SOIL AIR VOIDS METHOD FOR COMPACTION CONTROL

FHWA/MT-05-010/8117-23

Final Report

prepared for
THE STATE OF MONTANA
DEPARTMENT OF TRANSPORTATION

in cooperation with
THE U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

August 2005

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RESEARCH PROGRAMS

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Prepared for:

Montana Department of Transportation
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August 2005

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/MT-05-010/8117-23	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Soil Air Voids Method for Compaction Control**	5. Report Date **August 2005** 6. Performing Organization Code	
7. Author(s) **Robert L. Mokwa and Stefan Fridleifsson**	8. Performing Organization Report No.	
9. Performing Organization Name and Address **Civil Engineering Department Montana State University Bozeman, MT 59717**	10. Work Unit No. 11. Contract or Grant No. **8117-23**	
12. Sponsoring Agency Name and Address **Research Programs Montana Department of Transportation 2701 Prospect Avenue PO Box 201001 Helena MT 59620-1001**	13. Type of Report and Period Covered **Final Report, For the period covering: June 1, 2004 to May 31, 2005** 14. Sponsoring Agency Code **5401**	

15. Supplementary Notes **Research performed in cooperation with the Montana Department of Transportation and the US Department of Transportation, Federal Highway Administration. This report can be found at http://www.mdt.mt.gov/research/projects/mat/airvoids.shtml.**

16. Abstract

This research project was structured to evaluate the air voids method as a means of assessing the quality of a compacted layer of soil. A literature review was conducted to examine existing published information on the air voids method and to explore how extensively others have used the method. Laboratory testing was conducted to gather information for a variety of soils and to identify potentially suitable and potentially problematic soil types. The laboratory testing program included particle size gradation, hydrometer, Atterberg limits, relative density, specific gravity and impact compaction tests. Data from over 20 Montana Department of Transportation soil survey reports was collected, categorized, and reviewed to statistically examine trends in regards to compaction parameters and the use of the air voids method.

The advantages of the air voids method lie in its practicality and ease of use. However, based on the testing and analyses conducted, it is clear that this method should be considered applicable on a limited basis, only. Results from this study indicate that the air voids method of compaction control should not be used on a project unless the relationship between air voids and percent relative compaction is carefully established. The approach should only be considered on projects that have been thoroughly evaluated during the soil survey study using recommendations described in this report as guidelines.

17. Key Words **Soil Air Voids, Field Compaction Control, Proctor**		18. Distribution Statement **Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.**	
19. Security Classif. (of this report) **Unclassified**	20. Security Classif. (of this page) **Unclassified**	21. No. of Pages **104**	22. Price

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ACKNOWLEDGEMENTS

The author gratefully acknowledges the valuable contributions of Bob Weber, Scott Barnes, Roger Warner, Jim Blossom, Gary Nessan, Bill Henning, Steve Helms, and Kent Barnes for their assistance in providing information and materials for this study. Additional acknowledgements are extended to Montana State University students Cole Peebles and Eli Robinson for their hard work and assistance in the laboratory.

Acknowledgement of financial support for this research is extended to the: Montana Department of Transportation, Montana State University Undergraduate Scholars Program (USP), Montana State University Civil Engineering Department, and the American Indian Research Opportunities (AIRO) Program.

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EXECUTIVE SUMMARY

Compaction is a process of mechanical soil improvement; and is by far the most commonly used method of soil stabilization. Compaction is used to alter the engineering properties of a soil for a specific application, such as supporting a pavement section, building foundation, or bridge abutment. Density measurements are used in the field to indirectly gauge the effectiveness of the compaction process with the goal of improving soil behavior for the intended application.

The soil air voids method was initially implemented by the Montana Department of Transportation (MDT) in the 1970's as an alternate approach to the traditional Proctor method of field compaction control because of its timesaving benefits and relative simplicity. In theory, a field inspector can rapidly determine if a compacted soil layer meets the specified compaction criteria without obtaining a soil sample for laboratory Proctor compaction testing. *The air voids approach saves time* by eliminating the necessity of conducting Proctor moisture-density tests, which can delay the field compaction evaluation by one to two days. *The air voids approach is simple* because to evaluate the suitability of a compacted layer, the inspector only needs to plot a data point on the appropriate air voids graph.

This research project was structured to evaluate the air voids method as a means of assessing the quality of a compacted layer of soil. A literature review was conducted to examine existing published information on the air voids method and to explore how extensively others have used the method. Laboratory testing was conducted to gather information for a variety of soils and to identify potentially suitable and potentially problematic soil types. The laboratory testing program included particle size gradation, hydrometer, Atterberg limits, relative density, specific gravity and impact compaction tests. MDT project data from over 20 soil survey reports was collected, categorized, and reviewed to statistically examine trends in regards to compaction parameters and the use of the air voids method.

The results of this study indicate the air voids method provides an indirect check on the dry density of the compacted layer; however, the soil water content is not directly assessed during the field evaluation. Using data from laboratory tests and field test records, examples are provided of problems that may occur with certain soil types if inherent water content limits are relied upon during compaction. Potential problems include excessive shrink or swell, excessive settlement, and stability problems due to high excess pore water pressures. It was demonstrated in this study that some materials could pass the air voids test, but fail the conventional Proctor criteria (i.e., 95% of the Proctor maximum dry density). This condition can be identified in the laboratory, prior to construction, if Proctor compaction and specific gravity tests are conducted and analyzed using plots similar to those shown in this report.

It is recommended that the air voids method of compaction control should not be used on a project unless the relationship between air voids and percent relative compaction is carefully established during design, using data from the soil survey report. In addition, the air voids method may not be suitable if tests indicate the specific gravity of materials varies significantly along the project alignment. Statistical analyses conducted during this study indicate a typical standard deviation of specific gravity is about ± 0.065.

The researchers involved with this study recognize the advantages and practicality of the air voids method. However, based on the testing and analyses conducted, it is clear that this method should be considered applicable on a limited basis, only. The approach should only be considered on projects that have been thoroughly evaluated during the soil survey study, prior to issuing contract documents.

1. INTRODUCTION

1.1. Overview

The soil air voids test is a simplified method that can be used by field inspectors to quickly evaluate the suitability of a compacted layer of soil. The test procedure used by the Montana Department of Transportation (MDT) is based on the premise that the future performance of a compacted layer of soil can be evaluated by comparing the measured air voids to a standard predetermined value. An air voids content of 10% is most often used as the standard (Montana Materials Manual of Test Procedures (1988), MT-229).

Although the air voids method has been used by earthwork inspectors on MDT projects for many years, there are questions regarding the scientific basis and the appropriateness of the method, and there are inconsistencies between MDT district offices regarding application of the method. In the course of this study, experimental, analytical, and statistical methods have been employed to address the use of the air voids method for conducting field evaluations of soils typically encountered on Montana transportation projects.

The primary objective of this study is to evaluate the suitability of the soil air voids method as a means of evaluating the quality of a compacted layer of soil in terms of desired engineering properties. An extensive literature review was conducted to obtain information on the air voids method, to examine how the method has been used in the past, and to determine the benefits and disadvantages of the method. Laboratory research was conducted on soils from eight different AASHTO (2002) classification categories to evaluate the suitability of the method for a wide range of soil types under controlled laboratory conditions. Data obtained from MDT projects was collected and assimilated to evaluate the suitability of the method on a statistical basis using field and laboratory results from over 1,000 tests. This data was also used to evaluate approximate empirical methods for predicting the optimum water content (w_{opt}) and maximum dry density (γ_{max}) of soil samples, in lieu of the Proctor compaction test.

An extensive review of available technical literature was conducted to collect and review published information on the soil air voids approach. Particular emphasis was placed on obtaining information on experimental studies and construction case studies. In parallel with the literature review, a survey was distributed to transportation departments and other agencies throughout North America soliciting information regarding experiences that materials personnel and geotechnical engineers have had with the air voids method.

1.2. Theory

The soil air voids method was initially implemented because of its timesaving benefits and relative simplicity. In theory, a field inspector can rapidly determine if a compacted soil layer meets the specified compaction criteria without obtaining a soil sample for laboratory Proctor compaction testing. *The air voids approach saves time* by eliminating the necessity of conducting Proctor moisture-density tests, which can delay the field compaction evaluation by one to two days. This lag is of course undesirable because a contractor could place a substantial amount of additional fill during the delay. *The air voids approach is simple* because to evaluate the suitability of a compacted layer, the inspector only needs to plot a data point on the appropriate air voids graph.

The **percent air voids (N_a)** is defined as the ratio of the volume of air to the total volume of solids, water, and air (Trenter 2001, Parsons 1992). In equation form:

$$N_a = \frac{V_a}{V_t} \times 100\% = \frac{V_a}{V_s + V_w + V_a} \times 100\% \qquad (1)$$

where, N_a = percent soil air voids,
V_a = volume of air,
V_s = volume of soil solids,
V_w = volume of water, and
V_t = total volume.

It is more useful to work with N_a in terms of common compaction parameters. The percentage of air voids, N_a, can be determined in terms of more familiar parameters using the following expression:

$$N_a = \left\{1 - \frac{\gamma_{dry}}{\gamma_w}\left(\frac{1}{G_s} + w\right)\right\} \times 100\% \qquad (2)$$

where, γ_{dry} = soil dry unit weight,
γ_w = unit weight of water,
w = water content (decimal form), and
G_s = specific gravity of solids.

The air voids content of a compacted soil layer can be determined by measuring the compaction state of a soil layer in the field (dry unit weight and water content), and examining the relative position of this data point with respect to the location of the zero air voids line and the 10% air voids line on a plot of γ_{dry} versus *w*, as shown in Figure 1. The nuclear moisture-density gage is most often used to obtain the field measurements. The zero air voids line corresponds to a condition of 100% saturation, which implies the soil voids are completely filled with water. Theoretically, it is impossible to obtain a data point on the right side of the zero air voids line.

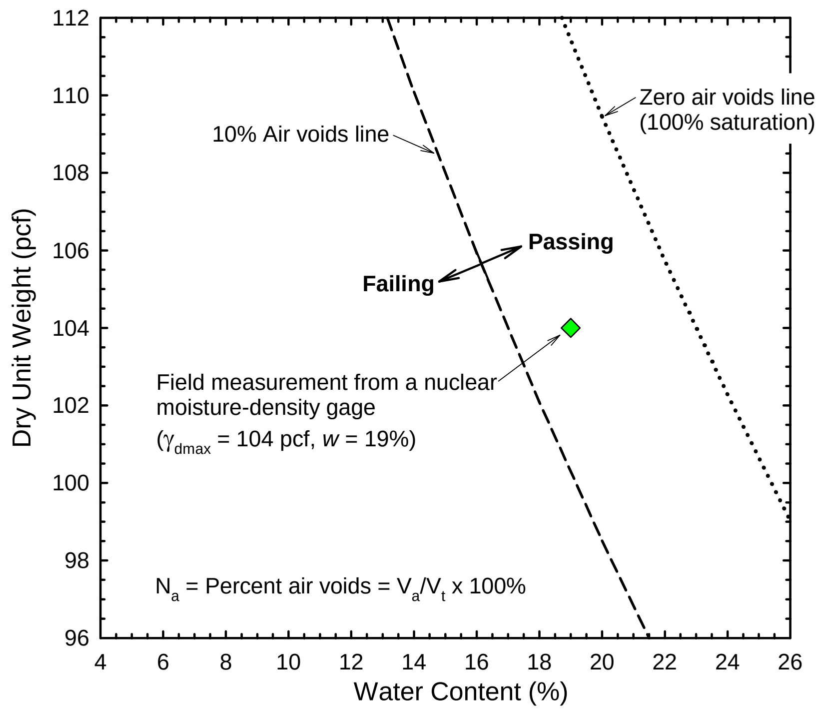


FIGURE 1. Example of the 10% air voids field evaluation method, G_s = 2.70.

As shown in Figure 1, field compaction test results (from nuclear density gage measurements) are plotted on a graph containing an air voids line that represents the predetermined maximum acceptable value of air voids. In this example, a line representing 10% air voids is plotted as the limiting criteria. According to the procedure, the field compaction test is considered passing and the lift of compacted soil is approved if the field compaction data point (γ_{dry} and *w*) plots on the right side of the 10% air voids line. A data point that falls on the left side of the 10% air voids line indicates the compacted soil layer does not meet the specified compaction criteria.

Occasionally, a data point may plot on the right side of the zero air voids curve. This indicates that a mistake was made in the procedure, or that an incorrect value of specific gravity was assumed. As shown in Figure 2, air voids lines are functions of specific gravity, G_s. As G_s increases, the 10% air voids line will correspondingly move to the right on the γ_{dry} versus *w* plot. The Montana Materials Manual of Test Procedures (1988) provides a number of graphs with plots of zero air voids lines and 10% air voids lines for G_s values ranging from 2.60 to 2.70. The field inspector must select the appropriate air voids graph to correctly apply the test method.

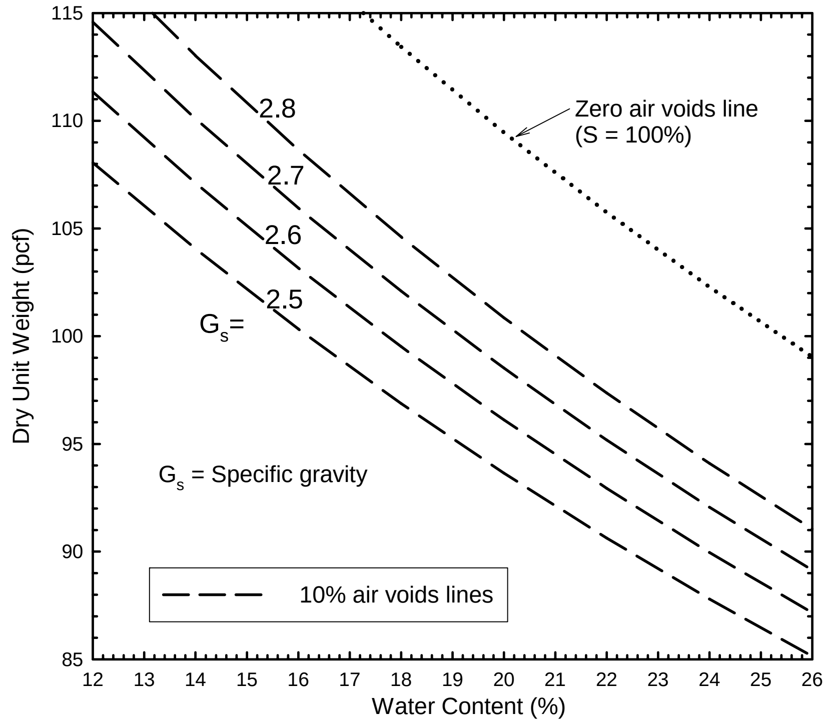


FIGURE 2. Variation of air voids lines with specific gravity, N_a = 10%.

1.3. Background and History

Compaction is a process of mechanical soil improvement, and it is by far the most commonly used method of soil stabilization. Compaction is used to alter the engineering properties of a soil for a specific application such as supporting a pavement section, building foundation, or bridge abutment. As described by Mitchell (1964), field compaction results in potential improvements to a number of engineering characteristics of soil, including: 1) reduced compressibility, 2) increased strength, 3) reduced volume change tendencies, 4) decreased permeability, 5) improved resilience properties, and 6) reduced frost susceptibility. It is evident that a wide variety of soil properties are affected by compaction. Interestingly, even though density is one of the most important parameters measured in the field during an earthwork operation, it does not appear on this list. Density measurements are used in the field to indirectly gauge the effectiveness of the compaction process with the goal of improving soil behavior for the intended application. As discussed in later sections, the compaction water content may also have an important influence on the engineering characteristics of certain soils. The influence of water depends on both macro and micro properties of the soil, including: structure, fabric, grain size distribution, plasticity, electro-chemical interactions, and particle shape. In general terms, fine-grained soils are typically more sensitive to the compaction water content than coarse-grained soils.

R. R. Proctor was reportedly the first to develop practical applications to earthwork control by applying scientific principles to the process of soil compaction in the 1930's and 1940's (Burmsiter 1964). The Proctor laboratory method for quantifying the relationship between 1) soil density, 2) water content, 3) soil type, and 4) compaction energy is still the most commonly used approach on most earthwork projects (Trenter 2001, Holtz and Kovacs 1981). The Proctor laboratory compaction test is not without fault; however, because of its long track record of mostly successful use, the test and evaluation procedure has become recognized as the industry standard. Consequently, the Proctor method is often used as the gauge of effectiveness for any alternative (new or modified) compaction procedure. Proctor curves developed for the soils tested in this study are provided in Appendix A.

The air voids approach for field compaction control represents an alternative approach to the Proctor method. One of the earliest published references to this approach appeared in a 1942 Public Roads Journal article by the Federal Works Agency (Allen 1942). This work was followed a decade later by a Road Research Laboratory Report published in London by W. A. Lewis (1954). These publications and a later publication by Lewis (1962) provide general descriptions of the air voids method of compaction control, but very little data pertaining to the validity of the method.

In addition to being a relatively easy method to implement, Lewis (1962 and 1954) suggests the method may be most appropriate when variations in soil type occur over small distances, because in this circumstance the change in specific gravity may be small in comparison to the potential change in maximum dry density. These qualities represent the primary advantages of the air voids method, which can be used in the field by inspectors who may have minimal training or experience working with the technical aspects of soils.

The air voids method has not gained widespread acceptance after being first introduced to the engineering community in the 1940's. This may be related to some of the potential shortcomings of the approach, which are summarized below:

1. The most prevalent shortcoming described in the literature is that soil air voids can be reduced to relatively low values simply by increasing the soil water content (Parsons 1992, Johnson and Sallberg 1960, Lewis 1954).
2. Errors could result if the soil specific gravity is substantially different than the specific gravity used to develop the air voids line (Lewis 1962). Schmertmann (1989) describes a statistical study in which he concludes that the variation of specific gravity can mathematically be modeled using the ordinary Gaussian normal distribution.
3. Some materials cannot readily be compacted to 10% or less air voids using typical construction procedures (Lewis 1962).
4. Problems may arise with some fine-grained soils if they are compacted either excessively wet or excessively dry of the optimum water content (Trenter 2001, Holtz and Kovacs 1981, Mitchell 1964). Trenter (2001) concludes that a limit or an acceptable range of water content must be specified if the air voids method is used for construction control purposes.

A number of possible options are discussed in the literature for bracketing or controlling the allowable field water content, these include: 1) conducting Proctor compaction tests to determine the optimum water content (Lewis 1962), 2) relating the optimum water content to the liquid and plastic limits determined using the Atterberg limits tests (Al-Khafaji 1993), and 3) estimating the optimum water content as a function of the liquid limit, degree of saturation, and the percentage (by weight) of material finer than the #4 sieve (Omar et al. 2003 and Pandian et al. 1997). Trenter (2001) describes a method that was originally proposed by Paez (1980) for determining the maximum dry unit weight (γ_{dry}) and the optimum water content (w_{opt}) using a mathematical approach for plotting the compaction curve. The approach eliminates some of the subjectivity that occurs when drawing a curve through sets of laboratory data points. The Al-Khafaji, Pandian, Omar, and Paez methods are described in more detail in later sections of this report.

The disadvantages and shortcomings described in the previous paragraphs are logical and not readily disputed from a theoretical viewpoint, but their practical impact on a project-by-project basis has not been evaluated. The authors referenced above provide scarce data to quantify the effects of the shortcomings in which they describe. From a practical consideration, no method is foolproof. For example, there are many shortcomings in the Proctor approach, which have been well documented (Trenter 2001, Terzaghi et al. 1996, Whals 1967, Johnson and Sallberg 1960 and 1962, Hveem 1957, Carey 1957, Lewis 1954). Nevertheless, the Proctor method of compaction control has been used for many years with great success. In terms of the air voids approach, this study provides quantitative information for addressing the following questions. 1) Are there certain types of projects or geologic conditions in which the air voids method is suitable for evaluating soil compaction? 2) Are there specific situations in which the air voids method should not be used?

1.4. Unpublished Information

Most of the useful information on the soil air voids method comes from unpublished sources, because much of the previous work on the air voids method was conducted "in-house" by MDT, or is based on valuable anecdotal experiences by materials technicians and engineers. A well-circulated, but unpublished report written in the 1970's by Jack Hogan, Kenneth Jones, and Arthur Braut presents an overview discussion of the soil air voids method of compaction control and describes a case study in which data from a highway project is used to illustrate how the method can be applied for field compaction control. The authors discuss some of the disadvantages of relying on an inherent upper limit to control the maximum allowable compaction water content. The inherent limit in this context presupposes that a contractor will not apply excessive water because the soil will become unworkable and will not support construction equipment. The authors provide examples of problems that may occur with certain soil types if inherent water content limits are relied upon during compaction. Most of the problems are associated with certain fine-grained clayey soils. Potential problems with some clayey soils include excessive shrink or swell, excessive settlement, and stability problems due to high excess pore water pressures in the interior of the fill.

Ken Neumiller conducted a workshop on the soil air voids test at a training conference at the Montana State University Bozeman campus in January 2003. The accompanying course notes authored by Mr. Neumiller (dated January 9, 2003) present a historical perspective on the method. Based on this document, it appears that MDT first started using the air voids test for compaction control in the early 1970's, and that personnel in the Miles City area were largely responsible for introducing the method to projects in eastern Montana. The document contains a copy of an apparently old chart labeled "Exhibit D", with a caption that indicates the source of the figure originated from the Bureau of Public Roads. This chart has since been located in a report published by Allen (1942) of the Federal Works Agency.

1.5. Survey of Others

Using e-mail listservs, a written survey was sent to materials personnel in all 50 states and to geotechnical professors throughout North America seeking information pertaining to research or experiences that others have had with the soil air voids method. Slightly different wording was used in the surveys; but in general, responses were solicited to the following questions:

1. Are you aware if the soil air voids method is being used (or has it ever been used) by any State agency other than MDT?
2. Are you aware of previously published information or research projects on this topic?

The survey was sent to the following:

- State DOT materials bureaus
- United States University Council on Geotechnical Education and Research (USUCGER) listserv
- MT Geo-Professional Society listserv
- FHWA Turner-Fairbanks Lab
- FHWA – Helena office

At this writing, we have received unanimous negative (no) responses to both questions from individuals representing 30 state departments of transportation, and from 8 academicians. We received a few general comments in which respondents expressed concern regarding the lack of moisture control in the air voids method. There was also some confusion between air voids and percent saturation among some respondents. The confusion lies in the relationship between air voids and saturation. That is, based on the accepted definitions of saturation (V_w/V_v x 100%) and air voids (V_a/V_t x 100%), percent air voids does <u>not</u> equal 100% - S (where S = degree of saturation), except for one case, and that occurs only when S = 100%.

2. LABORATORY TESTING

Laboratory index tests were conducted on nine different soil types that were deemed exemplary of the types of materials commonly encountered on Montana transportation projects. The laboratory testing program consisted of geotechnical index testing and an extensive series of compaction tests. Index tests included: sieve analyses, hydrometer, Atterberg limits, and specific gravity tests. Compaction tests included a suite of Proctor moisture-density impact tests conducted at four different compaction energies, and relative density tests. The tests were conducted in general conformance with one or more of the following standards:

- American Association for State Highway and Transportation Officials, AASHTO (2002),
- Montana Materials Manual of Test Procedures (1988), and
- American Society for Testing and Materials, ASTM (2002).

An overview of the laboratory testing program, and a summary of the test results are provided in the following sections.

2.1. Soil Samples

The soils examined in this study are described in Table 1. Five of the soils were obtained from Montana Department of Transportation (MDT) projects, and four were manufactured from materials available in the Montana State University - Bozeman (MSU) geotechnical laboratory. Soil samples were specially selected to cover the majority of AASHTO soil classifications, as shown in Figure 3, which groups the soils according to the plasticity of the finer fraction of material. A considerable amount of time and effort was expended to manufacture soils that were not available from MDT projects. These soils were manufactured using combinations of the following materials: concrete sand, asphalt bag house fines obtained from the JTL asphalt plant in Belgrade, powdered kaolinite from England obtained from a distributor in New Jersey, and powdered Wyoming bentonite obtained from a distributor in Bozeman.

After numerous trials, we were unsuccessful in obtaining or manufacturing material for the A-2-5 and A-5 categories. With the generous assistance of Bob Weber from MDT, we contacted all of the MDT materials labs across the state, and based on the responses that we received it appears that A-2-5 and A-5 materials are not commonly encountered nor readily available. Because these soil types are relatively rare occurrences on MDT projects and are usually not encountered in very large quantities, they were not included in this study to avoid biasing the results. Soil No. 9 (AASHTO classification A-7-6), was sent to our facilities relatively late in the research study after the laboratory testing phase was nearly complete; therefore, only compaction testing was conducted on this soil. Data obtained from the MDT soil report, including specific gravity, Atterberg limits, and gradation was used in the study for this soil.

TABLE 1. Summary of Materials Examined in this Study

Soil Number	AASHTO Classification	General Description
1	A-2-4(0)	Natural material obtained from an MDT project located 8 mi north of Big Timber. This material consisted of a mixture of silt with some larger gravel-sized particles. MDT Project No. STPP 45-1(17)8.
2	A-2-6(0)	Manufactured in the lab by combining soil No. 6 (A-6 material) with concrete sand. This material consists of a mixture of sand, clay, and some silt.
3	A-2-7(1)	Manufactured in the lab by combining concrete sand, powdered bentonite clay, and bag-house asphalt fines collected from the JTL asphalt plant in Belgrade, MT.
4	A-3(0)	Manufactured in the lab by combining concrete sand with bag-house asphalt fines collected from the JTL asphalt plant in Belgrade, MT.
5	A-4(8)	Natural material obtained from MSU's Agricultural Research Farm (Post Farm) located about 5 mi west of the MSU campus.
6	A-6(2)	Natural material obtained from an MDT project located 7.5 mi east of Jordan, MT. MDT Project No. NH 57-5(25)220[4399].
7	A-7-5(10)	Manufactured in the lab by combining powdered kaolinite clay with powdered bentonite clay.
8	A-7-6(5)	Natural material obtained from an MDT project located 7.5 mi east of Jordan. MDT Project No. NH 57-5(25)220[4399]. (Same project as soil no. 6.)
9	A-7-6(50)	Natural material obtained from an MDT project located 25 mi south of Ekalaka. MDT Project No. STPS 323-1(16)25[4138].

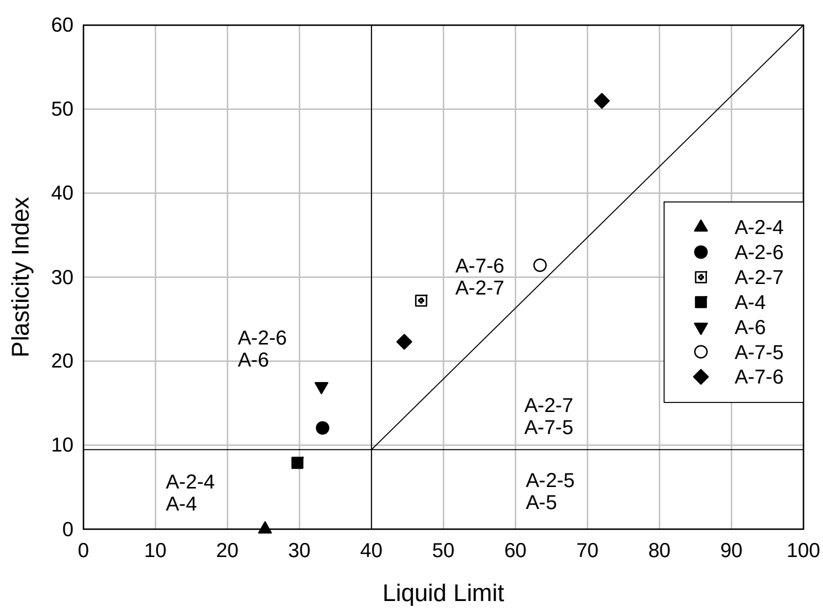


FIGURE 3. AASHTO classification of finer fraction.

2.2. Grain Size Distribution Analyses

Three sieve analyses and three hydrometer tests were conducted on each soil sample in general accordance with AASHTO T-88. A summary of pertinent grain sizes is provided in Table 2. Information from the gradation analyses were used to classify the soils in general accordance with the AASHTO soil classification system (MT-214 and AASHTO M145). Grain size distribution curves are included in Appendix B.

TABLE 2. Summary of Grain Size Analyses

		Percent Passing Sieve Size (Opening mm)				
Soil No.	AASHTO Classification	#10 (2 mm)	#40 (0.425 mm)	#200 (0.075 mm)	(0.005 mm)[a]	(0.001mm)[a]
1	A-2-4(0)	69.5	55.7	6.4	1.6	1.4
2	A-2-6(0)	93.3	63.5	17.2	5.3	4.1
3	A-2-7(1)	96.9	64.7	32.7	5.4	4.8
4	A-3(0)	95.9	52.0	9.1	1.0	0.95
5	A-4(8)	99.6	81.4	57.4	19.8	15.6
6	A-6(2)	100	97.4	38.2	17.8	12.3
7	A-7-5(10)	100	98.4	46.0	35.3	27.8
8	A-7-6(5)	100	95.8	43.4	20.7	15.5
9	A-7-6(50)	98.0	95.0	88.9	--[b]	--[b]

[a]Determined from hydrometer tests.
[b]Data not available.

2.3. Atterberg Limits

The Atterberg limits are water contents at certain limiting stages of soil behavior. The most important limits used for classifying fine-grained soils are the liquid limit (LL) and the plastic limit (PL). At least four liquid limit (LL) and plastic limit (PL) tests were conducted on each soil sample in general accordance to AASHTO T-89. Information from the Atterberg limit tests (summarized in Table 3) were used to classify the soils used in this study in accordance with the AASHTO soil classification system (MT-214, AASHTO M145).

TABLE 3. Summary of Atterberg Limit Test Results

Soil No.	AASHTO Classification	LL	PL	PI = LL - PL
1	A-2-4(0)	25.2	NP	NP
2	A-2-6(0)	33.2	12.0	21.2
3	A-2-7(1)	46.9	27.2	19.7
4	A-3(0)	NP	NP	NP
5	A-4(8)	29.7	7.9	21.8
6	A-6(2)	33.1	17.0	16.1
7	A-7-5(10)	63.4	31.4	32.0
8	A-7-6(5)	44.6	22.3	22.3
9	A-7-6-(50)	72	21	51

Note: LL = liquid limit, PL = plastic limit, PI = plasticity index, and NP = nonplastic material

2.4. Relative Density

Relative density tests were conducted on each soil type to determine the theoretical minimum and maximum void ratios (e_{min} and e_{max}) using test methodologies described in ASTM D-4253 and D-4254. Results from these tests provide an alternate method for comparing calculated soil air voids to a reference compaction value (i.e., the soil relative density). Results from the relative density tests are summarized in Table 4.

TABLE 4. Summary of Relative Density Test Results

Soil Number	AASHTO Classification	e_{min}	e_{max}	γ_{dmax} [lb/ft^3]	γ_{dmin} [lb/ft^3]
1	A-2-4(0)	0.48	0.89	112.5	87.8
2	A-2-6(0)	0.51	1.01	109.8	82.3
3	A-2-7(1)	0.35	0.81	123.1	91.7
4	A-3(0)	0.41	0.68	117.6	98.9
5	A-4(8)	0.81	1.24	90.3	72.7
6	A-6(2)	0.69	0.92	98.0	86.3
7	A-7-5(10)	2.76	5.34	44.1	26.4
8	A-7-6(50)	0.64	1.19	101.0	75.8

2.5. Specific Gravity

Specific gravity is defined as the ratio of the unit weight of soil solids to the unit weight of water, and is represented by the symbol G_s. The calculation of soil air voids is contingent upon the value of G_s; consequently, specific gravity values for the soils examined in this study were scrutinized in detail to further explore the sensitivity of the soil air voids calculation in relationship to G_s. Specific gravity tests were conducted in the MSU geotechnical lab, and matching samples were sent to the following five MDT soils labs for comparison testing:

1. Glendive
2. Lewistown
3. Great Falls
4. Helena
5. Billings

The results are summarized in Table 5. The MSU tests were conducted in general accordance with AASHTO T100 and T209 with one exception in that a larger specimen size was tested to provide greater accuracy, especially for the coarse-grained soils. To ensure the specimen was completely de-aired, a larger vessel (0.16 ft^3) with a 25 psi vacuum pump and mechanical shaker was used in place of the pyncometer flask. This device provided a means of testing up to 5 lb of soil at one time. The basic principles of the test were unchanged, and direct comparisons with the standard method using smaller sample sizes yielded similar results for the fine-grained portion of the soil samples.

TABLE 5. Summary of Specific Gravity Test Results from Different Labs[a]

Soil No.	AASHTO Classification	No. of Tests	Avg. G_s	Standard Deviation	Maximum Test Value	Minimum Test Value
1	A-2-4(0)	17	2.65	0.054	2.74	2.56
2	A-2-6(0)	17	2.61	0.047	2.68	2.51
3	A-2-7(1)	17	2.63	0.075	2.71	2.46
4	A-3(0)	17	2.63	0.073	2.73	2.48
5	A-4(8)	20	2.66	0.073	2.81	2.55
6	A-6(2)	19	2.72	0.049	2.82	2.63
7	A-7-5(10)	17	2.62	0.069	2.77	2.45
8	A-7-6(5)	18	2.66	0.061	2.75	2.55
9	A-7-6(50)	--[b]	2.74	--[b]	--[b]	--[b]
	AVERAGES	18	2.65	0.061	2.75	2.52

[a]Includes test results from the MSU geotechnical lab, and the MDT Glendive, Lewistown, Great Falls, Helena, and Billings labs.
[b]Data not available.

Results from the cooperative study indicate the soils had a range of average G_s values from 2.61 to2.74. The overall average was 2.65. The maximum value for each soil type ranged from 2.68 to 2.82, and the minimum values ranged from 2.46 to 2.63. The lowest average specific gravity, 2.61, was recorded for the A-2-6(0) soil. The highest average specific gravity was 2.74, which was obtained for the A-7-6(50) soil. Standard deviation values ranged from 0.047 to 0.075, with an average value of 0.061. An average of 18 specific gravity tests were conducted on each soil sample. Figure 4 shows the specific gravity frequency distribution for each soil type, and Figure 5 shows the complete data set for all the specific gravity laboratory tests.

Upon examination of the frequency distribution plots, there does not appear to be a discernable pattern between different soil types. Variations from the mean appear to be randomly distributed. Even though extra precautions and careful controls were established to ensure each lab was supplied with nearly identical samples, there were likely small variations between specimens. In addition, there appears to be subtle differences in test procedures between labs and technicians.

In summary, this cooperative laboratory testing study indicates that the reliability of any one specific gravity test is most likely no better than about ± 0.06. This is probably a *best case* value. In a normal project situation, it is expected that the deviation from a *true* value could easily exceed 0.06. Even in this controlled study, the standard deviations for three of the soils (A-2-7, A-3, and A-4) were about 0.073.

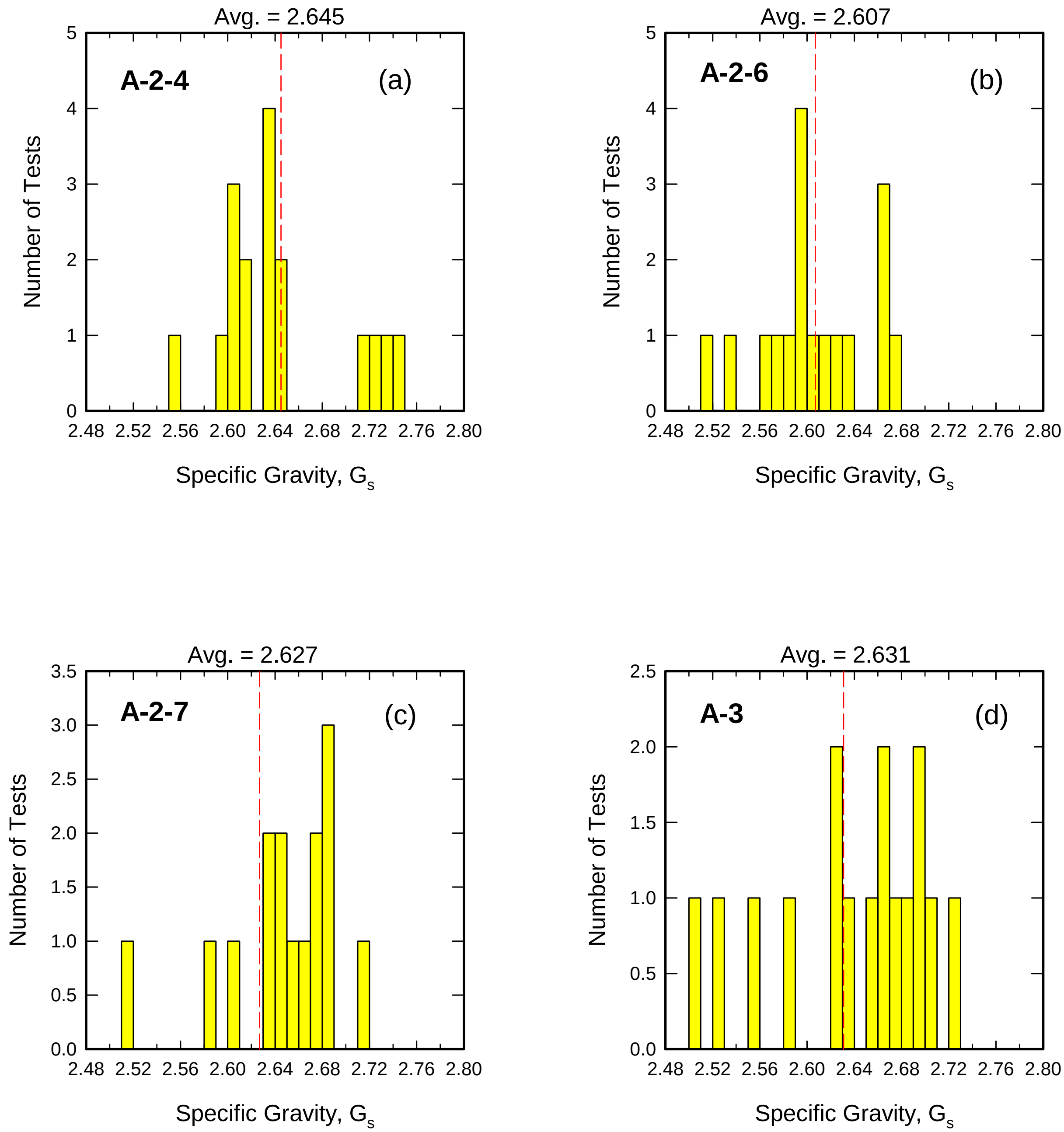


FIGURE 4. Specific gravity frequency distribution results from the comparison study: (a)A-2-4, (b) A-2-6, (c) A-2-7, and (d) A-3.

