EVALUATION OF

ELECTRICAL DENSITY GAUGE FOR

FIELD COMPACTION CONTROL

by

Jason S. Hertz

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Civil Engineering

Summer 2015

EVALUATION OF

ELECTRICAL DENSITY GAUGE FOR

FIELD COMPACTION CONTROL

by
Jason S. Hertz

Approved: ____

Christopher L. Meehan, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: ____

Harry W. Shenton III, Ph.D.
Chair of the Department of Civil and Environmental Engineering

Approved: ____

Babatunde A. Ogunnaike, Ph.D.
Dean of the College of Engineering

Approved: ____

James G. Richards, Ph.D.
Vice Provost for Graduate and Professional Education

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor, Dr. Christopher L. Meehan, for taking a chance on me as one of his first few master's students as a professor at the University of Delaware. He constantly pushed me to expand my knowledge and I am extremely grateful for his guidance throughout this process that has taken quite a long time for me to achieve.

I would also like to express my thanks to the Delaware Department of Transportation who financially supported me thoughout the duration of the field studies conducted in this project.

I would also like to thank Greggo & Ferrarra, Inc. for supporting this study with their donation of the soil used to conduct a portion of my research. In addition, I would like to thank Jim Pappas, Ed Hall, and Dennis Anderson for their valuable assistance with the field studies, equipment donations, and associated data analysis.

I would also like to express my appreciation to my fellow graduate and undergraduate students at the University of Delaware, Farshid Vahedifard, Majid Khabbazian, Yueru Chen, Baris Imamoglu, Faraz Tehrani, Mohammad Khosravi, Alexandra Patrone, Daniel Cacciola, James Bailey, and Olivia Dalton. They all helped me with my analysis and lab work at some point during the duration of my research, and I am extremely grateful for that.

Finally, I would like to thank my mother for constantly being there to support me in finishing this work while working full time in New York City for the past 5 years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Compacted soil is a vital element in the construction of any civil engineering project. Measurements of in-situ soil density and moisture content are commonly used in the residential, commercial, and transportation industries to control the process of soil compaction. Various methods currently exist to monitor compaction in soils for construction projects. The nuclear density gauge is currently the most commonly utilized test device for this purpose; however, there are strict regulations with respect to the handling, transport, and storage of this device because it contains radioactive material. A relatively new non-nuclear alternative is the electrical density gauge (EDG), which uses a series of electrical measurements in conjunction with calibrated soil models to infer in-situ soil density and moisture content. Two approaches currently exist for building soil models with the electrical density gauge: the first is calibration with in-situ measurements of density and water content provided by the nuclear density gauge, sand cone test, or an equivalent in-situ density test, and the second is calibration with "large mold" Proctor-type tests.

In this study, both calibration methods were evaluated. Additionally, field compaction conditions were simulated in a "large" box where EDG tests and three

common in-situ density tests (nuclear density gauge, sand cone, and drive cylinder) were performed to provide comparative results.

In addition, the effect of temperature on EDG electrical measurements was explored using the “large-molds” and alternative temperature correction and calibration procedures were investigated as well. The findings from this study provide guidance for interpreting the results from future electrical density gauge studies, and are useful for engineers that may be considering the use of this technology for compaction control.

Chapter 1

INTRODUCTION

Compacted soil is a vital element in the construction of highways, airports, buildings, sewers, and bridges. Therefore, measurements of in-situ soil density and moisture content are commonly used to control the process of soil compaction in the construction industry. Various methods currently exist to monitor compaction in soils.

In the State of Delaware the current approach that is used compares measurements of in situ soil density and moisture content with measurements of soil density and moisture content that are obtained from a standard-energy compaction test approach (1-Point Standard Proctor Compaction). Measurements of in situ soil density and moisture content are typically obtained via a nuclear density gauge (NDG). The results of NDG tests exhibit significant scatter when compared to previous in-situ density test standards (e.g. sand cone tests, rubber balloon tests, etc). Despite these characteristics of the test, the nuclear density gauge has become the accepted industry standard for quality control of soil compaction. This is because tests can be taken rapidly and are much easier to perform than other density-based quality control tests. In addition to the inherent inaccuracies of NDG testing, there are significant regulatory compliance issues that are present when dealing with NDG test equipment. The NDG contains radioactive material, which is heavily regulated by the Nuclear Regulatory Council. This regulation requires strict protection standards for employees working with the equipment. Particularly for large-scale NDG operations, such as those at the Delaware DOT, these nuclear regulatory issues can present a significant obstacle to operations, and compliance can be difficult. Thus, using a non-nuclear based approach for in-situ density testing has become more desirable.

Recent technological innovations currently provide many alternative opportunities to use non-nuclear technology for compaction control. Some non-nuclear methods to monitor soil moisture currently exist and methods to measure density for geotechnical engineering applications are being developed as well. Time domain reflectometry (TDR), capacitance sensors, and electrical impedance spectroscopy (EIS) are some of the methods that are currently utilized.

A relatively new non-nuclear alternative is the electrical density gauge (EDG), which uses a series of electrical measurements in conjunction with calibrated soil models to infer in-situ soil density and moisture content. Two approaches currently exist for building soil models with the electrical density gauge: the first is calibration with in-situ measurements of density and water content provided by the nuclear density gauge or the sand cone test, and the second is calibration with "large mold" Proctor-type tests.

In order to evaluate the accuracy of the EDG and to assess whether the instrument can and should be implemented for the Delaware Department of Transportation, two experimental studies have been performed. In the first phase of this project, in-situ measurements of soil on active construction projects were taken. After considerable time trying to get the necessary data on active construction projects to fairly assess the EDG, it was determined that this was not feasible. The inability to control moisture content and temperature of the soil in the field, as well as the demands of contractors to not slow down progress on projects led to a second experimental study. Large box testing of soil in conjunction with large mold testing was performed to acquire the necessary data to evaluate the accuracy of the EDG.

The goal of this thesis is to present the results from the aforementioned research project, providing a detailed description of the activities that were performed from the beginning to the end of this project. In Chapter 2, a summary of relevant literature that was reviewed will be presented. In Chapter 3, the operating principles and basic fundamentals of the EDG will be explained. In Chapter 4, the initial experimental field studies that were performed will be explained in detail. Results from the experimental studies will be presented and explained in Chapter 4 as well. In Chapter 5, "large mold" calibration procedures and testing results will be explained in detail. Experimental studies simulating field conditions undertaken in "large box" tests will be presented and explained in Chapter 6. The procedure and basic results of the temperature testing experiments performed on the molds is presented in Chapter 7. A new temperature correction algorithm is developed from the data acquired in Chapter 7 and applied to various data sets from this research study and the results are presented in Chapter 8. Alternative calibration procedures combined with the newly developed temperature correction algorithm are applied to various data sets from this research study and the results are presented in Chapter 9. Ultimately, Chapter 10 provides the most significant conclusions from this research project and recommendations for future research in this area. The findings from this research project will provide guidance for interpreting the results from future electrical density gauge studies, and are useful for engineers that may be considering the use of this technology for compaction control.

Chapter 2

LITERATURE REVIEW

2.1 In-Situ Moisture Content and Density Testing

The compaction of soil in embankments, subbase or base course layers is one of the most important aspects of construction of highways, buildings, sewers, bridges, and airports. In order to ensure that soil is placed as specified and with uniformity, frequent testing of the compacted soil is necessary. Using conventional quality assurance / quality control (QA/QC) procedures, this testing typically requires that the in-place dry density (or dry unit weight) of the soil be measured along with the soil moisture content (e.g., DelDOT 2001). The measured in situ density is compared to a specified reference value, which is typically determined as a percentage of the standard (or modified) Proctor density value (ASTM D 698, ASTM D 1557). The measured in situ moisture content is typically required to be within a specified range of the optimum moisture content (e.g., $\pm$ 2%), which is determined as a percentage of the standard (or modified) Proctor optimum moisture content value (e.g., DelDOT 2001).

The standard approach used for controlling the degree of compaction in soil is to measure the in situ dry density (or dry unit weight) and moisture content of the compacted soil at random locations throughout the area of construction. The measured values are then compared with acceptable ranges of dry unit weight and moisture content for that specific material. Two methods to specify a target range for the dry unit weight and moisture content exist.

The first method is the 5-pt Proctor test, in which five or more specimens are compacted in a uniform, controlled manner at different moisture contents. After the compaction tests are performed, the moisture contents and dry unit weights of the specimens are determined. A compaction curve derived from the measured data is then plotted that shows the relationship between the measured dry unit weight and the water content. From this curve, a maximum dry unit weight can be determined, and this value and the corresponding optimum moisture content for compaction are recorded. In general, two types of 5-point Proctor tests are commonly used; the standard Proctor test (ASTM D 698) and the modified Proctor test (ASTM D 1557).

The second method is the 1-pt Proctor test (AASHTO T 272) in which only one compaction test is performed and the resulting dry unit weight and moisture content are used with a group of compaction curves to determine the optimum moisture content and maximum dry unit weight. The group of curves that are used for a given soil are developed over time, based on long-term experience with 5-point Proctor tests for a given borrow material. Consequently, it is necessary to have a separate group of curves for each material type that is placed.

Values of dry unit weight obtained from in situ measurements on a compacted lift are then divided by the maximum dry unit weight that is achieved from either the 1-point Proctor or 5-point Proctor, providing the relative compaction (RC), which is also commonly referred to as the degree of compaction. The measured field moisture content (ω_{field}) is compared with the optimum moisture content (ω_{opt}) obtained from either the 1-point Proctor or 5-point Proctor. Both the relative compaction and moisture content must meet the corresponding acceptance criteria (e.g. RC $\geq$ 95% and $\omega_{opt} - 2\% \leq \omega_{field} \leq \omega_{opt} + 2\%$ (DelDOT 2001), otherwise compaction of the lift that was placed in the field must be repeated. As noted above, the most commonly used methods for compaction control use measurements of in situ soil density and moisture content to assess the effectiveness of the compaction process. The most common in situ tests that are utilized with this approach are the nuclear density gauge test (ASTM D 6938-10), the sand cone test (ASTM D 1556-07), and the rubber balloon test (ASTM D 2167-08).

2.1.1 The Nuclear Density Gauge Test

The nuclear density gauge (Figure 2.1) is currently one of the most commonly used devices to determine the in situ unit weight and water content of soil (ASTM D 6938-10). Nuclear density gauges are relatively simple to use, determine soil characteristics rapidly, and are relatively accurate (e.g., Randrup et al 2001). However, there are strict regulations with respect to the handling, transport, and storage of these devices because they contain radioactive material. This has led to ongoing research into non-nuclear alternatives for speedy determination of in situ unit weight and water content of compacted soils (e.g., Electrical Density Gauge, Soil Density Gauge (Transtech)).

Figure 2.1 Troxler 3440 Nuclear Density Gauge

The nuclear density gauge is a measuring device that is used to indirectly measure in-situ dry density and moisture content of aggregate and soil layers by means of radioactive particles emitted into the ground. A typical nuclear density gauge consists of a 20 cm or 30 cm (8 or 12-in.) retractable rod, a Geiger-Muller detector, and a display screen. The nuclear gauge can operates in two different ways, the backscatter mode and the direct transmission mode (Figure 2.2). In the backscatter mode, the nuclear source and probe are both located on the ground surface. When operating in direct transmission mode, a retractable rod with a nuclear source is placed in the ground, while the detector remains located on the ground surface. The direct transmission mode is considered more accurate and is always used on soil density tests. Backscatter mode is mostly used for testing asphalt, concrete, and materials that cannot be penetrated easily such as densely compacted stone.

