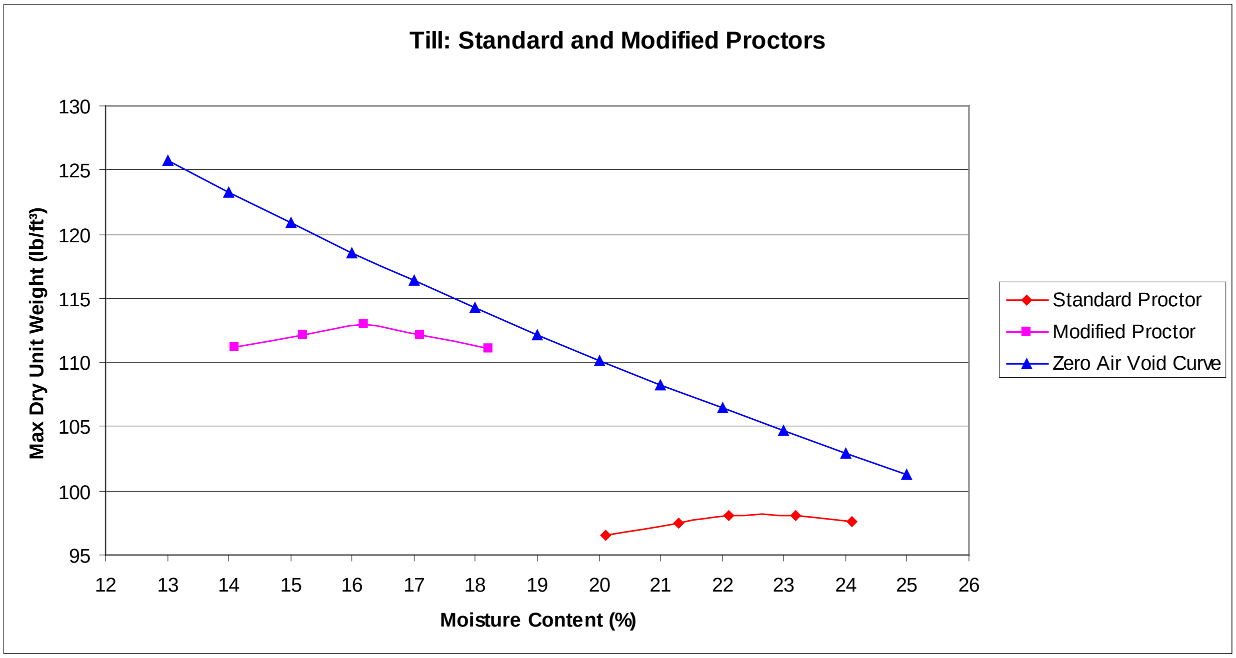


Figure 4. Till Compaction Curves

4.3 Loess-Till

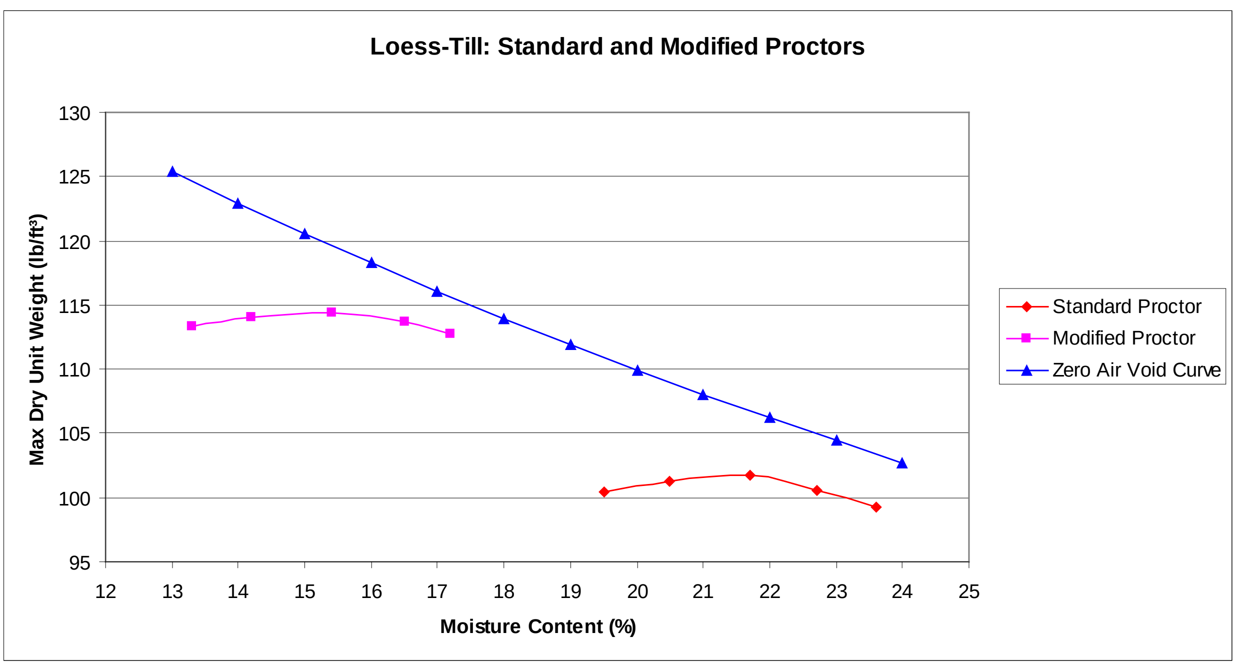


Figure 5. Loess-Till Compaction Curves

4.4 Loess

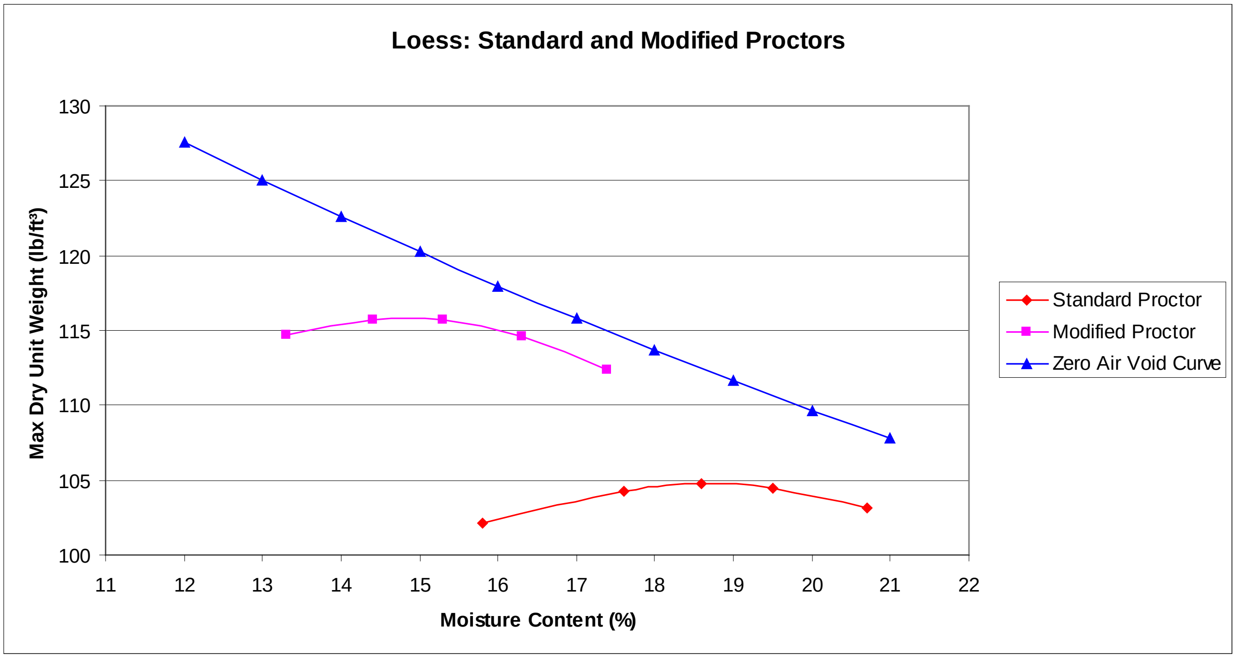


Figure 6. Loess Compaction Curves