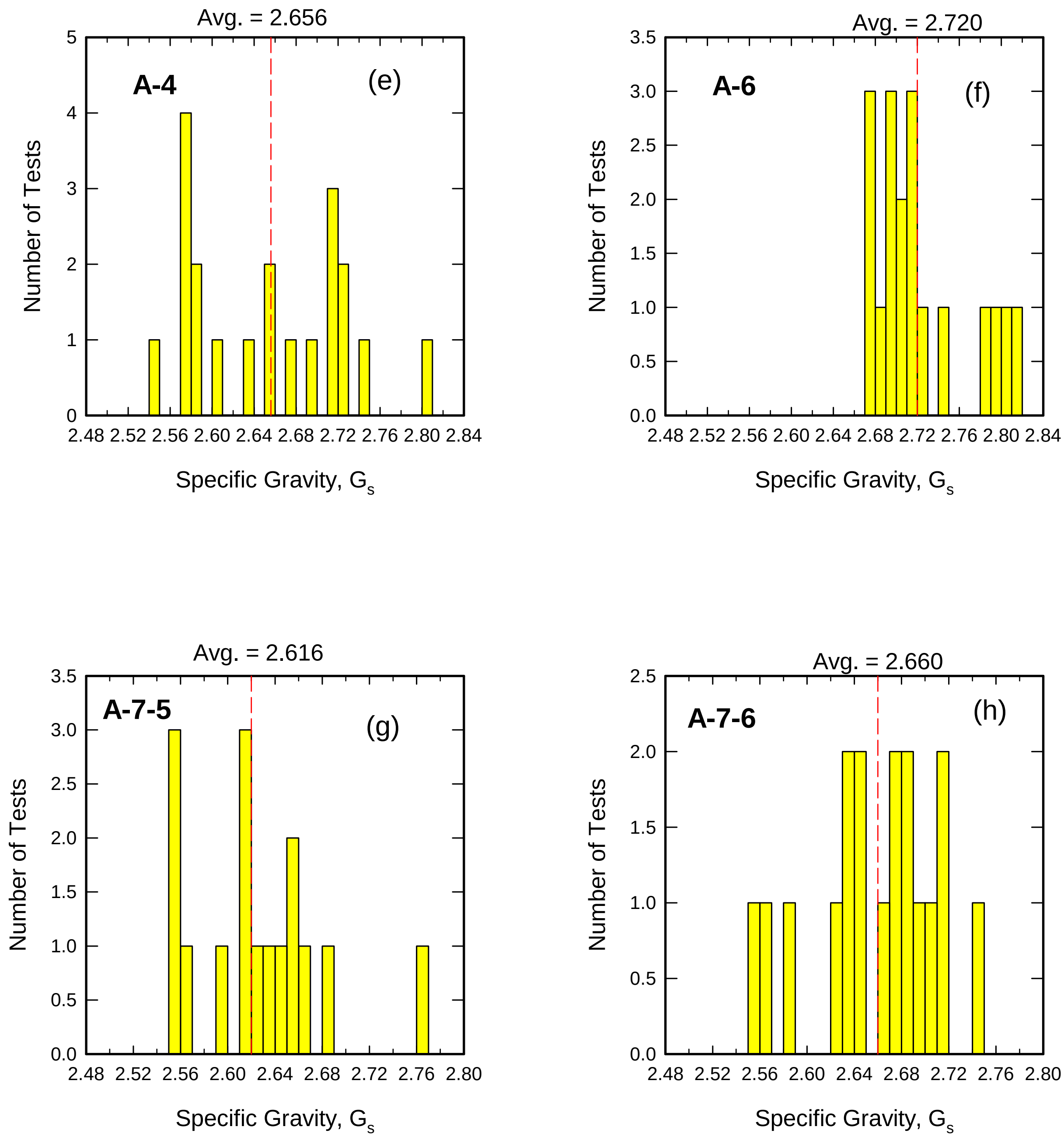


FIGURE 4 continued. Specific gravity frequency distribution results form the comparison study: (e)A-4, (f) A-6, (g) A-7-5, and (h) A-7-6.

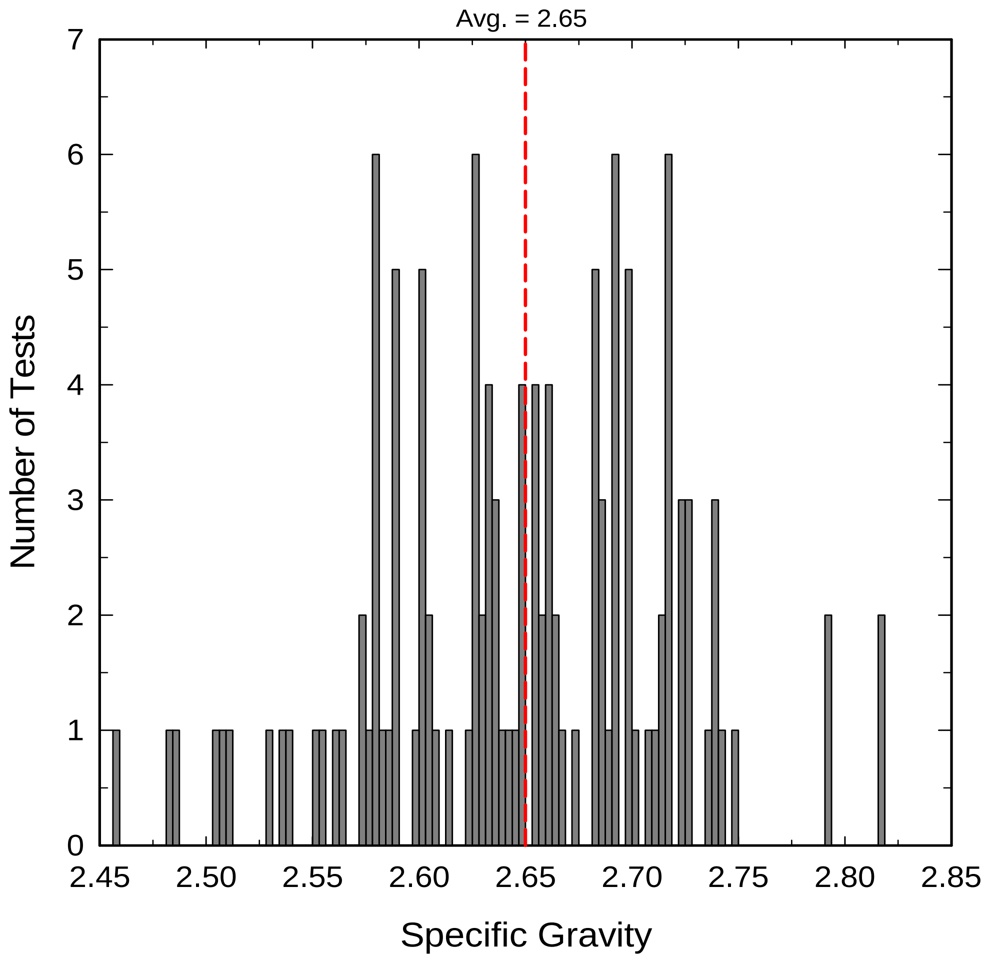


FIGURE 5. Specific gravity frequency distribution for all soils tested in the comparison study.

2.6. Impact Compaction Tests

A suite of Proctor-style impact compaction tests were conducted on each soil type using a range of compaction energies to examine the relationship between compaction energy and air voids, and the relationship between the line of optimums and the air voids lines. Four different compaction energies were achieved by varying one or more of the primary components of the Proctor test, as detailed in Table 6. Method A (AASHTO T-99-01 and T-180-01) with the 4-inch-diameter, 1/30 ft^3 standard Proctor mold was used for all tests. Compaction test results for the nine soils tested in this study are summarized in Tables 7 through 15. Compaction curves for each test are provided in Appendix A.

TABLE 6. Compaction Energies Used for Impact Compaction Tests

Label	Compaction Test	Hammer Weight (lbs)	Drop (ft)	No. of Layers	Blows/Layer	Energy (ft-lbf/ft^3)
E_1	Modified Proctor	10	1.5	5	25	56,250
E_2	Reduced Modified	10	1.5	5	15	33,750
E_3	Standard Proctor	5.5	1.0	3	25	12,375
E_4	Reduced Standard	5.5	1.0	3	12	5,940

TABLE 7. Compaction Results for Soil No. 1: A-2-4(0)

Energy	γ_{dmax} (pcf)	W_{opt} (%)	N_a (%)	$0.95\gamma_{dmax}$ (pcf)	N_a at 0.95 γ_{dmax} (%)
56,250[a]	123.0	11.0	3.9	116.9	8.7
33,750	119.0	13.0	3.2	113.1	8.1
12,375[b]	**114.0**	**15.0**	**3.7**	**108.3**	**8.5**
5,940	107.0	16.0	7.9	101.7	12.5

TABLE 8. Compaction Results for Soil No. 2: A-2-6(0)

Energy	γ_{dmax} (pcf)	W_{opt} (%)	N_a (%)	$0.95\gamma_{dmax}$ (pcf)	N_a at 0.95 γ_{dmax} (%)
56,250[a]	119.0	10.0	7.9	113.1	12.5
33,750	115.0	13.0	5.4	109.3	10.2
12,375[b]	**108.0**	**16.0**	**6.0**	**102.6**	**10.7**
5,940	100.0	18.0	9.8	95.0	14.3

TABLE 9. Compaction Results for Soil No. 3: A-2-7(1)

Energy	γ_{dmax} (pcf)	W_{opt} (%)	N_a (%)	$0.95\gamma_{dmax}$ (pcf)	N_a at 0.95 γ_{dmax} (%)
56,250[a]	128.0	8.0	5.6	121.6	10.3
33,750	125.0	9.0	5.8	118.8	10.5
12,375[b]	**121.0**	**10.0**	**6.9**	**115.0**	**11.5**
5,940	114.0	12.0	8.6	108.3	13.2

TABLE 10. Compaction Results for Soil No. 4: A-3(0)

Energy	γ_{dmax} (pcf)	W_{opt} (%)	N_a (%)	$0.95\gamma_{dmax}$ (pcf)	N_a at 0.95 γ_{dmax} (%)
56,250[a]	117.0	11.0	8.1	111.2	12.7
33,750	114.0	12.0	8.6	108.3	13.2
12,375[b]	**111.0**	**12.0**	**11.0**	**105.5**	**15.5**
5,940	108.0	12.0	13.4	102.6	17.8

TABLE 11. Compaction Results for Soil No. 5: A-4(8)

Energy	γ_{dmax} (pcf)	W_{opt} (%)	N_a (%)	$0.95\gamma_{dmax}$ (pcf)	N_a at 0.95 γ_{dmax} (%)
56,250[a]	117.5	14.0	2.8	111.6	7.7
33,750	115.8	15.0	2.4	110.0	7.3
12,375[b]	**107.5**	**16.4**	**7.0**	**102.1**	**11.6**
5,940	101.0	20.0	6.8	96.0	11.4

TABLE 12. Compaction Results for Soil No. 6: A-6(2)

Energy	γ_{dmax} (pcf)	W_{opt} (%)	N_a (%)	$0.95\gamma_{dmax}$ (pcf)	N_a at 0.95 γ_{dmax} (%)
56,250[a]	128.0	9.0	6.1	121.6	10.8
33,750	121.0	13.0	3.5	115.0	8.3
12,375[b]	**110.0**	**17.0**	**5.2**	**104.5**	**10.0**
5,940	107.0	17.0	7.8	101.7	12.4

TABLE 13. Compaction Results for Soil No. 7: A-7-5(10)

Energy	γ_{dmax} (pcf)	W_{opt} (%)	N_a (%)	$0.95\gamma_{dmax}$ (pcf)	N_a at 0.95 γ_{dmax} (%)
56,250[a]	97.0	18.0	12.7	92.2	16.6
33,750	95.0	18.0	14.5	91.3	20.4
12,375[b]	**89.0**	**24.0**	**11.3**	**84.4**	**16.7**
5,940	80.0	31.0	11.3	76.0	17.7

TABLE 14. Compaction Results for Soil No. 8: A-7-6(5)

Energy	γ_{dmax} (pcf)	W_{opt} (%)	N_a (%)	$0.95\gamma_{dmax}$ (pcf)	N_a at 0.95 γ_{dmax} (%)
56,250[a]	115.0	12.0	8.6	109.3	13.2
33,750	113.0	11.0	12.0	107.4	16.4
12,375[b]	**103.0**	**18.0**	**8.2**	**97.9**	**12.8**
5,940	99.0	19.0	10.2	94.1	14.7

TABLE 15. Compaction Results for Soil No. 9: A-7-6(50)

Energy	γ_{dmax} (pcf)	W_{opt} (%)	N_a (%)	$0.95\gamma_{dmax}$ (pcf)	N_a at 0.95 γ_{dmax} (%)
56,250[a]	101.0	22.0	2.8	96.0	7.7
33,750	100.0	19.0	8.6	95.0	13.2
12,375[b]	**88.0**	**29.0**	**5.5**	**83.6**	**10.2**
5,940	87.0	28.0	7.9	82.7	12.6

Notes for Tables 7-15:
N_a = soil air voids as calculated using Eq. (2).
[a]Modified Proctor Energy (AASHTO T180)
[b]Standard Proctor Energy (AASHTO T99)

A number of interesting trends can be observed by comparing information from Tables 7 through 15.

1. For a given soil type, as the compaction energy is increased, the maximum dry density increases and the optimum water content decreases. This causes some fluctuation in the computed air voids content, because N_a is a direct function of both density and water content.
2. At a constant compaction energy, a different value of N_a will be achieved depending on the soil characteristics. Simply put, some soils compact better than others. At the standard Proctor energy, all of the materials except the A-3(0) and the A-7-5(10), compacted readily to an air voids content that is less than 10%. Even at the modified Proctor energy, the A-7-5(10) soil had an air voids content greater than 10%.
3. At the modified Proctor energy, the air voids contents ranged from a low of 2.8% to a high of 12.7%.
4. For the nine soils tested, the average air voids content at the standard Proctor energy was 7.2%, and the average air voids content at 95% of the standard Proctor energy was 11.9%. The average maximum dry densities for the standard Proctor and 95% of the standard Proctor energies were 105.7 and 100.4 pcf, respectively.

2.7. Line of Optimums

Using compaction data from the laboratory tests, a line of optimums was developed for each soil tested in this study. The line of optimums is important for this study because it provides a means of relating compaction curves produced using different energies to the 10% air voids line. This relationship for each soil type is shown in Figures 6 through 14.

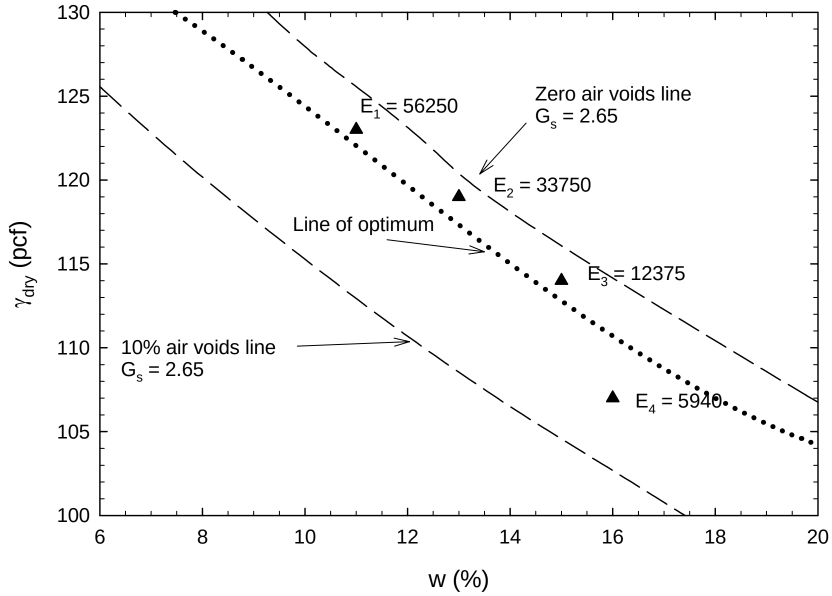


FIGURE 6. Line of optimum for soil No. 1: A-2-4(0).

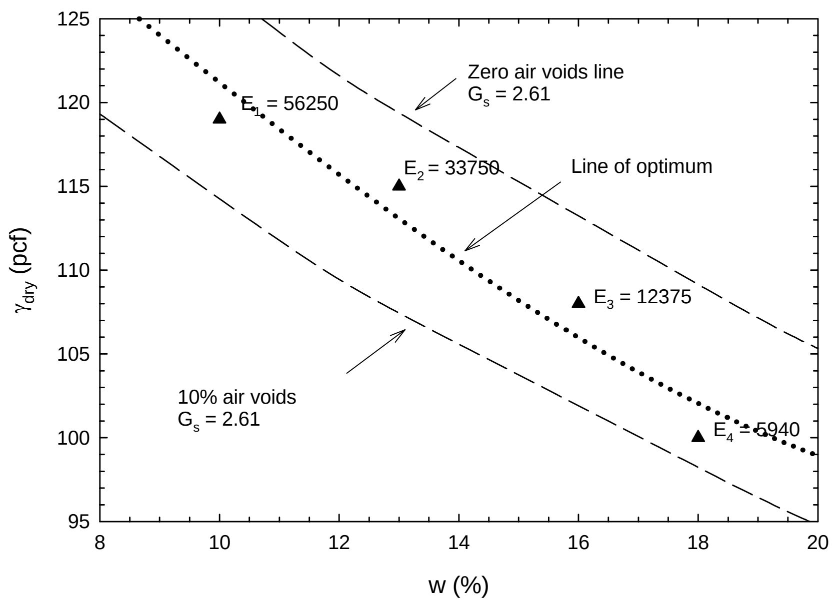


FIGURE 7. Line of optimum for soil No. 2: A-2-6(0).

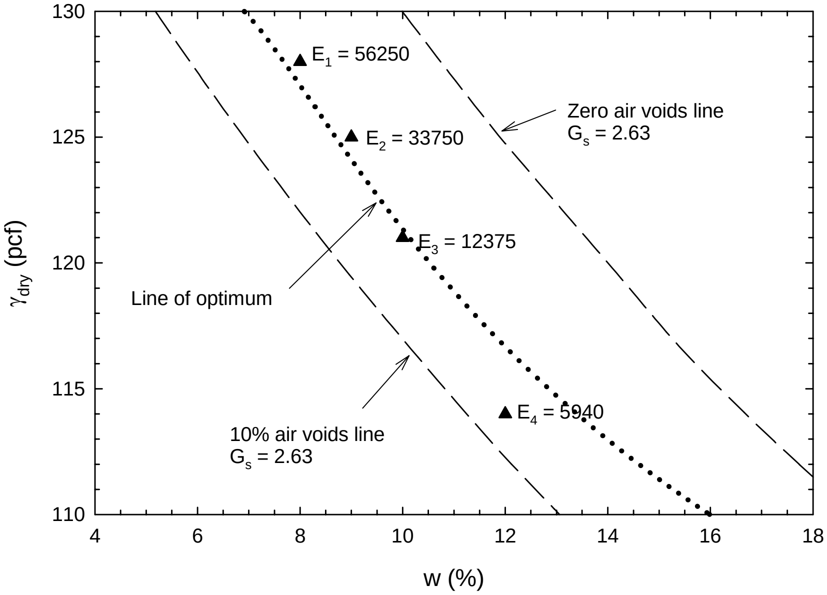


FIGURE 8. Line of optimum for soil No. 3: A-2-7(1).

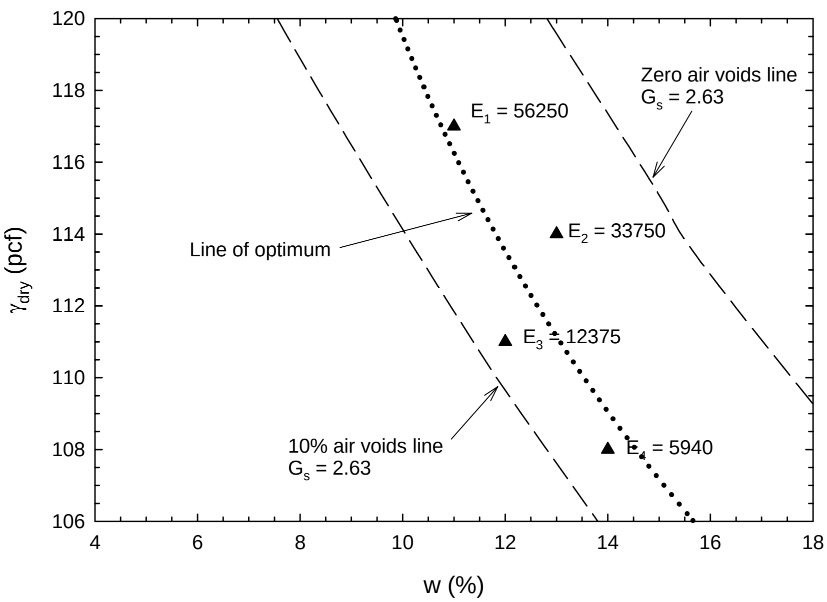


FIGURE 9. Line of optimum for soil No. 4: A-3(0).

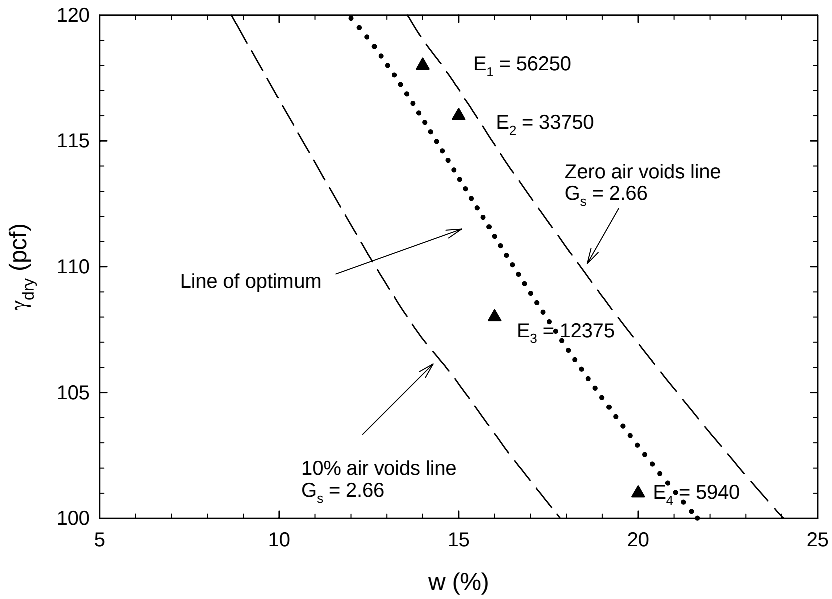


FIGURE 10. Line of optimum for soil No. 5: A-4(8).

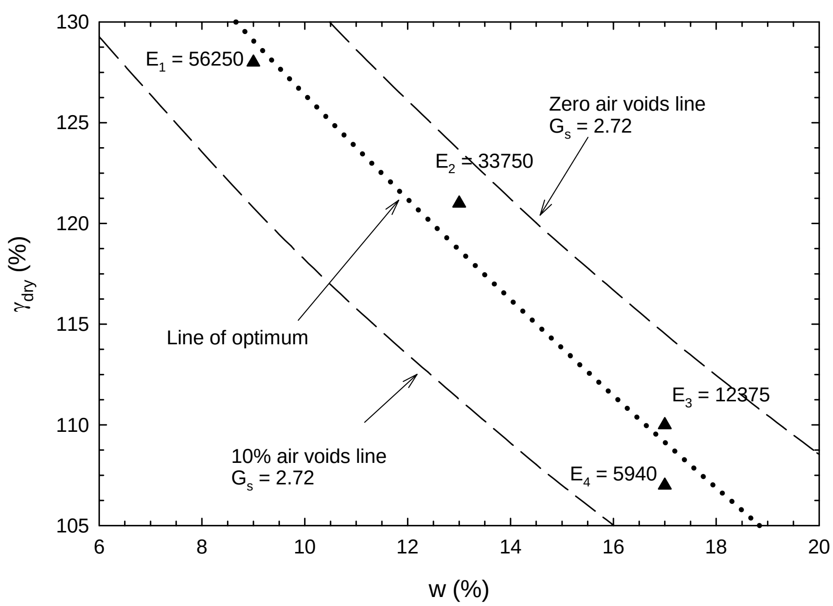


FIGURE 11. Line of optimum for soil No. 6: A-6(2).

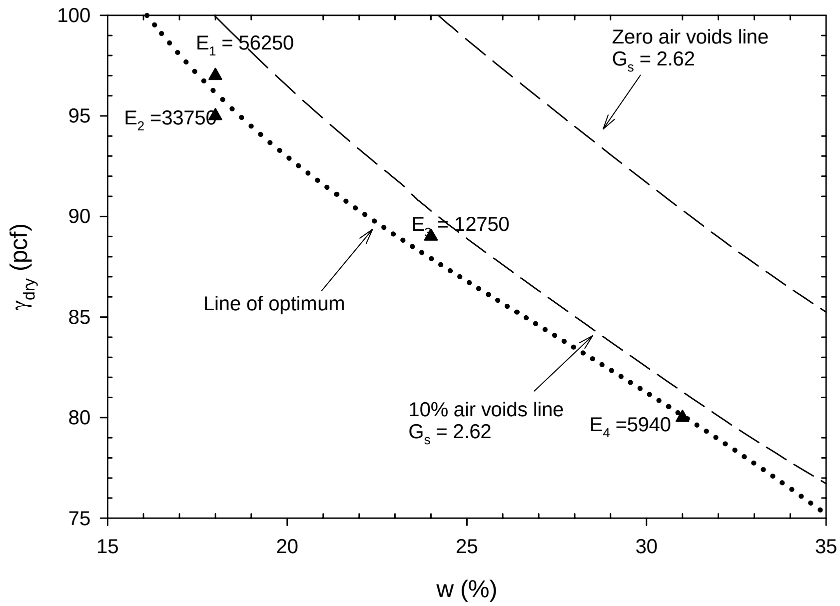


FIGURE 12. Line of optimum for soil No. 7: A-7-5(10).

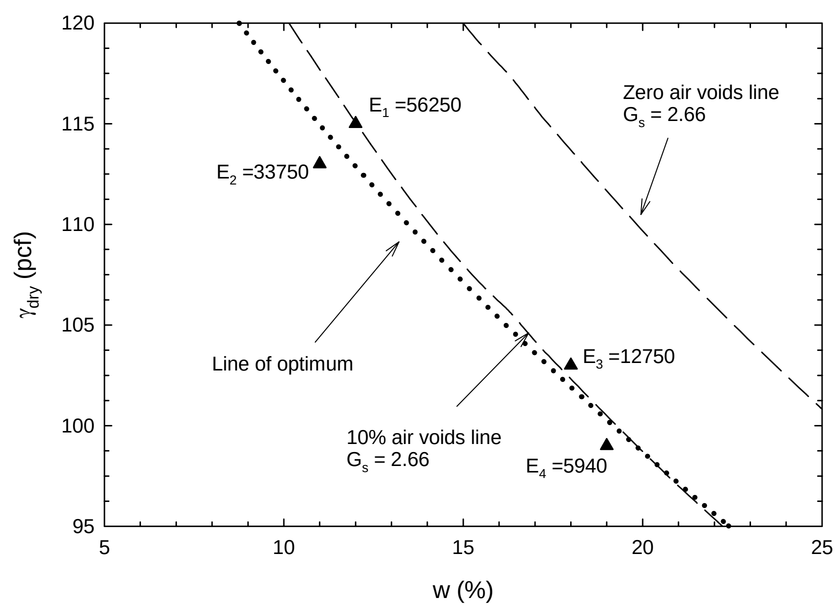


FIGURE 13. Line of optimum for soil No. 8: A-7-6(5).

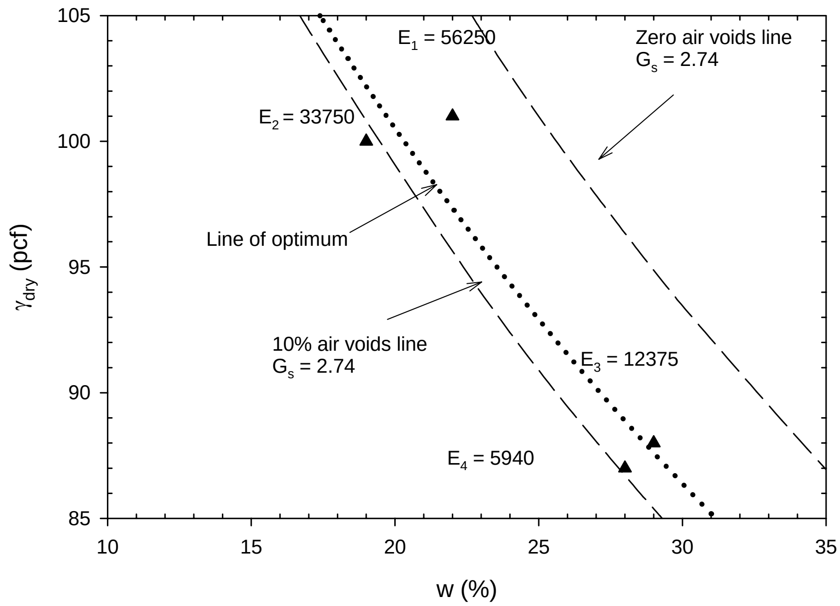


FIGURE 14. Line of optimum for soil No. 9: A-7-6(50).

As can be observed in the plotted results, the soil types used in this research project compact differently. All of the material except the A-7-5(10) and A-7-6(5) compact to optimum conditions at air voids less than 10%. For most of the materials, the line of optimums falls approximately midway between the zero air voids line and the 10% air voids line. However, the line of optimums for the A-7-5(10) and A-7-6(5) materials fall to the left of the 10% air voids line, and the line of optimum for the A-7-6(50) material falls close to the 10% air voids line. This seems to indicate that some A-7 materials may not be ideal for use in the air voids method because there may not be a strong correlation between densities achieved using the Proctor impact compaction test and the corresponding air voids.

This relationship for A-7 soils was examined in greater detail using data from the MDT projects listed in Table 16. The data is plotted in terms of G_s and N_a at values of maximum dry density and optimum water content determined from the standard Proctor test. As shown in Figure 15, there is considerable scatter of data points about the 10% air voids line. One hypothesis to explain the varying results for A-7 soils is that compaction results generated using the Proctor procedure on highly plastic clayey material can occasionally result in irregular-shaped compaction curves. An example of this is shown in Figure 16, which shows a compaction curve for an A-7-6(20) soil generated using Proctor test data from MDT project number F 86(17). Because of the potential for irregular-shaped compaction curves, it is possible that for some of the A-7 soils, the peak of the compaction curve may not have been truly established. As shown in Figure 16, it would take many closely spaced points (small water content interval) to ensure that the peak was not missed because it fell between water content values. Consequently, there may be some inaccuracies in the percent air voids relationships shown in Figures 12 - 14 because of the difficulty in obtaining a true peak compaction value. The following conclusions are drawn from these observations:

1. When these types of soil are encountered, it is recommended that extra care be taken in the lab to develop a representative compaction curve. For some soils, this may require 8 to 10 Proctor compaction points.
2. The 10% air voids method should not be used on these soils because of their high sensitivity to changes in moisture.
3. For these types of soil, the compaction water content may be more important than a target density in terms of long-term performance in highway construction.

TABLE 16. MDT Projects used in Data Analyses

Designation	Project No.
Roundup-east	F14-5(9)170
Madison River East	F84-2(1)12
Miles City Project	F86(17)
12 Km East of Jordan	NH 57-5(25)220
NW of Sidney – North	F 62-2(9)21 [1041]
Volborg –North & South	F23-1(15)33PE
Sidney West	STPP 51-3(2)60PE
Miles City – Cohagen	STPP 18-1(5)18
Jct. MT7 – East	STPS 336-1(2)0 [4881]
37 Km N.W. of Terry – North	STPS 253-1(5)23 [2824]
30 Km of Glendive – NE	NH 20-1(15)19
Baker - South	STPP 27-2(13)27PE [4052]

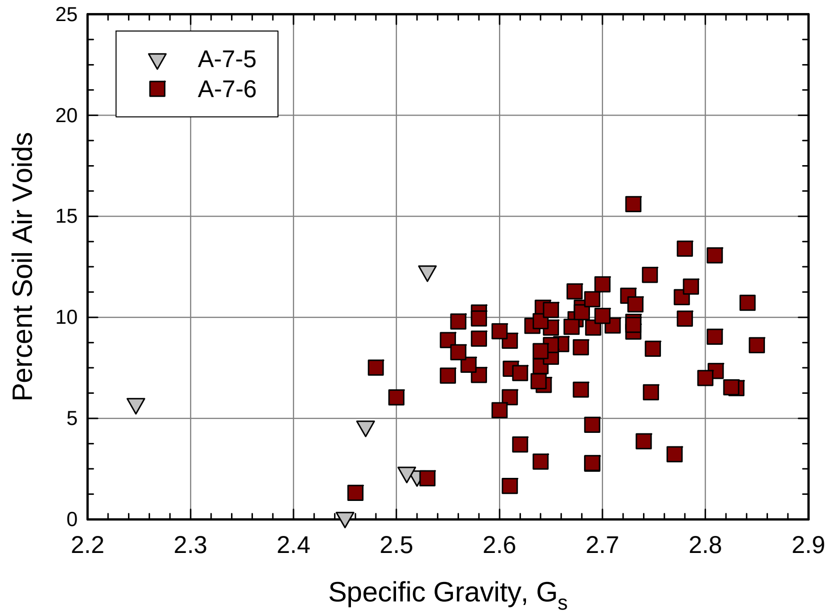


FIGURE 15. Percent soil air voids at optimum Proctor density and water content.

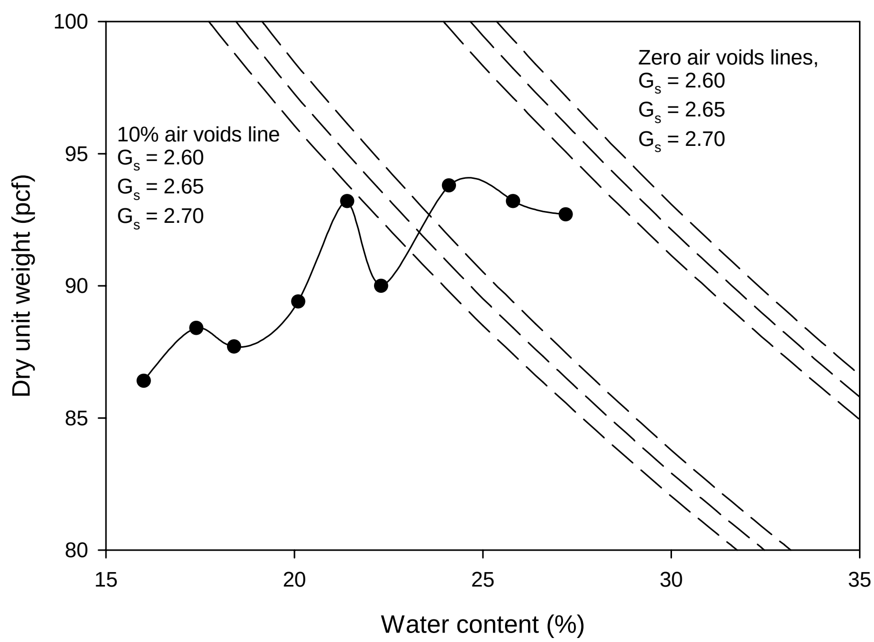


FIGURE 16. Example of irregular compaction curve for A-7-6(20) soil.