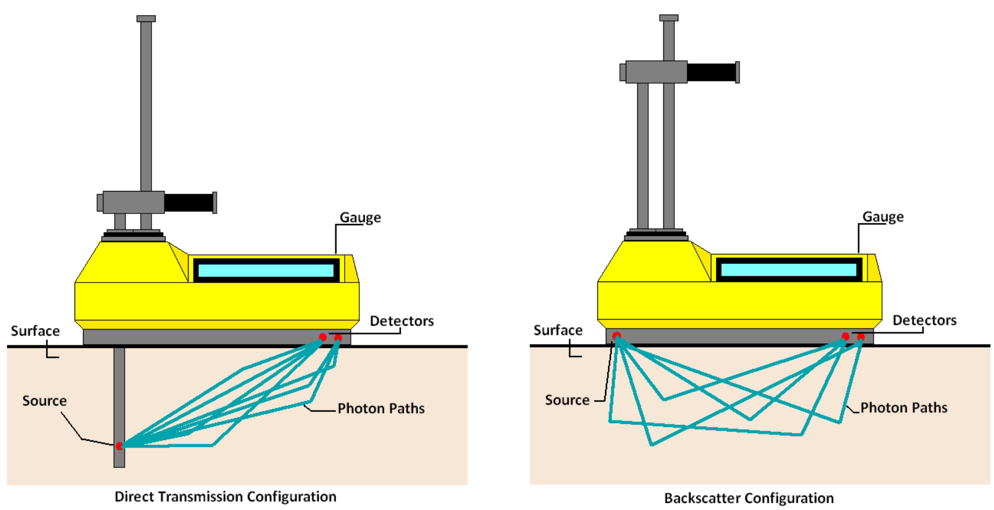


Figure 2.2 Nuclear Density Gauge Transmission Modes (modified from Troxler Model 3430 Manual of Operation and Instruction, 1990-2006)

In order to measure in situ unit weight, an isotope source, usually Cesium 137, is fixed upon the end of the retractable rod, where it continuously emits photons and gamma rays. The gamma rays interact with electrons in the base material and are counted when they return to the Geiger-Muller detector. The lower the number of photons measured by the detector, the higher the density of the material being tested.

For measurement of in situ moisture content, neutrons emitted by the radioactive source are thermalized by contact with hydrogen atoms. Thermalization is the loss of kinetic energy to the degree that further collisions with hydrogen or other materials will not continue to slow the neutron. Since the neutron detector in the nuclear density gauge is sensitive only to thermalized neutrons, the returning neutron count obtained by the detector is directly proportional to the hydrogen count and subsequently to the water content of the material. Moisture measurements typically utilize Americium-241:Beryllium as a source neutron emitter in conjunction with a neutron detector referred to as an He-3 tube, which is used due to its high sensitivity to thermalized neutrons and insensitivity to fast neutrons. When the gauge is placed on an area to be measured, the neutrons emitted by the Americium 241: Beryllium source are thermalized by hydrogen molecules contained in the measured material and these thermalized neutrons are detected by the He-3 tube and displayed as the moisture count.

Nuclear density gauges undergo an initial calibration every day using a reference block. The reference block is made of polyethylene due to the presence of hydrogen in the molecular structure of the material. The hydrogen molecules in the block simulate a specific amount of water, which is what the gauge detects during calibration testing. Since the polyethylene block’s molecular structure does not change and is very consistent, it is used for the daily standard calibration count. Standardization involves recording four readings on a reference block, and computing their mean value. Then a comparison to the current standardization count is performed, and if it falls with the acceptable limits outlined in ASTM D 6938-10, the gauge is acceptable to use. This process is done to ensure that the gauge is performing accurately and consistently from day to day.

2.1.2 The Sand Cone Test

The sand cone test is a sand replacement method for determining the in situ unit weight or density of natural or compacted soil (ASTM D 1556-07). This method is limited to materials with a maximum particle size of 5.1 cm (2 in) and is applicable for soils without appreciable amounts of rock or coarse materials in excess of 38 mm (1.5 in.) in diameter as well. This test method is not recommended for soils that are soft and crumble easily or in conditions where water can seep into the hand excavated hole (ASTM D 1556-07).

Figure 2.3 Sand Cone apparatus

To perform a sand cone test, a hole is excavated by hand with a small shovel in the area where the soil has been compacted. The dry weight of the soil is obtained by determining the weight of the moist soil that is excavated from the hole and its moisture content. The moisture content is typically determined by standard oven-drying procedures, or can be done in the field with a hot plate or microwave (e.g., ASTM D 2216-10, ASTM D 4643-08). The volume of the excavated hole is determined by filling the hole with a uniform sand. The sand cone apparatus (see Figure 2.3) is used to fill the hole and is weighed before and after the placement of sand to determine the volume of sand that is in the hole. The in situ dry unit weight of the soil is then calculated by dividing the dry weight of the soil by the volume of the hole.

2.1.3 The Rubber Balloon Test

The rubber balloon test for in-situ soil density testing (ASTM D2167-08) is very similar in principle to the sand cone method. As with the sand cone test, a hole is excavated by hand with a small shovel in the desired location and the soil removed from the hole is stored in an air-tight container for weight and moisture content determination. An apparatus consisting of a graduated cylinder and rubber balloon (see Figure 2.4) is used to measure the volume of fluid that is needed to fill the excavated hole.

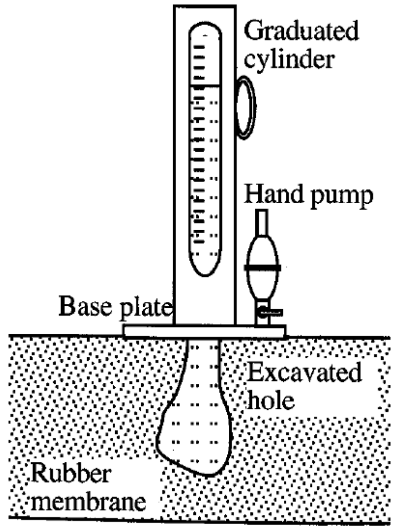


Figure 2.4 Rubber Balloon Test Apparatus

This test method can be used to determine the in-place density and unit weight of natural soil deposits, soil-aggregate mixtures, or other similar materials. The use of this test method is limited to soil with low water contents and is not recommended for soils that are soft or deform easily. Certain soils may undergo a volume change when pressure is applied during testing. Soils with crushed rock or jagged edges are not suitable for this test because they may puncture the rubber balloon membrane as well.

2.1.4 Time Domain Reflectometry (TDR)

The time domain reflectometry (TDR) method of monitoring subgrade water content was introduced in the area of pavement engineering around 1989 (Neiber and Baker 1989). A TDR measurement system typically includes a transmission line, a coaxial connecting cable, a TDR instrument, and probes inserted in the soil. A typical TDR setup in the field is shown in Figure 2.5.

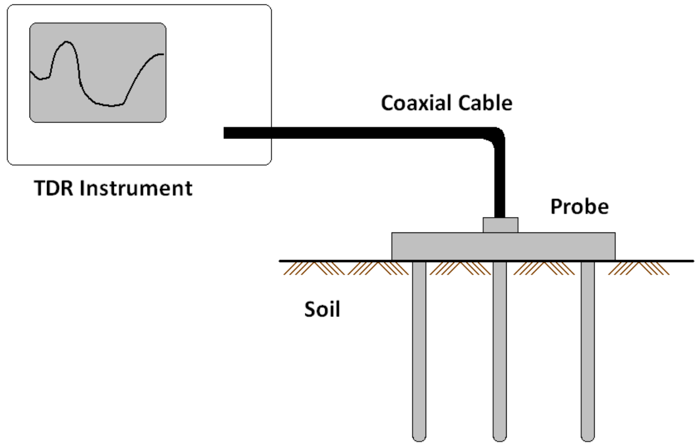


Figure 2.5 Typical TDR Field Setup (modified from Yu et al 2006)

The TDR method measures the velocity of an electromagnetic wave travelling in a transmission line. The velocity (v) of the wave running through the line is related to the apparent dielectric constant (K_a) of the insulating medium between the conductors of the transmission line (Krauss 1984). The associated relationship is as follows (Equation 2.1):

$$v = \frac{c}{\sqrt{K_a}} \tag{2.1}$$

where c is the velocity of light in a vacuum and K_a is given by Equation 2.2

$$K_a = \frac{K'}{2}\left(1 + \sqrt{1 + \left[\frac{K'' + \frac{\sigma_{dc}}{\omega\varepsilon_0}}{K'}\right]^2}\right) \tag{2.2}$$

where ω is the angular frequency, ε_0 is the permittivity of a vacuum, K' and K'' are the real and imaginary parts of the complex dielectric constant, and σ_{dc} is the direct current electrical conductivity.

When used in soil science and geotechnical engineering applications, the TDR probe is the transmission line and the insulating medium is the soil. The TDR instrument sends a step voltage pulse through the coaxial cable and when the signal reaches the beginning of the probe, part of the pulse is reflected back to the TDR instrument. This occurs because of a mismatch in impedance between the coaxial cable and the soil probe. When the remaining portion of the signal reaches the end of the probe, a reflection of the signal occurs again. Both reflections cause two discontinuities in the signal which is recorded by the TDR instrument, and the time difference between these two discontinuities is the time (*t*) required by the signal to travel twice the length (L) of the probe in the soil. Therefore the wave propagation velocity in the soil is represented by Equation 2.3:

$$v = \frac{2L}{t} \tag{2.3}$$

The dielectric constant of the soil is represented by Equation 2.4:

$$K_a = \left(\frac{ct}{2L} \right)^2 \tag{2.4}$$

Topp et al. (1980) developed an empirical relationship that is based on a correlation between the dielectric constant of a soil and its volumetric water content (θ). The following equation describes this relationship (Equation 2.5, Topp et al. 1980):

$$\theta = -0.053 + 2.92\times10^{-2}K_a - 5.5\times10^{-4}K_a^2 + 4.3\times10^{-6}K_a^3 \quad (2.5)$$

The equation above can be used for all types of soils, but more specific equations for different soil types exist as well. For geotechnical engineering applications, gravimetric water content is more commonly used. The following relationship exists between volumetric and gravimetric water content (Equation 2.6):

$$w = \theta\frac{\rho_w}{\rho_d} \quad (2.6)$$

where ρ_d and ρ_w are the dry density of soil and water respectively.

Siddiqui and Drnevich (1995) have been able to extend TDR to geotechnical applications. They developed a calibration equation relating soil gravimetric water content and dry density to apparent dielectric constant. With the use of their calibration equation, they designed a procedure that uses a TDR approach for geotechnical compaction control. First, a laboratory calibration is performed to obtain constants that are dependent on soil type for further field measurements. Calibration is performed in conjunction with compaction tests to create compaction quality control criteria. The procedure in the field consists of two TDR tests. One TDR test is taken with a probe with four coaxially configured spikes driven into the soil, and one test is conducted in a compaction mold on the same soil that was immediately excavated from within the four spikes and hand compacted into the mold. The gravimetric water content for both tests, the apparent dielectric constants from both TDR readings, and the measured total density of the soil in the mold are used to calculate soil water content and dry density. Laboratory and field evaluations indicate the method has sufficient accuracy for geotechnical purposes (Lin 1999; Siddiqui et al. 2000; Drnevich et al. 2001a, 2002). ASTM D6780 currently exists to govern the use of TDR for typical geotechnical engineering compaction control applications.

2.1.5 Capacitance Sensors

Capacitance sensors or dielectric sensors (e.g., Figure 2.6) use capacitance to measure the dielectric permittivity of materials (e.g., Kelleners et al 2004). Capacitance sensors are configured similarly to neutron probes in which a tube made of PVC is installed and inserted into the soil (Kelleners et al 2004). The probe inside the tube is made up of a sensing head that is located at a fixed depth. Within the sensing head are an oscillator circuit, an annular electrode, and a fringe-effect capacitor, which are used in determining the dielectric constant of the soil. The capacitance sensors are made up of two metal rings that are attached to a circuit board at a specific distance from the top of the PVC access tube. The metal rings form the plates of the capacitor and are connected to an oscillator circuit. An electrical field is generated by the oscillator circuit between the two metal rings and flows from the walls of the access tube into the soil. The oscillator circuit and the capacitor form a circuit and detect changes in the dielectric constant of the material within the access tube by changing the operating frequency. Most capacitance sensors are designed to oscillate in excess of 100 MHz inside the access tube, and the output of the sensor is the frequency response of the soil's capacitance due to the moisture content in the soil.