4.5 Sandy Silt

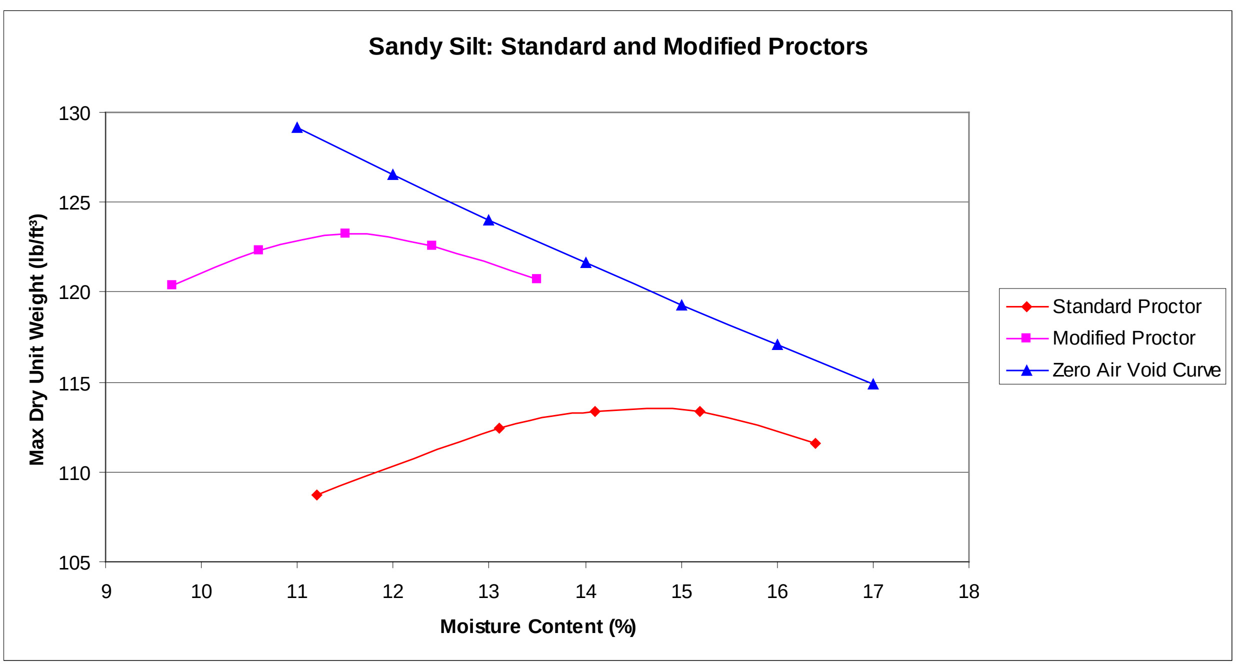


Figure 7. Sandy Silt Compaction Curves

4.6 Fine Sand

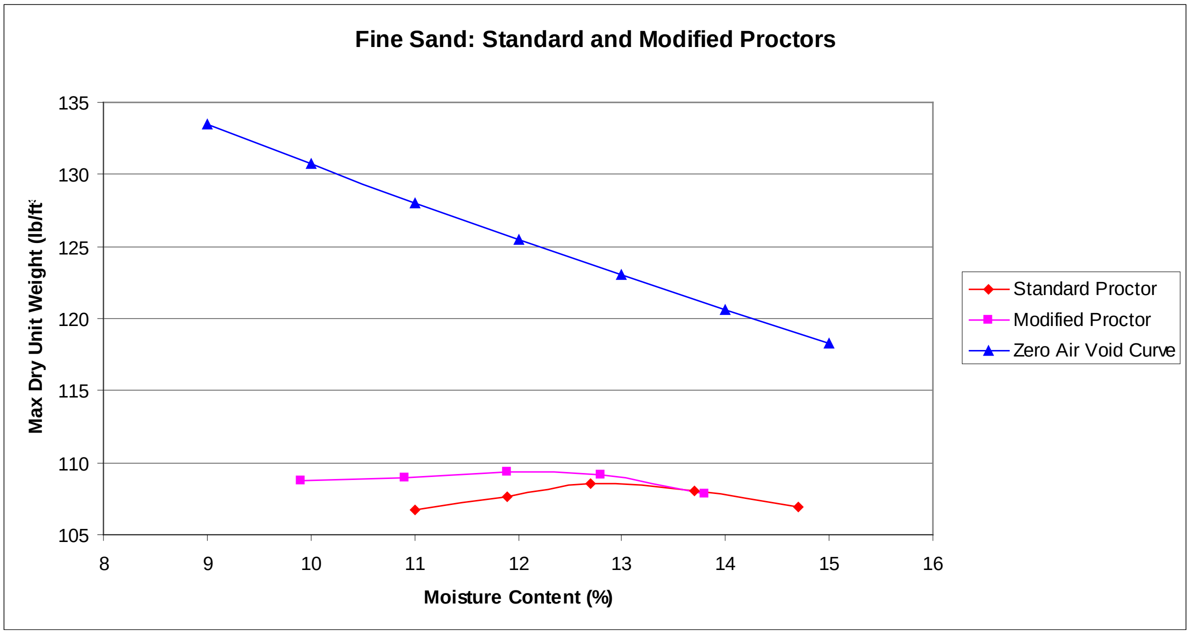


Figure 8. Fine Sand Compaction Curves

4.7 Gravel

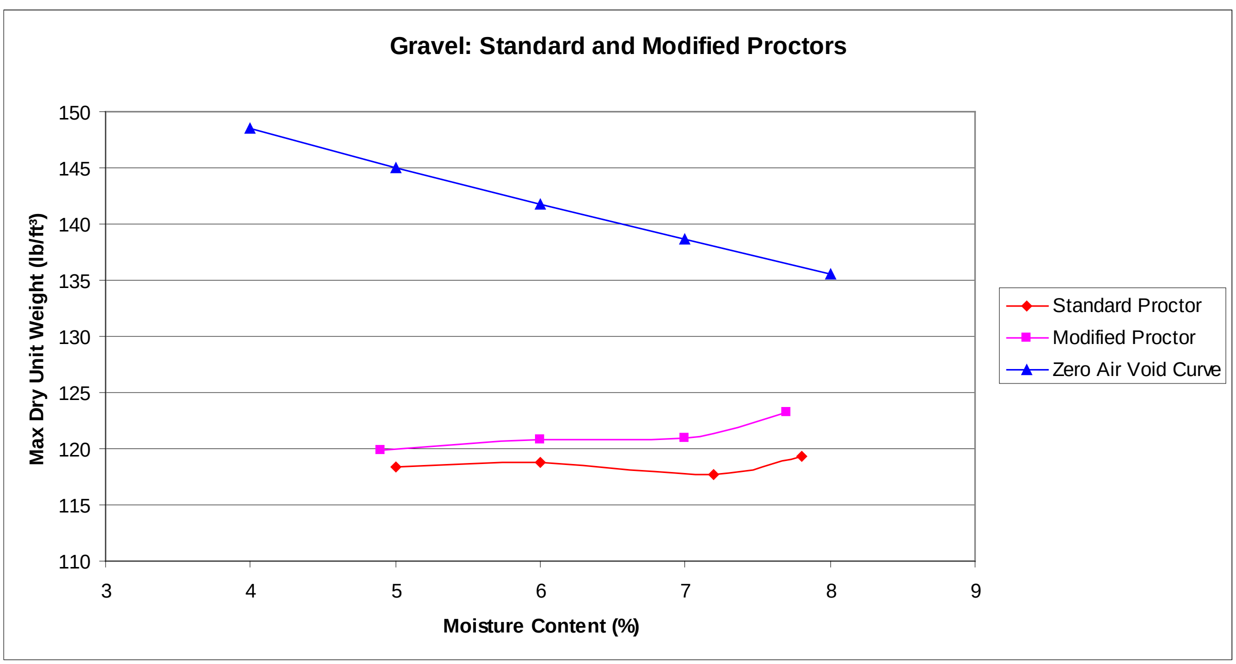


Figure 9. Gravel Compaction Curves

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 5. Conversion Formulas

Soil Type	**NGI Range**	**Standard To Modified**	**Modified To Standard**
Gravel	-4 to -2	γ_d + 0 OMC -2	γ_d - 0 OMC +2
Fine Sand	-1 to 1	γ_d +1 OMC -1	γ_d -1 OMC +1
Sandy Silt	2 to 7	γ_d +10 OMC -3	γ_d -10 OMC +3
Loess	8 to 12	γ_d +10 OMC -4	γ_d -10 OMC +4
Loess-Till	13 to 14	γ_d +12 OMC -6.5	γ_d -12 OMC +6.5
Till	15 to 21	γ_d +15 OMC -6.5	γ_d -15 OMC +6.5
Shale	22 to 24	γ_d +13 OMC -7	γ_d -13 OMC +7