2.8. Paez Method for Evaluating Proctor Test Results

Estimating the optimum water content (w_{opt}) and maximum dry density (γ_{dmax}) from Proctor data is a subjective process unless there are data points on both sides of w_{opt} and close to the extreme value. This can result in inconsistencies in the interpolated peak values between different labs and operators. Computer software is available to make this interpolation, or a numerical approach can be used to estimate the peak values of the compaction curve.

One such approach is the equation transformation method developed by Paez (1980), which uses simple variable transformation equations to plot the dry and wet legs of the compaction curve as straight lines. The wet leg plots parallel to the air voids line while the dry leg plots at an obtuse angle. As shown in Figure 17, the intersection of these two lines defines the theoretical peak point of the compaction curve based on volumetric and gravimetric phase relationships. This method provides a consistent and repeatable approach for determining w_{opt} and γ_{dmax}, and eliminates operator subjectivity. The Paez method was further investigated using compaction data from this study to determine if the numerically interpolated values of γ_{dmax} and w_{opt} are accurate enough to use in practical applications. The derivation of the Paez equations are presented in Appendix C of this report because the original Paez (1980) paper is in French and many steps of the derivation are skipped or omitted in the paper.

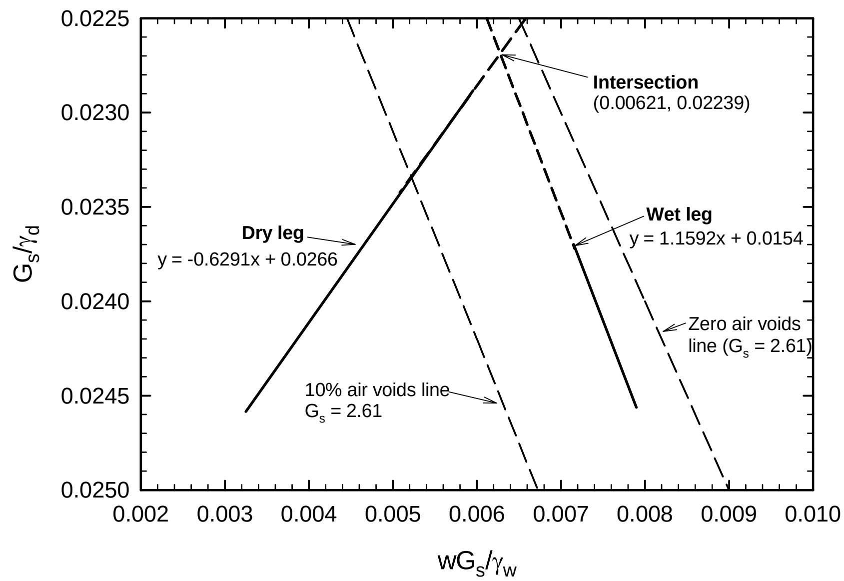


FIGURE 17. Transformed compaction plot using the Paez method.

For comparison purposes, this method was applied to the compaction test results developed during the laboratory phase of this study. The results of this comparison are tabulated in Appendix C.

The numerically interpolated results for maximum dry density using the Paez method correlate reasonably well with the values determined using the common procedure. The maximum density estimates using the Paez method for all the different compaction energies and soil types (36 values) differ on a percentage basis from the common procedure by a range of: +3.8% to -2.70%. The optimum water content predictions are not as good and do not appear to accurately reflect the true optimum value that would manually be selected from the data points. The percentage difference for the optimum water contents varied over a relatively large range from +19.81% to -26.04%. Based on this error range for the optimum water content predictions, it appears that the Paez method is probably not precise enough to use for interpolating peak values from compaction data.

In conclusion, the Paez method provides a consistent approach for evaluating compaction data, and the process is readily automated using a computer spreadsheet. Applying the method to the soils tested in this study yielded results that were not reasonably consistent with the traditional approach. Therefore, based on the data considered in this study, the Paez method should not be used on a stand-alone basis for evaluating compaction parameters from a Proctor compaction test. It appears the method is not accurate enough to use on a project basis for soils typical to Montana. It is possible that the Paez method could be improved by investigating a larger pool of data. The study of this published numerical interpolation approach further emphasizes the importance of checking any approximate method for reasonableness using carefully controlled tests on a variety of soil types.

3. ALTERNATE APPROACHES FOR ESTIMATING THE OPTIMUM WATER CONTENT

3.1. Introduction

The conventional approach for evaluating the suitability of a compacted soil layer in the field relies on two parameters obtained from laboratory Proctor compaction tests: the maximum dry density (γ_{max}) and the optimum water content (w_{opt}). The soil air voids method provides an indirect check on the dry density of the compacted layer; however, the soil water content is essentially ignored during the field evaluation. This results in one of the previously identified major shortcomings of the air voids approach, which is a lack of control on compaction water content. A lack of control occurs because the typical procedure for estimating the optimum compaction water content requires data from a Proctor laboratory test. This means a soil sample must be collected and sent to the lab for testing, or alternately the inspector may be tasked with the responsibility of correctly choosing the applicable Proctor values (w_{opt} and γ_{max}) from a collection of results that were developed during the soil survey phase of the project.

Unfortunately, it usually takes at least 24 hours for the field inspector to receive results from the Proctor test. On most transportation and embankment projects this may be too long. Consequently, one of the primary advantages of implementing the air voids test is the savings in time that occurs when the Proctor test is eliminated during the construction phase of a project. This section evaluates the reasonableness of using approximate empirical methods for estimating the optimum water content of a soil.

Over the years, a number of researchers have proposed alternative empirical methods for estimating optimum compaction parameters in lieu of the Proctor test. Three methods that are relatively straightforward to apply were identified in the literature. These methods reportedly provide approximate values that can be used to verify results from laboratory tests and may provide a means of estimating the optimum water content independent of the Proctor test. Basic soil index parameters including Atterberg limits, gradation, and specific gravity are commonly used in these approximate methods. These parameters are advantageous because: 1) they are usually determined during the soil survey phase of a project, 2) they are easier and quicker to measure in a field laboratory, and 3) with experience they can be approximately estimated in the field by trained technicians. The suitability and practicality of the approximate methods were evaluated in this study using laboratory test results and data obtained from MDT soil survey reports. Our evaluations of the Pandian, Al-Khafaji, and the Omar methods are described in the following subsections.

3.2. Pandian Method

Pandian et al. (1997) developed a method of evaluating the optimum water content using the liquid limit and degree of saturation. The method evolved from trends that were observed in the dry and wet legs of standard Proctor compaction curves. Pandian et al. (1997) used data points from the three compaction curves shown in Figure 18 to develop the plots shown in Figure 19, which relate water content to the liquid limit. Figure 19a applies to the dry legs of the compaction curves ($w < w_{opt}$) and Figure 19b applies to the wet legs of the compaction curves ($w > w_{opt}$). For this data, a nearly linear relationship exists between the water content and the liquid limit for a particular degree of saturation. The plots shown in Figure 20 were developed by extrapolating and normalizing the data points from Figure 19 in terms of water content divided by the square root of saturation for the dry leg, and water content divided by saturation squared for the wet leg of the compaction curve.

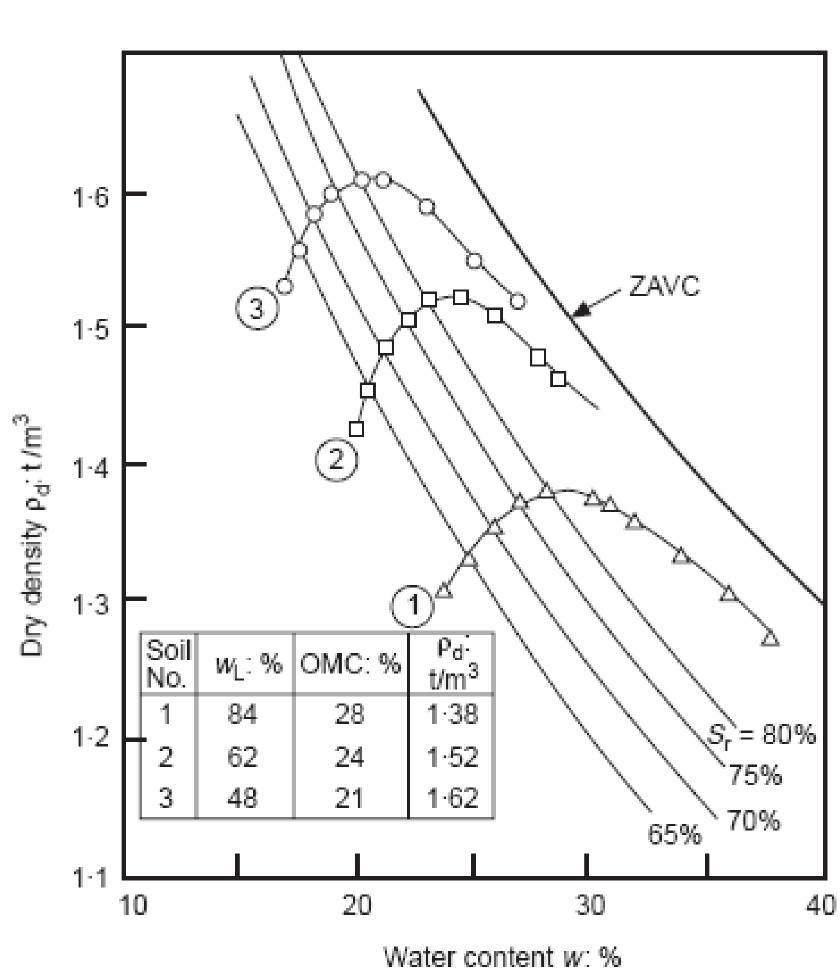


FIGURE 18. Data used to develop the Pandian equations (Pandian et al. 1997).

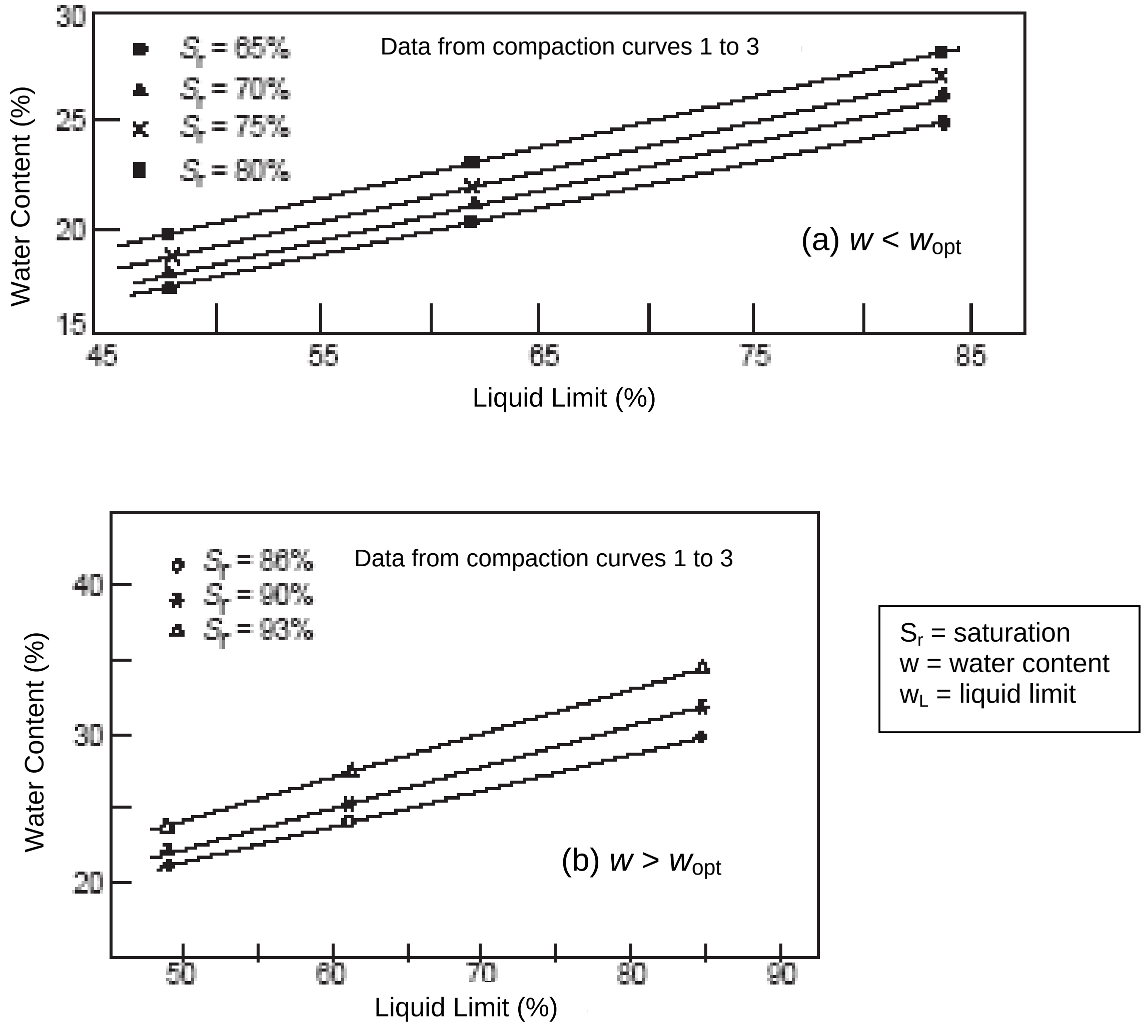


FIGURE 19. Relationship between *w* and LL as a function of saturation, (a) dry leg of compaction curve (b) wet leg of compaction curve (from Pandian et al. 1997).

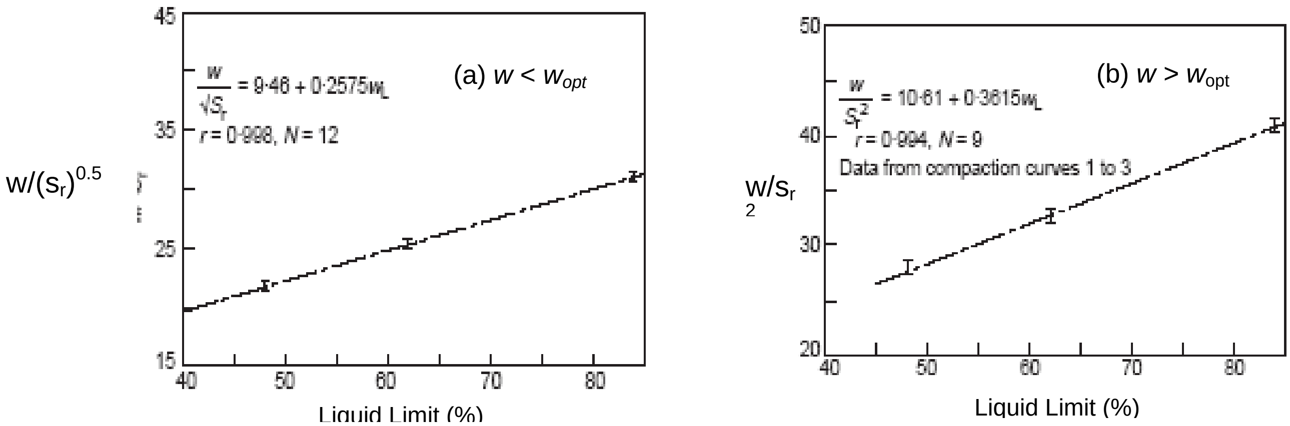


FIGURE 20. Normalized relationship between w and S, (a) dry leg of compaction curve (b) wet leg of compaction curve (from Pandian et al. 1997).

The following equations were developed by fitting a straight line to the data shown in Figure 20:

$$w_{opt} = (a + b \cdot LL) \cdot \sqrt{S} \tag{3}$$

$$w_{opt} = (c + d \cdot LL) \cdot S^2 \tag{4}$$

where, S is the degree of saturation (decimal form), LL = liquid limit (%) and a, b, c, and d are curve-fit constants. For the soils tested in the Pandian et al. (1997) study; a = 9.46, b = 0.258, c = 10.61, and d = 0.362.

By equating Eq.s (3) and (4) and solving for S, the author of this study developed the following expression that can be used to estimate the degree of saturation of a soil that is at a water content equal to the standard Proctor optimum water content:

$$S = \left\{ \frac{a^2 + 2ab(LL) + b^2(LL)^2}{c^2 + 2cd(LL) + d^2(LL)^2} \right\}^{1/3} \tag{5}$$

Equation (5) can be used to estimate the degree of saturation of a soil based only on the Atterberg liquid limit. Once *S* is determined from Eq. (5), the optimum water content can be calculated using either Eq. (3) or (4).

This method provides an empirical approach for estimating w_{opt} providing the soil is similar to the soils that were used to develop the empirical curve-fit variables (a through d). These variables were developed by Pandian et al. (1997) using a series of standard Proctor compaction tests conducted on three soil samples described as:

1. 43% montmorillonite and 57% quartz,
2. 19% kaolinite, 11% montmorillonite, 8% muscovite, and 62% quartz, and
3. 17% kaolinite, 10% montmorillonite, 6% muscovite, and 67% quartz.

The Pandian method was used to calculate the optimum water content and the maximum dry density using data obtained from MDT projects, and the results are compared in Figures 21 and 22. The MDT projects used in this comparison are listed in Table 16.

The liquid limit test is typically conducted only on material that is finer than the #40 sieve. For soils that have coarser material, the liquid limit value may not truly reflect the properties of the entire sample. For this reason, a correction factor propose by Nagaraj and Murthy (1985) was used to correct the liquid limit values to account for material that is coarser than the #40 sieve. The corrected liquid limit, $(LL)_{corrected}$, is calculated as follows:

$$(LL)_{corrected} = LL \cdot \left(1 - \frac{R\#40}{100}\right) \qquad (6)$$

where, R#40 = percent retained on the #40 sieve (0.0165 in), and LL = liquid limit (%).

This correction was used in the calculations for data gathered from the MDT projects and the laboratory test results. As can be seen in Figure 21, predictions for the optimum water content generally fall within a ± 5% confidence value. Predictions for the maximum dry density shown in Figure 22 generally fall inside a ± 10% confidence value. From the results shown in Figures 21 and 22, it appears the Pandian method has potential; however, considerably more data should be used to further calibrate the model before the predictions could be relied upon for estimating w_{opt} in the field. Pandian et al. (1997) do not provide information regarding the soil classification or index properties of the samples used in his study. It may be worthwhile in the future to evaluate and possibly modify the Pandian variables (a, b, c, and d in Eq.s 3-5) for soils typically encountered in Montana.

In summary, it is hypothesized that this method could be a viable addition to the air voids approach by providing a means of bracketing an allowable compaction water content. Results generated using this method could be improved if the curve-fit variables were further refined using soil that is more region specific. It is suggested that soils from the Glendive District would be opportune for calibrating this approach for possible application to a project in that region of the state.

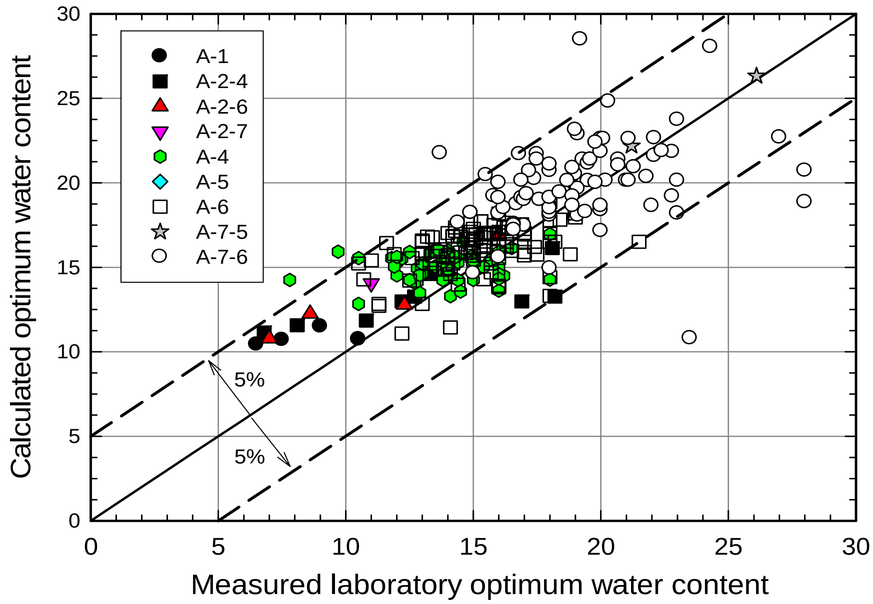


FIGURE 21. Pandian optimum water content prediction.

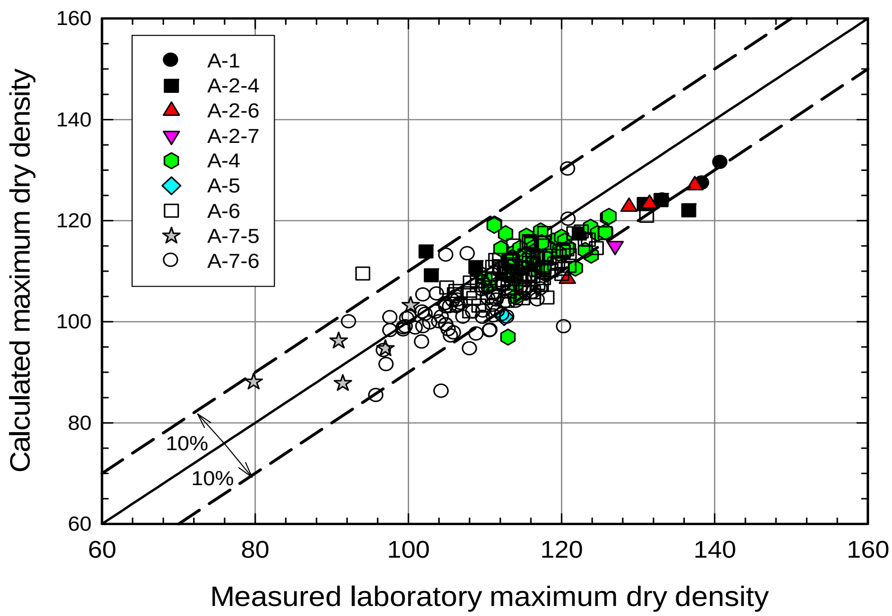


FIGURE 22. Pandian maximum dry density prediction.

3.3. Al-Khafaji Method

The Al-Khafaji (1993) method represents another empirical approach based on data obtained from sites in the United States. Empirical equations were developed using curve fitting techniques that make it possible to estimate the optimum water content and the maximum dry density from the Atterberg liquid limit (LL) and plastic limit (PL). The equations are:

$$\gamma_{d\,\max} = 141.71 - 1.186 \cdot PL - 0.5 \cdot LL \qquad (7)$$

and

$$w_{opt} = 0.14 \cdot LL + 0.54 \cdot PL \qquad (8)$$

where, LL = liquid limit (%), PL = plastic limit (%), and w_{opt} = water content (%).

The soils tested by Al-Khafaji had plastic limits ranging from 10% to 40%, and liquid limits between 20% and 90%. No specific information is provided on the origin or geologic history of the soils used to develop the equations. However, the reported variation in the Atterberg limits suggests the data includes a wide range of soil types.

Similar to the Pandian method, MDT data from the projects listed in Table 16 and from the laboratory tests were used to calculate the optimum water content and maximum dry density using the Al-Khafaji method. Equation (6) was used to correct the liquid limit values to account for material that is coarser than the #40 sieve. The calculated results were then compared to actual measured values. As shown in Figure 23, most of the optimum water content data is within about a ± 5% confidence interval. As shown in Figure 24, the maximum dry density predictions generally fall inside a minus 20% to plus 10% confidence interval. Based on this data study, it appears the AL-Khafaji method is not as precise as the Pandian method in terms of maximum dry density predictions. The two approaches appear to yield similar results for optimum water content predictions.

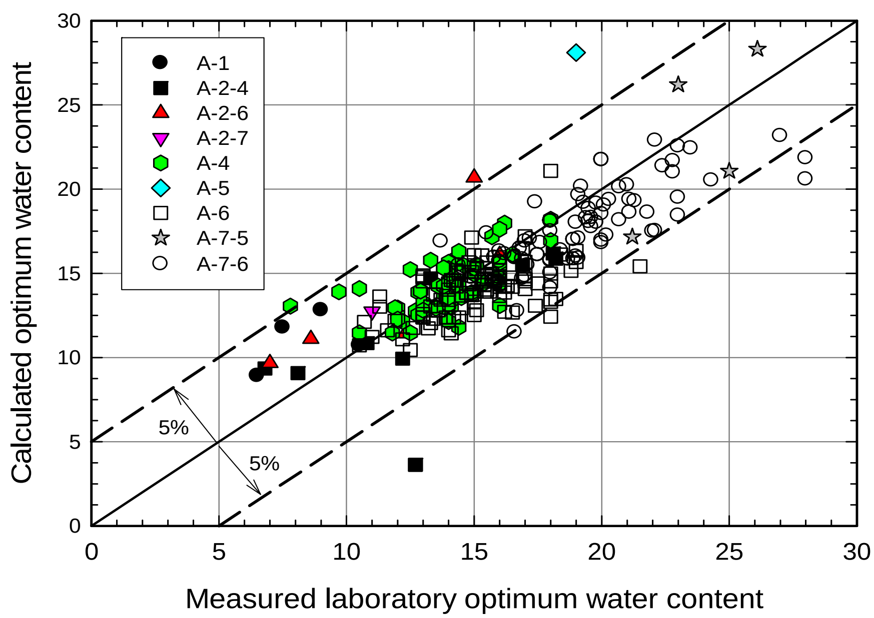


FIGURE 23. AL-Khafaji optimum water content prediction.

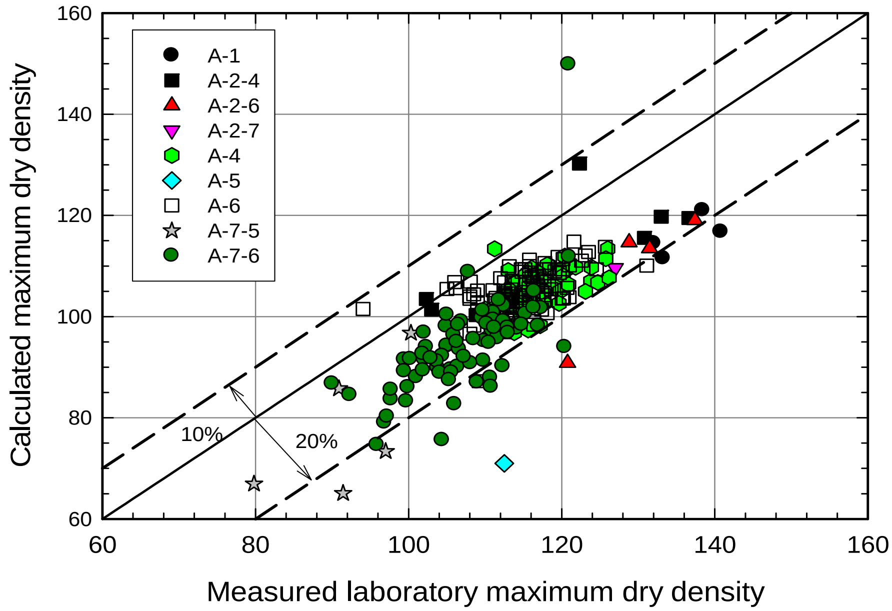


FIGURE 24. AL-Khafaji maximum dry density prediction.

3.4. Omar Method

The Omar et al. (2003) method represents a third empirical approach for estimating the optimum water content and maximum dry density. Empirical equations in the Omar method were developed using results from modified Proctor compaction tests on 311 soils collected from various parts of the United Arab Emirates. Of these samples, 45 were identified as gravelly soil, 264 were predominately sandy soils, and 2 were clays of low plasticity. Index properties for these soils ranged as follows:

- percent retained on #4 sieve = 0 to 68%,
- percent passing #200 sieve = 1 to 26%,
- liquid limit = 0 to 56%,
- plasticity index = 0 to 28%, and
- specific gravity of soil solids = 2.55 to 2.8.

These parameters were correlated with modified Proctor compaction test results to obtain the following equations, which were developed using multiple regression analyses:

$$\gamma_{d\,\max}[pcf] = \left[4{,}804{,}574 \cdot G_s - 195.55 \cdot LL^2 + 156{,}971 \cdot (R\#4)^{0.5} - 9{,}527{,}830\right]^{0.5} \cdot 0.6243 \quad (9)$$

$$\ln(w_{opt}) = 1.195 \times 10^{-4} \cdot LL^2 - 1.964 \cdot G_s - 6.617 \times 10^{-5} \cdot (R\#4) + 7.651 \quad (10)$$

where, R#4 = percent retained on No. 4 sieve, LL = liquid limit (%), PL = plastic limit (%) and G_s = specific gravity.

Comparison between the Omar method and the laboratory results are provided in Tables 17 and 18 for the soils tested in this study. Graphical results of this comparison are shown in Figures 25 and 26. The percent error in maximum dry density ranged from 0.0 to -21.88% and the percent error in optimum moisture content ranged from +50 to -18.18%. The largest percent error occurred in the A-2-6(0) and A-2-7(1) soils, while the A-4(8) soil had the smallest percent error for optimum water content, and the A-7-6(50) soil had the smallest percent error for maximum dry density. Based on this comparison, it appears that the Omar method is not a very precise method for evaluating the optimum moisture content or the maximum dry density for the soils examined in this project. The Omar method was developed using soil samples from the United Arab Emirates; consequently, the regression equations may not be valid for soils typically encountered in Montana. It was not possible to use data from the MDT projects in this comparison because the Omar method requires the percent passing the #4 sieve from the gradation analysis, and this information was not readily available from the soil survey reports.

TABLE 17. Maximum Dry Density Predictions using the Omar Method

	Maximum dry unit weight (pcf)		
	Omar	**Lab**	**Error (%)**
A-2-4(0)	120	123	-2.44
A-2-6(0)	104	119	-12.61
A-2-7(1)	100	128	-21.88
A-3(0)	109	117	-6.84
A-4(8)	106	117,5	-1.40
A-6(2)	114	128	-10.94
A-7-5(10)	92	97	-5.15
A-7-6(5)	107	115	-6.96
A-7-6(50)	101	101	0.00

TABLE 18. Optimum Water Content Predictions using the Omar Method

	Optimum water content (%)		
	Omar	**Lab**	**Error (%)**
A-2-4(0)	13	11	18.18
A-2-6(0)	15	10	50.0
A-2-7(1)	16	8	50.0
A-3(0)	13	11	18.18
A-4(8)	14	14	-2.9
A-6(2)	11	9	22.22
A-7-5(10)	21	18	16.67
A-7-6(5)	14	12	16.67
A-7-6(50)	18	22	-18.18

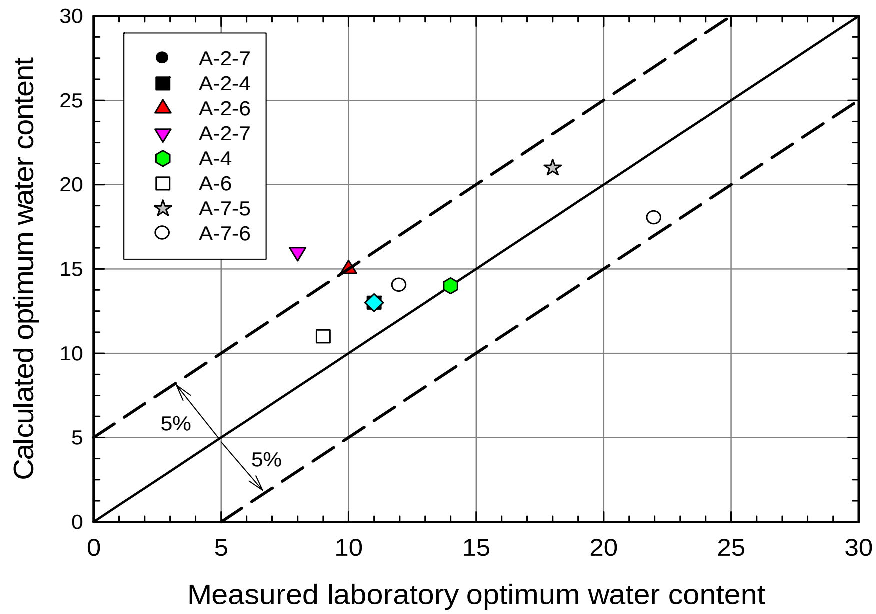


FIGURE 25. Omar optimum water content prediction.

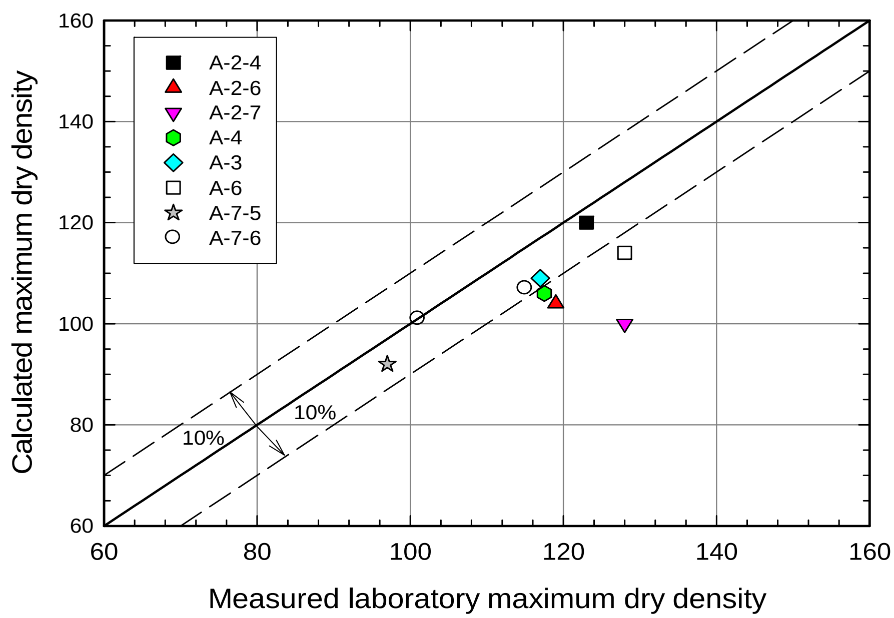


FIGURE 26. Omar maximum dry density prediction.

4. EVALUATION OF AIR VOIDS METHOD

4.1. Introduction

Previous sections of this report provided background information on the air voids approach, and presented an overview of the method based on laboratory tests conducted for this study supplemented with data from MDT projects. This section examines the suitability of the air voids method as a tool for enforcing compaction control on earthwork projects. The following questions are addressed:

1. How sensitive is the computed air voids value to changes in specific gravity?
2. On a project-by-project basis, how does the variation of specific gravity compare to the variation of the Proctor maximum dry density?
3. How does the variation in computed air voids compare with the variation that occurs in conventional compaction testing as a result of limitations in the Proctor method of testing?
4. What is the statistical relationship between air voids and 95% of the Proctor maximum dry density?

The evaluation presented in this section is based on the laboratory test results described in earlier sections of this report and construction test data obtained from MDT projects. Over 1,300 test results from 24 different MDT projects were compiled and statistically evaluated for this study. General information for each project is summarized in Table 19. The information includes the MDT project number, the date of the original soil survey, the county in which the project is located, the approximate length of the project, and the number of specific gravity and Proctor compaction tests conducted for the project. Figures and tables discussed in the remainder of this section identify the projects by the number shown in the first column in Table 19.