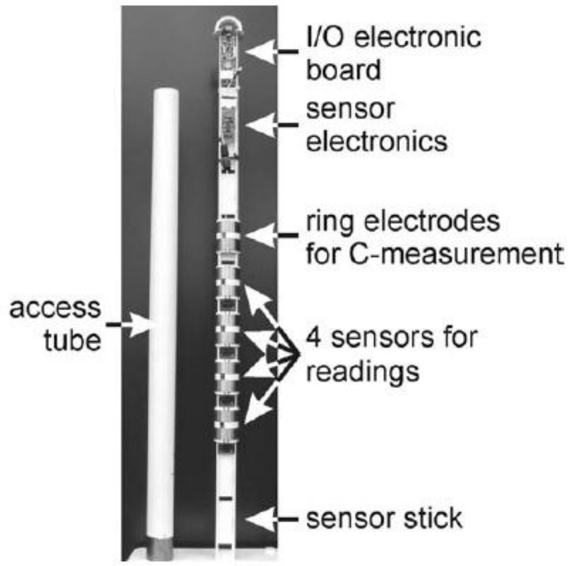


Figure 2.6 Capacitance Sensor (modified from Schwank et al. 2006)

The resonant frequenct of an oscillator circuit that includes the soil is represented by the following equation (Equation 2.7) (Kelleners et al. 2004, Fares et al. 2007):

$$F = \left[2\pi \sqrt{L\left(C_s + \frac{C_p C_m}{C_p + C_m} \right)} \right]^{-1} \tag{2.7}$$

where C_m, C_p, and C_s are the capacitances of the medium, plastic access tube, and capacitance due to stray electric fields, respectively. The observed frequency is used to determine the scaled frequency, SF, by the following equation (Equation 2.8):

$$SF = \frac{F_a - F_s}{F_a - F_w} \tag{2.8}$$

where F_a, F_w, F_s, are the frequency readings of the sensor inside the plastic tube of air, water, and soil respectively at room temperature.

The value of the scaled frequency varies between 0 and 1 depending on the ratio of air to water in the soil medium. The scaled frequency value is the used in a calibration equation to estimate the soil water content. The following equation (Equation 2.9) is one empirical equation that has been developed that can be used to estimate the volumetric water content using a capacitance sensor (Fares et al. 2007):

$$\theta_v = \left(\frac{SF - 0.02852}{0.1957} \right)^{\frac{1}{0.404}} \tag{2.9}$$

Currently, capacitance sensors are being tested and used mainly by soil scientists to monitor and measure the moisture content of soils for agricultural purposes.

2.1.6 Electrical Impedance Spectroscopy

The Soil Density Gauge (SDG) manufactured by Transtech Systems employs Electrical Impedance Spectroscopy (EIS) to infer the density and moisture content of soil. EIS measures the dielectric properties of a medium as a function of frequency. EIS theory is based on the interaction of an external electrical field with the electric dipole moment of the medium (Gamache et al. 2009). This method measures the impedance of a medium over a range of frequencies. The frequency response of the system is captured and various relationships can be deciphered from these responses.

In soil, the electromagnetic response is primarily determined by the dielectric properties of the materials in the soil. The non-uniformity of the soil combined with interfacial effects between polar water molecules and soil solids results in a complex electrical response. The three primary polarization mechanisms in soil that contribute to this response are bound water polarization, double layer polarization, and the Maxwell-Wagner effect. Since water can be electrostatically bound to the soil matrix it contributes heavily to the measured complex electrical response. The separation of cations and anions, which leads to double layer polarization, occurs more frequently in soils with large clay fractions. In addition, the Maxwell-Wagner effect is the most critical phenomenon that affects the low radio frequency dielectric spectrum of soils. The Maxwell-Wagner effect depends on the differences in dielectric properties of the soil elements resulting from the distribution of non-conducting and conducting areas in the soil matrix (Gamache et al. 2009).

TransTech Systems has found that well-graded sandy soils suitable for engineering fill exhibit a single Maxwell-Wagner relaxation in the 1-10 MHz range. In frequency ranges above this, the dielectric response is described by using empirically derived mixing equations in which the matrix bulk dielectric constant is proportional to the sum of the products of the volume fractions and dielectric constants of the soil elements. When soil undergoes compaction, the volume fraction of air is reduced and the volume fractions of soil and water are increased, which results in an increase in both the permittivity and conductivity of the soil (Gamache et al. 2009). Through detailed study, Transtech Systems has learned that certain characteristics of the impedance response in the Maxwell-Wagner portion of the spectrum can be used in a parametric inversion method to measure wet density and volumetric moisture content (Gamache et al. 2009). Specific parameters in the impedance response contain moisture and density information and are converted to wet density and volumetric moisture content using simple regression analysis. In the current model, specific parameters related to soil type and gradations at each job site are used to adjust the standard laboratory calibration equations (Gamache et al. 2009).

2.2 Statistical Analyses of Standard In-Situ Density Tests

In order to have a better understanding of the accuracy and relative error of the most common in-situ soil density tests, a review of previously published test studies was performed.

2.2.1 Comparisons of Field Density Test Results (Kaderabek & Ferris 1979)

Kaderabek & Ferris (1979) describe the results from compaction control tests conducted during a large earthwork project in Georgia, where 6 test fill areas were constructed to investigate compaction procedures. Proctor tests were performed at each field density test location, as well as nuclear density tests and sand cone tests. At each test fill location either 24 or 30 nuclear density gauge tests and 24 or 30 sand cone tests were performed. Two different soil types were used in the construction of the test fill areas: Slightly silty slightly clayey fine to medium sand (SM) (Stockpile A-Test Fill Numbers 3, 4 & 5), and slightly silty fine to medium sand (SM-SW) (Stockpile C-Test Fill Numbers 1, 2 & 6) (Kaderabek & Ferris 1979).

In order to evaluate the relative agreement of testing parameters for both the nuclear density gauge and sand cone tests, the standard deviation of each type of test at each test fill location were compared. Figures 2.7 through 2.9 show the standard deviation of moist unit weight, moisture content, and relative compaction for the NDG and SC tests that were performed at all test fill locations. The standard deviation of moist unit weight test values for the NDG is greater than the standard deviation of the SC method values at 5 of the 6 test fill locations. In terms of moisture content, the NDG standard deviation is nearly double the standard deviation of the SC method (oven dried). The standard deviation for relative degree of compaction is approximately equal for the nuclear density gauge and sand cone method. Table 2.1 and Table 2.2 list all the values that were used to generate the figures in this section.

The overall conclusion derived from this test study is that the sand cone method determines dry unit weight and moist unit weight that are consistently greater than the values measured by the nuclear density gauge. In addition, the moisture content values measured by the sand cone method (oven dried) are lower than the values determined by the nuclear density gauge. Also, the standard deviation of the nuclear density gauge when measuring moisture content is nearly double the standard deviation of the sand cone method (oven dried).

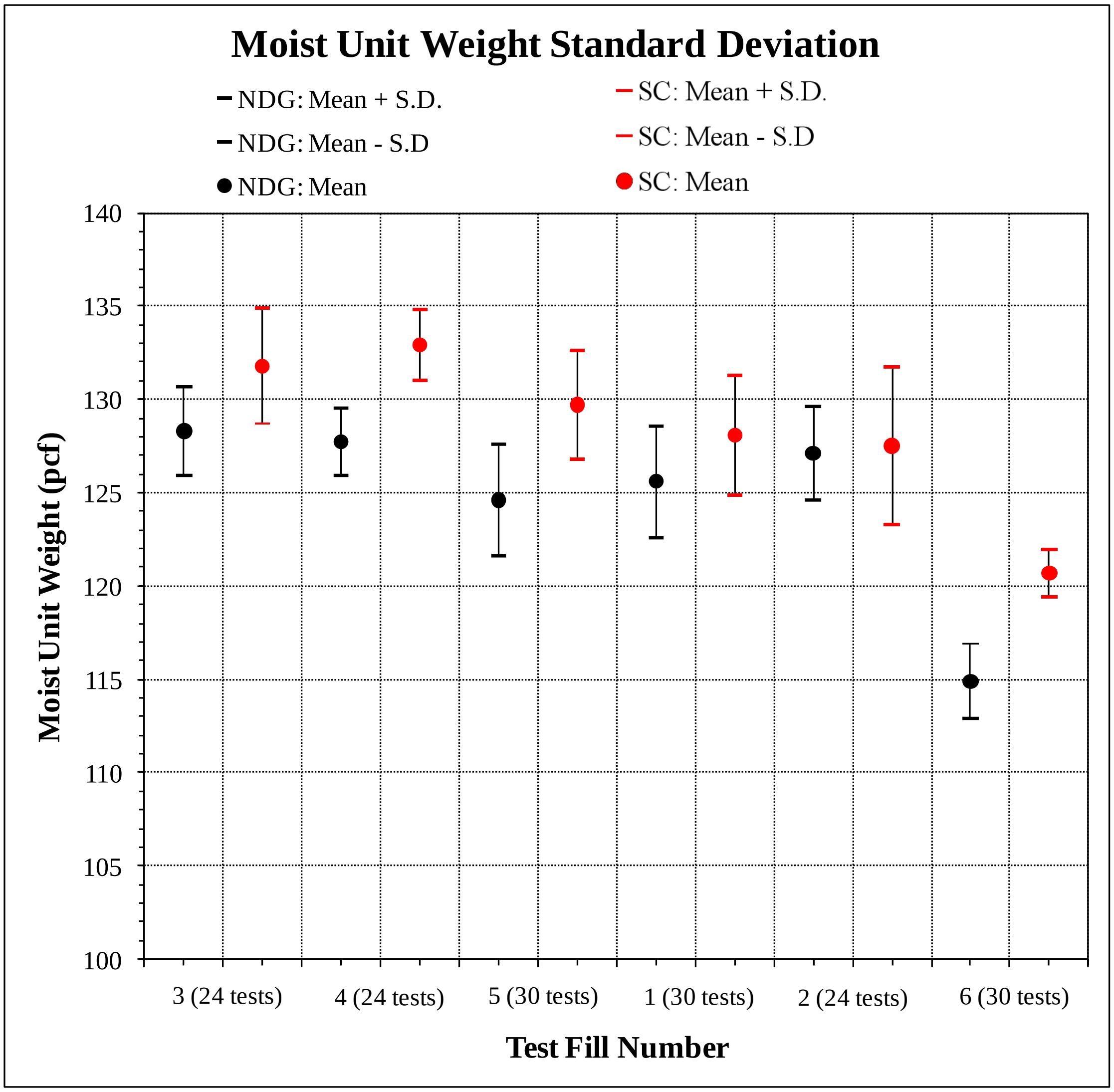


Figure 2.7 Moist Unit Weight Standard Deviation (Data from Kaderabek & Ferris, 1979)

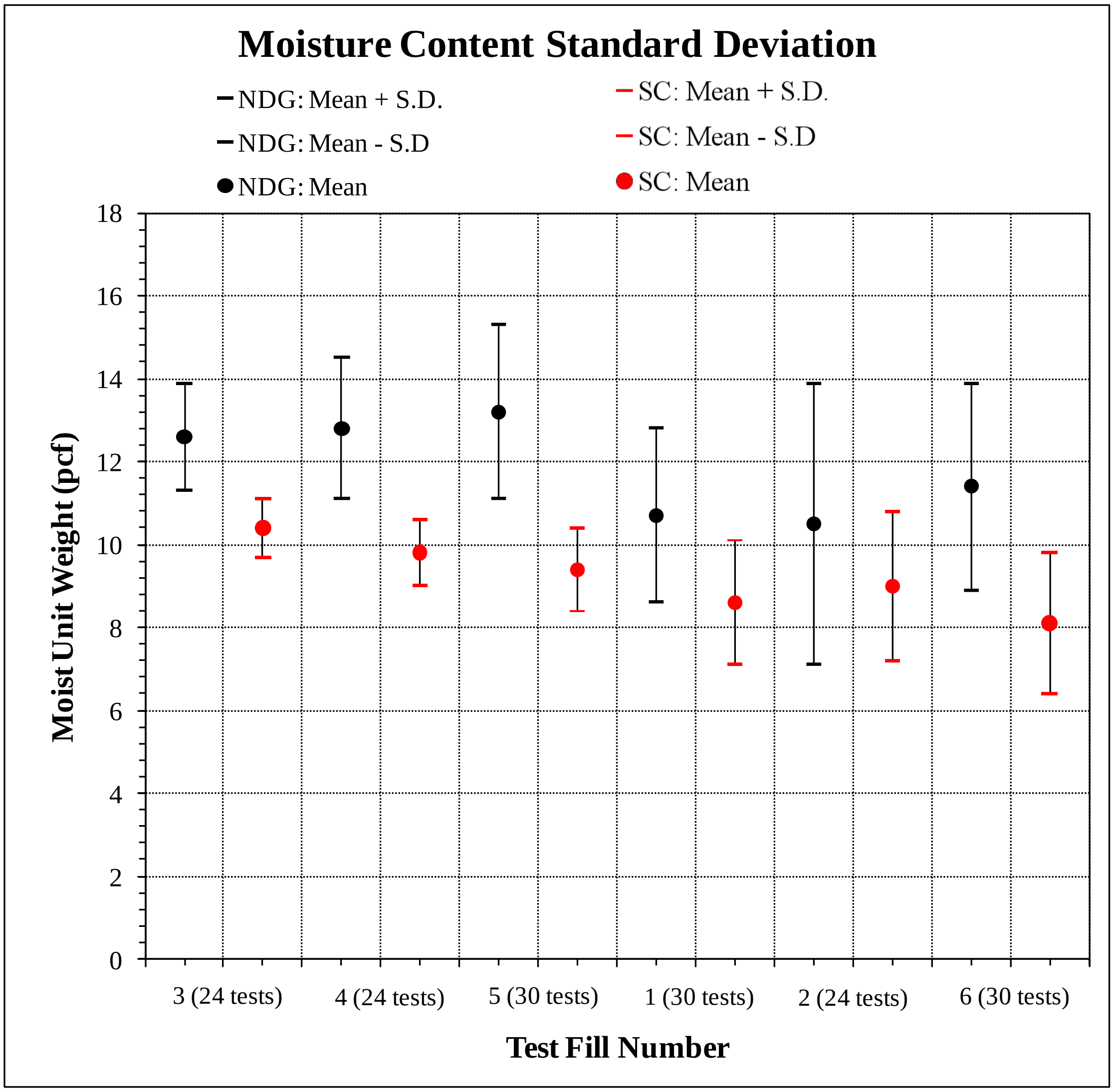


Figure 2.8 Moisture Content Standard Deviation (Data from Kaderabek & Ferris, 1979)