where γ_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

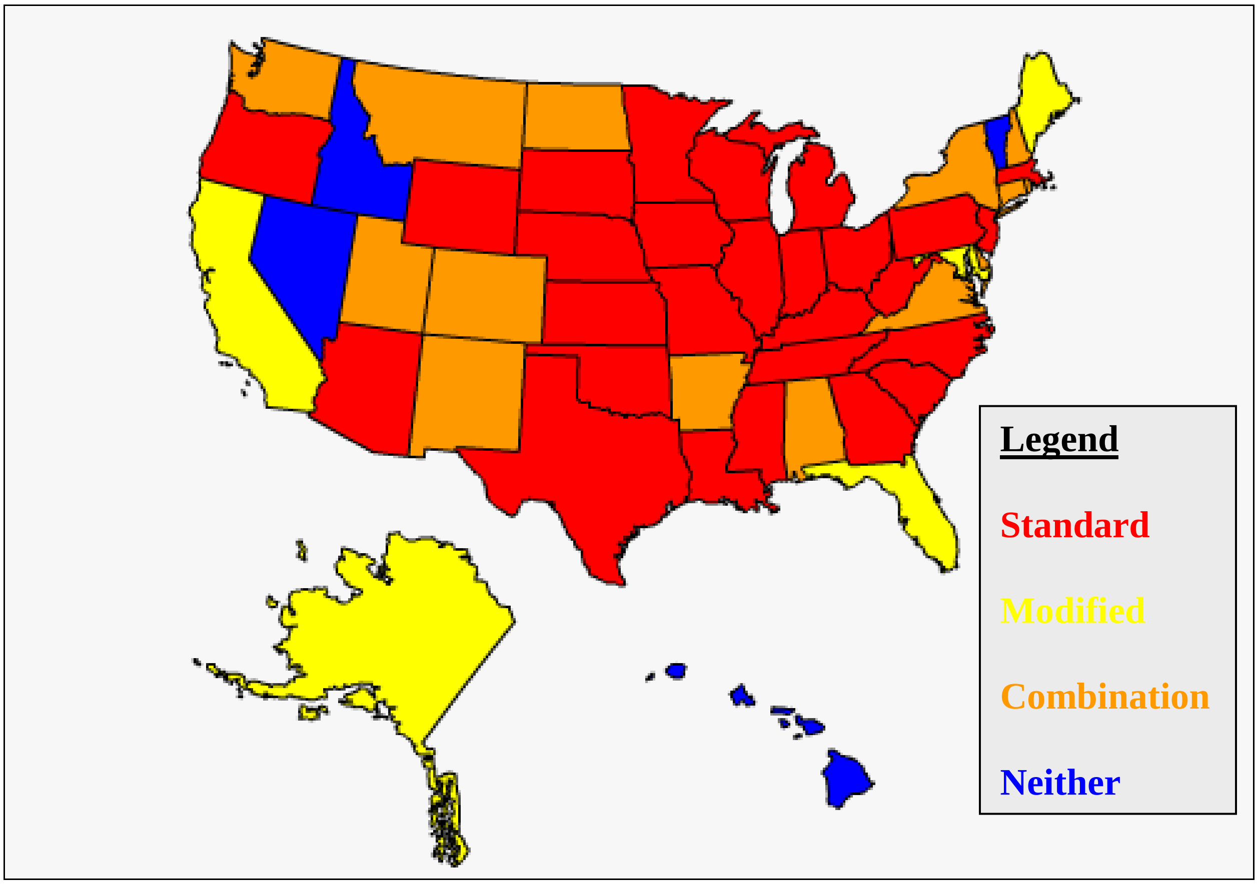


Figure 10. Map of Compaction Specifications by State

each state agency. Hawaii, Idaho, Nevada, and Vermont use localized procedures which do not correspond directly with either standard or modified Proctor. The 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, γ_w, of this soil was approximately 120 lbs/ft^3 at 14.75% moisture content. The dry unit weight, γ_d, can be calculated by dividing the wet unit weight by one plus the water content.

$$\gamma_{\mathrm{d}} = \frac{\gamma_w}{1+\omega} = \frac{120\ \mathrm{lbs/ft}^3}{1+0.1475} = 104.6\ \mathrm{lbs/ft}^3$$

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%).

$$106.4\ \text{lbs/ft}^3\ \text{x}\ 0.04 = 4.18\ \text{lbs/ft}^3$$
$$4.18\ \text{lbs/ft}^3\ \text{x}\ 27\ \text{ft}^3\text{/cy} = 112.9\ \text{lbs/cy}$$

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.

$$30\ \text{ft x}\ 8\text{"}/12\text{"}/\text{ft}\ \ \text{x}\ \ 5\ \text{miles}\ \ \text{x}\ \ 5{,}280\ \text{ft/mile}\ =\ 528{,}264\ \text{ft}^3$$

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

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.

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

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

This study was funded by the Nebraska Department of Roads as a research project under the title SG-10 “Proctor Compaction Testing.” The project was completed under the direction of Dr. Wayne Jensen, P.E. and Paul Harmon, P.E. at the University of Nebraska- Lincoln. Joshua Connelly, a Construction Management major at UNL, completed most of the research for this project.

The authors would like Rich Gloe from NDOR Materials and Testing Division for his guidance, collaboration and sharing his lab to complete the testing. John Miller with NDOR Estimating Unit of Contracting Division cheerfully provided information concerning the cost of materials. Many other individuals from the NDOR’s Materials and Research Division also made significant contributions to this study.

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.

ASTM D 422, Standard Test Method for Particle-Size Analysis of Soils

ASTM D 698, Standard Test Methods for Laboratory Compaction Characteristics of Soil.

ASTM D 1557, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort.

ASTM D 4318, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.

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

Nebraska Department of Roads. (1990) *Earthwork Engineering Guide*, p. 1.48.
1500 Highway 2, Lincoln, NE 68509-4759.