TABLE 19. Project Information from MDT Soil Survey Reports

No.	Abbreviated Project Name	MDT Project No.	Survey Date	Montana County	Length (mile)	Quantity G_s/(MDD)
1	12km E. of Jordan	NH57-5(25)220	March 2004	Garfield	9.6	37 (26)
2	Alzada-East & West	STPP23-3(6)130	Dec. 1993	Custer	9.6	19 (6)
3	NW of Sidney - North	F62-2(9)21	February 1994	Richland	5.4	86 (24)
4	Broadus East	F23-1(15)33PE	October 1992	Custer	4.7	81 (22)
5	Sidney West	STPP51-3(2)60PE	July 1994	Richland	11.2	120 (46)
6	40 km No. of Havre-No.	STPS233-1(7)22PE	February 2001	Hill	9.0	106 (75)
7	2 km No. Great Falls-No.	STPS225-1(1)0 PE	February 2003	Cascade	11.4	76 (80)
8	Dupuyer – So.	STPP3-2(27)28 PE	January 2005	Pondera	6.2	75 (80)
9	Boulder River E.	IM90-7(79)369	July 2001	Stillwater	8.7	62 (9)
10	Wheatland County Line-E.	STPP14-3(17)77	October 2003	Wheatland	10.1	29 (14)
11	Waco Interchange - Custer	IM94-1(67)36	February 2004	Yellowstone	10.7	56 (24)
12	Garryowen-Lodge Grass	IM90-9(95)517	May 2004	Big Horn	15.1	67 (14)
13	Big Horn County East	IM90-9(94)473	June 2001	Big Horn	13.0	2 (12)
14	Garryowen	IM90-9(96)509	Dec. 2004	Big Horn	7.9	9 (36)
15	Pompeys Pillar - Waco Interchange	IM94-1(66)24	March 2004	Yellowstone	12.0	28 (34)
16	Park City - Mossmain	IM90-8(146)427	July 2001	Stillwater/ Yellowstone	10.6	48 (30)
17	7 km E. of Windham-East	NH57-2922)47	May 2004	Judith Basin	10.5	39 (15)
18	Curves-N. of Tracy	STPHS227-1(10)2PE	Nov. 2004	Cascade	1.7	18 (16)
19	2nd Avenue, 7th to Park Dr.	STPU5299(51)/STPU5236 (1)	March 2001	Cascade	1.8	36 (42)
20	Cut Bank-West	NH1-3(40)247	October 2004	Glacier	8.0	17 (19)
21	Milk River Bridge	NH1-7(35)398PE	January 2004	Blaine	1.2	18 (19)
22	USRS Canal	BR9-2(9)47PE	January 2001	Teton	1.0	17 (17)
23	Lincoln - East	NH24-3(25)76PE	Dec. 2004	Lewis and Clark	7.22	8 (17)
24	Meriwether - East	NH1-3(36)234FPE	April 2003	Glacier	13.0	7 (12)

4.2. Variation in Specific Gravity Measurements

One of the major difficulties in monitoring the construction of embankments, fill sections, and subgrade surfaces on highway projects is that the materials frequently change along the length of the alignment. When this occurs, it is difficult for the inspector to choose a correct Proctor curve, especially if materials are obtained from different sources or if mixing of materials occurs prior to placement. Natural in-situ materials along a highway alignment can change significantly even over short distances resulting in a wide range of soil parameters. Test results from the projects listed in Table 19 indicate that values of Proctor maximum dry density within a project could easily vary by 30 pcf, or more. For example, on the Cut Bank West Project (No. 20), 19 Proctor density tests were conducted, with results varying from 97.7 to 141.2 pcf; a range of 43.5 pcf. Forty-two Proctor tests conducted for the 2nd Avenue Project (No. 19) resulted in maximum dry density values from 90.2 to 124.5 pcf; a range of 34.3 pcf. Even for well-trained and experienced inspectors, it can be a challenging and difficult task to consistently select a Proctor curve that correctly corresponds to each field density test. The options in this case are:

1. Use judgment based on visual examination of the soil to select a Proctor curve from a set of curves that were developed from soil samples obtained during earlier phases of the project.
2. Obtain a sample for a one point Proctor test. Based on that result, select a Proctor curve from a “family of curves” that was developed during earlier phases of the project.
3. Obtain a sample of soil from the compacted layer and send it to the field or District laboratory for a conventional Proctor test.

The degree of accuracy of these three options increases from 1 to 3. Unfortunately, the necessary investment of time also increases from 1 to 3. In other words, the degree of accuracy in obtaining the correct value of maximum dry density and optimum water content is directly proportional to time spent conducting the tests. As previously discussed, there can be significant disadvantages in waiting over a day to obtain results, even if the results are more accurate.

The air voids method provides a fourth option that takes considerably less time than conducting a Proctor test, and does not require experience in selecting the correct Proctor curve. The following paragraphs examine the sensitivity of the air voids method to changes that may occur in soil type along a project alignment.

A premise of the air voids method is that the specific gravity on a project will vary less than the maximum dry density, if the soils along a project alignment are derived from the same geologic source. This presupposition was investigated by examining the variation of specific gravity and maximum dry density that occurred on the 24 MDT projects listed in Table 19. To provide a normalized basis of comparison, the data was evaluated in terms of the coefficient of variation, which is defined as the standard deviation divided by the mean value. A comparison for all 24 projects is shown graphically in Figure 27. As shown in the bar chart, the maximum dry density coefficient of variation (COV) varies considerably between projects. Within any single project, the COV for the maximum dry density was much larger than the COV for the specific gravity. Results from this large amount of data obtained from construction projects in Montana lends credence to the premise that on a project-by-project basis specific gravity varies considerably less than the Proctor maximum dry density. The chart in Figure 27 was developed using data from 995 specific gravity tests and 682 Proctor density tests.

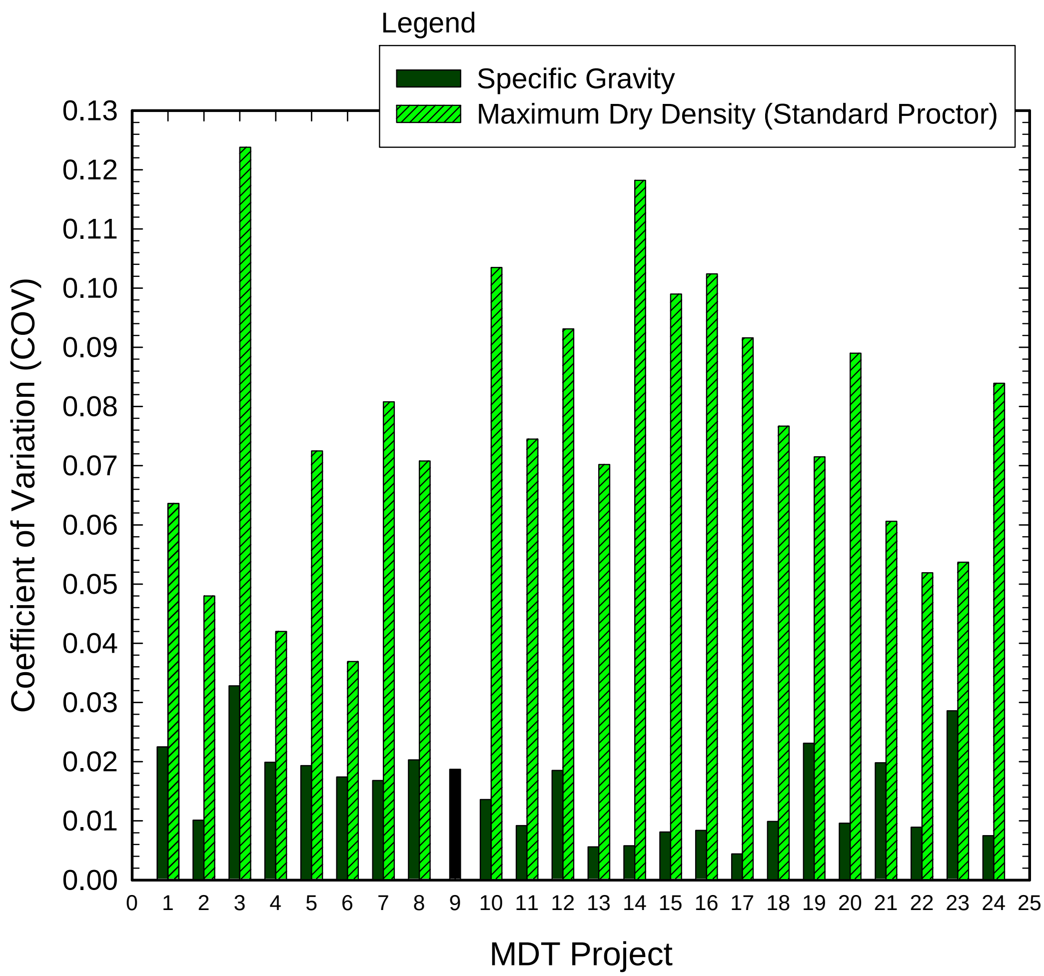


FIGURE 27. Variation of specific gravity and Proctor density on 24 projects.

The variation in average specific gravity for all 24 projects was relatively small. For the 995 G_s tests, the COV was 0.024. This corresponds to an average G_s value of 2.67, with a standard deviation of 0.065. Interestingly, the round robin comparison laboratory study described in Section 2.5 resulted in similar statistical results. For the laboratory comparison study of nine different soil types, the average value for G_s was 2.65 with a standard deviation of 0.061 and a coefficient of variation of 0.023.

From the extensive amount of data that was examined in this study, the following observations are made in regards to specific gravity measurements:

1. Within a project, the relative variation in specific gravity will likely be less than the variation of Proctor maximum dry density.

2. From a statistical basis, there is a high probability that for a soil in Montana, the specific gravity will likely fall within a range of about 2.60 to 2.73.
3. The accuracy of any specific gravity measurement is no better than about 0.06.

4.3. Sensitivity of Air Voids Calculations

The primary variable in the air voids method is the specific gravity (G_s). As shown in Figure 28, the location of the air voids line is solely dependent on the value of G_s used in the computations. The previous section discussed the variability that could be expected with this parameter. This section examines the sensitivity of the air voids method to changes in G_s.

Figure 28 contains a hypothetical graph in which the zero air voids and 10% air voids lines are plotted for two values of G_s, 2.6 and 2.7. This diagram illustrates that the dry unit weight will change by about 3 pcf for a 0.1 change in specific gravity. For a variation in G_s of 0.06, the change in dry density would be less than 2 pcf.

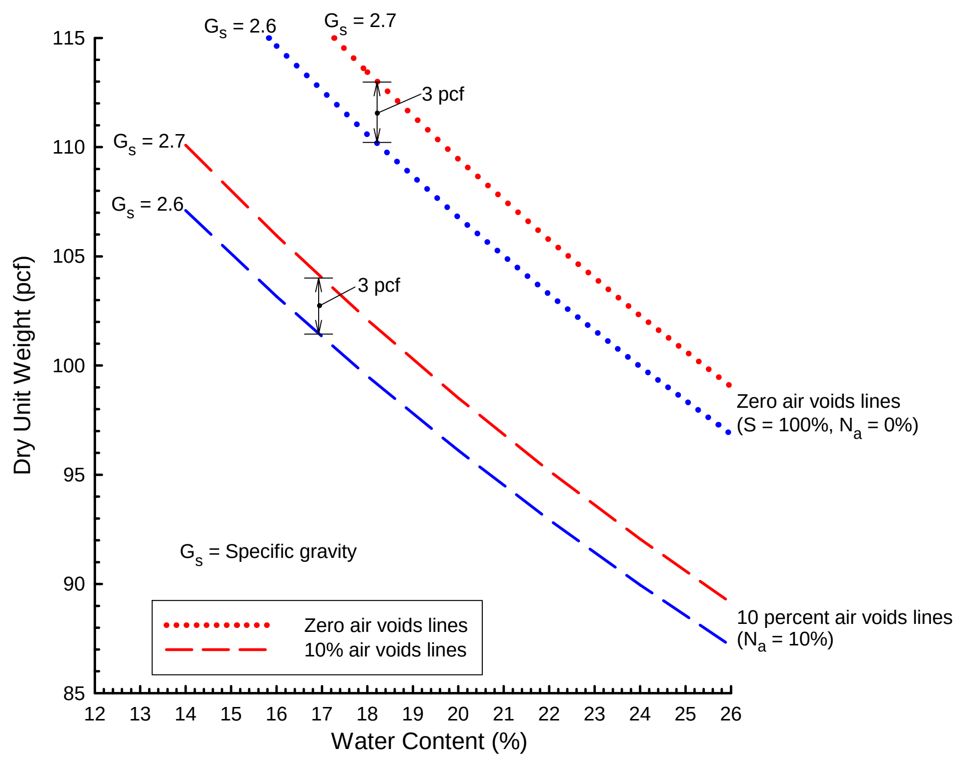


FIGURE 28. Sensitivity of dry density to changes in specific gravity (modified from Jones, 1973).

Another approach for examining the sensitivity of N_a to changes in G_s is shown in Figure 29, in which the variation of N_a is computed over a range of G_s values for three specific sets of dry densities and water contents. The slopes of the lines shown in this plot represent the sensitivity of N_a to changes in G_s; or, in equation form:

$$slope = \frac{\Delta N_a}{\Delta G_s} \tag{11}$$

The threes sets of dry density and water content values in Figure 29 were chosen to represent the range of typical compaction data that could be encountered for a subgrade or fill soil. The computed slope (from Eq. 11) for these three sets of compaction parameters ranged from 17.9 to 29.2. The slopes of lines drawn in this plot can be used to examine the sensitivity of N_a to errors or deviations in the measured value of G_s. For example, the largest value of slope, 29.2, corresponds to the compaction parameters γ_{dry} = 130 pcf and w = 6%. For this set of parameters, a change in G_s of 0.06 will result in a change to N_a of 1.75%. Using the smallest value of slope, 17.9, which corresponds to the compaction parameters γ_{dry} = 105 pcf and w = 16%, results in a change of N_a of only 1.1% for a 0.06 change in G_s. This evaluation validates the observation by Lewis (1954) who suggested that an error of ± 0.05 in G_s would result in an error of only ± 1 to 1.5% in the calculation of air voids.

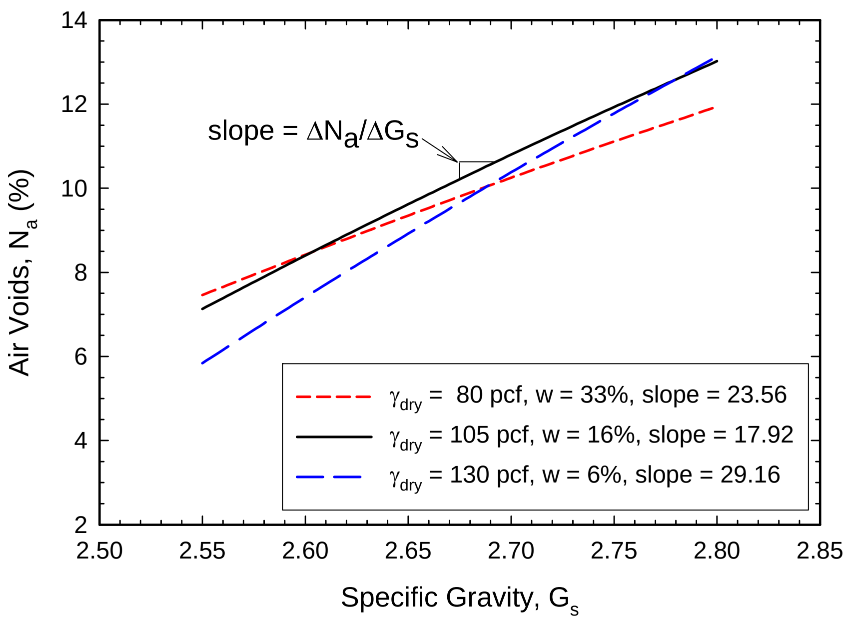


FIGURE 29. Sensitivity of air voids to changes in specific gravity.

Compaction data from MDT projects was examined to determine if any trends could be observed between soil type, G_s, and N_a. Figure 30 shows this comparison graphically for data obtained from the projects listed in Table 19. The data points were plotted for values of N_a computed at 100% of the standard Proctor maximum dry density at optimum water content. As can be seen in the figure, the majority of the data points are clustered in the region bounded by G_s = 2.59 to 2.72, and N_a = 2 to 7%. Based on this data set, no discernable trend appears to exist between soil type, G_s, and N_a.

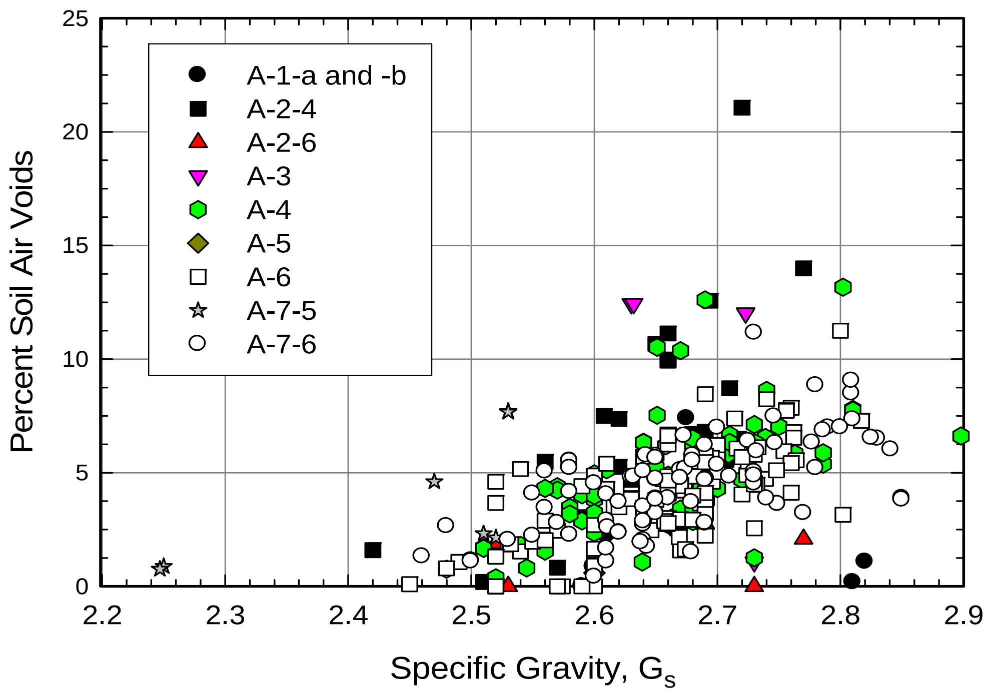


FIGURE 30. Soil air voids at standard Proctor maximum density and optimum water content.

The same data set is plotted in Figure 31 in terms of percent saturation (S). As can be seen in the figure, the majority of samples were at a saturation level of 70 to 90% when compacted at the peak values of density and water content. Based on this data set, no discernable trend appears to exist between soil type, compaction, and degree of saturation.

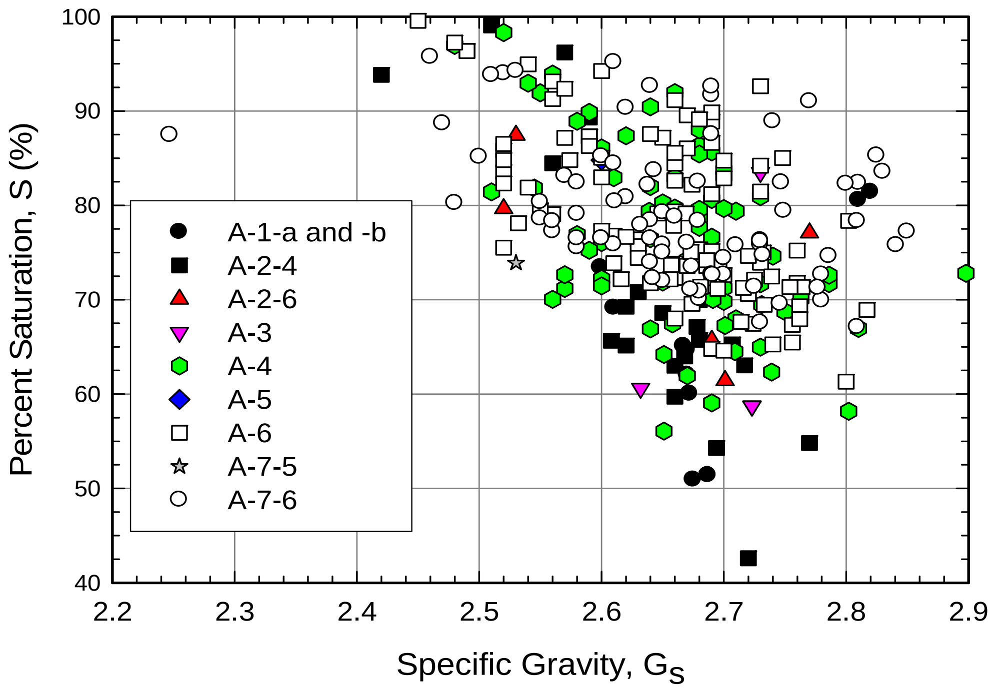


FIGURE 31. Percent saturation at standard Proctor maximum density and optimum water content.

4.4. Limitations of the Proctor Procedure

The typical Proctor method of compaction control involves two measures of soil density:

1) A laboratory impact test to measure the maximum dry density and optimum moisture content of the soil in relation to an applied energy (Proctor test).
2) A field test to measure the in-place density and water content of a compacted layer of soil. This test is most often conducted using either a nuclear density gauge or a sand cone test.

In the conventional compaction inspection approach, the results of these two measures are compared and the inspector makes a decision whether the compacted layer meets the criteria established in the project specifications.

In this report, the Proctor method is used as one of the metrics or standards for evaluating the air voids method. This is done out of necessity because there is no other readily available standard for field compaction control. Nonetheless, this is not an ideal comparison because the Proctor method has limitations as a result of variances in both the laboratory and field tests. This section summarizes some of the variations that have been observed and measured in these popular tests.

Johnson and Sallberg (1962) report on a cooperative study in which 44 different agencies conducted standard Proctor tests on an AASHO road test material (identified as yellow-brown clay). The standard deviation for the optimum water content (w_{opt}) was 1% moisture and the <u>standard deviation for maximum dry density (MDD) was 2.2 pcf</u>, with a range of 114.0 to 125.1 pcf.

Johnson and Sallberg (1962) report on another cooperative study that was administered by a subcommittee of ASTM (Committee D-18 - Soils for Engineering Purposes) in which six independent laboratories tested six different cohesionless soils. The soils ranged from fine sand to crushed rock. The standard deviation for w_{opt} ranged from 0.5 to 5.5% and the <u>standard deviation for MDD ranged from 4.0 to 7.5 pcf</u>.

Jones (1973) reported results from two cooperative studies by the Corps of Engineers and the American Council of Independent Laboratories in which <u>maximum dry density values for the same soil (but from different labs) was found to vary by 2 to 4 pcf</u>. These tests were reportedly conducted by trained technicians in high-quality soils laboratories.

Carey (1957) described an extensive study in which 300 standard Proctor tests were conducted on samples obtained from different locations and depths from a borrow source that was reported to be composed of "highly uniform material". The average value of MDD for the tests was 117.2 pcf with a range of values from 110 to 126 pcf and a <u>standard deviation of 2 pcf</u>. After this material was placed and compacted, about 1,500 field density tests were conducted. It was reported that tests taken only inches apart often yielded <u>variations in dry density values of 2 to 3 pcf</u>. Greater variability was observed for more widely separated points.

These controlled studies indicate that any single Proctor test is likely no more accurate than about ± 2 to 4 pcf from the *true* value.

Another potential problem with the Proctor method occurs when testing some high plasticity A-7 soils that are sensitive to small changes in water content. To explore the impacts of this potential sensitivity in greater detail, test results for A-7-5 and A-7-6 soils were extracted from the MDT projects examined in this study. The standard Proctor MDD and w_{opt} were used to calculate the air voids content using the measured value of G_s for each sample. As can be observed in Figure 32, there is considerable scatter of the results. One hypothesis to explain the highly variable results for A-7 soils is that compaction curves generated using the Proctor procedure on highly plastic clayey material can be quite irregular, as shown in Figure 33. This plot was generated using standard Proctor compaction test data from MDT project number F 86(17). As illustrated in the compaction plot, obtaining accurate values of MDD and w_{opt} for this type of material is difficult unless numerous (8 to 10) Proctor compaction points are generated at closely spaced water content intervals. Also, it is important to allow sufficient soak time for these samples to absorb added water prior to testing. It is the author's contention that for these types of materials, controlling compaction water content in the field is more critical than obtaining a specific density or air voids content. Consequently, the air voids method is not recommended for these soils because of the lack of control on water content.

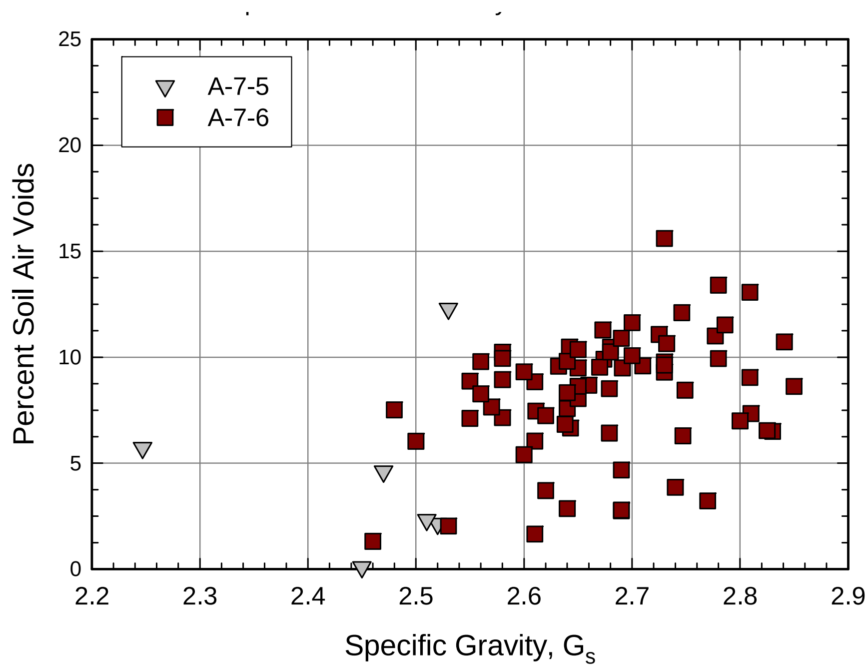


FIGURE 32. Air void content for A-7 soils at optimum standard Proctor values.

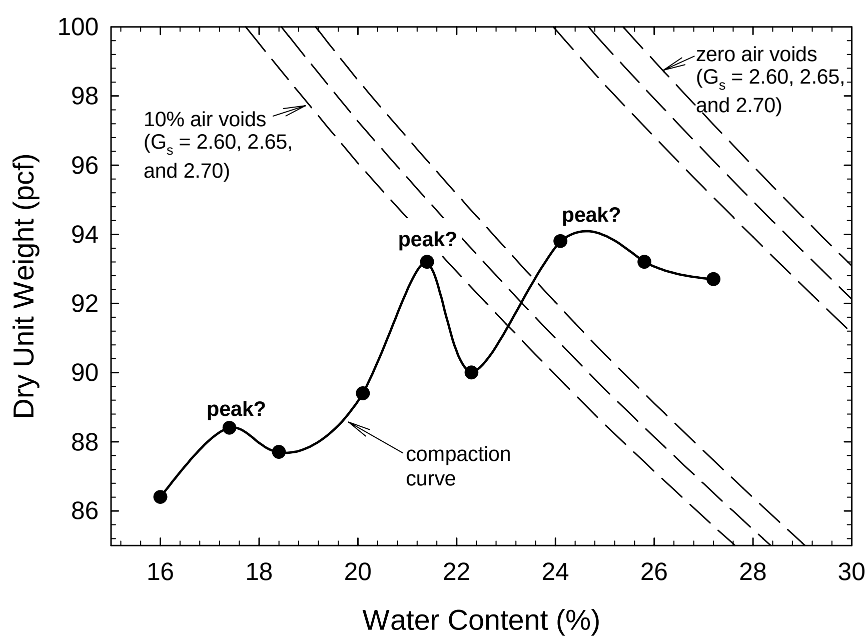


FIGURE 33. Example of an irregular compaction curve for A-7-6(20) soil.

4.5. Evaluation of Field Data

Test results obtained from the 24 projects listed in Table 19 were examined to compare measured values of compaction based on the conventional Proctor approach to computed values of N_a, over the large sample of data. Pertinent information from these projects is summarized statistically in Table 20 in terms of G_s, standard Proctor maximum dry density (MDD), and N_a.

The large data set represented in Table 20 is plotted in Figure 34 in terms of specific gravity, 95% maximum dry density, and optimum water content. These values are plotted versus percent air voids computed at 95% of the MDD. To accurately calculate air voids content (N_a), measured values of G_s, w, and MDD are necessary. The calculated values of N_a shown in Figure 34 are based on measured values of G_s for soil compacted to 95% of the standard Proctor MDD, at optimum water content (w_{opt}). The MDT projects examined in this study contained 570 sets of tests in which these calculations could be performed.

At 95% of MDD, the average value of N_a was 9.64% with a standard deviation of 2.60. This average value is relatively close to the commonly used criteria of 10% air voids. However, as can be seen in Figure 34b, there is considerable scatter of individual data points. Data points that lie below the horizontal line at 10% N_a represent tests that would have passed using either the 10% air voids criteria or the conventional Proctor approach. Data points above the 10% air voids line would have failed the 10% air voids check, but would be considered passing based on a typical criteria of 95% of the standard Proctor maximum dry density.

Another way to examine this relationship is through the cumulative frequency distribution shown in Figure 35. As shown in Figure 35a, the data is almost normally distributed about the average value of 9.64%.

In Figure 35b, the same data set is reconfigured in terms of percent compaction at 10% air voids. The average percent compaction at 10% air voids was 94.7% with a standard deviation of 2.96%. An important point to note in this plot is that 60.9% of the data points fell below a value of 95% relative compaction. In terms of field compaction control, this means that if compaction acceptance criteria for these projects was based on the 10% air voids method, it is possible that over 50% of the compacted soil could have passed the 10% air voids test at a value of relative compaction that was less than 95% of the standard Proctor maximum dry density.

TABLE 20. Soil Survey Statistical Data

No.[a]	MDT Project No.	Specific Gravity, G_s				Max. Dry Density, MDD (pcf)				Avg. N_a at 0.95 x MDD[b]
		Avg.	Std. Dev.	COV	Count	Avg.	Std. Dev.	COV	Count	
1	NH57-5(25)220	2.710	.0610	.0225	36	114.95	7.30	.0636	25	9.39
2	STPP23-3(6)130	2.776	.0282	.0101	19	104.90	5.03	.0480	6	11.54
3	F62-2(9)21	2.653	.0869	.0328	86	113.00	13.99	.1238	24	8.82
4	F23-1(15)33PE	2.660	.053	.0199	81	112.24	4.713	.042	22	9.254
5	STPP51-3(2)60PE	2.735	.053	.0193	120	118.55	8.595	.0725	46	11.106
6	STPS233-1(7)22PE	2.658	.046	.0174	106	110.09	4.06	.0369	75	10.38
7	STPS225-1(1)0 PE	2.625	.044	.0168	76	104.59	8.45	.0808	80	9.36
8	STPP3-2(27)28 PE	2.656	.054	.0203	75	112.34	7.96	.0708	80	9.71
9	IM90-7(79)369	2.711	.051	.0187	62	--	--	--	--	--
10	STPP14-3(17)77	2.668	.036	.0136	29	114.41	11.84	.1035	14	16.18
11	IM94-1(67)36	2.623	.024	.0092	56	126.71	9.44	.0745	24	7.57
12	IM90-9(95)517	2.629	.049	.0185	66	117.25	10.91	.0931	14	8.00
13	IM90-9(94)473	2.665	.015	.0056	2	117.78	8.26	.0702	12	9.14
14	IM90-9(96)509	2.694	.016	.0058	9	116.69	13.79	.1182	36	9.75
15	IM94-1(66)24	2.714	.022	.0081	28	127.34	12.61	.0990	34	7.51
16	IM90-8(146)427	2.730	.023	.0084	48	132.21	13.54	.1024	30	8.92
17	NH57-2922)47	2.694	.012	.0044	39	128.93	11.81	.0916	15	10.16
18	STPHS227-1(10)2PE	2.594	.026	.0099	16	110.66	8.49	.0767	18	7.67
19	STPU5299(51)/STP	2.629	.061	.0231	36	108.59	7.77	.0715	42	9.99
20	NH1-3(40)247	2.674	.026	.0096	17	117.99	10.51	.0890	19	9.01
21	NH1-7(35)398PE	2.645	.052	.0198	18	112.88	6.84	.0606	19	10.42
22	BR9-2(9)47PE	2.647	.023	.0089	17	124.06	6.44	.0519	17	7.38
23	NH24-3(25)76PE	2.625	.075	.0286	8	120.69	6.48	.0537	17	10.42
24	NH1-3(36)234 FPE	2.650	.020	.0075	7	121.89	10.22	.0839	12	8.68

[a]Refer to Table 19 for specific project details.
[b]N_a computed using measured values of G_s, w_{opt}, and 0.95MDD.
COV = Coefficient of variation.
MDD = Standard Proctor maximum dry density (unit weight).
N_a = Percent air voids.
Count = Number of samples used in statistical analysis.

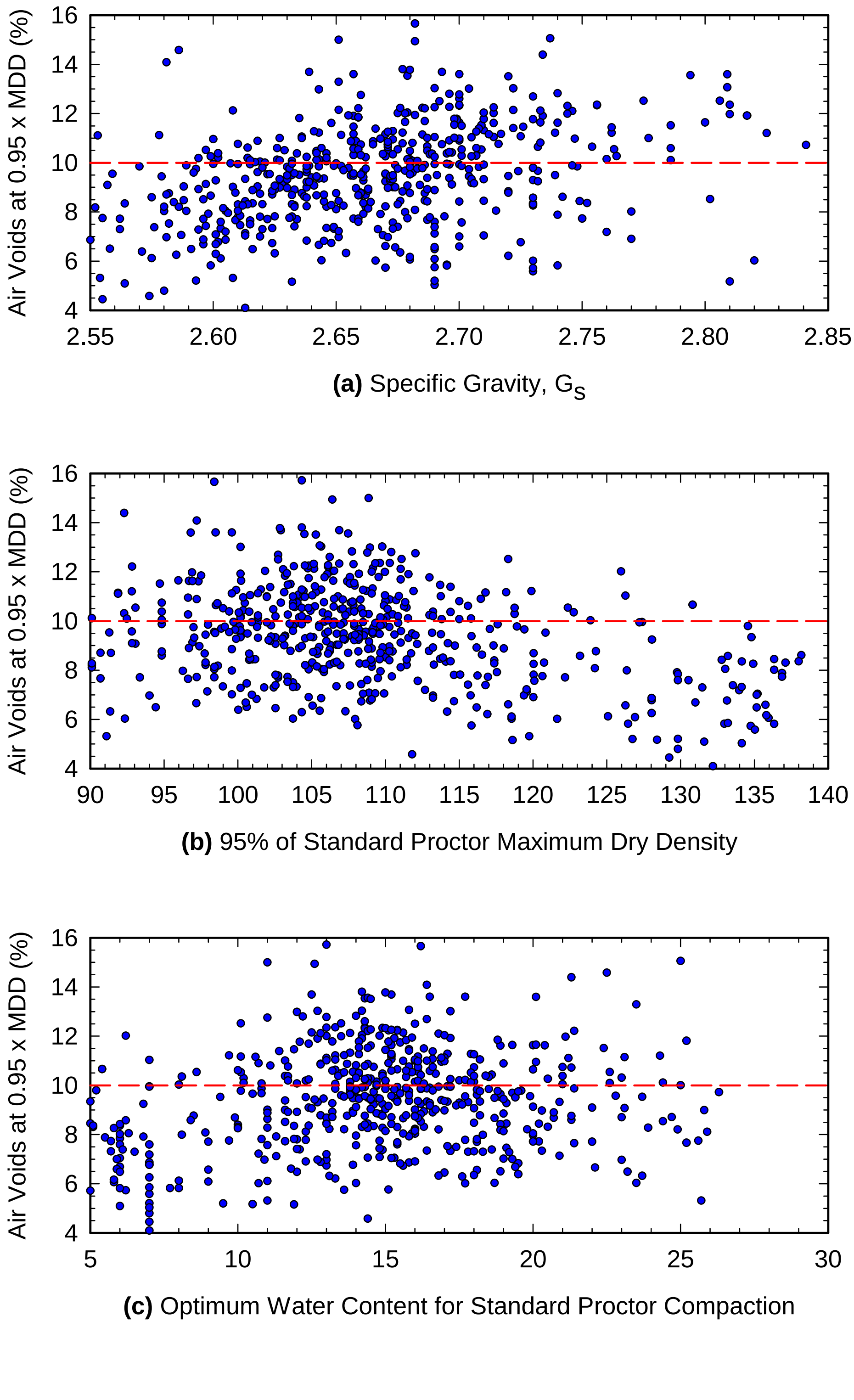
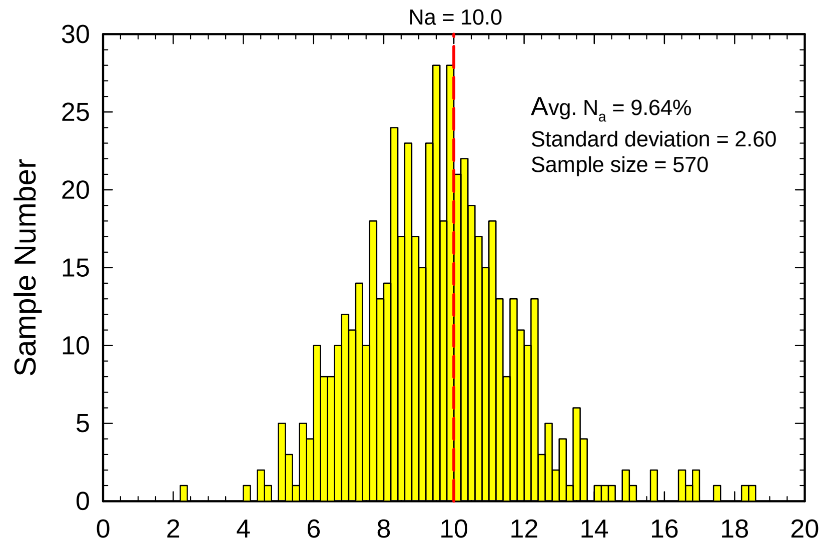
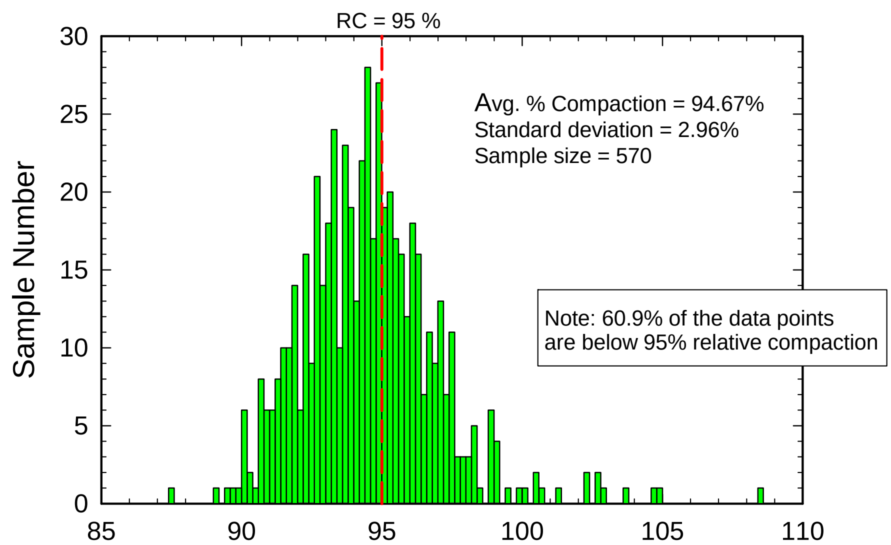


FIGURE 34. Variation of air voids on 24 MDT projects in terms of: a) G_s, b) MDD, and c) w_{opt}.