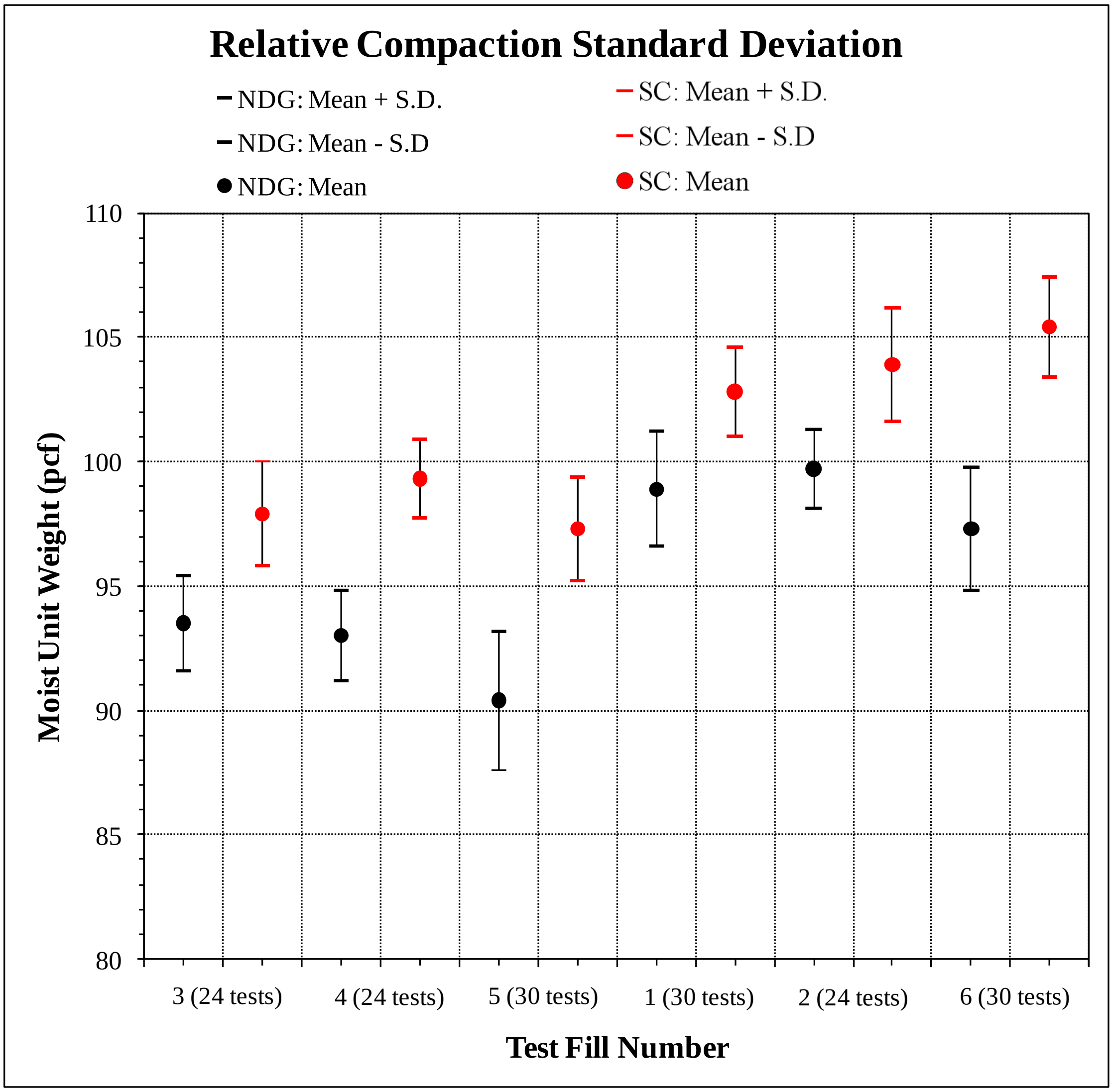


Figure 2.9 Relative Compaction Standard Deviation (Data from Kaderabek & Ferris, 1979)

Table 2.1 Nuclear Density Gauge data (Kaderabek & Ferris 1979)

Nuclear Density Gauge						
Test Fill Number	**Moist Unit Weight (pcf)**	**S.D.**	**Moisture Content (%)**	**S.D.**	**Relative Compaction (%)**	**S.D.**
3 (24 tests)	128.30	2.40	12.60	1.30	93.50	1.90
4 (24 Tests)	127.70	1.80	12.80	1.70	93.00	1.80
5 (30 Tests)	124.60	3.00	13.20	2.10	90.40	2.80
1 (30 Tests)	125.60	3.00	10.70	2.10	98.90	2.30
2 (24 Tests)	127.10	2.50	10.50	3.40	99.70	1.60
6 (30 Tests)	114.90	2.00	11.40	2.50	97.30	2.50
Average		2.45		2.18		2.15

Table 2.2 Sand Cone Method data (Kaderabek & Ferris 1979)

Sand Cone Method						
Test Fill Number	**Moist Unit Weight (pcf)**	**S.D.**	**Moisture Content (%)**	**S.D.**	**Relative Compaction (%)**	**S.D.**
3 (24 tests)	131.80	3.10	10.40	0.70	97.90	2.10
4 (24 Tests)	132.90	1.90	9.80	0.80	99.30	1.60
5 (30 Tests)	129.70	2.90	9.40	1.00	97.30	2.10
1 (30 Tests)	128.10	3.20	8.60	1.50	102.80	1.80
2 (24 Tests)	127.50	4.20	9.00	1.80	103.90	2.30
6 (30 Tests)	120.70	1.30	8.10	1.70	105.40	2.00
Average		2.77		1.25		1.98

2.2.2 Comparative Accuracy of In-Situ Nuclear Density Testing (Ishai & Livneh 1983)

Ishai and Livneh (1983) performed a field study to assess field density testing approaches during the construction of the Etzion and Ouvda Airports in southern Israel in 1983. In order to evaluate the accuracy of the nuclear density gauges, Ishai & Livneh felt it was necessary to study the accuracy of the conventional sand-cone density test and oven-drying moisture test first.

Conventional sand-cone density and oven-drying moisture tests were performed on four road sections of the Tel Aviv-Haifa freeway on clay subgrade, sandstone subbase, and limestone-dolomite base courses. The following conclusions were determined from this initial study:

1) There is significant variability in field density and moisture content values due to the inherent variable nature of material, and due to human errors in measurement. Coefficients of variation were as high as 8% for density.
2) Comparisons between two testing operators showed that the criterion for maximum deviation in field density and moisture content were not fulfilled in 85% of the cases, signifying the effect of human errors in measurement on results.

After the initial study analyzing conventional density and moisture testing was performed, a second study was carried out. A test section of 24 meters by 45 meters was constructed in which the following tests were performed: two sand cone tests by two operators at the same time (Series A - 21 tests), two sand cone tests by two operators at different times (Series B - 18 tests), which were conducted not knowing in advance that a second test would be taken, and nuclear density gauge tests that utilized the backscatter method (Series C - 18 tests). The following conclusions were determined from the second phase of this study:

1) Significant scatter in wet density results from sand cone tests were obtained, mainly caused by material variability, construction and human factors. The maximum coefficient of variation for wet density was 37%.
2) More variability was observed in Series A than in Series B. This occurred mainly because each operator knew that he would be checked by a second test and operator.
3) The accuracy of the sand cone and oven-drying method is not highly accurate, as many engineers typically assume. In addition, accuracy in the oven-drying test was found to be higher in granular material than that in fine-grained plastic materials.

The final phase of this study was aimed at evaluating the accuracy and repeatability of the nuclear density gauge. The following conclusions were determined from the final phase of this study:

1) The repeatability characteristics of the nuclear density gauge were very high. In most cases, the standard deviation for moist unit weight did not exceed 0.20 kN/m^3.
2) The repeatability characteristics of moisture content for the nuclear density gauge were still relatively high (e.g., their probability of deviating more than 0.16 kN/m^3 was between 2 and 67 percent); however, the observed repeatability was lower than that which was observed for the moist unit weight.

Ultimately, the final conclusions Ishai & Livneh determined from their study were:

1) The material presented in this study cannot lead to the conclusion that the nuclear method for density and moisture content is more accurate than the conventional tests, due to the fact that it is not possible to repeat a sand cone or oven-drying moisture test in the same exact location. This inherently leads to a natural variability due to material composition.
2) The repeatability characteristics of nuclear testing are very high and justify its practical usage. Also, it is suggested that three readings taken after rotating the gauge by 120º should be averaged for most accurate results.

2.2.3 Nuclear Density Gage Tests on Soils Containing Various Sized Aggregates (Gabr et. al. 1995)

Gabr et. al. (1995) conducted a testing program on soil samples containing varying amounts of pre-sized limestone aggregates in order to investigate the accuracy of the nuclear density gauge (NDG) in gravelly soils. In this study, test specimens of known density were compacted with a 10 kg weight from a height of 0.61 meters in a 0.56 x 0.71 x 0.58 meter (width, length, height) acrylic box. Eight (8) sand cone tests were performed on each box at various locations, and nuclear density tests were performed in the backscatter mode, and at various depths in the direct transmission mode. The major conclusions Gabr and his colleagues determined from this test study are the following:

1) Variability in density predicted by the NDG increased as aggregate size was increased. Also, NDG variability was less than sand cone tests due to the difficulty of running sand cone tests in soils containing aggregates.
2) Coefficient of determination (R^2) values between box values and nuclear values decreased from 0.92 for soil with small aggregate to 0.51 for soil with large aggregate.
3) Oven-drying provided accurate values for moisture content for all soils tested, and results from NDG tests had slightly lower correlation coefficients than those obtained using oven-drying.
4) Moisture content data from NDG tests resulted in coefficients of determination increasing with an increase in aggregate size, thus indicating that the NDG may not be affected by the presence of aggregate.

2.2.4 Evaluation of Nuclear Methods of Determining Surface In Situ Soil Water Content and Density (U.S. Army Engineer Waterways Experiment Station 1969)

The U.S. Army Engineer Waterways Experiment Station (WES) conducted a laboratory investigation to evaluate the accuracy and reliability of measuring water content and density by the backscatter and direct transmission nuclear methods. In this study, boxes (2 ft by 2 ft by 9 in.) were constructed, filled with uniformly compacted soil, and then weighed to determine actual average soil density values. Five soil types were selected for testing in order to approximate a range of possible construction materials: heavy clay (CH), lean clay (CL), sand (SP), clayey gravelly sand (SP-SC), and a well-graded crushed limestone. Each of the soils was tested at eight different densities and water contents, resulting in 40 samples. In addition, two accepted conventional methods for determining density in the field, the sand cone and rubber balloon methods, were performed. Figure 2.10 and Figure 2.11 presents 1:1 plots of moist unit weight, dry unit weight, and moisture content for all the data obtained in this test study. It should be noted that the NDG data in Figure 2.10 and Figure 2.11 is from the direct transmission (DT) mode only.