(a) Air Voids at 95% of MDD, N_a (%)



(b) Percent Relative Compaction at 10% Air Voids

FIGURE 35. Cumulative frequency distribution diagrams for MDT project data.

To further examine this potentially undesirable trend, air voids values at 95% of MDD were computed for the soils tested in each of the projects listed in Table 20. As shown in Figure 36, on a project-by-project basis, the average value of N_a at 95% of MDD falls below 10% for 16 out of 23 projects (project No. 9 did not contain sufficient data for computational purposes). If these 16 projects were controlled using the 95% relative compaction criteria, the soils (on average) would have air voids values less than 10%. However, if the 10% air void criteria was used as the compaction control metric, it would be possible that the average value of relative compaction could be less than 95% of the standard Proctor MDD for 16 of these projects. The average N_a of four of the projects (No. 11, 15, 18, and 22) fell below 8% air voids at 95% relative compaction. The author of this study suggests that if the air voids method is used to control compaction on projects that exhibit similar trends, a different value of air voids (a value less than 10%) should be used as the acceptance/failure criteria. This decision could be made during the soil survey. It is important that a sufficient number of specific gravity and Proctor compaction tests are conducted, and the results evaluated using an approach similar to that described in this report. Based on the complete data set from the 24 MDT projects, at 95% relative compaction, 24% of the computed N_a values were less than 8% N_a, and 12% of the computed N_a values were greater than 12% N_a.

Project No. 10 had a disproportionately high value of average air voids (about 16%) at 95% of the standard Proctor MDD. Close examination of the soil parameters and test results for this project did not provide any conclusive geotechnical reasons to explain this apparent anomaly. If the 10% air voids method was used for compaction control on this project, the soils were likely compacted to values of relative compaction greater than 95% of the standard Proctor MDD. The author recommends that the air voids method of compaction control should not be used on projects that exhibit anomalous behavior such as shown in this example. This further supports the conclusion that the air voids method of compaction control should not be used on a project unless the relationship between air voids and percent relative compaction is carefully examined during design using measured soil parameters.

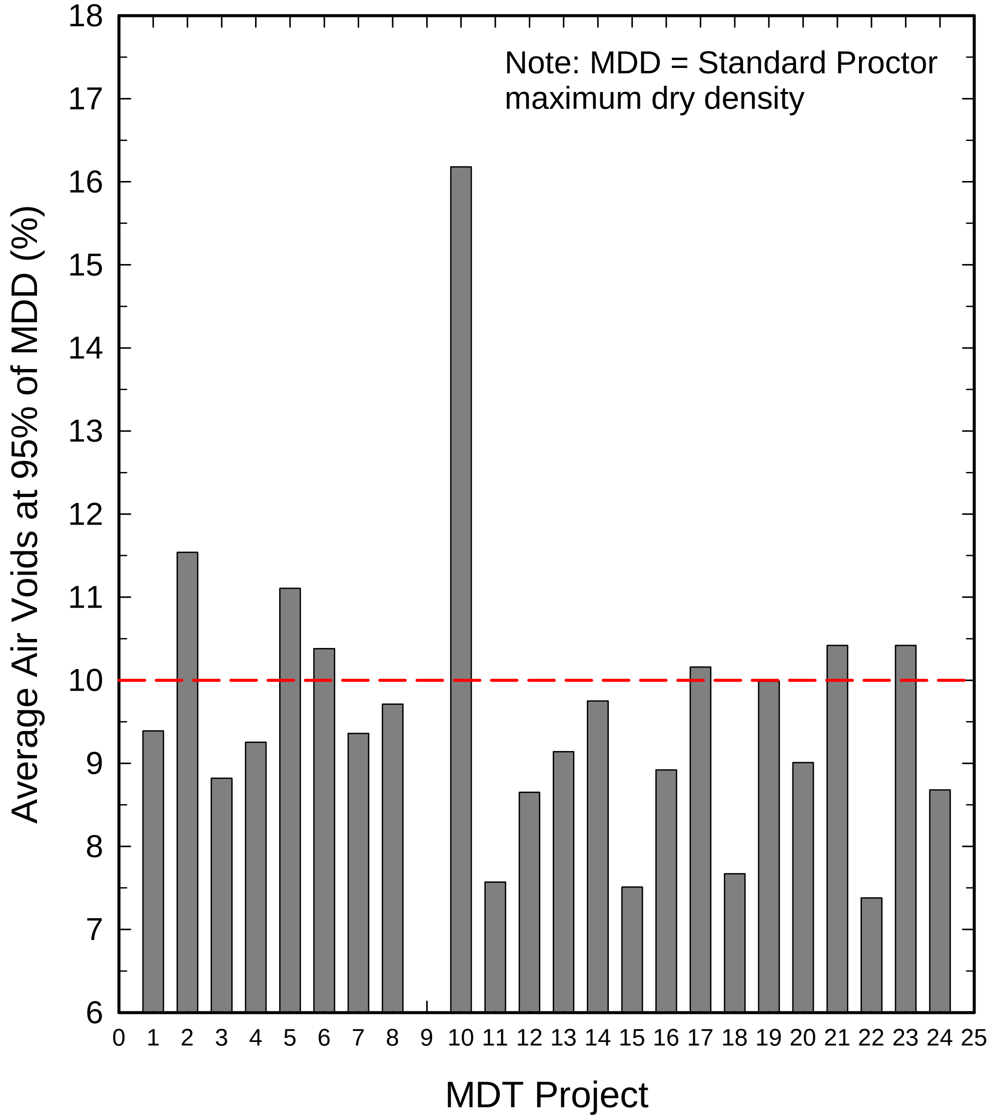


FIGURE 36. Average air voids for MDT projects at 95% of standard Proctor MDD.

4.6. Relationship Between the Compaction Curve and Air Voids Line

For the majority of soils examined in this study, the 10% air voids line crossed the Proctor compaction curve on the dry side (left side) of the optimum water content. An example typical of this behavior is shown in Figure 37 for soil No. 3 (A-2-7).

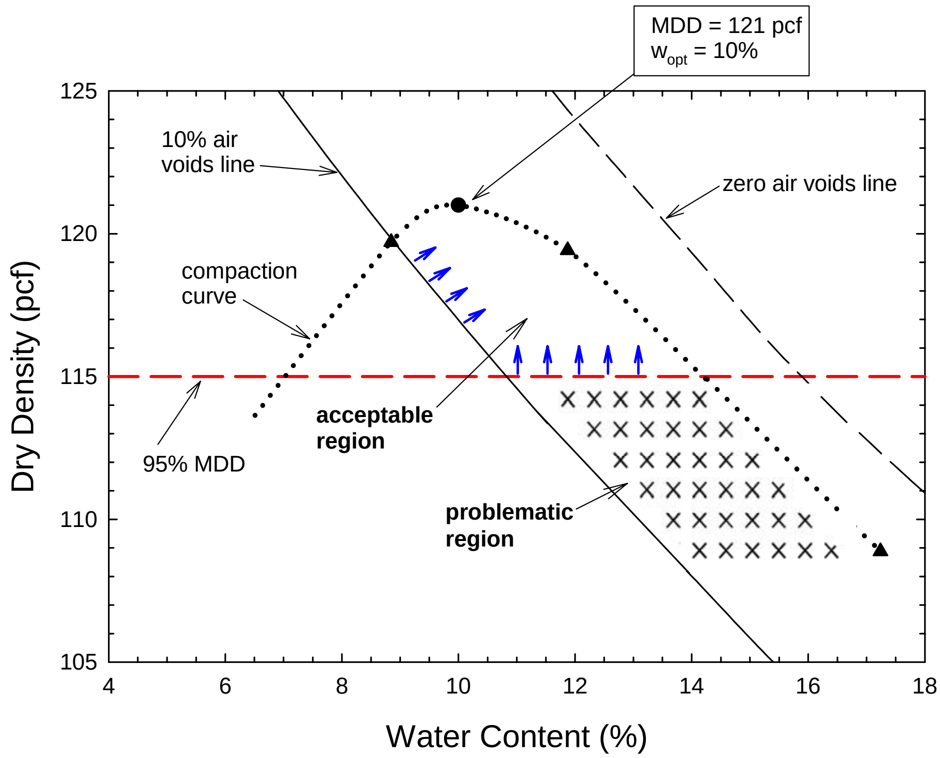


FIGURE 37. Standard Proctor compaction curve for soil No. 3: A-2-7(1).

For the example shown in Figure 37, a field-measured data point that plots in the "acceptable region" would be evaluated as a passing test for both the air voids and Proctor methods of compaction control. This would be considered an ideal scenario in regards to achieving a suitable density and air voids content. However, as observed in Section 1.3 of this report, it is possible to reduce the soil air voids to relatively low values simply by increasing the soil water content (Parsons 1992, Johnson and Sallberg 1960, Lewis 1954). The cross-hatched zone in Figure 37 identified as the "problematic region" exemplifies this primary shortcoming in the air voids method. A field-measured data point that plots in the problematic region would indicate the material is poorly compacted and excessively wet. Obviously, this would be an unfavorable condition for a subgrade or fill. The field test would clearly fail if the Proctor relative compaction test was used to evaluate the material; however, a passing result would be obtained if the air voids criterion was used.

Another potential problem with the relationship between the compaction curve and the air voids line is illustrated in Figure 38, for soil No. 7. The typical acceptable region based on Proctor criteria is shown in the figure. For this material, which was compacted using a higher energy for this example (modified Proctor), the entire acceptable Proctor region is located on the left side of the 10% air voids line. In this case there is a definite discontinuity between the air voids and Proctor methods. A sample that passed the air voids test would contain excessive water based on the conventional Proctor approach. This is an example of a material that would not be suitable for the 10% air voids method because of the potential for problems if the soil is compacted at an excessively high water content.

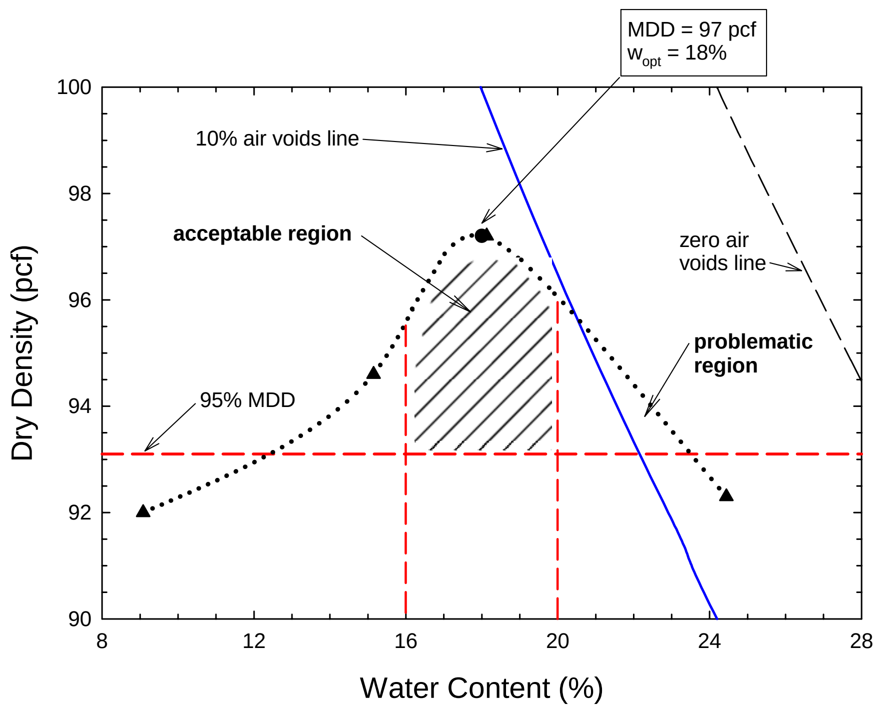


FIGURE 38. Modified Proctor compaction curve for soil No. 7: A-7-5(10).

In this case, the soil could easily pass the air voids test by adding water, which would decrease the bearing capacity of the soil and increase the potential for excessive settlement and shrink/swell problems. This issue can only be addressed in a controlled manner by placing an upper allowable limit on the compaction water content. It is this author's opinion that for these types of soils, reliance upon inherent controls of moisture during construction is too subjective of an approach on large earthwork projects, particularly if the inspector is not highly trained and experienced.

5. RESULTS AND RECOMMENDATIONS

5.1. Summary of Results

This research project was structured to evaluate the air voids method as a means of assessing the quality of a compacted layer of soil. An extensive literature review was conducted to examine existing published information on the air voids method and to explore how extensively others have used the method. Laboratory testing was conducted to gather information for a variety of soils and to identify potentially suitable and potentially problematic soil types. The laboratory testing program included sieve analyses, hydrometer, Atterberg limits, relative density, specific gravity and impact compaction tests. Information from MDT projects was gathered and evaluated to examine the suitability of approximate empirical approaches for estimating the optimum water content and maximum dry density of soils. MDT project data from 24 soil survey reports was collected, categorized, and reviewed to statistically examine trends in regards to compaction parameters and the use of the air voids method.

Following is a brief overview of the findings in this report:

1. The earliest reported information on the air voids method was located in a 1942 publication by the Journal of Highway Research (Allen 1942) in which an expression for air voids is derived and an approach for using this method in the field is first introduced.
2. The majority of published literature uncovered in this study focused on the shortcomings of the method, which include:
    - Air voids can be reduced by simply increasing the water content.
    - Incorrect conclusions could be made in the field if the in-place specific gravity is substantially different than the specific gravity used to develop the air voids line.
    - Not all materials can readily be compacted to 10% or less air voids.
    - A limiting range of acceptable compaction water contents should be specified if the air voids method is to be used for construction control.
3. Based on a survey sent to materials personnel in all 50 states and to geotechnical professors throughout North America, it appears the method currently is not used by any other agencies in the United States.
4. Laboratory testing was conducted on soil samples covering the majority of the AASHTO subgroups with the exception of A-2-5 and A-5 materials. These materials are not commonly encountered in Montana; consequently, they were not included in this research.
5. An approach called the Paez method was examined as a mean of eliminating subjectivity in the evaluation of Proctor compaction data points. It was determined that the Paez method may be useful as a check, but it is not accurate enough to replace manual determination of the optimum values of the compaction curve.
6. Three approximate empirical methods by Pandian et al. (1997), Al-Khafaji (1993), and Omar et al. (2003) were examined for estimating the optimum water content

and the maximum dry density, in lieu of Proctor compaction testing. These methods use basic index properties including Atterberg limits, particle size distribution, and specific gravity. The methods were examined using results from laboratory tests and MDT project data. It was determined in this study that the current formulations of these methods are not accurate enough for earthwork quality control on Montana soils.

7. The Pandian method may have future potential if it is further augmented (calibrated) using Montana soils to refine the soil constants. This may provide estimates that are more suitable for soils typically encountered in Montana.

8. A series of cooperative specific gravity test were conducted using five MDT laboratories and the MSU geotechnical soil laboratory. Results from this comparative laboratory study indicate that the average specific gravity for the nine soil types used in the study ranged from 2.60 to 2.74, and the standard deviation ranged from 0.28 to 0.84. The average value for G_s was 2.65 with a standard deviation of 0.061 and a coefficient of variation of 0.023. Based on data from 24 MDT projects, which included 995 specific gravity tests, the average value of specific gravity was 2.67 with a standard deviation of 0.065, and a coefficient of variation of 0.024. The variation in the standard Proctor maximum dry density was considerably greater (COV = 0.103). Based on this extensive study of specific gravity and Proctor test results, the following observations are made:

   - Within a project, the variation in specific gravity will likely be less than the variation of Proctor maximum dry density, on a relative basis.
   - The specific gravity for a typical Montana soil will most frequently occur within a range of about 2.60 to 2.73.
   - The accuracy of any specific gravity measurement is likely no better than about ± 0.06.
   - In a normal project situation, it is expected that the deviation from a *true* value could easily exceed 0.06.
   - The air voids line is not highly sensitive to small errors in the specific gravity. For example, for a variation in G_s of 0.06, the change in dry density would be less than 2 pcf. This translates to an error of only ± 1 to 1.5% in the calculation of air voids.

9. Based on previous studies conducted to evaluate the accuracy of Proctor compaction tests, it appears the reliability of any single Proctor maximum dry density value is about 2 to 4 pcf, at best.

10. Using test results reported in 24 MDT soil survey reports, it was determined that over 50% of the soils tested in these projects would have a density less than 95% of the standard Proctor maximum dry density if they were compacted to exactly 10% air voids.

11. A primary shortcoming of the air voids method is that low air voids can be achieved for nearly any soil type by simply increasing the water content. Inherent field water content limitations may be effective for many soil types; however, this

approach is subjective and requires adequate enforcement language in the earthwork specifications to minimize potential conflicts in the field. It is suggested that provisions be provided in the specifications for the inspector to order a Proctor test on any questionable material (i.e., excessively wet or pumping), and to use these results for assessment purposes.

12. Some materials may pass the air voids test, but fail the conventional Proctor criteria. These soils can be identified in the laboratory if Proctor and specific gravity tests are conducted and analyzed by developing plots similar to those shown in this report.
13. The air voids method should not be used on poorly graded granular soils (USCS classification SP and GP) because these soils may contain large void spaces; and consequently, they may not provide consistent results using the air voids method.
14. Plastic clayey soils require tight controls on compaction moisture content to minimize future problems with settlement, shrinkage upon drying, and swell during periods of hydration. The air voids method of compaction control is not suitable for these soil types (USCS classification CH and MH).
15. Silty soil and soil with high contents of fine sand are frost susceptible. The potential for frost heave and thaw weakening problems is greatly increased if these soils are not adequately compacted. High compaction water contents and low densities (as could theoretically be achieved with improper use of the air voids method) should be avoided when working with frost susceptible soils, which generally fall in the USCS classification of ML or SM.

5.2. Conclusions and Recommendations

The primary advantage of the air voids method is that it provides a relatively simple and time saving method to evaluate field compaction conditions, making it attractive for field quality control. The primary shortcoming of the air voids method is that air voids can be reduced to low values simply by increasing the soil water content.

This research study was structured to evaluate and if possible quantify the potential shortcomings and advantages of the air voids method by conducting specific laboratory tests on a range of soil types and by collecting and evaluating construction and laboratory test data from MDT highway projects.

Proponents of the air voids method point to the practical (inherent) limitations of using excessive water during construction. The inherent limit in this context presupposes that a contractor will not apply excessive water because the soil will become unworkable and will not adequately support construction equipment. In addition, water for construction can be expensive in Montana; consequently, contractors are prone to use water sparingly on most projects.

On the surface this premise appears logical; however, if universally true, why have engineers and inspectors enforced water content limitations for the past ± 60 years using the conventional Proctor approach? Why are no other agencies in the U. S. using this simple and easily implemented approach? The author provides examples in this report of problems that may occur with certain soil types if inherent water content limits are relied upon during compaction.

Most of the problems are associated with plastic clayey soils. Potential problems with these soils include excessive shrink or swell, excessive settlement, and stability problems due to high excess pore water pressures. It is this author's opinion that for these types of soils, reliance upon inherent controls of moisture during construction is too subjective of an approach on earthwork projects, particularly if the inspector is not highly trained and experienced.

In terms of density, it was determined in this study that for most materials the line of optimum compaction values falls approximately midway between the zero air voids line and the 10% air voids line. However, the line of optimums for some materials (A-7 soils in particular) may fall to the left of the 10% air voids line. This seems to indicate that some A-7 materials may not be ideal for use in the air voids method because there may not be a strong correlation between densities achieved using the Proctor impact compaction test and the corresponding air voids content. In other words, it was demonstrated in this study that some materials could pass the air voids test, but fail the conventional Proctor criteria (i.e., 95% of the maximum dry density). This condition can be identified in the laboratory if Proctor and specific gravity tests are conducted and analyzed by developing plots similar to those shown in this report.

The air voids method of compaction control should not be used on a project unless the relationship between air voids and percent relative compaction is carefully established during design, using data from the soil survey report. In addition, the air voids method may not be suitable if tests indicate the specific gravity of materials varies significantly along the project alignment. The statistical analyses conducted during this study indicate a typical standard deviation of specific gravity is about ± 0.065.

The researchers involved with this study recognize the advantages and practicality of the air voids method. However, based on the testing and analyses conducted, it is clear that this method should only be considered applicable on a limited basis. The approach should only be considered on projects that have been thoroughly evaluated during the soil survey study, prior to issuing construction contract documents.

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Appendix A

Compaction Curves

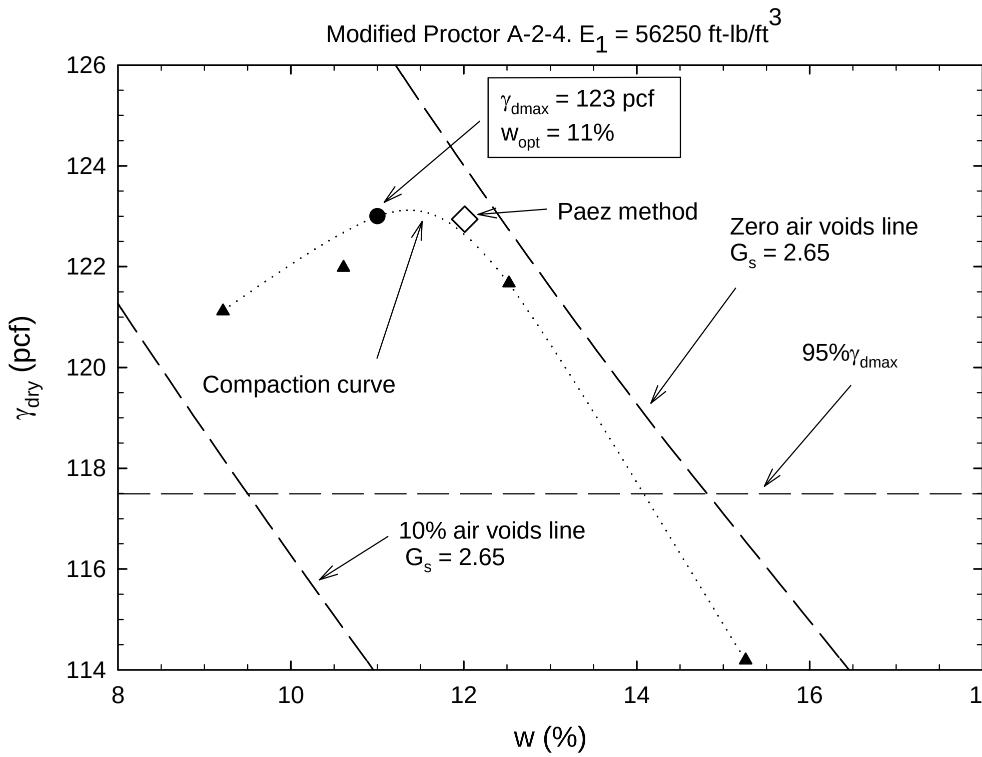

FIGURE A 1. Compaction curve for A-2-4(0), Soil No. 1

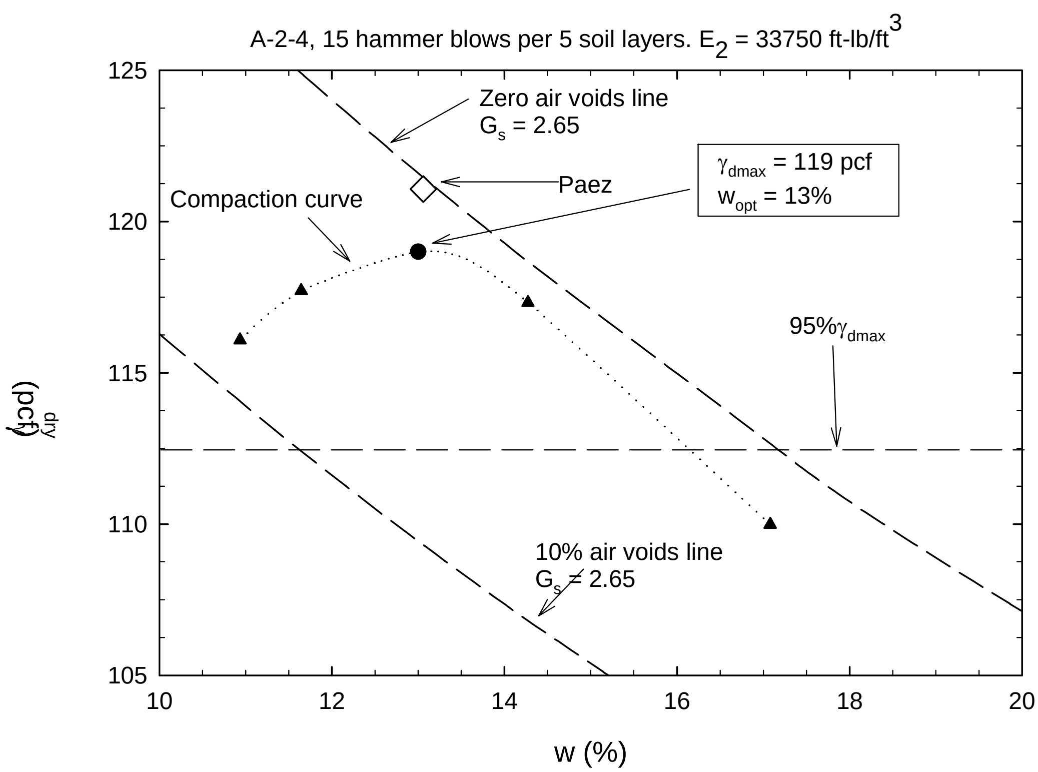

FIGURE A 2. Compaction curve for A-2-4(0), Soil No 1.

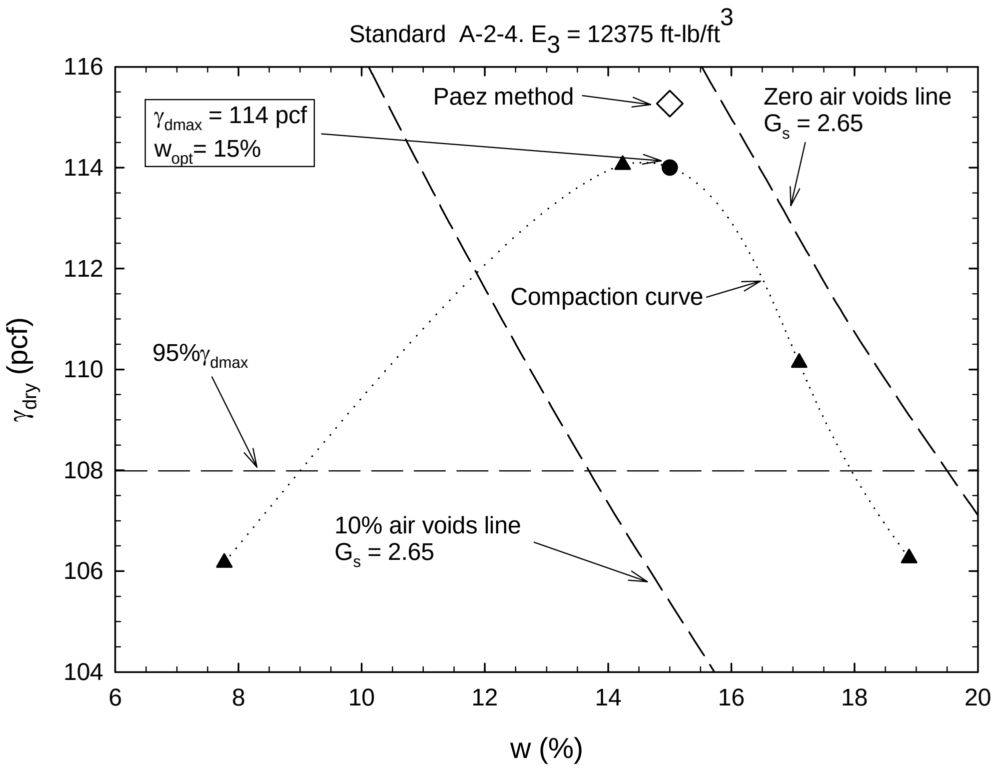

FIGURE A 3. Compaction curve for A-2-4(0), Soil No. 1.

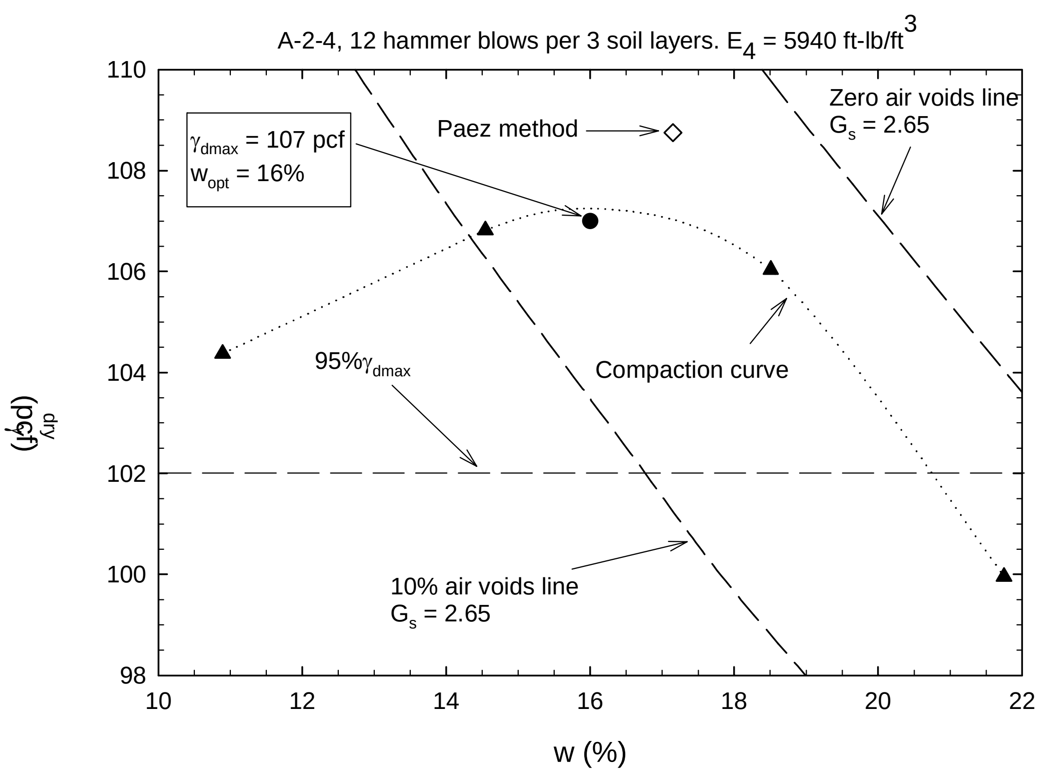

FIGURE A 4. Compaction curve for A-2-4(0), Soil No.1.

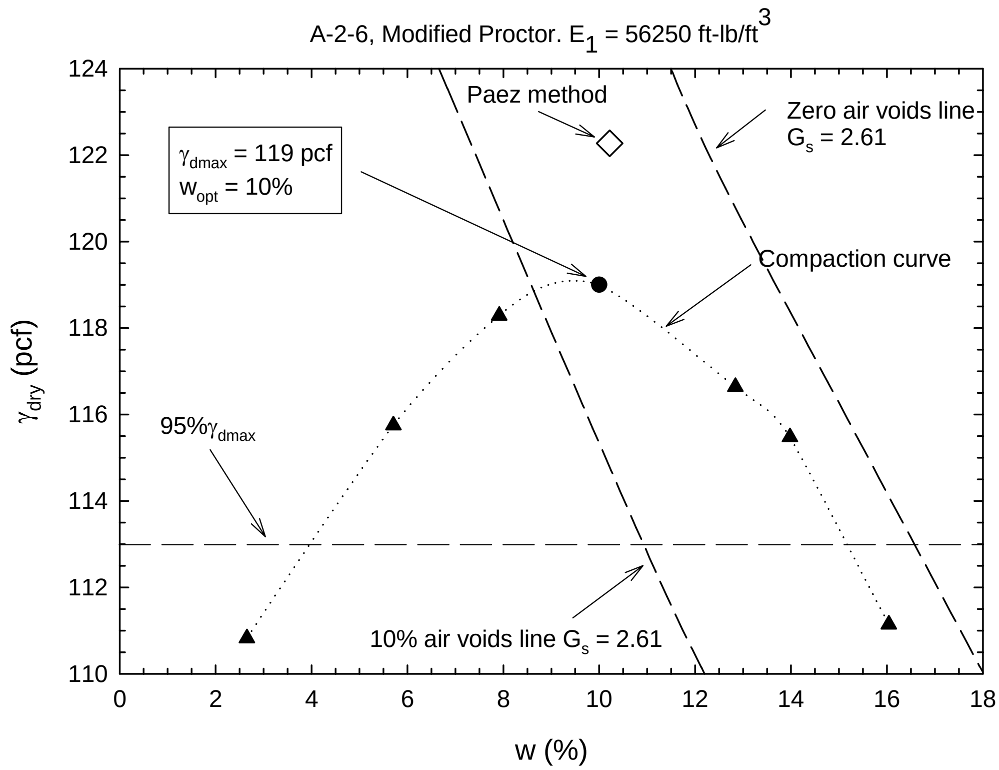

FIGURE A 5. Compaction curve for A-2-6(0), Soil No. 2.

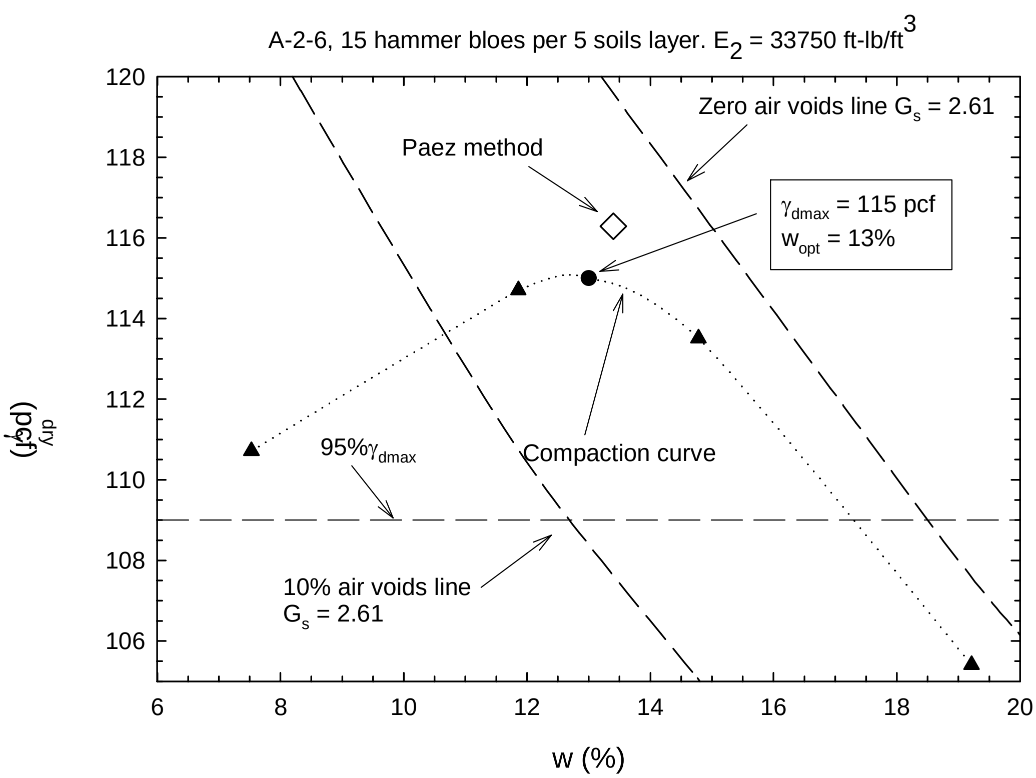

FIGURE A 6. Compaction curve for A-2-6(0), Soil No. 2.