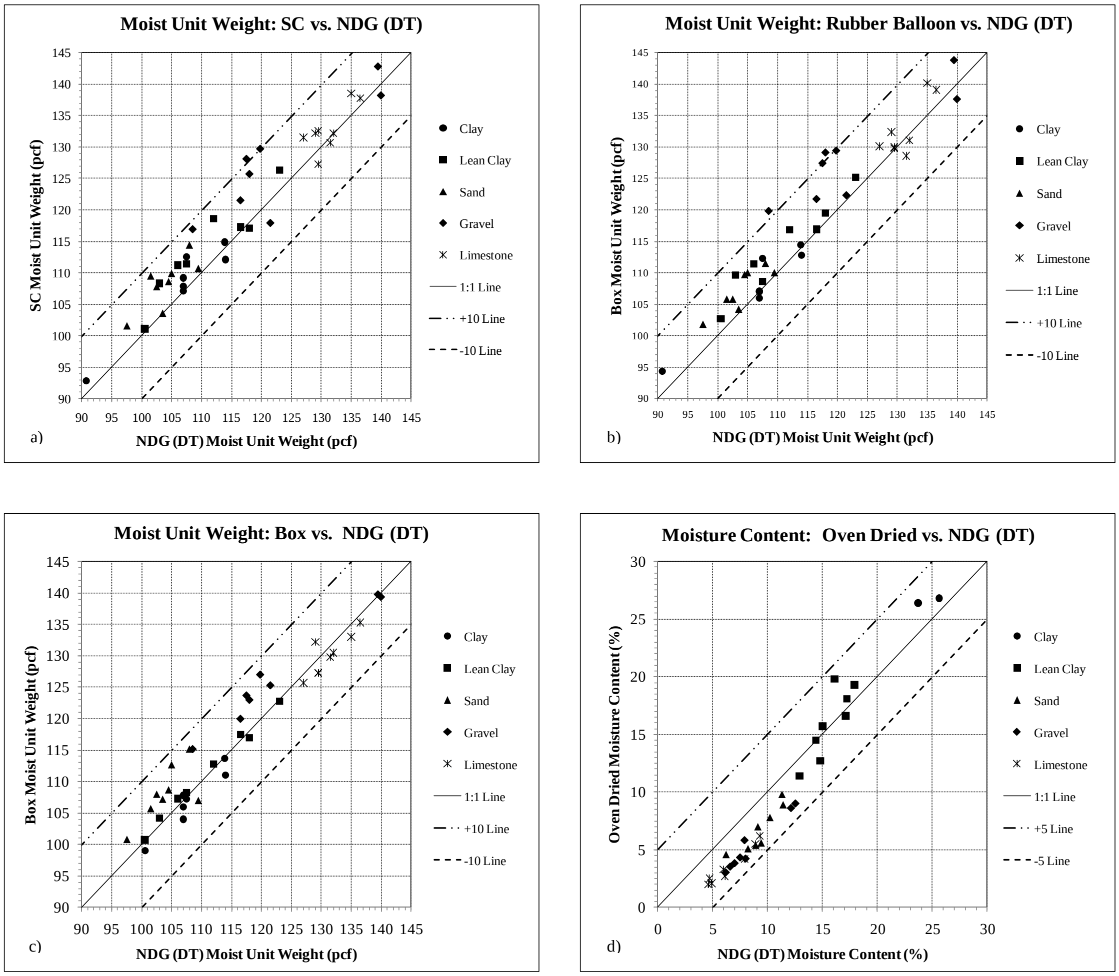


Figure 2.10 1:1 Plots – Moist Unit Weight and Moisture Content
a) Moist Unit Weight: SC vs. NDG (DT)
b) Moist Unit Weight: Rubber Balloon vs. NDG (DT)
c) Moist Unit Weight: Box vs. NDG (DT)
d) Moisture Content: Oven Dried vs. NDG (DT)

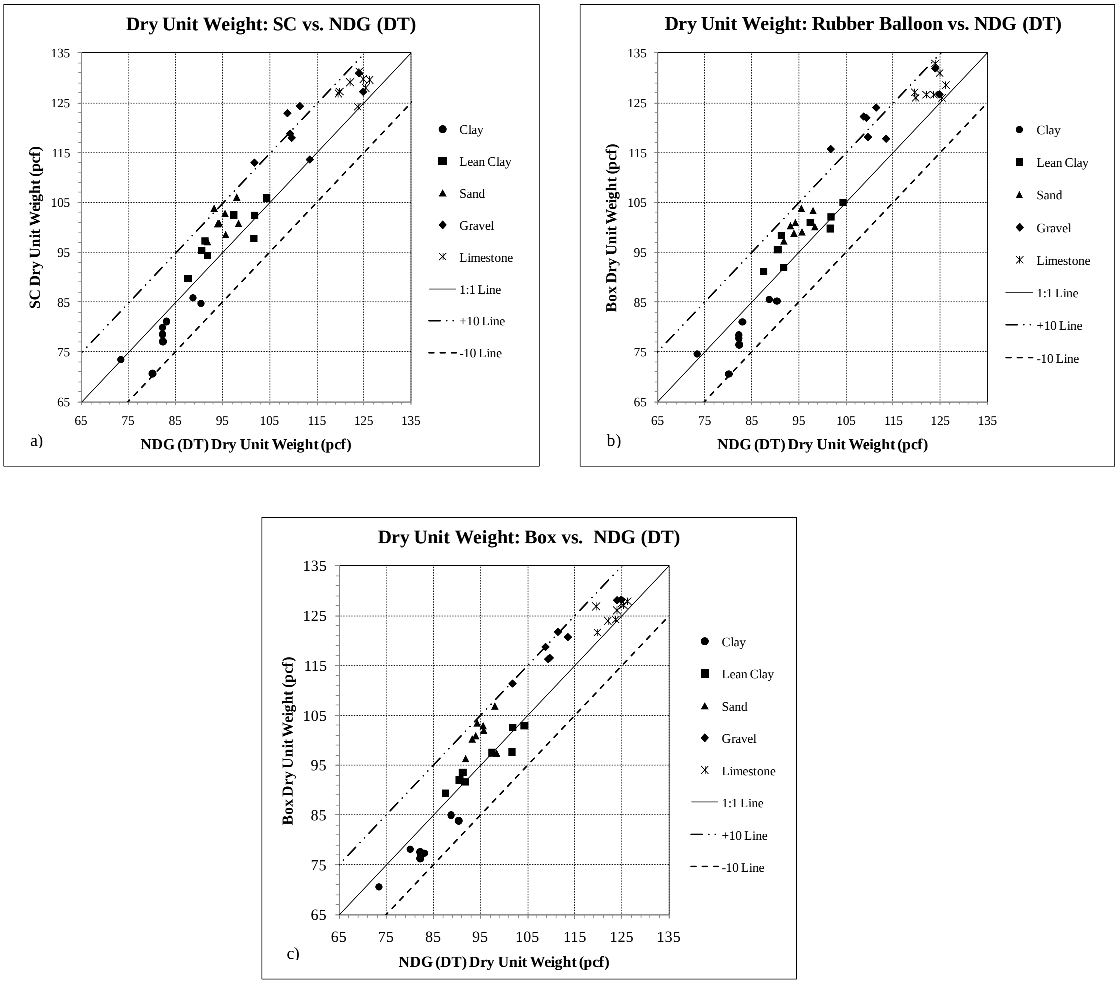


Figure 2.11 1:1 Plots – Dry Unit Weight
a) Dry Unit Weight: SC vs. NDG (DT)
b) Dry Unit Weight: Rubber Balloon vs. NDG (DT)
c) Dry Unit Weight: Box vs. NDG (DT)

Results from this test study indicated that in situ densities determined by the direct transmission (DT) nuclear method using the factory calibration curve were as accurate as the densities obtained by the sand cone and rubber balloon methods. The direct transmission nuclear method, utilizing a calibration curve developed by WES, obtained density results that were slightly more accurate than the sand cone or rubber balloon method. It should also be noted that densities determined by the surface backscatter method were not very accurate when compared to conventional methods. Water contents using the factory calibration curve were not considered accurate enough for field use (68% of nuclear water contents were within ±3.81% of oven dried water contents, and 95% were within ±7.62%). Water contents using a calibration curve developed by WES were determined to be accurate enough for field use (68% of nuclear water contents were within ±1.23% of oven dried water contents, and 95% were within ±2.46%).

2.2.5 Variability in Field Density Tests (Noorany et al. 2000)

Noorany et al. (2000) performed a comparative study of the three most commonly used field density tests: sand cone, nuclear, and drive cylinder. A large hydraulic soil compaction apparatus was constructed for this test study to compact the soil in 4 inch lifts in a 4 foot mold with an inside diameter of 46 inches. A cohesive soil with gravel up to ¾ inch that classified as a clayey sand (SC) was used for this test study. Sand cone, nuclear, and drive cylinder tests were performed in all five series of tests executed in this study. The major conclusions Noorany and his colleagues determined from this test study were the following:

1) The sand cone method was the most accurate of all of the in-situ density tests, with measured relative compaction values that were a maximum of 5% off the placement values.
2) The nuclear density gauge test had a significantly wider range of variability than any of the other tests, with measured relative compaction values that were a maximum of 10% off the placement values. It should be noted that a significant source of error in the nuclear method measurements are from the moisture content readings, which varied significantly from direct measurement of water content by the oven dried method.
3) This study pointed out that the standard procedure for calibrating the nuclear device with a density block does not guarantee accurate density and water content prediction, and that it is necessary to calibrate the nuclear device for every type of soil at every site against direct measurements made with the sand cone or a similar method. It should be noted that when the nuclear density data was adjusted based on water contents directly measured by oven drying, results were more accurate and had less variability.
4) The drive cylinder method generally underestimated the field density and relative compaction, with measured relative compaction values that were a maximum of 8% lower than the placement value. The main reason for measuring low densities in this test study was due to the presence of gravel in the soil. Gravel created voids along the side wall of the drive cylinder, thus producing lower densities when gravel had to be removed from the sample ends during the trimming process.

Chapter 3

ELECTRICAL DENSITY GAUGE OPERATING PRINCIPLES

3.1 Electrical Density Gauge

The Electrical Density Gauge (EDG) is a new product on the market that can be used for compaction control of soil on construction projects. The EDG is a lightweight and portable battery powered device that is not subject to calibration degradation over time, regulatory control, or any safety precautions. The EDG can also be referred to as a complex impedance measuring instrument (CIMI). ASTM D 7698-11, Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance was approved in March of 2011 and should be referenced when using and operating the EDG.

3.2 Operating Principles

The EDG contains a 3 MHz radio frequency source within the measurement circuit of the device. A radio frequency source is applied to the soil being tested through steel conical electrical probes that are pushed into the soil to a specific depth. A rubber hammer is used to push the 4 electrical probes into the ground in a square-shaped pattern using a plastic template, and alligator clips are then placed on each pair of electrical probes that are opposite from one another. The alligator clips are connected to an electrical soil measurement sensor that relays information to the onboard computer in the device. The EDG has a temperature probe that records the temperature of the soil as well. Electrical measurements of AC current, voltage, and phase are made between the electrical probes. Readings are taken in a cross pattern at the test location in N-S, S-N, E-W, and W-E directions, and the average values of current, voltage, and phase are then used to determine the equivalent values of soil capacitance, resistance, and impedance. Figure 3.1 displays a typical setup of the EDG.