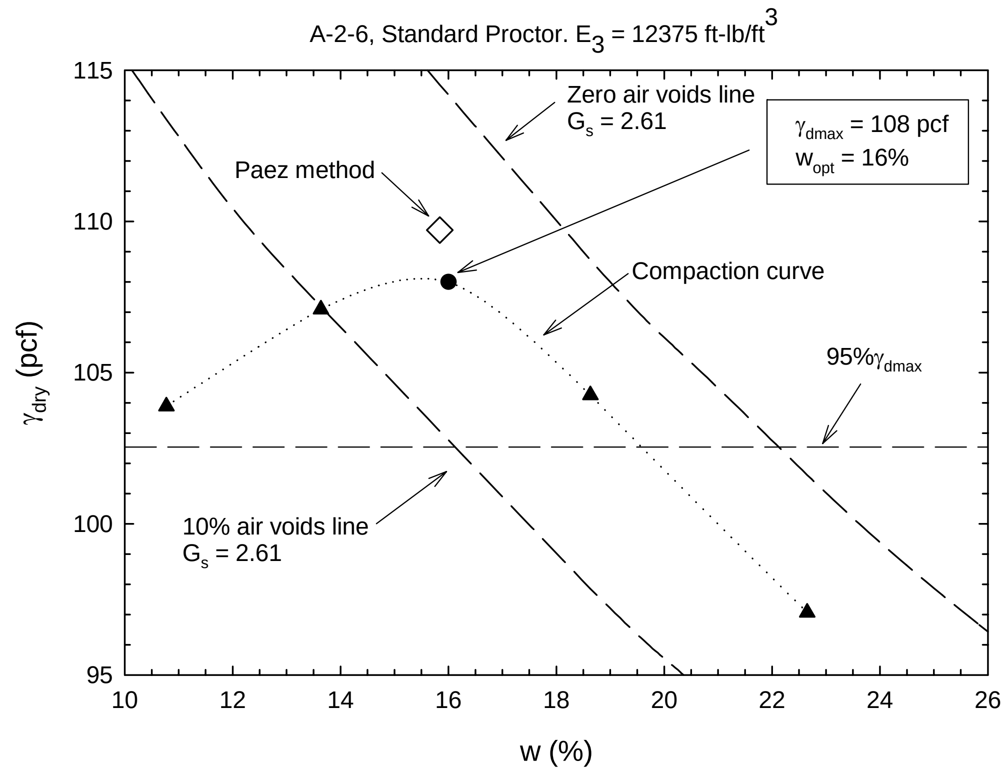

FIGURE A 7. Compaction curve for A-2-6(0), Soil No. 2.

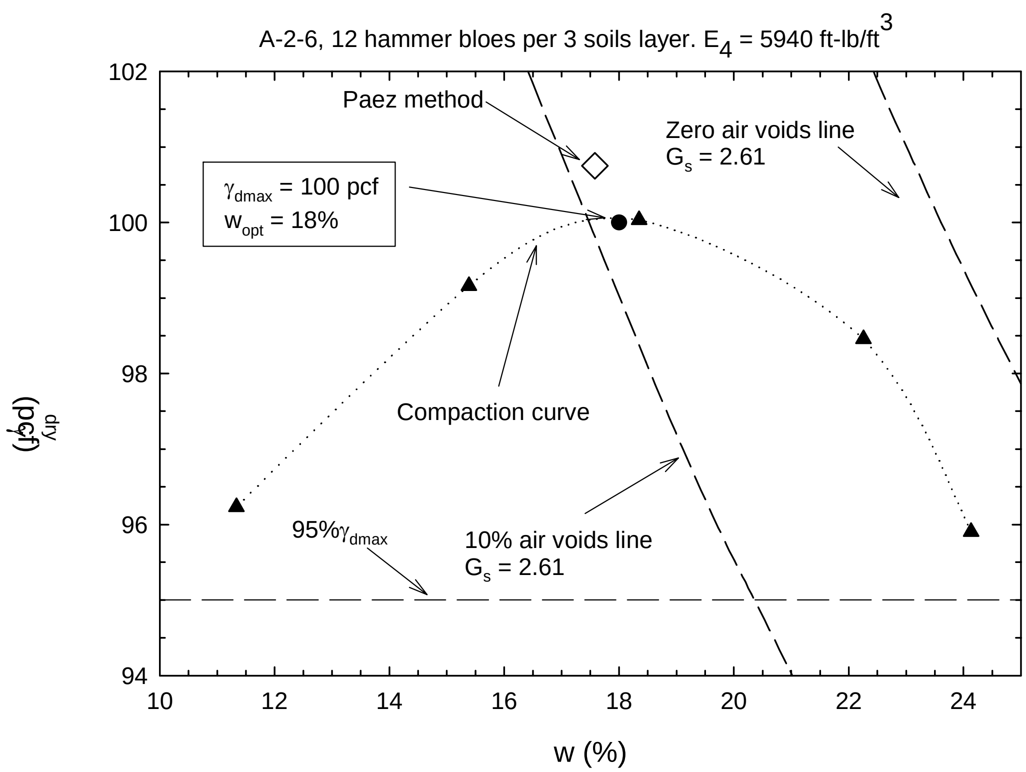

FIGURE A 8. Compaction curve for A-2-6(0), Soil No. 2.

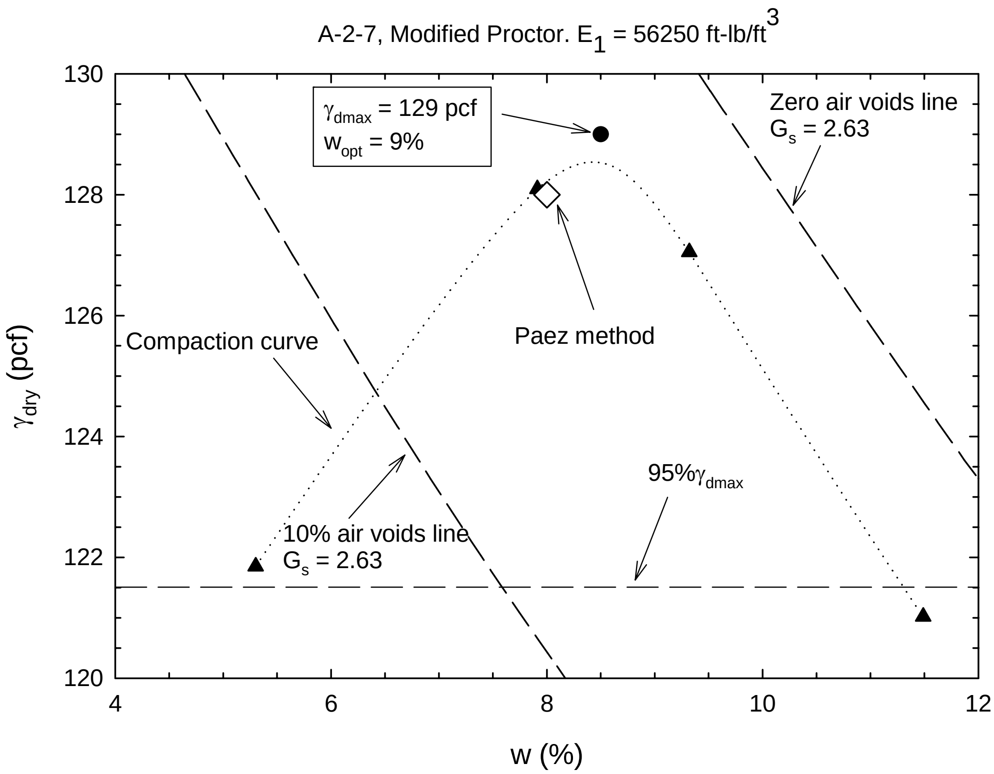

FIGURE A 9. Compaction curve for A-2-7(1), Soil No. 3.

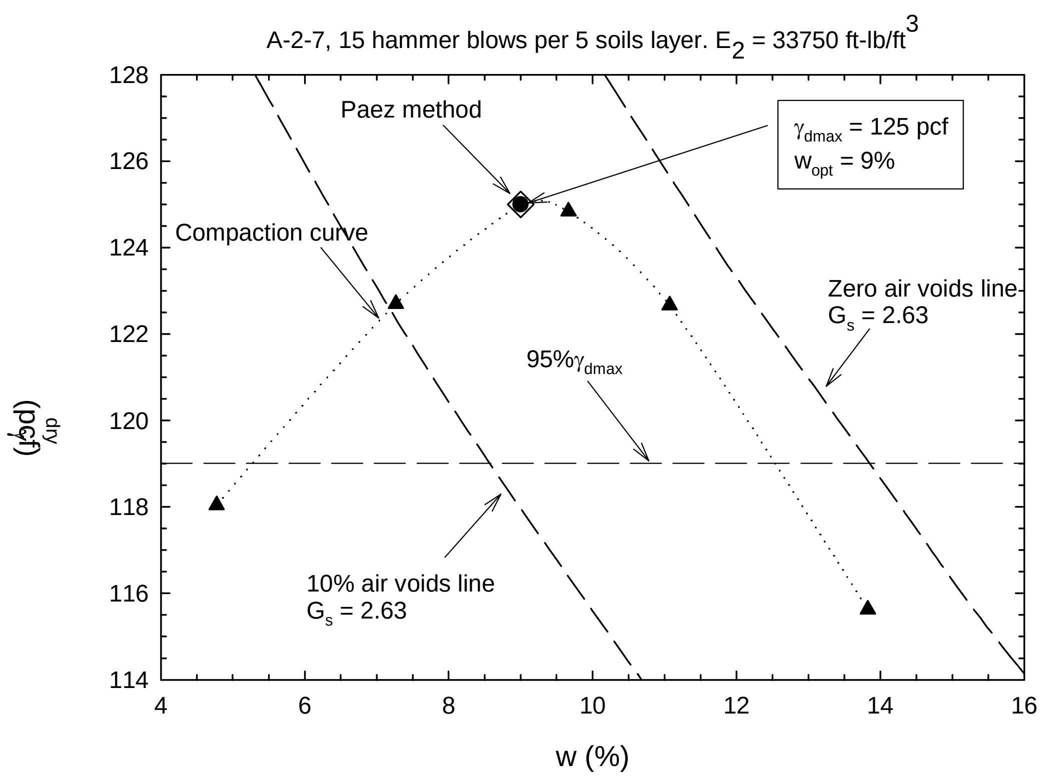

FIGURE A 10. Compaction curve for A-2-7(1), Soil No. 3.

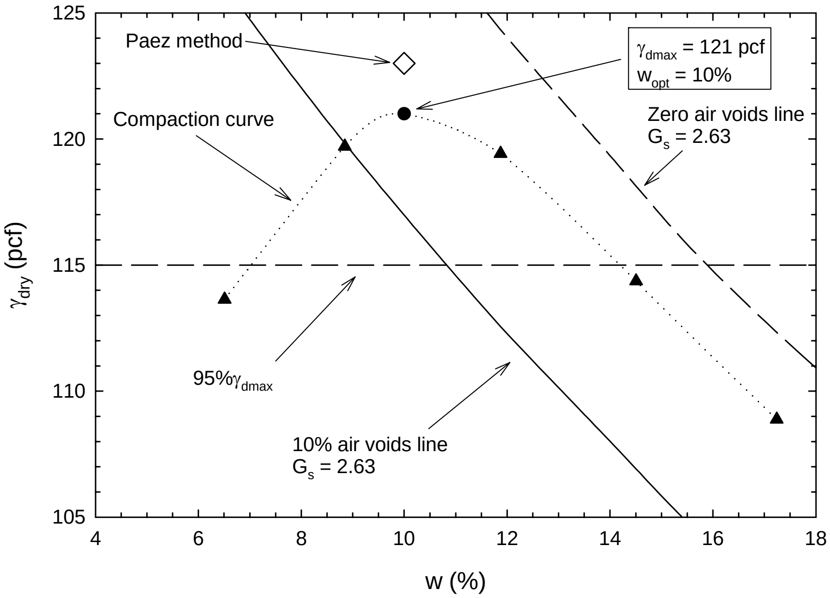

FIGURE A 11. Compaction curve for A-2-7(1), Soil No. 3.

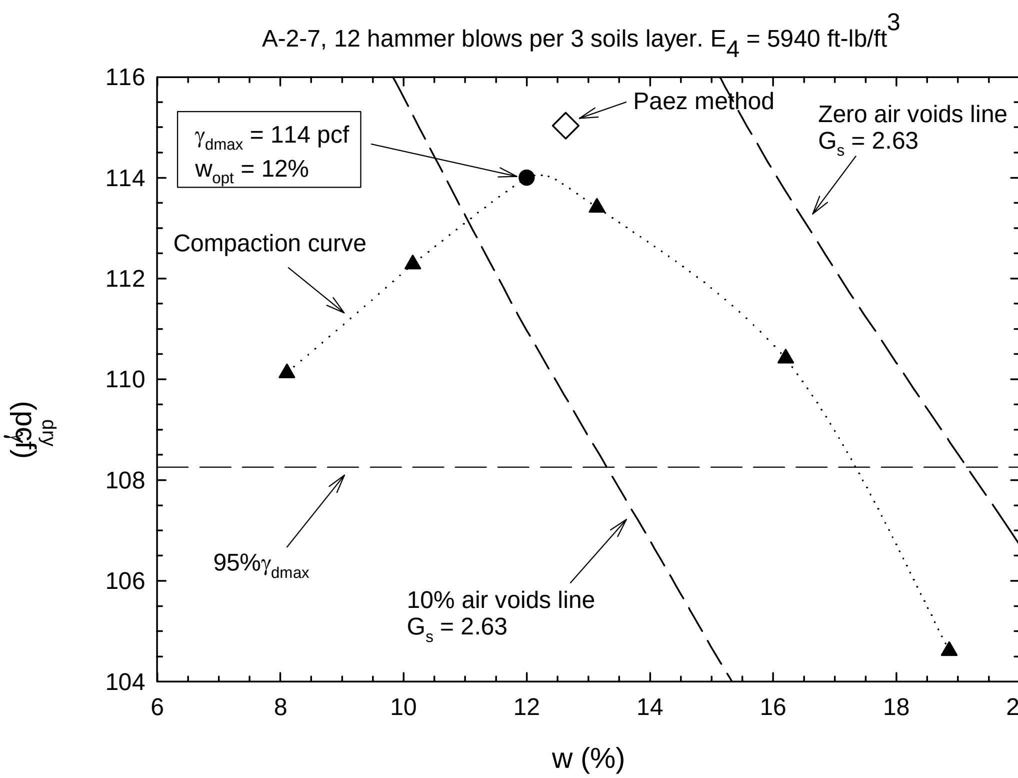

FIGURE A 12. Compaction curve for A-2-7(1), Soil No. 3.

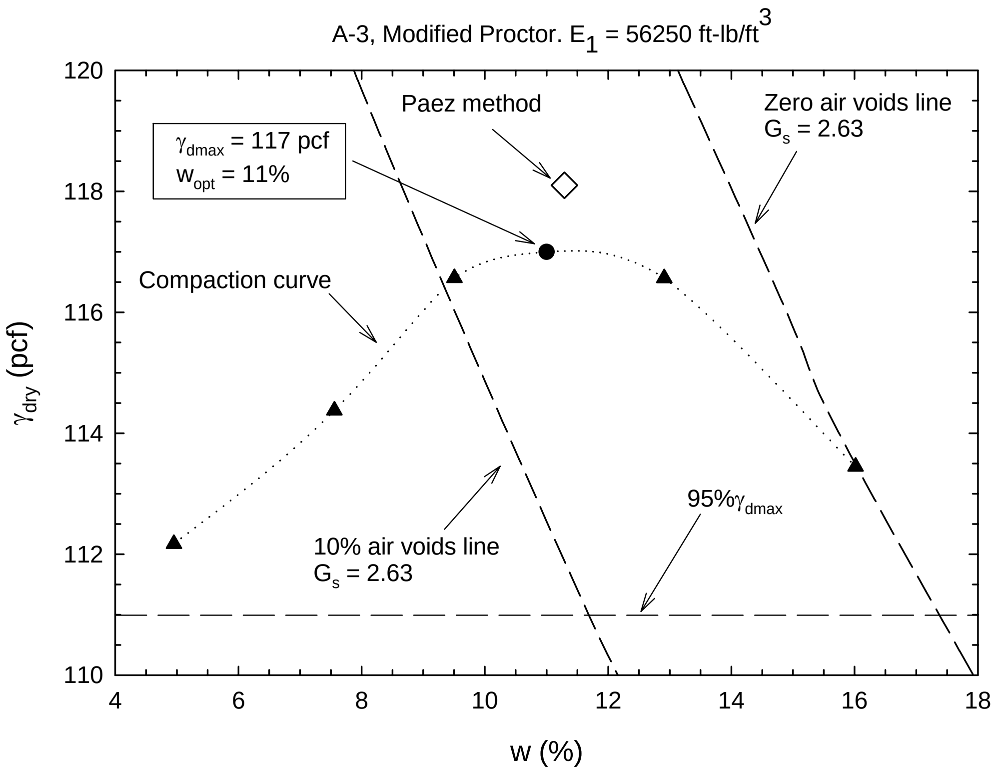

FIGURE A 13. Compaction curve for A-3(0), Soil No. 4.

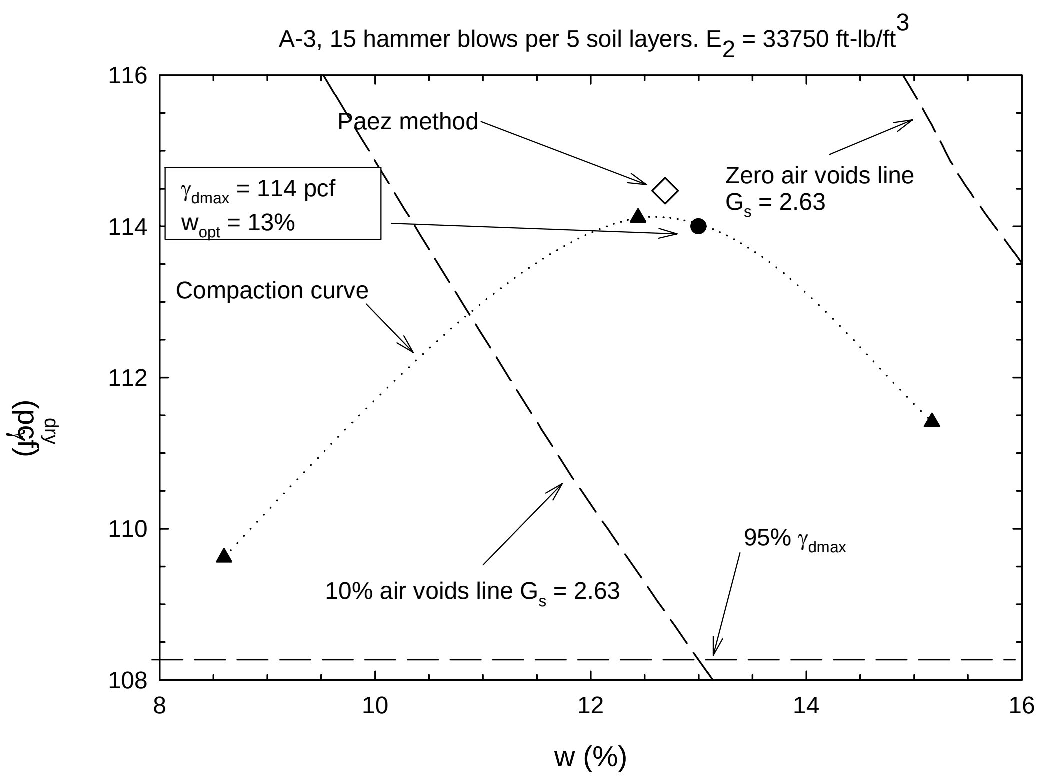

FIGURE A 14. Compaction curve for A-3(0), Soil No 4.

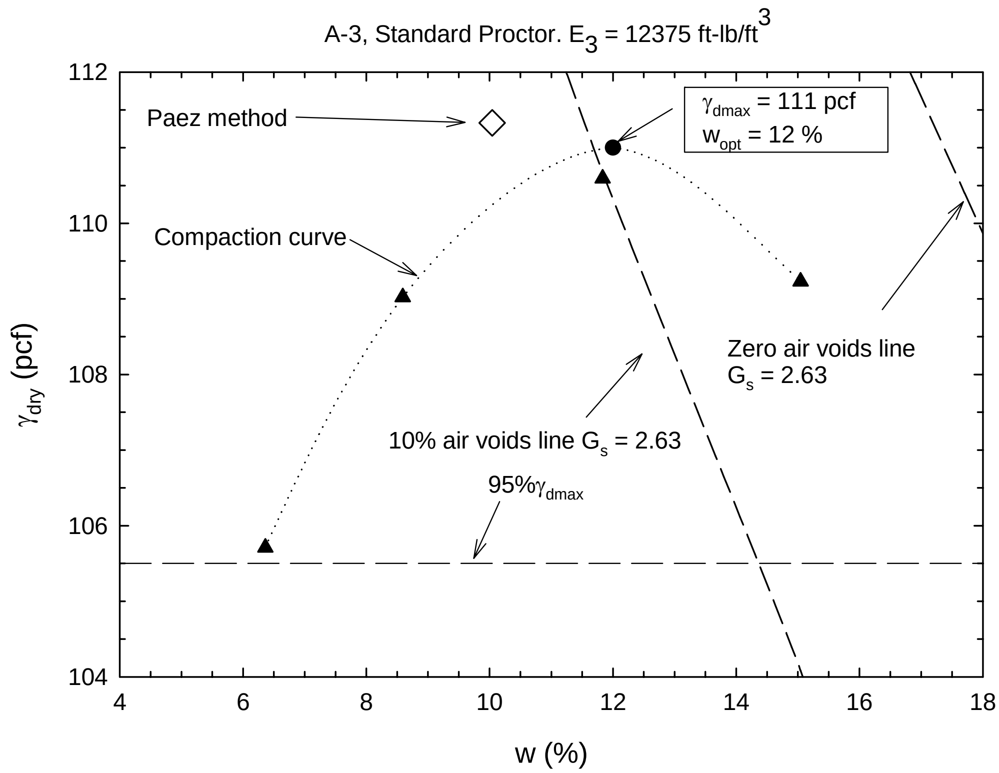

FIGURE A 15. Compaction curve for A-3(0), Soil No. 4.

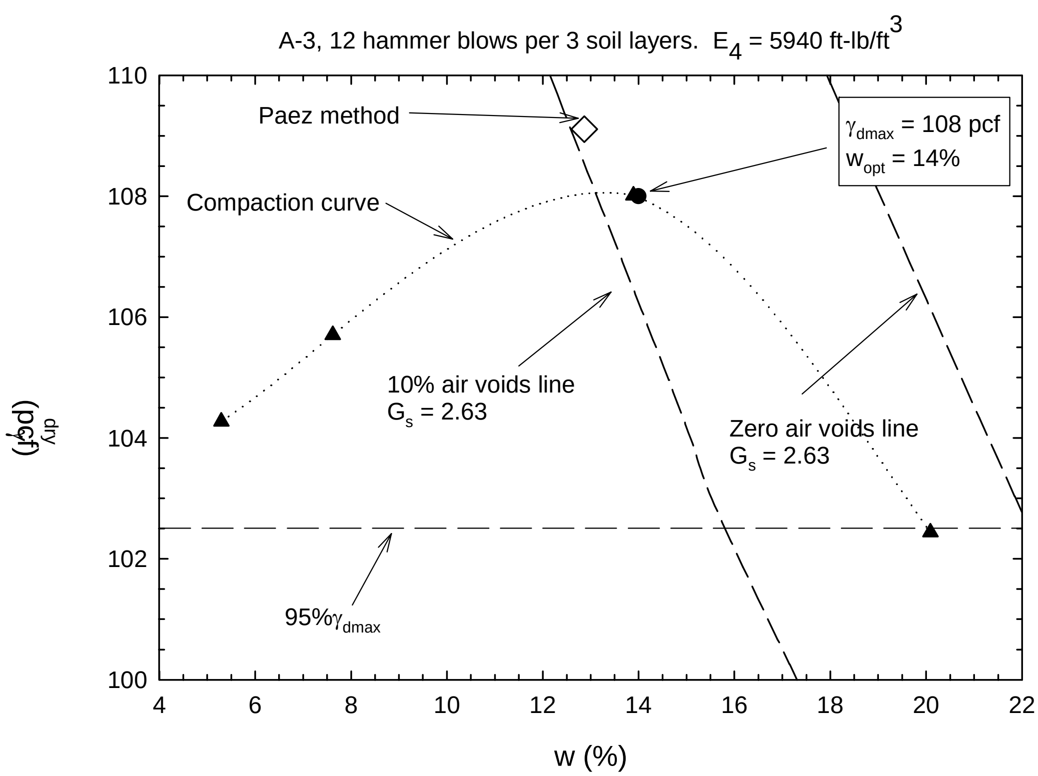

FIGURE A 16. Compaction curve for A-3(0), Soil No. 4.

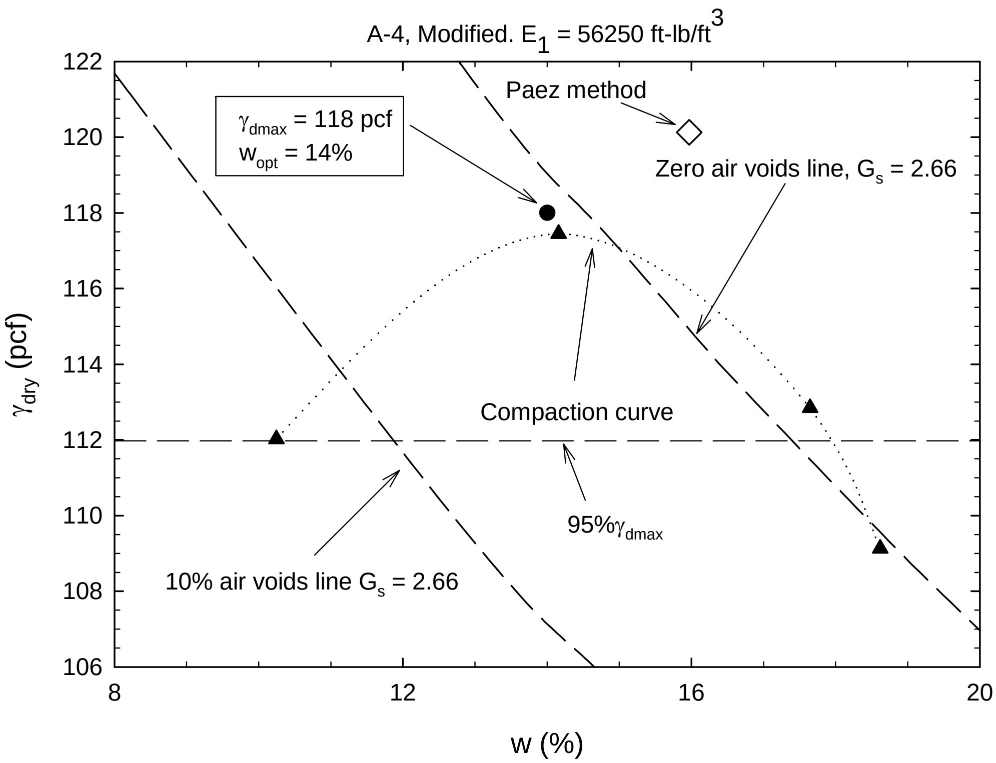

FIGURE A 17. Compaction curve for A-4(8), Soil No. 5.

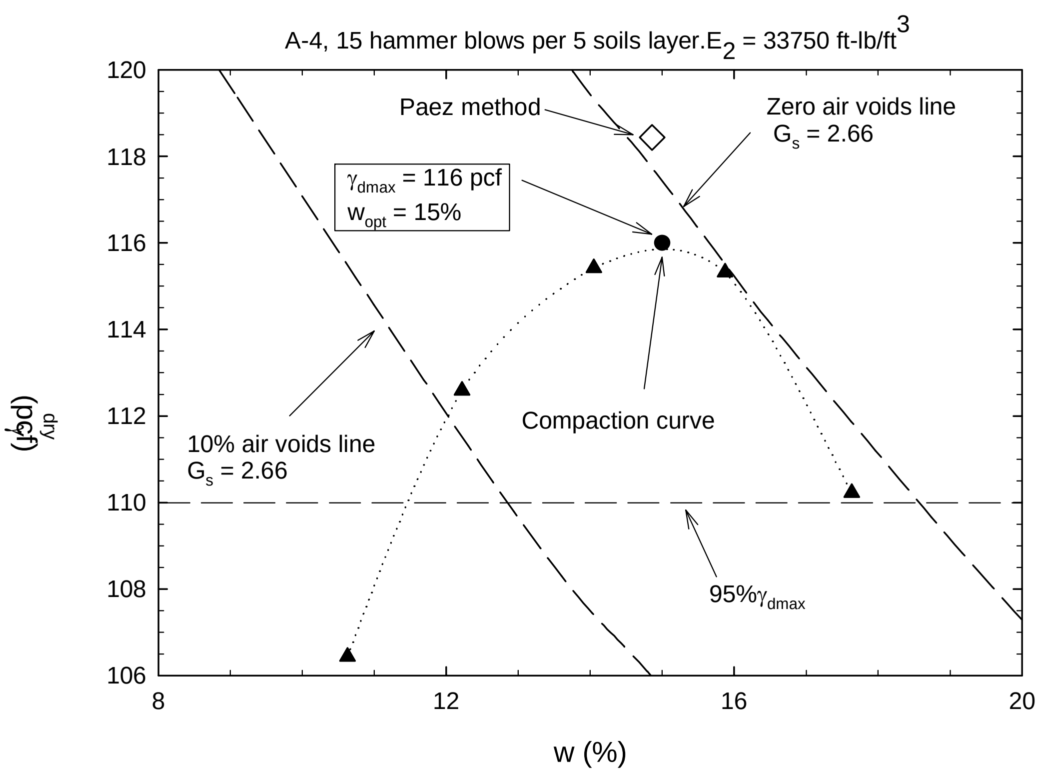

FIGURE A 18. Compaction curve for A-4(8), Soil No. 5.

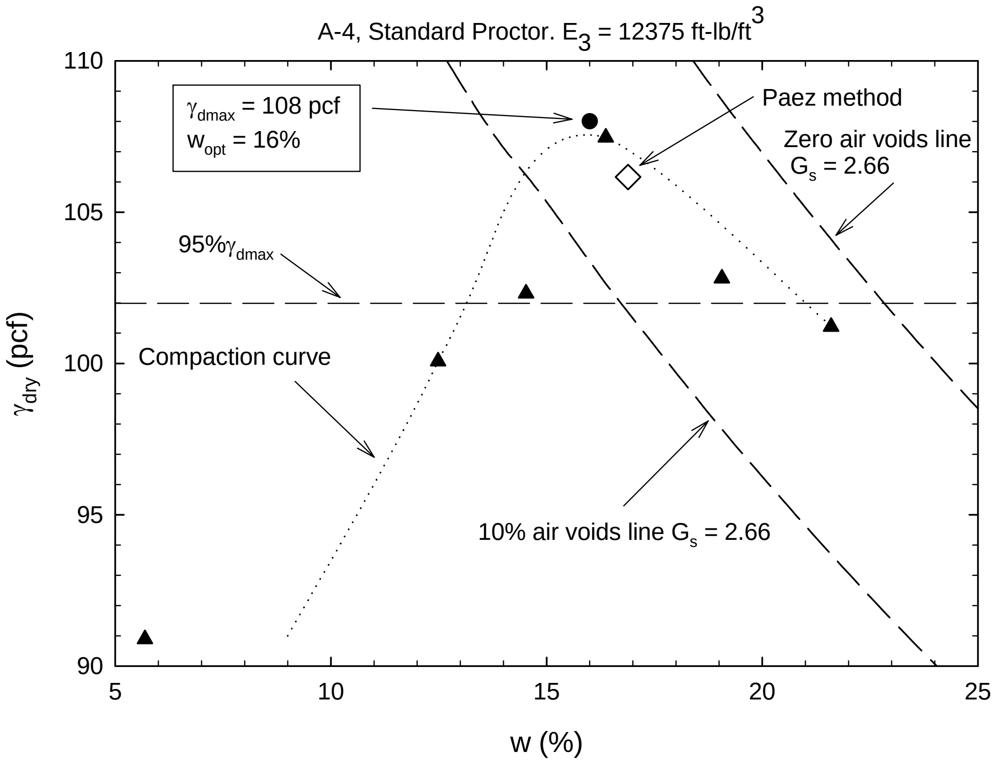

FIGURE A 19. Compaction curve for A-4(8), Soil No. 5.

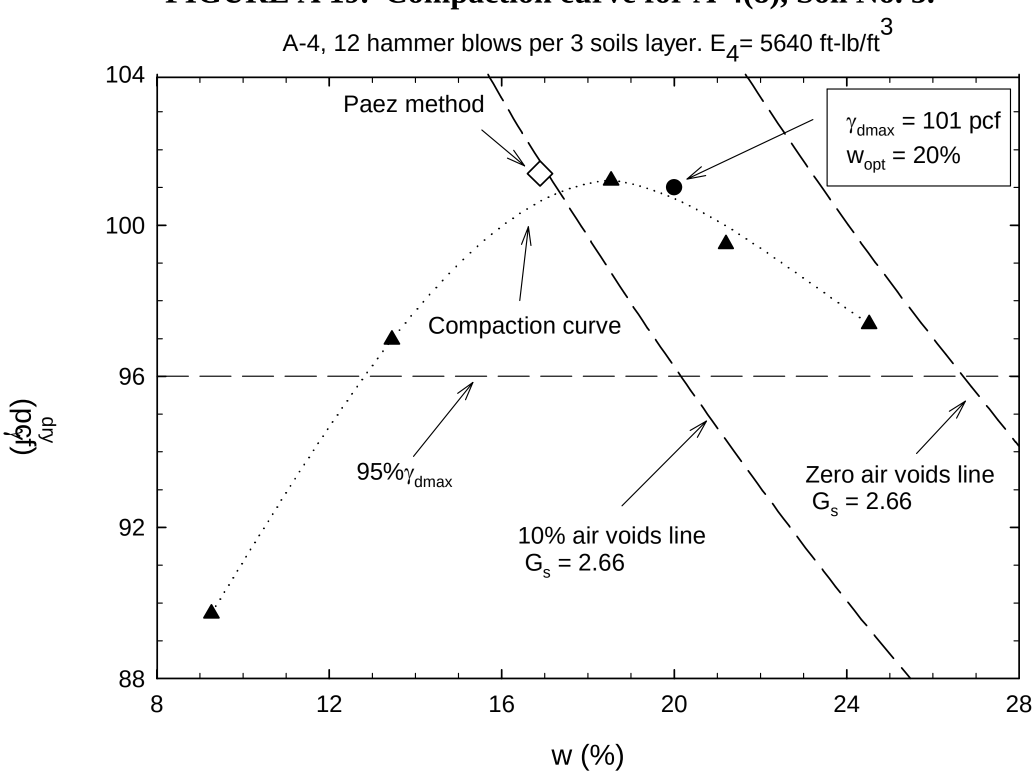

FIGURE A 20. Compaction curve for A-4(8), Soil No. 5.