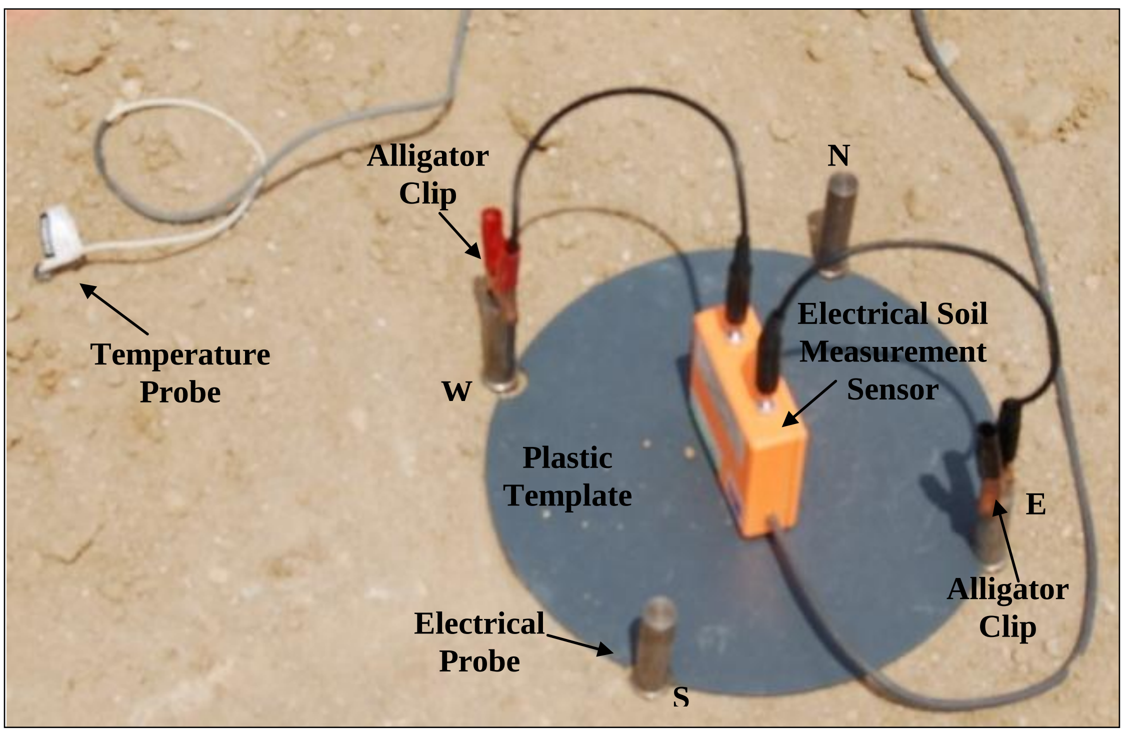


Figure 3.1 Typical EDG setup

The electrical dielectric parameters of the soil are calculated using standard electrical engineering equations that use current (I), voltage (V), and phase (θ) to determine the equivalent values of soil resistance (R) and soil capacitance (C). Once the soil resistance and soil capacitance are determined the complex impedance (Z) of the soil can be determined as well. It should be noted that a proprietary temperature compensation algorithm corrects the electrical values due to the effects of temperature if the temperature probe is used and the temperature correction mode is turned on.

From the electrical values measured and calculated by the EDG, correlations to physical soil properties obtained from the nuclear density gauge (NDG), sand cone, or other in-situ density and moisture content tests are made in order to develop a Soil Model. The following section will discuss how to create a Soil Model and the correlation relationships that are used to determine dry unit weight, moist unit weight, and moisture content at a given test location.

3.3 Field Calibration and Soil Model Development

A calibration Soil Model must be created before using the EDG for compaction control on a construction project. A Soil Model is the result of the calibration procedure that establishes a correlating linear function between measured electrical soil properties and measured physical soil properties. In order to create a Soil Model, the manufacturer recommends obtaining 6 field test points at three different moisture contents and two levels of compaction. For example, a user may want to try to obtain the following points to create a Soil Model:

1) 98% compaction at 5% moisture content

2) 98% compaction at 7.5% moisture content

3) 98% compaction at 10% moisture content

4) 92% compaction at 5% moisture content

5) 92% compaction at 7.5% moisture content

6) 92% compaction at 10% moisture content

After each EDG test is conducted at a specific test location, a NDG, sand cone, or other in-situ density test must be conducted at the same test location. The physical soil properties obtained from the NDG, sand cone, or other in situ test are then used to correlate to the electrical properties previously measured at the same test location. Once the physical soil properties are obtained from the NDG, sand cone, or other type of test they can be entered into the EDG. After all physical tests are completed and entered into the EDG, Soil Model calibration curves are developed and can be viewed on the device. The following linear calibration relationships are used to determine physical soil properties, where γ_m is the moist unit weight of soil obtained from a physical test, Z is the complex impedance determined from the EDG electrical measurements, m_1 is the slope of the linear equation obtained from correlating γ_m and Z, b_1 is the intercept of the linear equation obtained from correlating γ_m and Z, W_w is the weight of water per unit volume obtained from a physical test, (C/R) is the ratio of soil capacitance over soil resistance determined from the EDG electrical measurements, m_2 is the slope of the linear equation obtained from correlating W_w and (C/R), and b_2 is the intercept obtained from correlating W_w and (C/R):

$$\gamma_m = m_1 \times Z + b_1 \tag{3.1}$$

$$W_w = m_2 \times (C / R) + b_2 \tag{3.2}$$

It should be noted that there is an option to apply a proprietary temperature correction algorithm to the recorded values of Z and C/R, to account for the effect of temperature on the measured results. Once all calibration tests are completed and a soil model is created, the EDG is ready to be used on a field site. A new Job Site is created on the EDG, and the soil model previously developed is then assigned to the new job site (See EDG Product manual for instructions).

When an EDG test is performed in the field, the electrical properties of the specific test location are measured by the EDG and are used as input for the calibration equations that have been previously developed. The measured complex impedance (Z) and ratio of soil capacitance over soil resistance (C/R) for the given test location are plugged into the calibration equations, and the corresponding moist unit weight and weight of water per unit volume are calculated. The following standard geotechnical engineering equations are then used to determine dry unit weight and moisture content of the soil, where γ_d is dry unit weight and w is moisture content:

$$\gamma_m - W_w = \gamma_d \tag{3.3}$$

$$w = \frac{\gamma_m}{\gamma_d} - 1 \tag{3.4}$$

It should be noted that the relative compaction (in %) can also be measured by the EDG if a standard effort or modified effort compaction test (ASTM D

698-00a or ASTM D 1557-00) has been run on the soil that is being tested in the field. The maximum dry unit weight of the soil determined from the compaction test is entered into the EDG, and the percent compaction is calculated using the following equation, where RC(%) is the relative percent compaction, $\gamma_{d\text{-measured}}$ is the value of dry unit weight that is determined by the EDG at a given in situ location, and $\gamma_{d\text{-max}}$ is the maximum dry unit weight determined from the compaction test:

$$RC\ (\%) = \frac{\gamma_{d-measured}}{\gamma_{d-\max}} \tag{3.5}$$

After an EDG test has been performed, the computer monitor on the EDG displays the moist unit weight, dry unit weight, weight of water per unit volume, moisture content, and percent compaction of the test location immediately after the electrical measurements are taken.

CHAPTER 4

PRELIMINARY FIELD STUDIES: DOVER & MIDDLETOWN

4.1 Introduction

In July 2009, experimental field studies were performed on 2 different active construction projects in the state of Delaware to investigate the feasibility for the Delaware Department of Transportation (DELDOT) to adopt a new in-situ field compaction control device, the Electrical Density Gauge (EDG). One of these projects was located in Dover, DE, and the other was located in Middletown, DE; hereafter, for purposes of confidentiality, these projects will be generically referred to as the "Dover" and "Middletown" projects. For both of these active construction projects, DELDOT technicians aided in the execution of multiple small scale field studies.

4.2 Soil Properties

4.2.1 Soil Properties for Fill Materials Used on the Dover Project

The soil used as fill material at the construction site in Dover was taken from a borrow pit area across from the new overpass being constructed near Route 1 and the DELDOT main office. Soil samples at the Dover project site were generally a light gray to light brown silty clayey sand with trace amounts of fine gravel (ASTM D 2488-09a). Figure 4.1 and Figure 4.2 are photos from the construction site in Dover. During the in situ testing process with the EDG, the soils that were placed at each in situ test location were observed to be somewhat variable in nature. This observation was reinforced by visits to the soil borrow area, where distinct layers of silty sand and clayey silts were observed in the borrow pit (ASTM D 2488-09a).

Figure 4.1 Dover Construction Site

Figure 4.2 An EDG test location at the Dover site

In an attempt to quantify the soil variability that was observed, sieve analysis tests were conducted in general accordance with ASTM D 6913-04 on 8 samples that were taken from a few of the in situ test locations at the Dover site (Figure 4.3). Table 4.1 provides overall gradation information for the soil, as determined from the 8 samples that were analyzed from the field site.

Table 4.1 General summary table of classification results – DOVER

	MIN	MAX	MEAN	STD	CV (%)
No. 4 (%)	94.14	98.91	96.40	1.56	1.62%
No. 10 (%)	90.95	97.22	93.77	2.12	2.26%
No. 40 (%)	53.09	71.20	62.01	6.09	9.83%
No. 200 (%)	23.73	39.45	31.26	5.83	18.64%
% gravel	1.09	5.86	3.60	1.56	43.29%
% sand	57.03	70.41	65.14	5.47	8.40%
% fines	23.73	39.45	31.26	5.83	18.64%

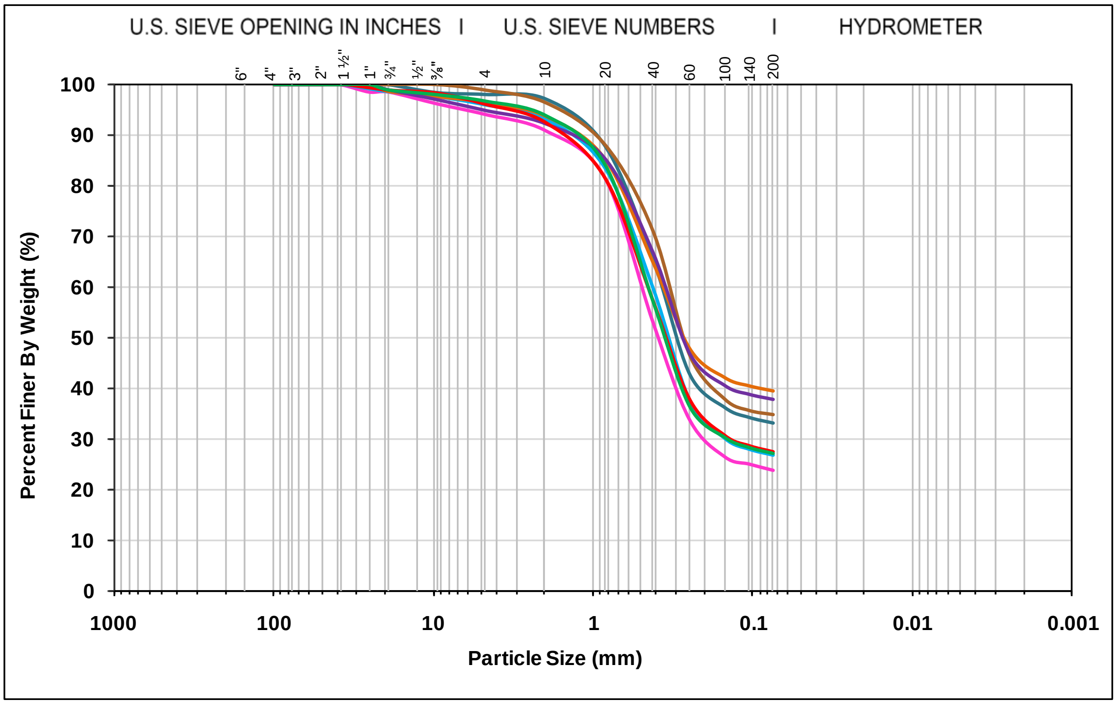


Figure 4.3 Gradation distributions for soil samples from Dover in situ test locations

4.2.2 Soil Properties for Fill Materials Used on the Middletown Project

The soil tested at the construction site in Middletown was from a borrow pit within a half mile of the site. Soil samples at the Middletown project site were generally a brown silty sand with trace amounts of fine gravel (ASTM D 2488-09a). Figure 4.4 and Figure 4.5 are photos from the construction site in Middletown.

Figure 4.4 Middletown Construction Site

Figure 4.5 An EDG test location at the Middletown site

Sieve analysis tests were conducted in general accordance with ASTM D 6913-04 on 8 samples that were taken from a few in situ test locations at the Middletown site (Figure 4.6). A few Atterberg limit tests (ASTM D 4318-05) conducted on the finer portion of the soils indicated that the soils examined in this study had fines that were nonplastic (NP) in nature. The soil samples consequently are classified as either silty sand (SM), or poorly-graded sand with silt (SP-SM) according to the Unified Soil Classification System (ASTM D 2487-10). Table 4.2 provides overall gradation information for the soil, as determined from the 8 samples that were analyzed from the field site. It should be noted that the coefficients of variation of the soil tested at the Middletown site are lower than the coefficient of variations for the soil tested from the Dover site.