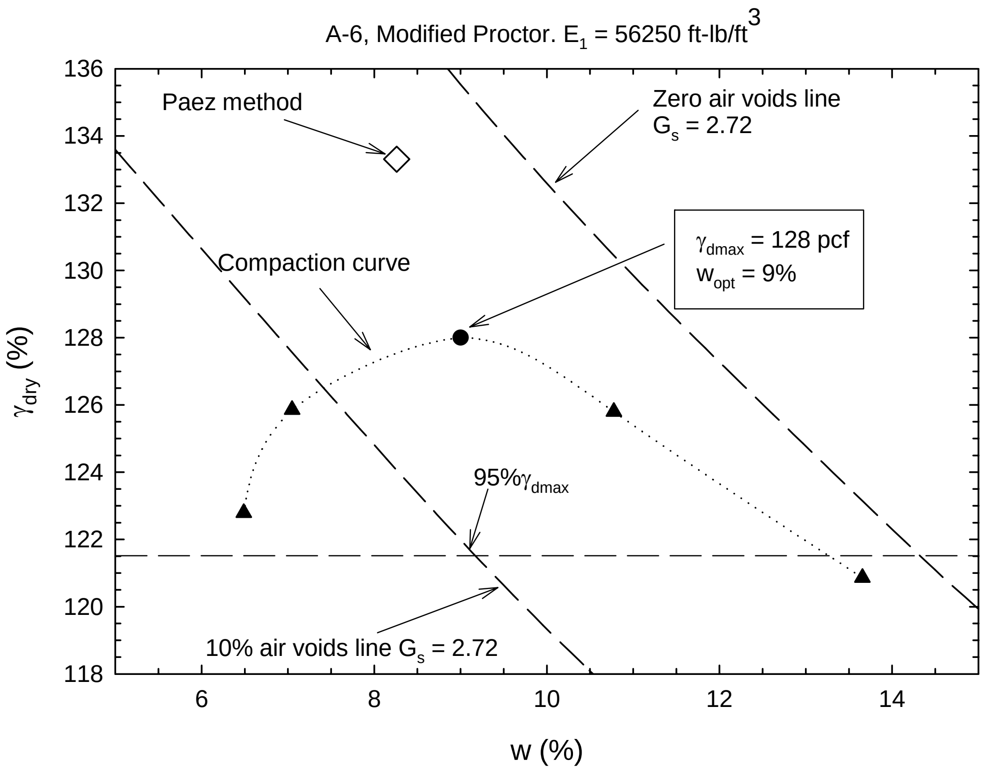

FIGURE A 21. Compaction curve for A-6(2), Soil No. 6.

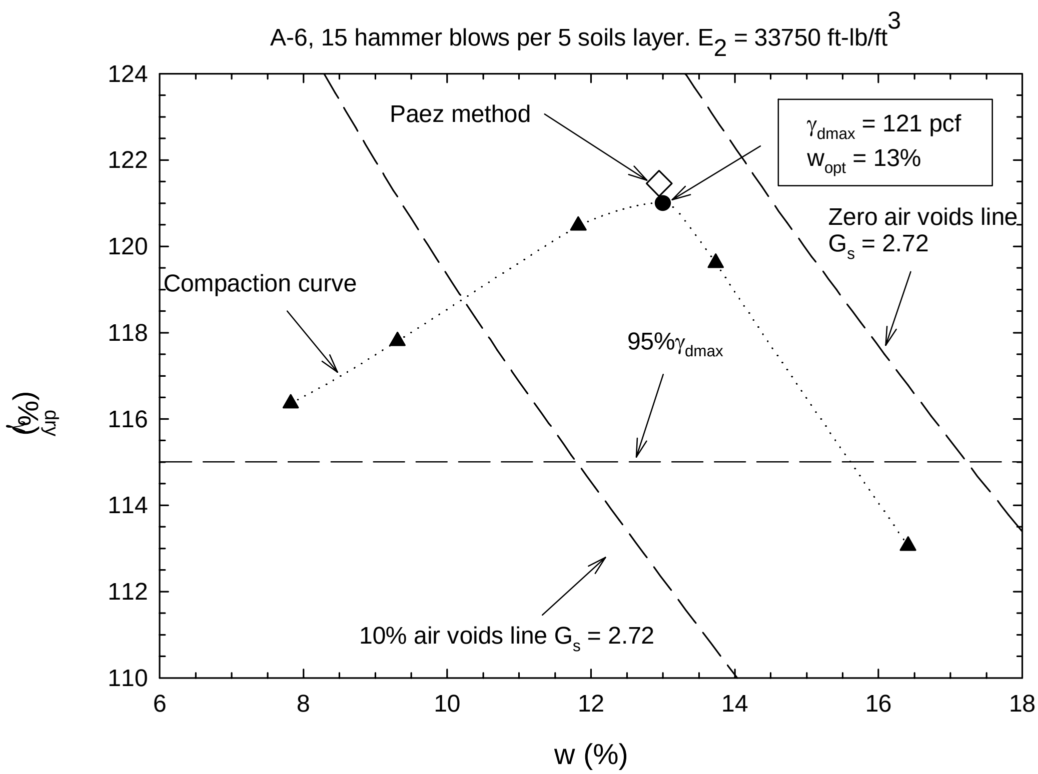

FIGURE A 22. Compaction curve for A-6(2), Soil No. 6.

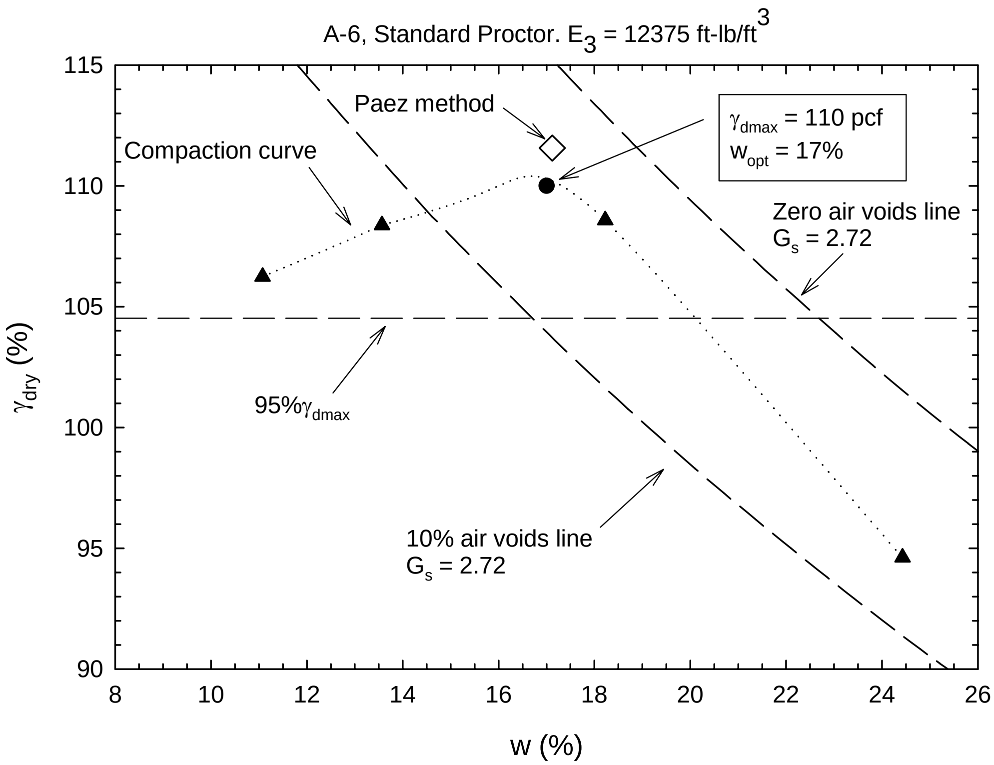

FIGURE A 23. Compaction curve for A-6(2), Soil No. 6.

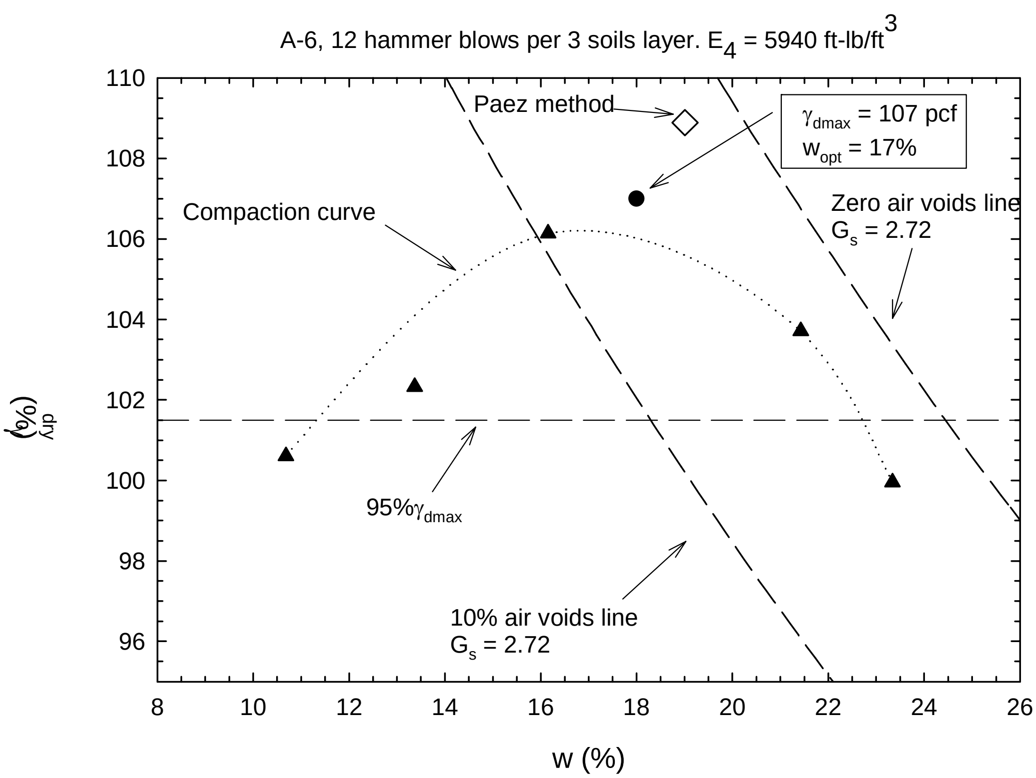

FIGURE A 24. Compaction curve for A-6(2), Soil No. 6.

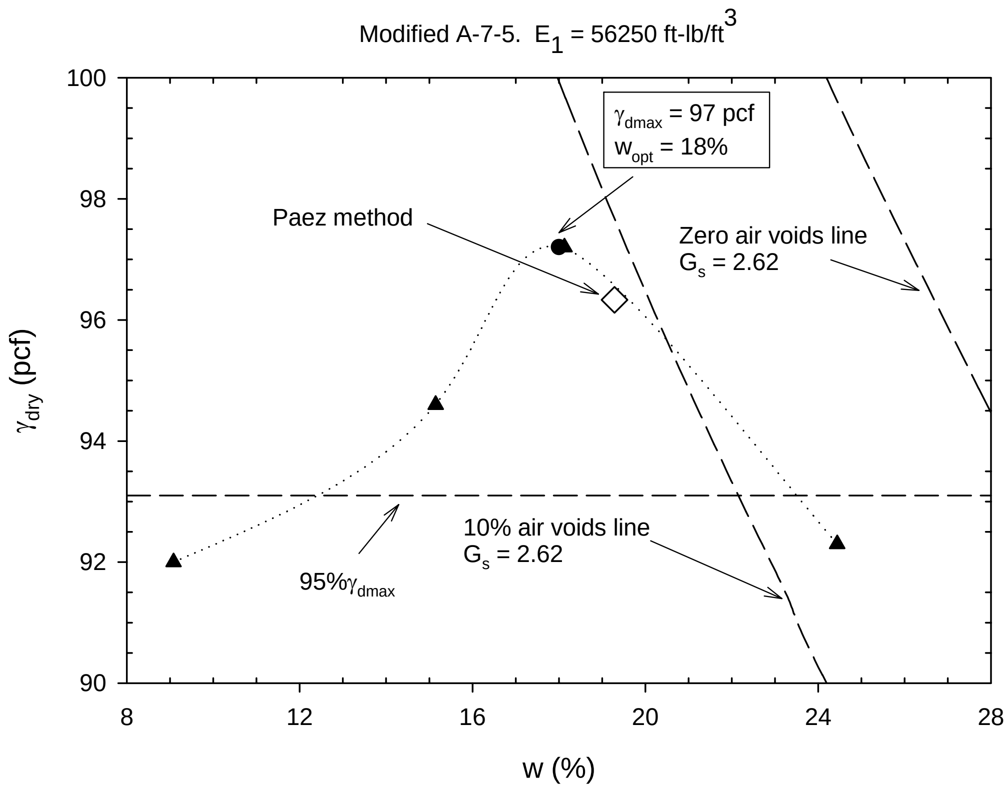

FIGURE A 25. Compaction curve for A-7-5(10), Soil No. 7.

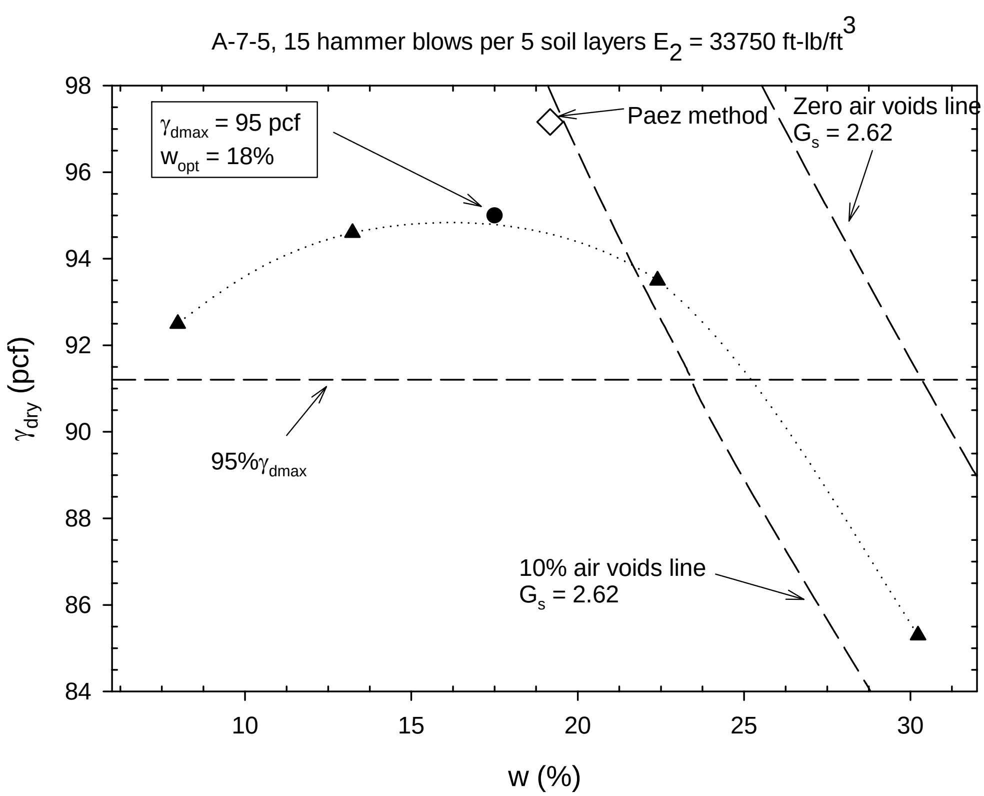

FIGURE A 26. Compaction curve for A-7-5(10), Soil No. 7.

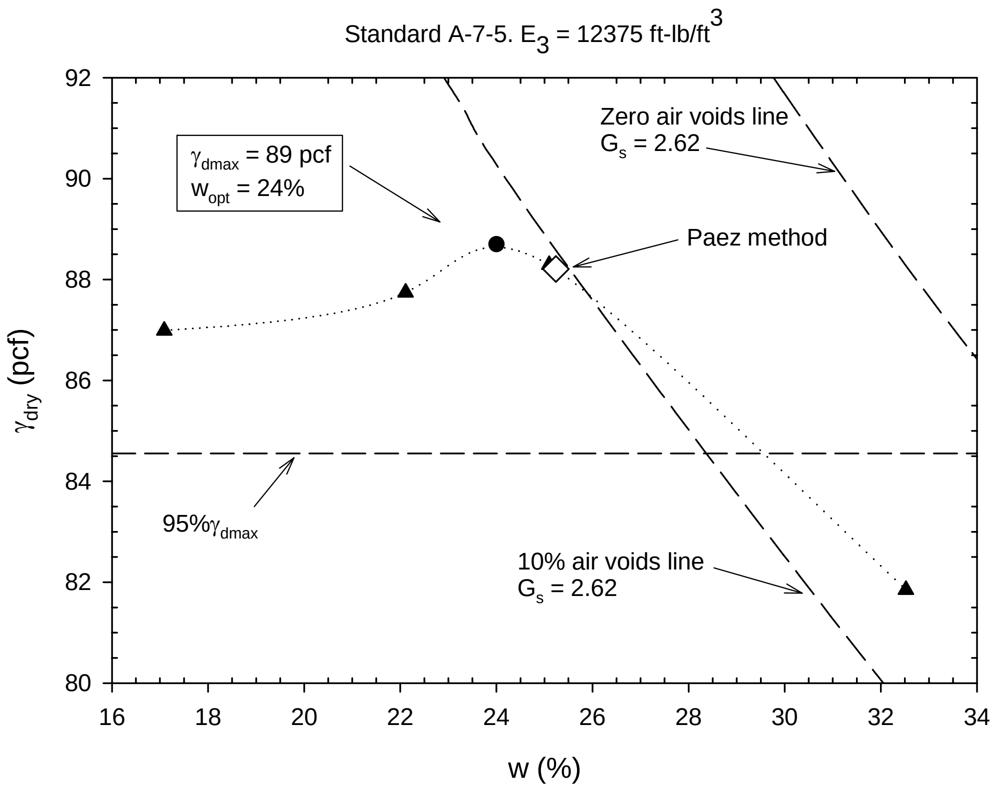

FIGURE A 27. Compaction curve for A-7-5(10), Soil No. 7.

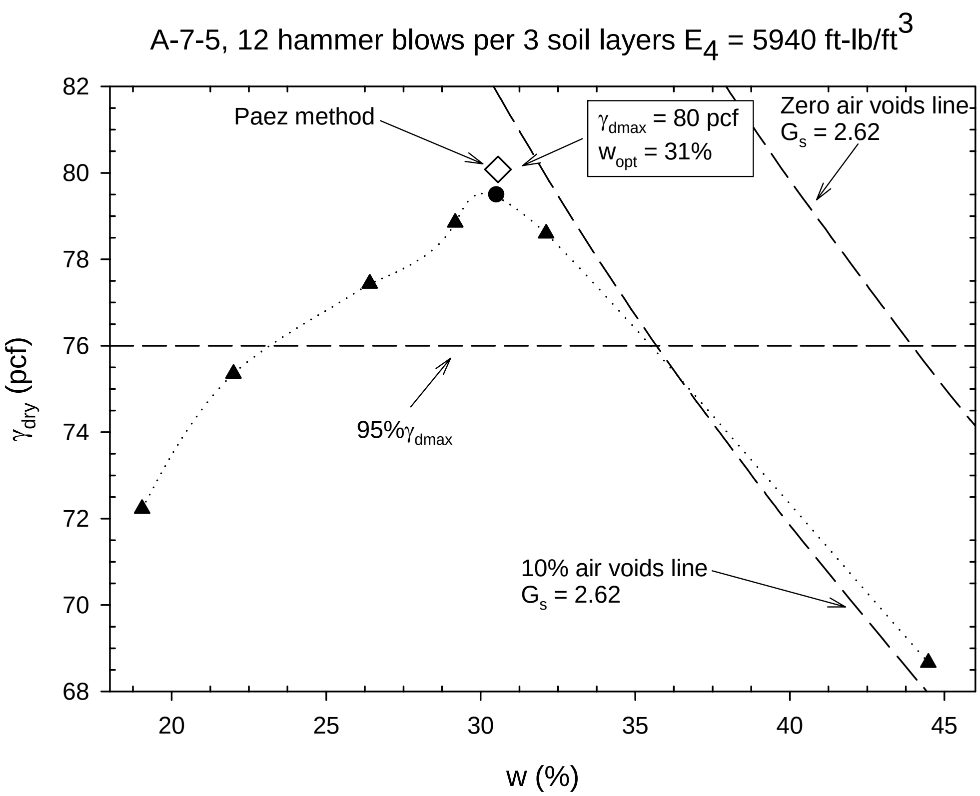

FIGURE A 28. Compaction curve for A-7-5(10), Soil No. 7.

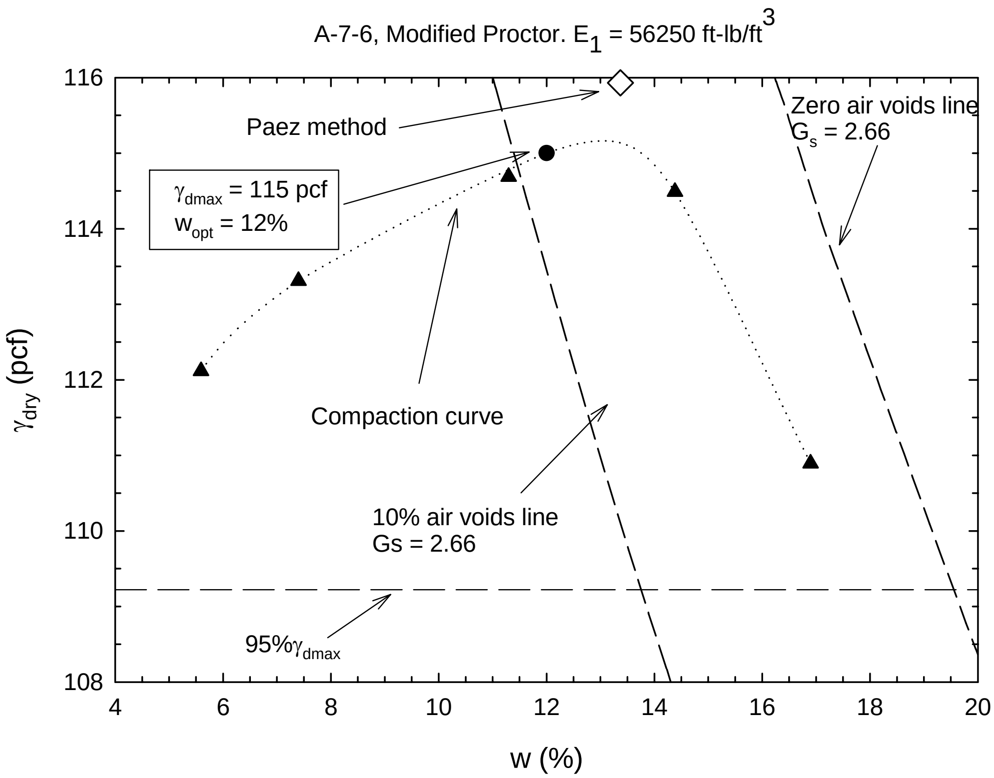

FIGURE A 29. Compaction curve for A-7-6(5), Soil No. 8.

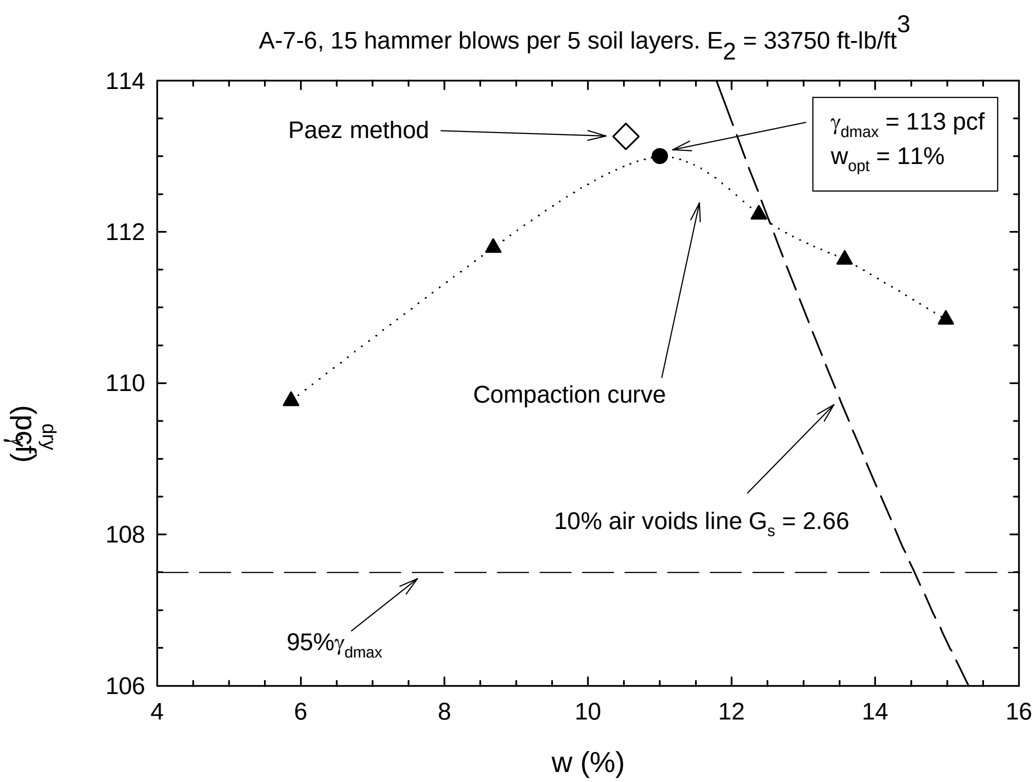

FIGURE A 30. Compaction curve for A-7-6(5), Soil No.8.

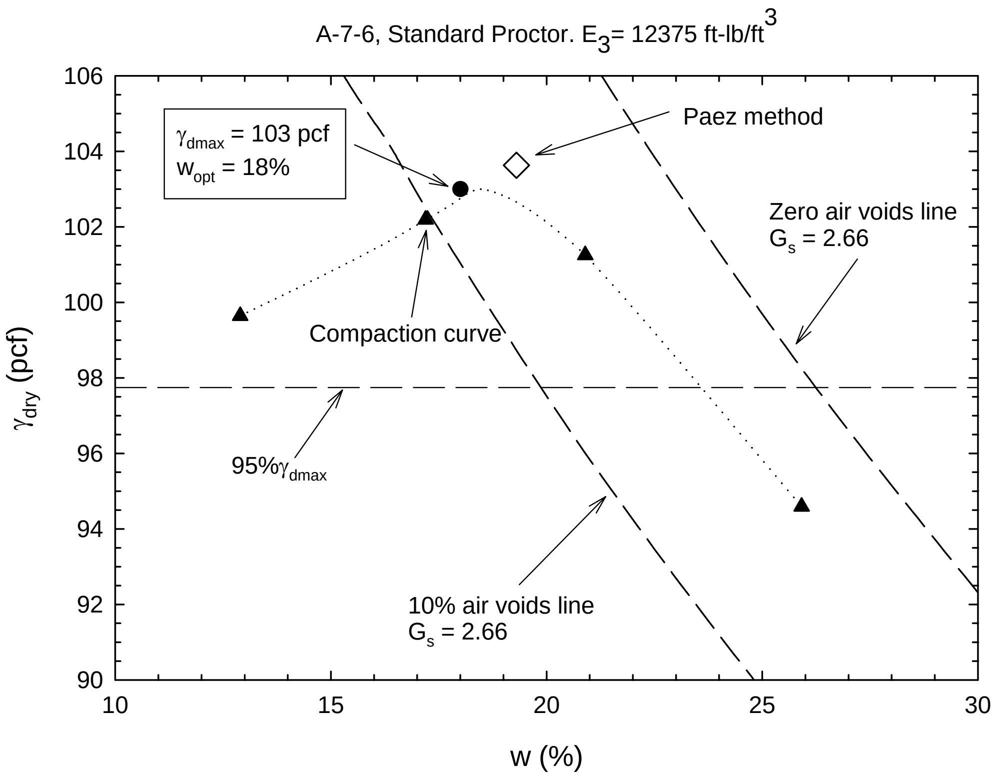

FIGURE A 31. Compaction curve for A-7-6(5), Soil No. 8.

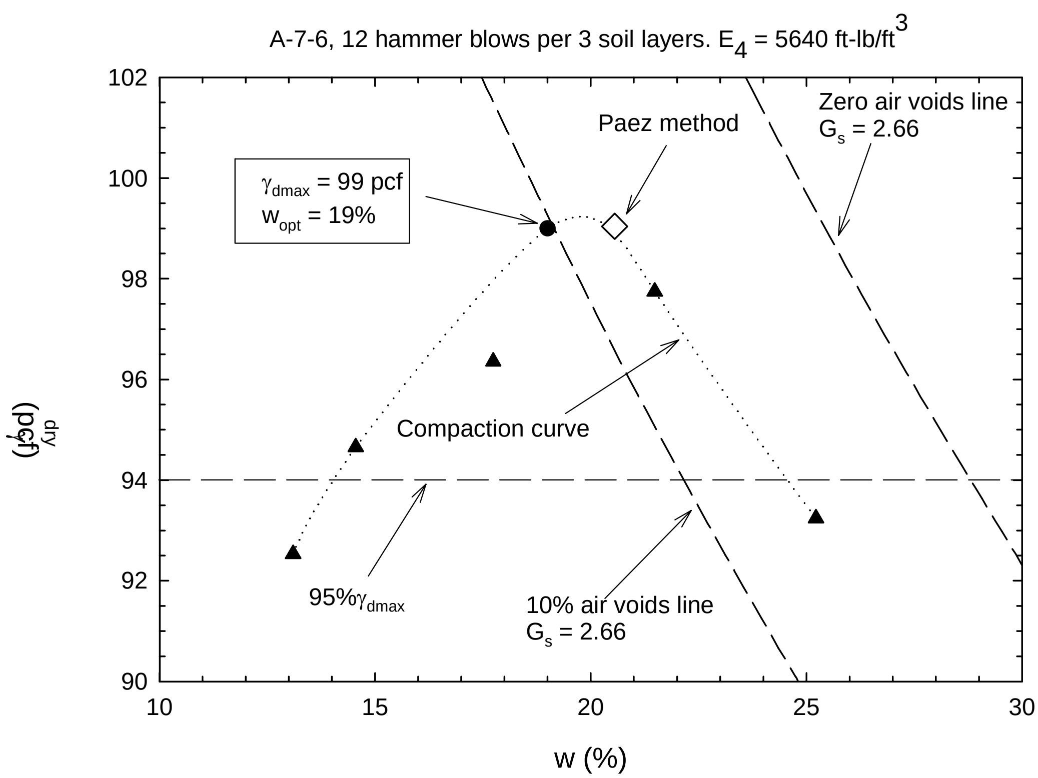

FIGURE A 32. Compaction curve for A-7-6(5), Soil No. 8.

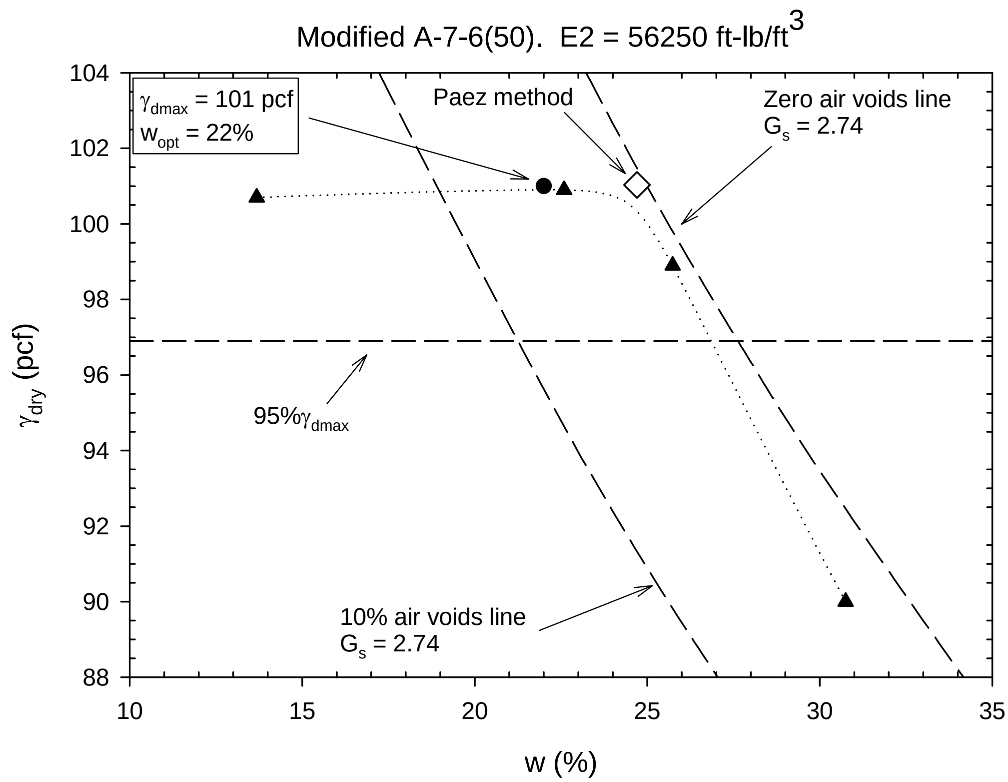

FIGURE A 33. Compaction curve for A-7-6(50), Soil No. 9.

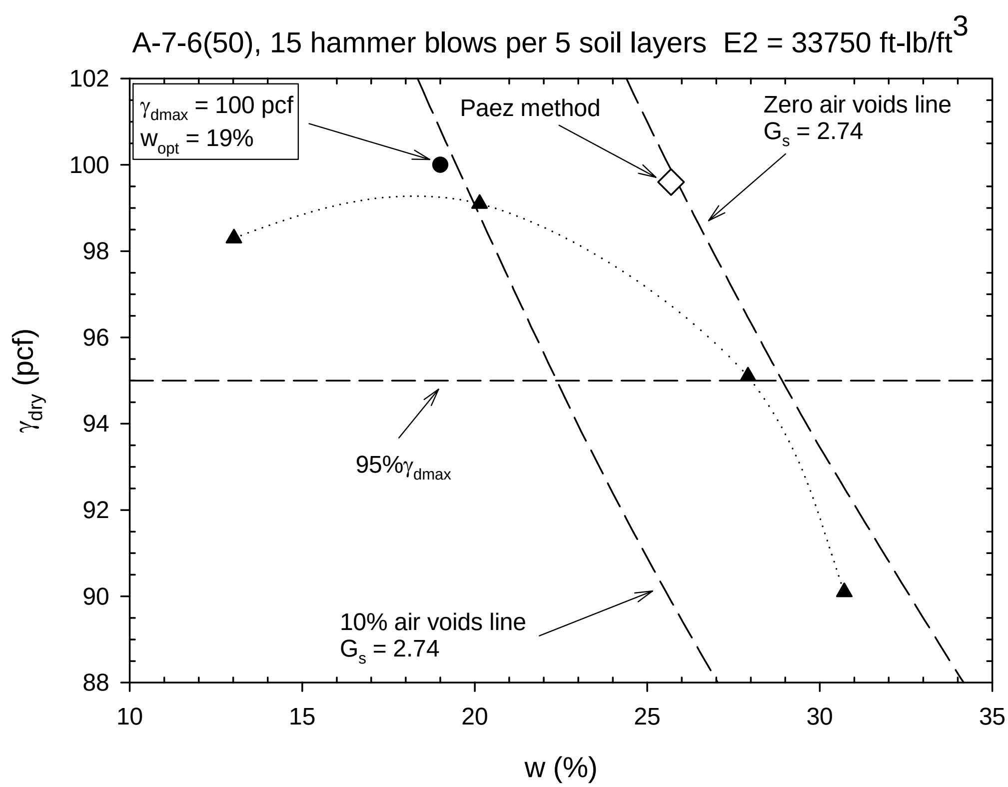

FIGURE A 34. Compaction curve for A-7-6(50), Soil No. 9.

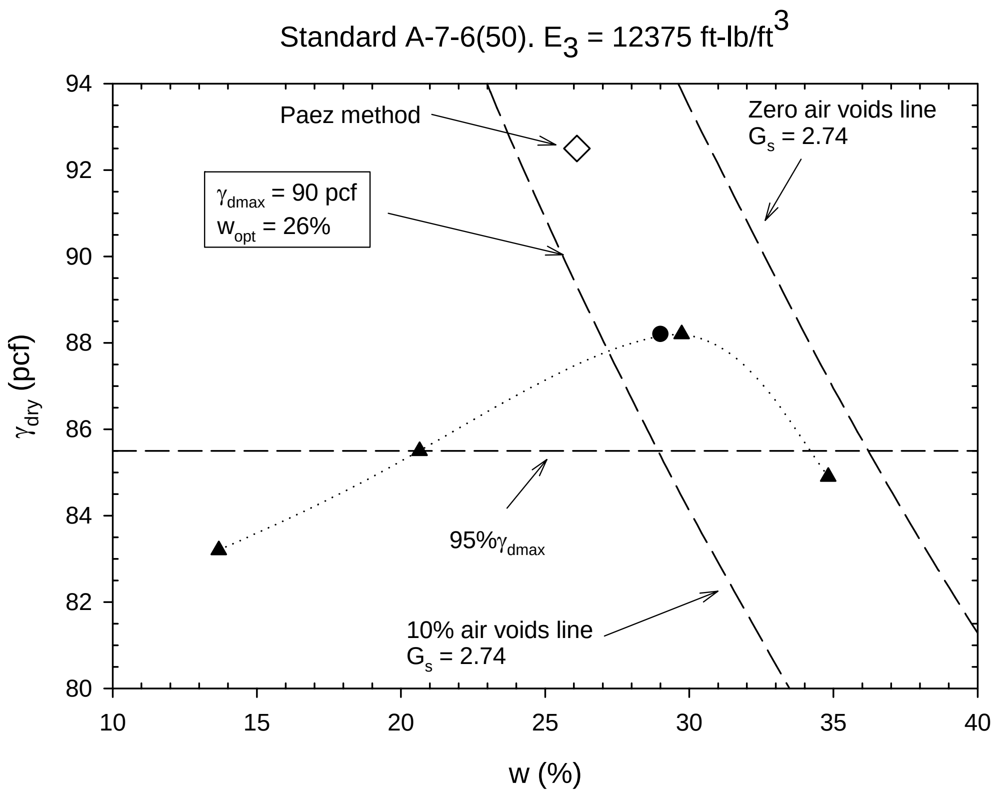

FIGURE A 35. Compaction curve for A-7-6(50), Soil No. 9.

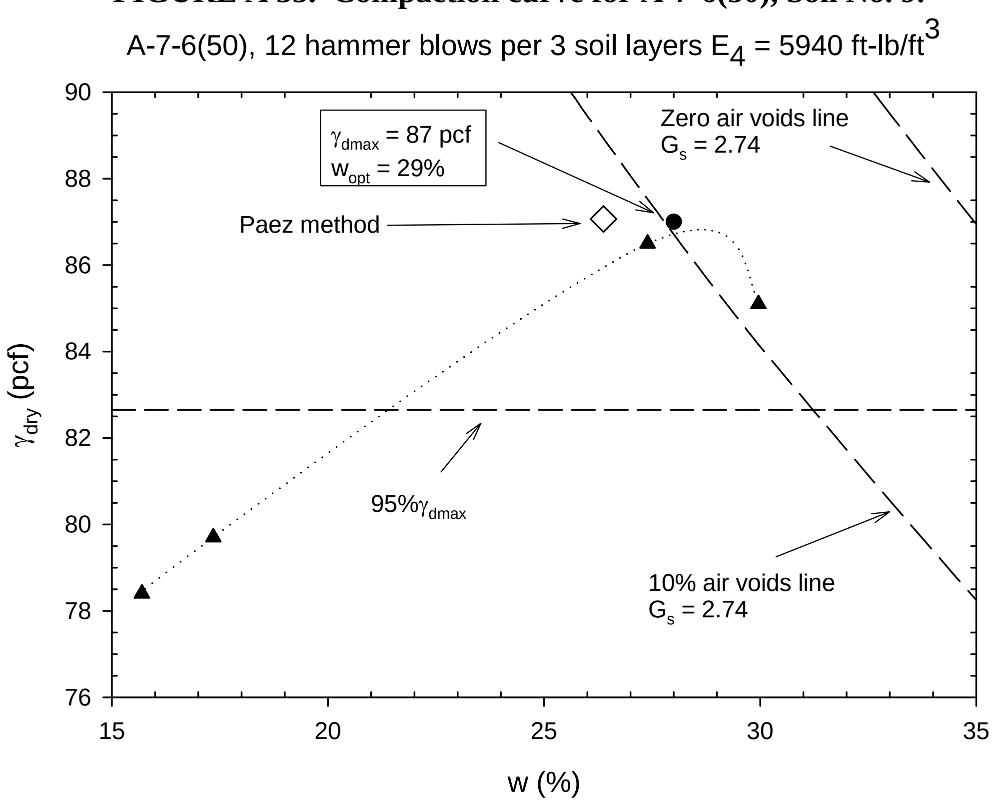

FIGURE A 36. Compaction curve for A-7-6(50), Soil No. 9.

Appendix B

Gradation Curves

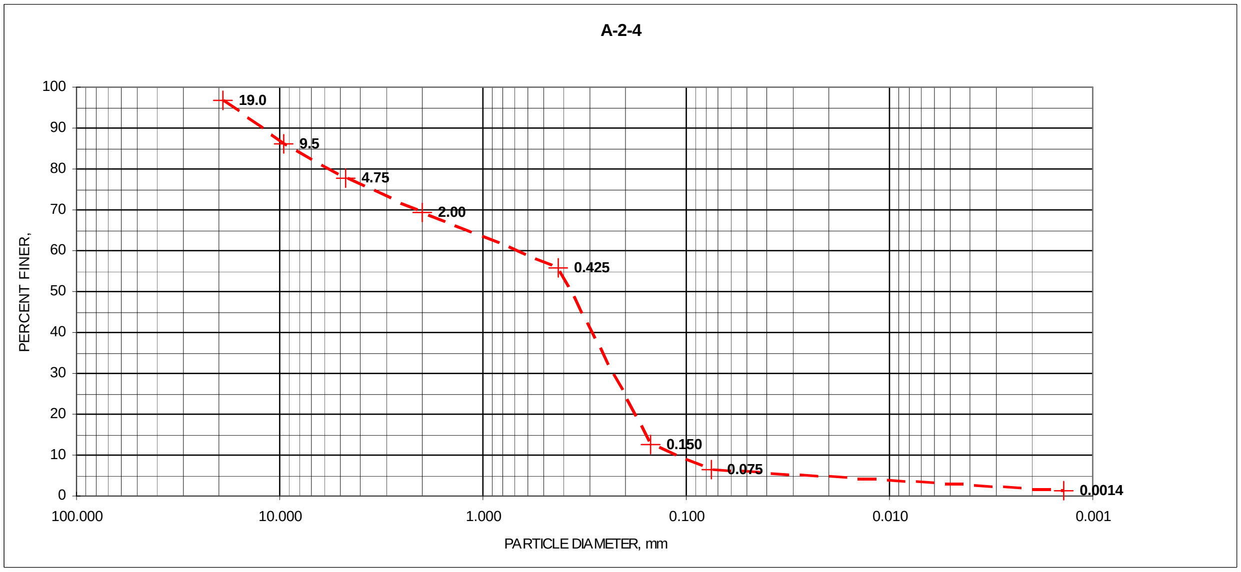

FIGURE B 1. Gradation curve for A-2-4(0), Soil No. 1.

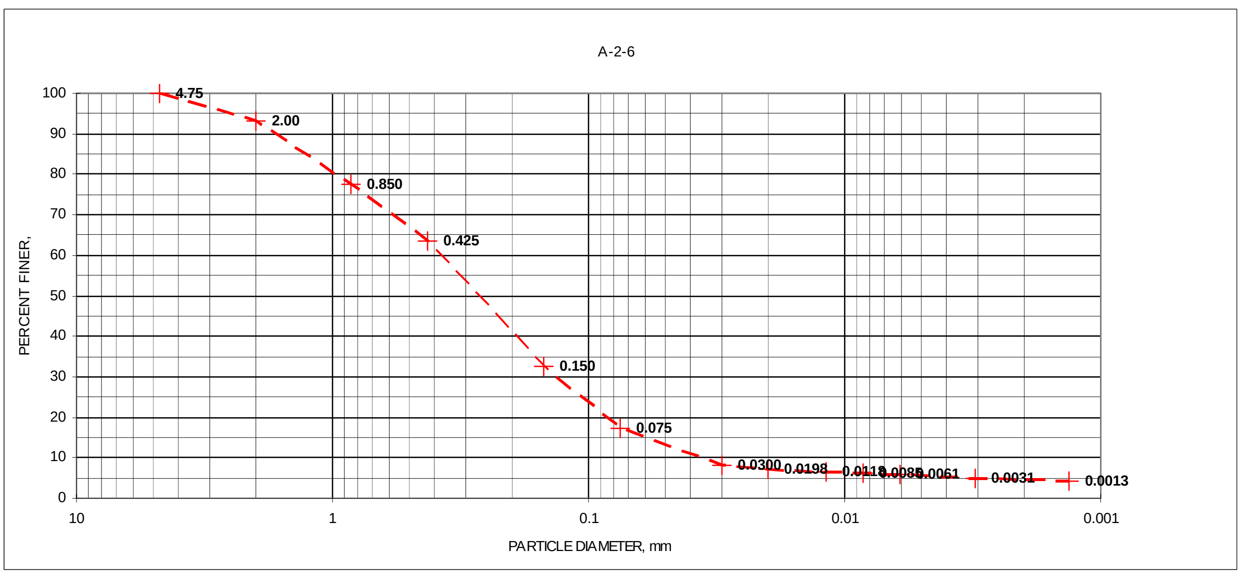

FIGURE B 2. Gradation curve for A-2-6(0), Soil No. 2.

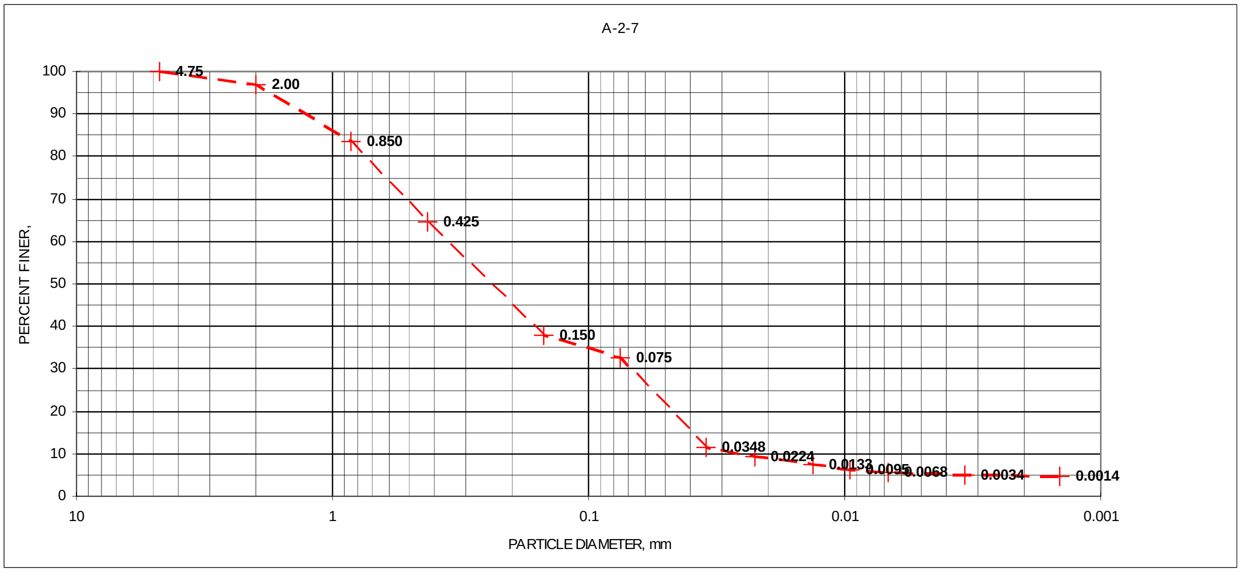

FIGURE B 3. Gradation curve for A-2-7(1), Soil No. 3.

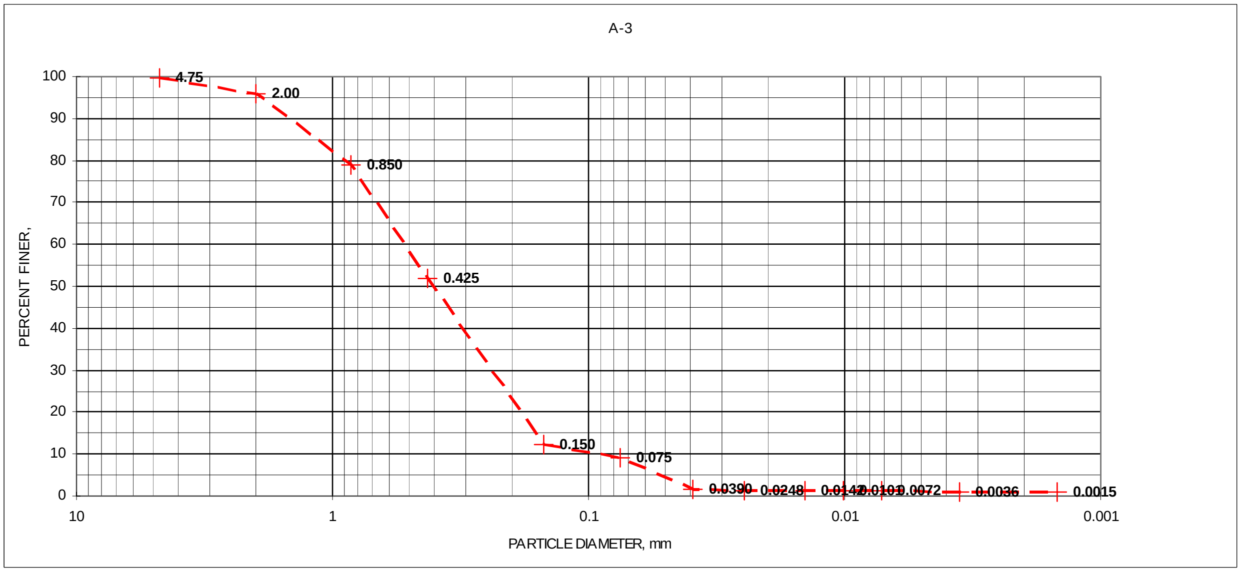

FIGURE B 4. Gradation curve for A-3(0), Soil No. 4.

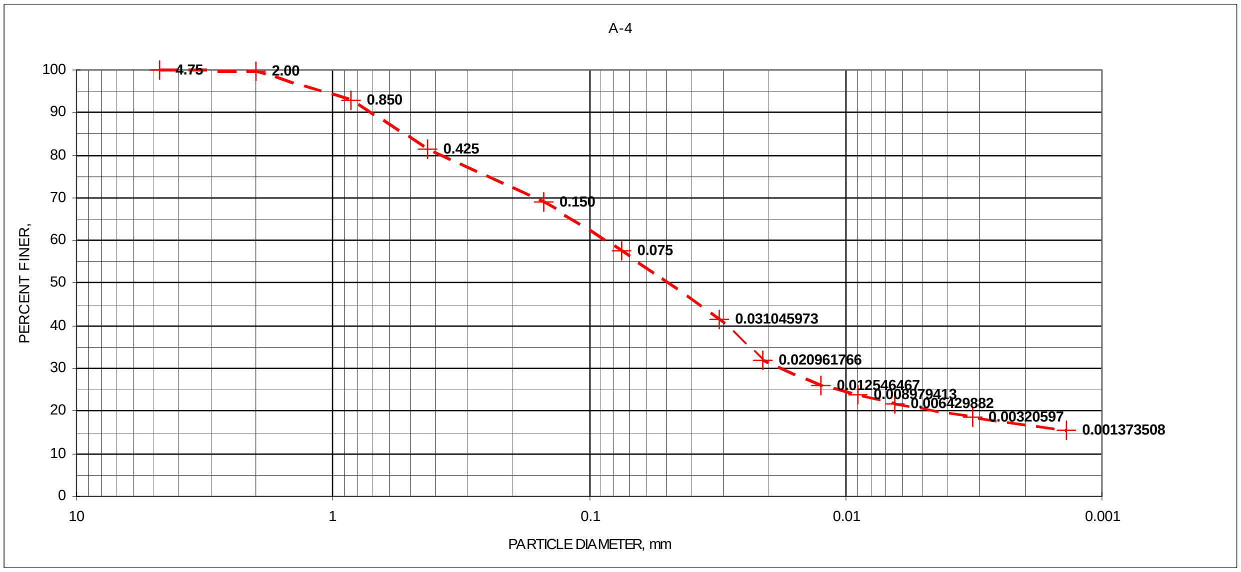

FIGURE B 5. Gradation curve for A-4(8), Soil No. 5.

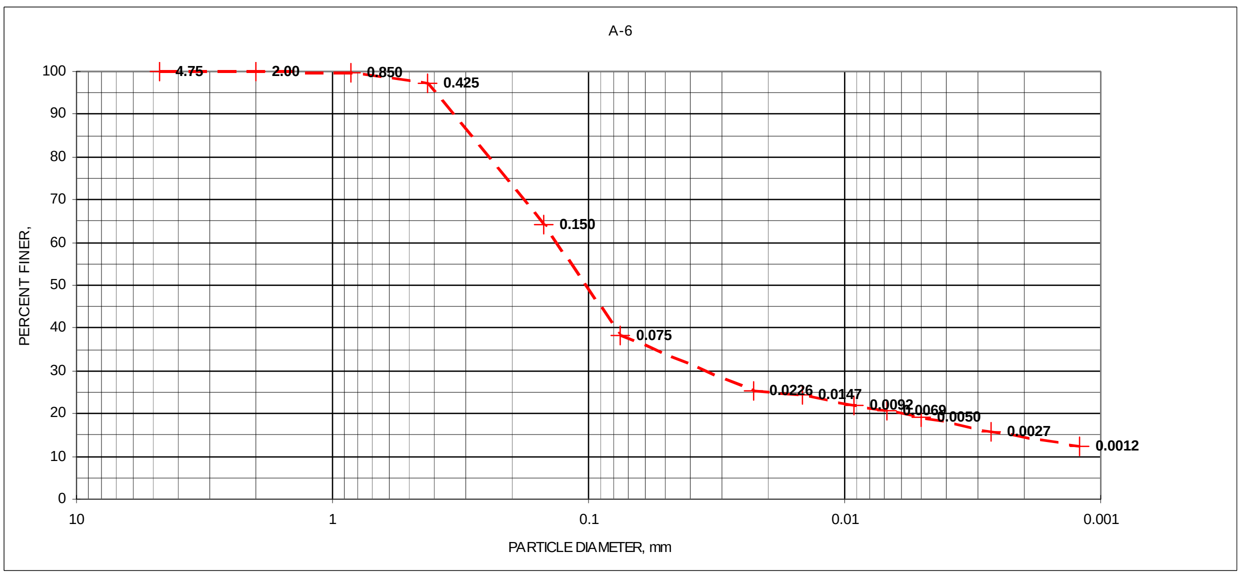

FIGURE B 6. Gradation curve for A-6(2), Soil No. 6.

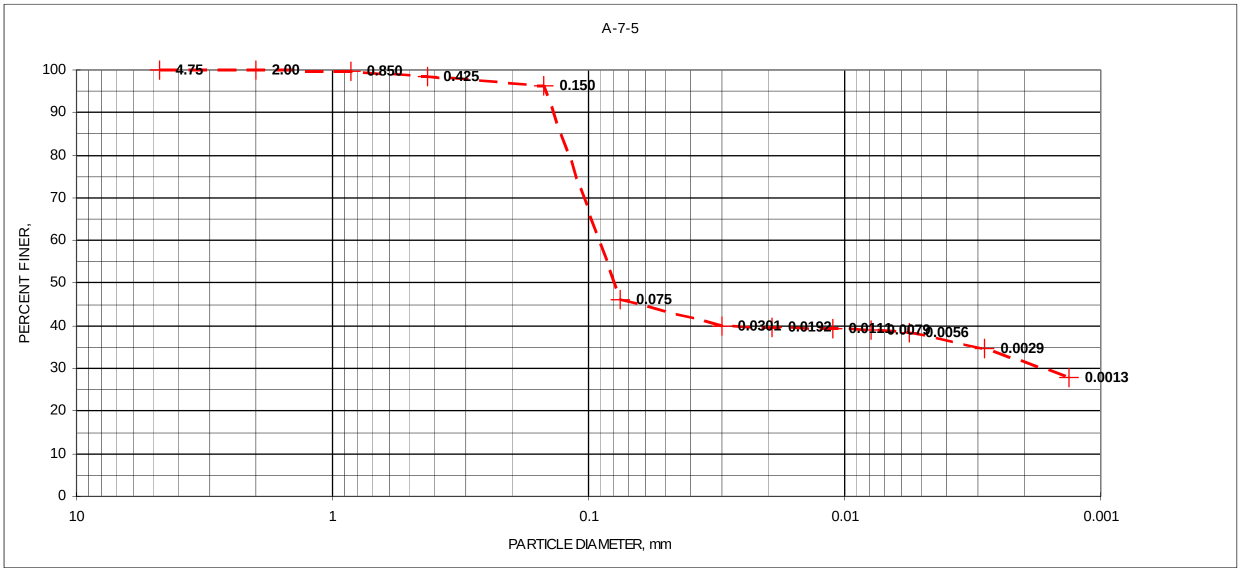

FIGURE B 7. Gradation curve for A-7-5(10), Soil No. 7.

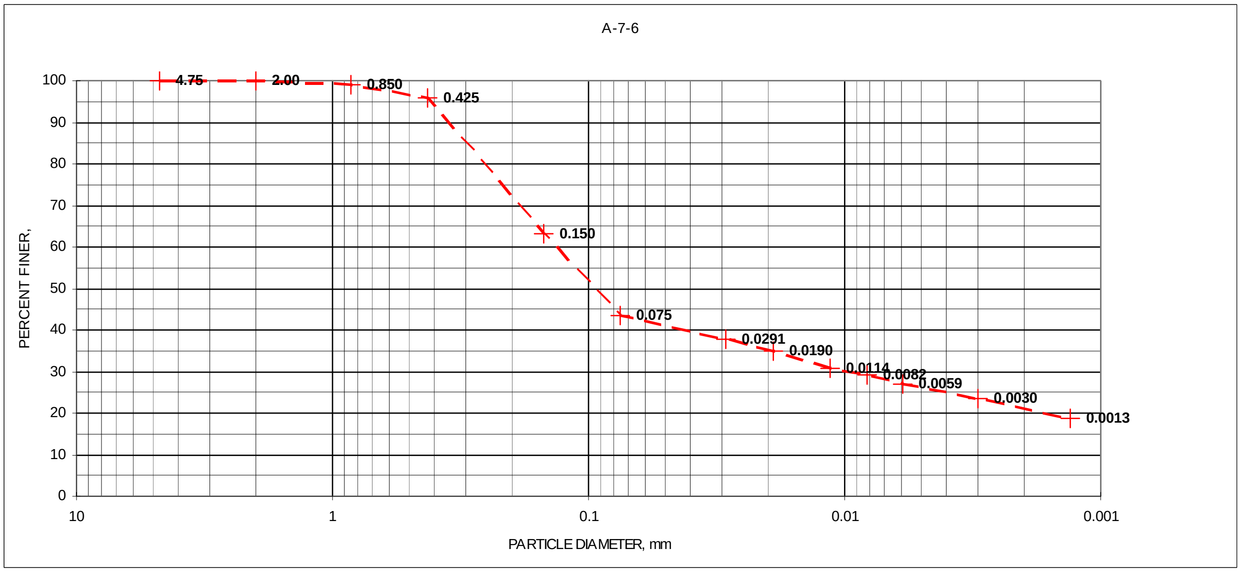

FIGURE B 8. Gradation curve for A-7-6(5), Soil No. 8.

Appendix C

Paez Method

Appendix C: Paez Method for Estimating Optimum Compaction Parameters

The equation transformation method developed by Paez (1980) uses simple variable transformation equations to plot the dry and wet legs of the compaction curve as straight lines. The wet leg plots parallel to the air voids line while the dry leg plots at an obtuse angle. The intersection of these two lines defines the theoretical peak point of the compaction curve based on volumetric and gravimetric phase relationships. This method provides a consistent and repeatable approach for determining w_{opt} and γ_{dmax}, and eliminates operator subjectivity. The Paez method was further investigated using compaction data from this study to determine if the numerically interpolated values of γ_{dmax} and w_{opt} were accurate enough to use in practical applications. The derivation of the Paez equations are presented in this report because the original Paez (1980) paper is in French, and many steps of the derivation are skipped or omitted in the paper. Thus, the following discourse presents a much clearer and easier to follow progression than can be found in the original published work. The derivation begins with basic values from the common volumetric-gravimetric 3-phase diagram (phase diagram), shown in Figure C1.

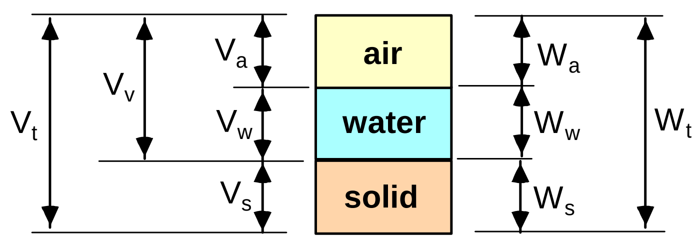

FIGURE C 1. Phase diagram illustrating basic weight and volume measures.

From the typical phase diagram shown in Figure 5, the following commonly used ratios are defined:

$$\gamma_d = \frac{W_s}{V} = \text{dry unit weight} \tag{C1}$$

$$G_s = \frac{W_s}{V_s \cdot \gamma_w} = \text{specific gravity} \tag{C2}$$

$$\gamma_w = \frac{W_w}{V_w} = \text{unit weight of water (62.4 pcf)} \tag{C3}$$

$$w = \frac{W_w}{W_s} = \text{water content (decimal form)} \tag{C4}$$

For a fully saturated soil there are no air voids; consequently the total volume of the soil is:

$$V_t = V_s + V_w \tag{C5}$$

Inserting the relationships defined in equations (C1) through (C4) into equation (C5) yields the following relationship, which is written in terms of gravimetric quantities:

$$\frac{W_s}{\gamma_d} = \frac{W_s}{G_s \cdot \gamma_w} + \frac{w \cdot W_s}{\gamma_w} \tag{C6}$$

Multiplying equation (8) through by $\frac{G_s}{W_s}$, yields:

$$\frac{G_s}{\gamma_d} = \frac{1}{\gamma_w} + \frac{w \cdot G_s}{\gamma_w} \tag{C7}$$

$$\frac{G_s}{\gamma_d} = 0.016 + \frac{w \cdot G_s}{\gamma_w} \tag{C8}$$

In terms of the common x-y Cartesian coordinates system, equation (C8) can be written in the form of:

$$y = 0.016 + x \tag{C9}$$

where the transformed y-axis is represented as:

$$y = \frac{G_s}{\gamma_d} \tag{C10}$$

and the transformed x-axis is represented as:

$$x = \frac{w \cdot G_s}{\gamma_w} \tag{C11}$$

An example of a compaction curve plotted on the transferred axes is shown in Figure C2. The relationship described by the previous equations is for a fully saturated soil. A similar relationship can be developed for a partially saturated soil by invoking the definition of percent soil air voids; N_a, defined as:

$$N_a = \frac{V_a}{V_t} \tag{C12}$$

For partially saturated soil, equation (C5) thus becomes:

$$V_t = V_s + V_w + V_a \tag{C13}$$

Substituting equation (C12) into equation (C13), and re-arranging terms yields the following expression:

$$V_t(1 - N_a) = V_s + V_w \tag{C14}$$

Using the same algebraic manipulations described previously yields the following equation for partially saturated soils in terms of the transformed x and y axes:

$$y(1 - N_a) = x + 0.016 \tag{C15}$$

where, y and x are defined in equations (C10) and (C11). Equation (C15) can be used to plot contour lines of any values of N_a on the transformed axes plot.

The axes of the familiar compaction plot can now be transformed from x-axis = water content and y-axis = dry unit weight , to x-axis = wG_s/γ_w and y-axis = G_s/γ_d. Straight lines representing data points located on the wet side of w_{opt} (wet leg) and on the dry side of w_{opt} (dry leg) are plotted on the transformed graph using linear regression. The intersection of these two lines defines the approximate peak value of the compaction curve. An example is illustrated in the following paragraphs.

Establish the wet and dry legs of the compaction curve as shown in Figure C2.

Plot the two legs as straight lines into the graph with the transformed axis as shown in Figure C3.

Find the point of intersection of the lines that represent the dry and wet legs.

Solve equations (C10) and (C11) with respect to *w* and γ_d to determine the optimum water and maximum dry density.

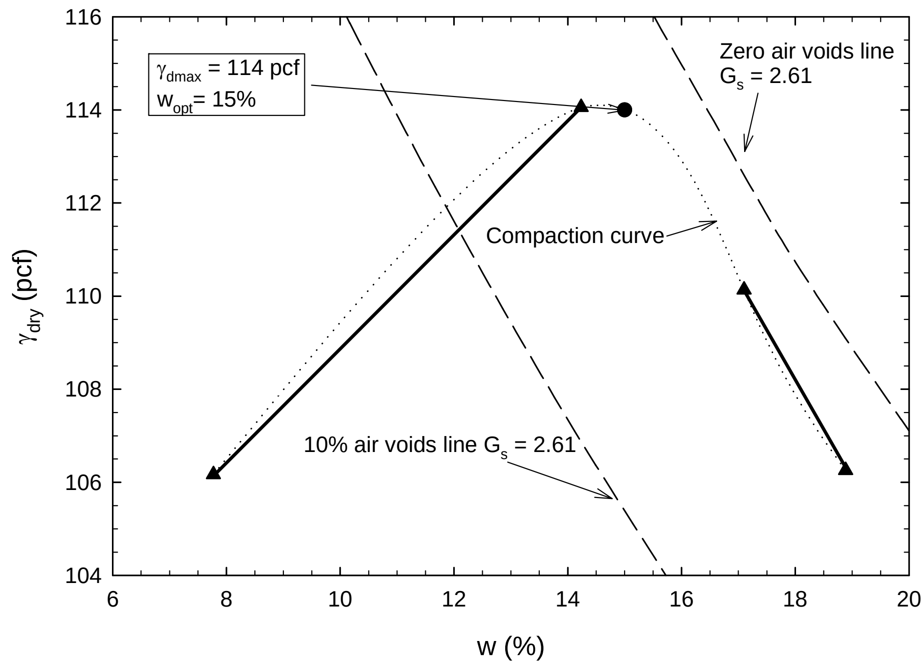

FIGURE C 2. Paez method applied to the standard Proctor compaction curve for an A-2-4(0) soil.

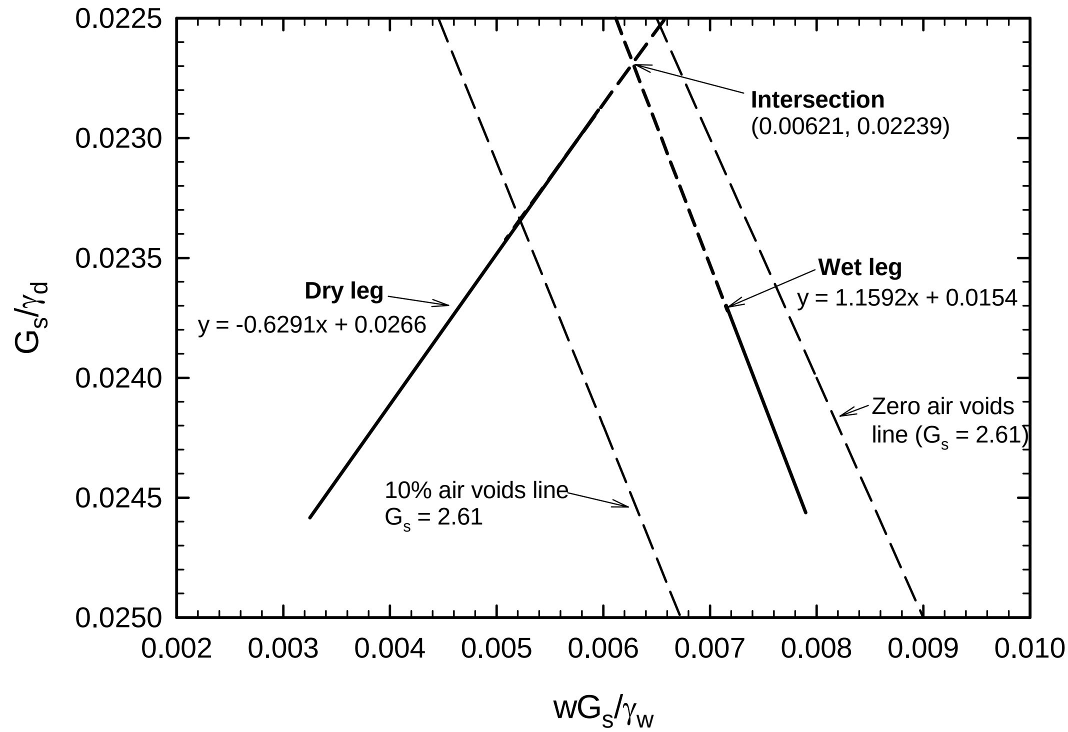

FIGURE C 3. Transformed compaction plot using the Paez method.

Applying the Paez method of data interpretation to the A-2-4 laboratory compaction data (as illustrated in Figures C2 and C3), yields the following results:

$$\gamma_d = \frac{G_s}{y} = \frac{2.61}{0.02239} = 116.5\,pcf \tag{C16}$$

and

$$w = \frac{x \cdot \gamma_w}{G_s} = \frac{0.00261 \cdot 62.4}{2.61} = 14.8\% \tag{C17}$$

In this example, the wet leg and the dry leg intersect at point (0.00621, 0.02239). Transforming these values yields: γ_{dmax} = 116.5 pcf and w_{opt} = 14.8 %, as shown in equations (C16) and (C17). These values can be compared to the results obtained using the common approach in which judgment is used to fit a smooth curve through the Proctor compaction data points, which in this case yielded values of γ_{dmax} = 114.0 pcf and w_{opt} = 14.0%.

For comparison purposes, this method was applied to the compaction test results developed during the laboratory phase of the study. The results of this comparison are summarized in Tables C1 through C9.

TABLE C1. Paez Results for Soil No. 1: A-2-4(0)

	γ_{dmax} (lb/ft^3)			w_{opt} (%)		
Energy	Paez	Lab	Error (%)	Paez	Lab	Error (%)
56,250[a]	123	123	-0.11	12	11	9.36
33,750	121	119	1.75	13	13	0.23
12,375[b]	115	114	1.11	15	15	0.07
5,940	109	107	1.66	17	16	7.38

TABLE C2. Paez Results for Soil No. 2: A-2-6(0)

	γ_{dmax} (lb/ft^3)			w_{opt} (%)		
Energy	Paez	Lab	Error (%)	Paez	Lab	Error (%)
56,250[a]	122	119	2.67	10	10	3.00
33,750	116	115	1.05	13	13	3.31
12,375[b]	110	108	1.56	16	16	0.12
5,940	101	100	0.77	18	18	-1.67

TABLE C3. Paez Results for Soil No. 3: A-2-7(1)

	γ_{dmax} (lb/ft^3)			w_{opt} (%)		
Energy	Paez	Lab	Error (%)	Paez	Lab	Error (%)
56,250[a]	130	128	1.18	8	8	5.25
33,750	127	125	1.25	9	9	1.78
12,375[b]	123	121	1.95	10	10	1.10
5,940	115	114	0.90	13	12	5.25

TABLE C4. Paez Results for Soil No. 4: A-3(0)

	γ_{dmax} (lb/ft^3)			w_{opt} (%)		
Energy	Paez	Lab	Error (%)	Paez	Lab	Error (%)
56,250[a]	118	117	1.09	11	11	1.82
33,750	114	114	0.42	13	12	5.92
12,375[b]	111	111	0.31	10	12	-16.92
5,940	109	108	0.94	13	12	6.25

TABLE C5. Paez Results for Soil No. 5: A-4(8)

	γ_{dmax} (lb/ft^3)			w_{opt} (%)		
Energy	Paez	Lab	Error (%)	Paez	Lab	Error (%)
56,250[a]	120	118	1.85	16	14	13.79
33,750	119	116	2.25	15	15	-0.73
12,375[b]	106	108	-1.69	17	16	5.38
5,940	102	101	0.54	18	20	-9.00

TABLE C6. Paez Results for Soil No. 6: A-6(2)

	γ_{dmax} (lb/ft^3)			w_{opt} (%)		
Energy	Paez	Lab	Error (%)	Paez	Lab	Error (%)
56,250[a]	133	128	3.80	8	9	-8.44
33,750	122	121	0.67	13	13	-1.23
12,375[b]	112	110	1.53	17	17	0.24
5,940	109	107	1.71	19	17	11.88

TABLE C7. Paez Results for Soil No. 7: A-7-5(10)

	γ_{dmax} (lb/ft^3)			w_{opt} (%)		
Energy	Paez	Lab	Error (%)	Paez	Lab	Error (%)
56,250[a]	96	97	-0.69	19	18	7.17
33,750	97	95	2.27	19	18	19.81
12,375[b]	88	89	-0.89	25	24	5.17
5,940	80	80	0.10	31	31	-1.42

TABLE C8. Paez Results for Soil No. 8: A-7-6(5)

	γ_{dmax} (lb/ft^3)			w_{opt} (%)		
Energy	Paez	Lab	Error (%)	Paez	Lab	Error (%)
56,250[a]	116	115	0.67	14	12	13.50
33,750	113	113	0.23	10	11	-5.82
12,375[b]	103	103	0.45	19	18	7.11
5,940	99	99	-0.05	20	19	7.53

TABLE C9. Paez Results for Soil No. 9: A-7-6(50)

	γ_{dmax} (lb/ft^3)			w_{opt} (%)		
Energy	Paez	Lab	Error (%)	Paez	Lab	Error (%)
56,250[a]	102	101	0.96	22	22	0
33,750	100	100	0.40	19	26	-26.04
12,375[b]	90	88	2.27	26	29	-10.34
5,940	87	87	-0.07	25	28	-10.71

Notes for Tables C1-C8:
[a]Modified Proctor Energy (AASHTO T180)
[b]Standard Proctor Energy (AASHTO T99)

150 copies of this public document were produced at an estimated cost of 2.17 each, for a total cost of $324.87. This includes $139.05 for postage and $185.82 for printing.