Table 4.2 General summary table of classification results – MDLTOWN

	MIN	MAX	MEAN	STD	CV (%)
No. 4 (%)	96.53	98.76	97.96	0.68	0.70%
No. 10 (%)	95.05	97.92	96.64	0.90	0.93%
No. 40 (%)	52.54	63.65	58.10	4.17	7.19%
No. 200 (%)	10.51	17.83	14.82	2.22	15.01%
% gravel	1.24	3.47	2.04	0.68	33.53%
% sand	80.81	87.44	83.14	2.13	2.56%
% fines	10.51	17.83	14.82	2.22	15.01%

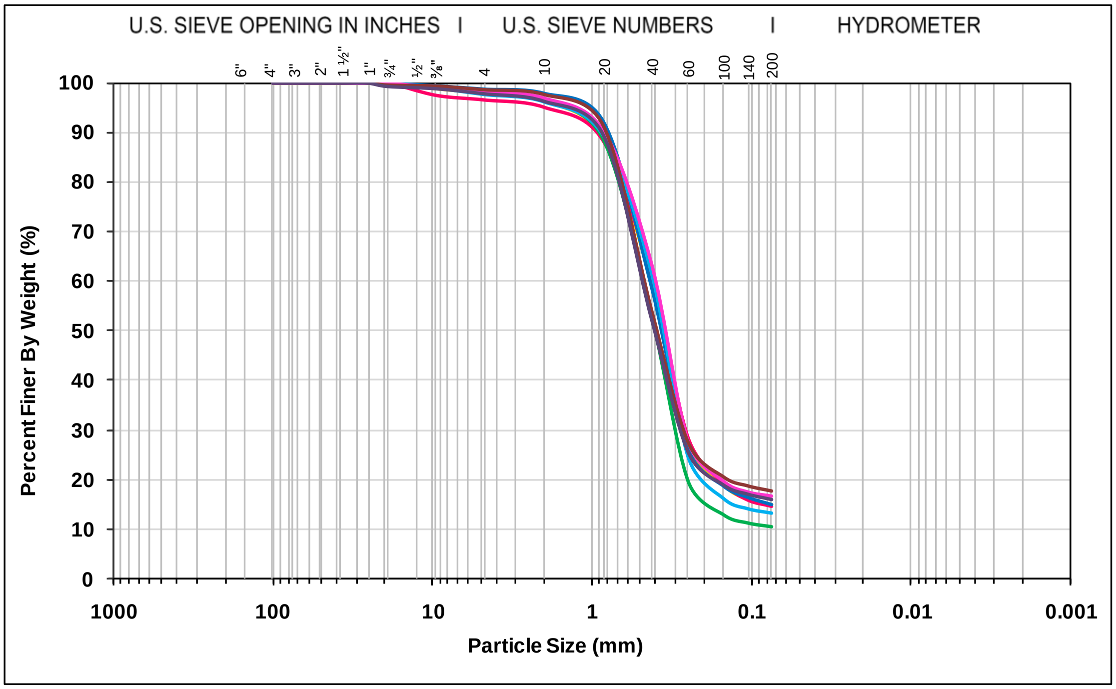


Figure 4.6 Gradation distributions for soil samples from Middletown in situ test locations

4.3 In-Situ Field Testing Procedure

On both active construction projects, Nuclear Density Gauge (NDG) and EDG tests were performed at the same approximate in situ locations on previously compacted areas of roadway subgrade. Three one-minute NDG readings and 1 EDG test were taken at each in situ test location. The average of the three one-minute NDG readings was used as a calibration input value for developing the appropriate EDG soil model for the fill materials used in each field project (See Chapter 3 for EDG soil model concepts). In addition, for both field projects, bag samples were taken at each in situ test location for later soil classification testing.

Following the approach presented in Chapter 3 (the manufacturer recommended approach for building soil models), EDG soil model calibration equations were developed for each specific testing site (DOVER and MDLTOWN) using the measured NDG test results for soil model calibration. The calibration equations developed for each individual soil model were then used to predict the in-situ soil property values for each test location.

As discussed in Chapter 3, temperature can sometimes have a significant effect on measured EDG test results. In order to investigate the effect of the temperature correction that is used on the EDG calibration relationships, soil models were developed with and without using the proprietary EDG temperature correction algorithm.

4.4 Results: In-Situ Field Testing

The in-situ field tests described in this section were conducted to create a series of soil models using the field calibration method that is recommended by the manufacturer of the electrical density gauge (EDG, LLC). From the measured NDG and EDG values, it is possible to build a series of series of calibration equations, and then use these equations to convert the measured raw electrical values to predictions of soil unit weight and soil moisture content. Following this approach, it is possible to perform comparisons between the measured NDG in-situ test values and the predicted EDG test values for each soil type.

Direct comparison of the EDG-predicted values with the measured NDG values provides a useful tool for assessing the effect of soil model calibration scatter on the actual engineering properties that result (e.g., unit weight, moisture content). However, this assessment procedure is inherently unreliable for assessing the ability of the EDG to make accurate predictions of soil moisture content and soil density (or unit weight). This is because the calibration data set is the same as the assessment data set, and consequently the results do not represent a truly "blind" assessment of the EDG's ability to measure the in situ soil properties of interest. A truly blind assessment of the type that is recommended is provided in Chapter 6, for a separate series of "box" assessment tests. However, as independent measurements of soil density and moisture content outside of the calibration data set were not performed during the field studies described in this section, the only option here was to use the same data set for forward prediction as what was used for soil model calibration.

Calibration equations for each of the soil models that were created are presented in the following sections. Also, 1:1 plots that compare NDG measured values versus EDG predicted values are presented, along with relative error histogram plots between the measured and predicted values. The in-situ measured soil properties assessed in this study were: moist unit weight (γ_m,), weight of water per unit volume (W_W), dry unit weight (γ_d,), and moisture content (*w*).

4.4.1 Dover Calibration

At the Dover project site, the fill material from the borrow source was observed to be somewhat variable, as noted previously. The associated calibration equations for the soil model are presented in Figure 4.7. The coefficient of determination (R^2) values are presented on each graph in Figure 4.7 as well. It should be noted that the soil model calibration equations in Figure 4.7a and Figure 4.7c for the DOVER Soil Model (TC OFF & TC ON), show an increase in R^2 from 0.0259 to 0.3639 when the EDG temperature correction algorithm is applied. For the DOVER Soil Model, the R^2 values for the calibration equations with the EDG temperature correction algorithm applied are greater than the R^2 values for the calibration equations with no EDG temperature correction algorithm applied. Table 4.3 provides a summary of the R^2 values, slopes, and intercepts of the calibration equations for the DOVER Soil Model (TC OFF & TC ON).

4.4.2 Middletown Calibration

The EDG soil model created in this study was carried out at multiple locations throughout the Middletown construction site. The in-situ field tests were performed on different sections of previously compacted roadway subgrade.

The associated calibration equations for the soil model are presented in Figure 4.7. The coefficient of determination (R^2) values are presented on each graph in Figure 4.7 as well. For the MDLTOWN Soil Model, the R^2 values for the calibration equations with the EDG temperature correction algorithm applied are basically the same as the R^2 values for the calibration equations with no EDG temperature correction algorithm applied. Table 4.4 provides a summary of the R^2 values, slopes, and intercepts of the calibration equations for the MDLTOWN Soil Model (TC OFF & TC ON).

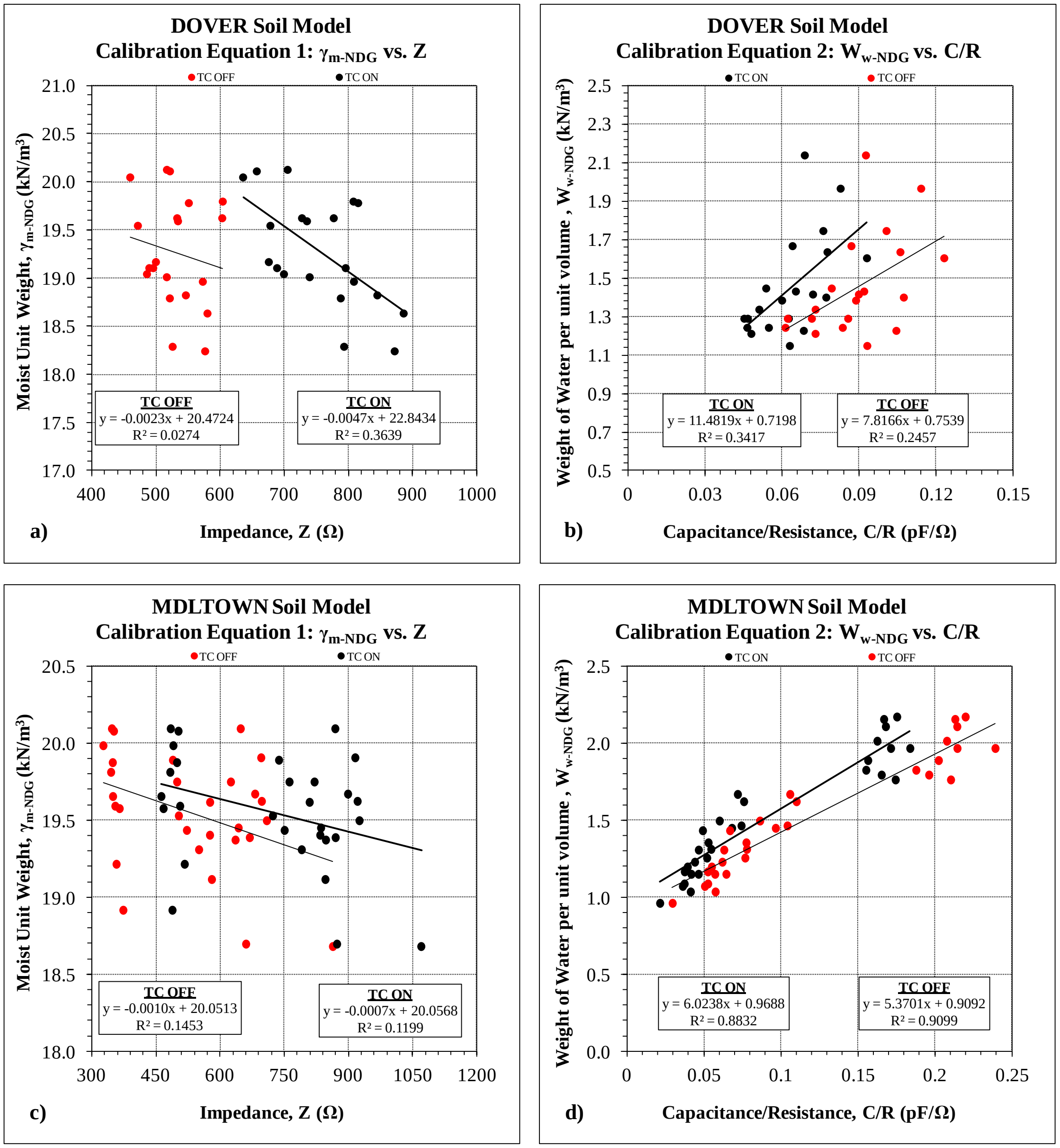


Figure 4.7 Calibration Equations
a) DOVER Soil Model: $\gamma_{m\text{-}NDG}$ vs. Z
b) DOVER Soil Model: $W_{w\text{-}NDG}$ vs. C/R
c) MDLTOWN Soil Model: $\gamma_{m\text{-}NDG}$ vs. Z
d) MDLTOWN Soil Model: $W_{w\text{-}NDG}$ vs. C/R

Table 4.3 General summary table of calibration equations – DOVER Soil Model

DOVER Soil Model				
	Calibration Equation	$\mathbf{R^2}$	**Slope**	**Intercept**
TC OFF	$\gamma_{m\text{-}NDG}$ vs. Z	0.0274	-0.0023	20.4724
TC ON	$\gamma_{m\text{-}NDG}$ vs. Z	0.3639	-0.0047	22.8434
TC OFF	$W_{w\text{-}NDG}$ vs. C/R	0.2457	7.8166	0.7539
TC ON	$W_{w\text{-}NDG}$ vs. C/R	0.3417	11.4819	0.7198

Table 4.4 General summary table of calibration equations – MDLTOWN Soil Model

MDLTOWN Soil Model				
	Calibration Equation	$\mathbf{R^2}$	**Slope**	**Intercept**
TC OFF	$\gamma_{m\text{-}NDG}$ vs. Z	0.0274	-0.0023	20.4724
TC ON	$\gamma_{m\text{-}NDG}$ vs. Z	0.3639	-0.0047	22.8434
TC OFF	$W_{w\text{-}NDG}$ vs. C/R	0.2457	7.8166	0.7539
TC ON	$W_{w\text{-}NDG}$ vs. C/R	0.3417	11.4819	0.7198

4.5 1:1 Plots

The following sections show 1:1 plots that compare NDG measured values versus EDG predicted values. An explanation of statistical variables used to interpret the 1:1 plots is given below prior to explanation of the 1:1 plots.

4.5.1 Statistical Measures

The root-mean-square error (RMSE) is a frequently used measure of the differences between values predicted by a model and the values actually observed from the variable being estimated, and is a good measure of precision. RMSE is calculated by taking the square root of the mean square error; for an unbiased estimator, the RMSE is the square root of the variance (Freedman 1998) (Equation 4.1):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(x_{1,i} - x_{2,i}\right)^2}{n}} \tag{4.1}$$

The coefficient of variation of the RMSE (CV(RMSE)), is defined as the RMSE normalized to the mean of the observed values (Freedman 1998). It is the same concept as the coefficient of variation except that RMSE replaces the standard deviation.

$$CV(RMSE) = \frac{RMSE}{\bar{x}} \tag{4.2}$$

The normalized root-mean-square error (NRMSE) is the RMSE divided by the range of observed values and is often expressed as a percentage, where lower values indicate less residual variance (Freedman 1998).

$$NRMSE = \frac{RMSE}{x_{\max} - x_{\min}} \tag{4.3}$$

4.5.2 1:1 Plots – DOVER Soil

The DOVER Soil Model calibration equations were used to predict the EDG values that are presented in this section. Figure 4.8a shows NDG measured moist unit weights ($\gamma_{m\text{-}NDG}$) versus EDG predicted moist unit weights ($\gamma_{m\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). Figure 4.8b shows NDG measured dry unit weights ($\gamma_{d\text{-}NDG}$) versus EDG predicted dry unit weights ($\gamma_{d\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). Figure 4.8c shows NDG measured weight of water per unit volume ($W_{W\text{-}NDG}$) versus EDG predicted weight of water per unit volume ($W_{W\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). Figure 4.8d shows NDG measured moisture contents (w_{NDG}) versus EDG predicted moisture contents (w_{EDG}) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). It should be noted that the solid line in Figure 4.8a, 4.8b, 4.8c, and 4.8d is a 1:1 line, and the dashed lines are ±0.5 kN/m^3 in Figure 4.8a, 4.8b, and 4.8c, and ±0.5 % lines in Figure 4.8d, which are provided for reference.

For the DOVER Soil, the RMSE, CV(RMSE), and NRMSE values for moist unit weight, dry unit weight, weight of water per unit volume, and moisture content are all slightly greater with no EDG temperature correction algorithm applied. Table 4.5 summarizes the statistical values for the DOVER Soil.

Table 4.5 Summary of Statistical Measures – DOVER Soil

	DOVER Soil							
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	0.5467	0.4852	0.2225	1.2550	0.4421	0.4256	0.2078	1.2135
CV(RMSE)	0.0284	0.0272	0.1530	0.1537	0.0229	0.0239	0.1430	0.1486
NRMSE	0.2900	0.2709	0.2248	0.2334	0.2345	0.2377	0.2100	0.2257

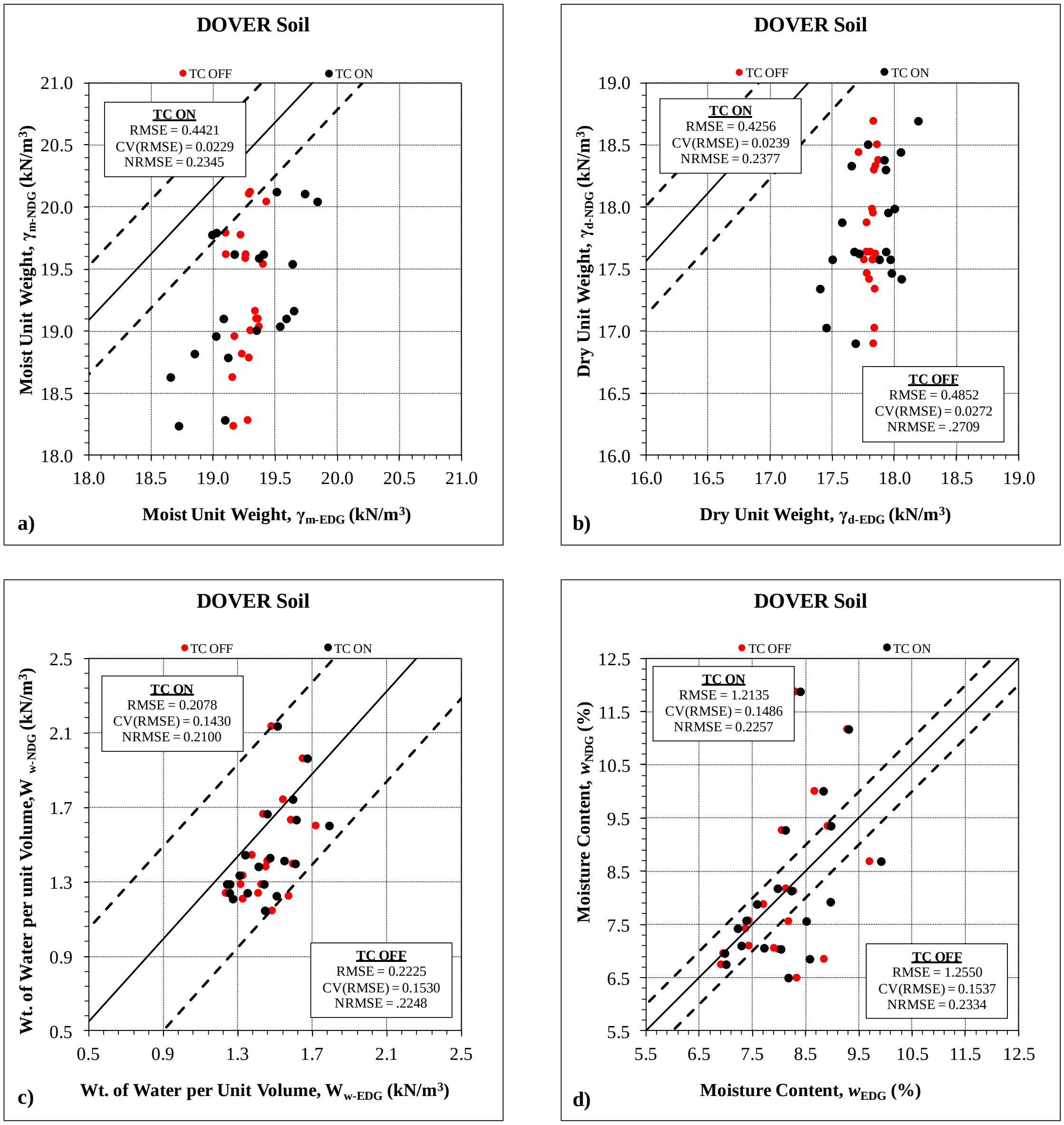


Figure 4.8 **1:1 Plots – DOVER Soil**
a) 1:1 Plot – Moist Unit Weight
b) 1:1 Plot – Dry Unit Weight
c) 1:1 Plot – Wt. of Water per Unit Volume
d) 1:1 Plot – Moisture Content

4.5.3 1:1 Plots – MDLTOWN Soil

The MDLTOWN Soil Model calibration equations were used to predict the EDG values that are presented in this section. Figure 4.9a shows NDG measured moist unit weights ($\gamma_{m\text{-}NDG}$) versus EDG predicted moist unit weights ($\gamma_{m\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). Figure 4.9b shows NDG measured dry unit weights ($\gamma_{d\text{-}NDG}$) versus EDG predicted dry unit weights ($\gamma_{d\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). Figure 4.9c shows NDG measured weight of water per unit volume ($W_{W\text{-}NDG}$) versus EDG predicted weight of water per unit volume ($W_{W\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). Figure 4.9d shows NDG measured moisture contents (w_{NDG}) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). It should be noted that the solid line in Figure 4.9a, 4.9b, 4.9c, and 4.9d is a 1:1 line, and the dashed lines are ±0.5 kN/m^3 in Figure 4.9a, 4.9b, and 4.9c, and ±0.5 % lines in Figure 4.9d for reference.

For the MDLTOWN Soil, the RMSE, CV(RMSE), and NRMSE values for moist unit weight, weight of water per unit volume, and moisture content are all slightly greater with the EDG temperature correction algorithm applied. For SM MDLTOWN, the RMSE, CV(RMSE), and NRMSE values for dry unit weight are slightly greater with no EDG temperature correction algorithm applied. Table 4.6 summarizes the statistical values for the MDLTOWN Soil.

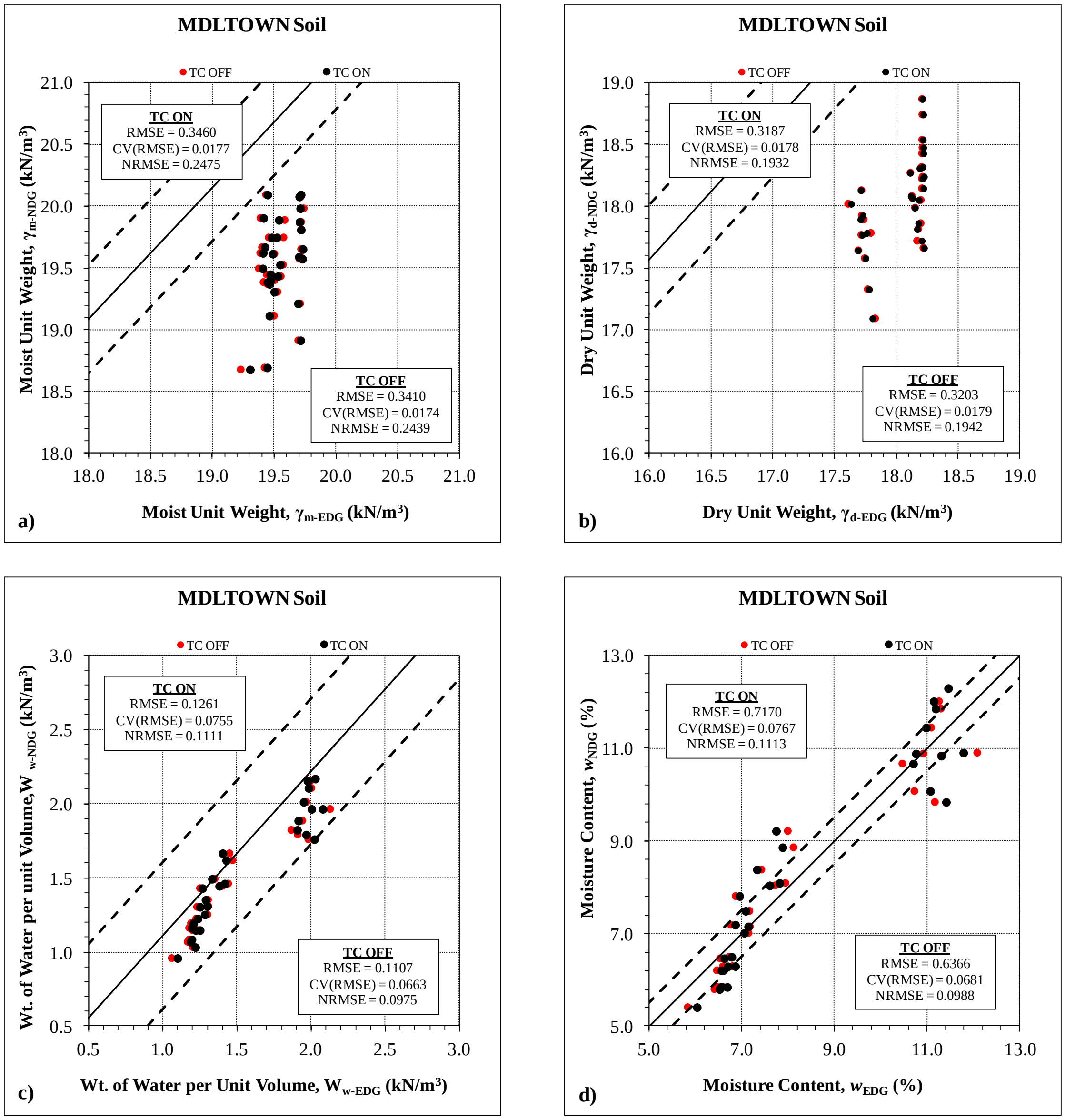


Figure 4.9 1:1 Plots - MDLTOWN Soil
a) 1:1 Plot – Moist Unit Weight
b) 1:1 Plot – Dry Unit Weight
c) 1:1 Plot – Wt. of Water per Unit Volume
d) 1:1 Plot – Moisture Content

Table 4.6 Summary of Statistical Measures –MDLTOWN Soil

MDLTOWN Soil								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	0.3410	0.3203	0.1107	0.6366	0.3460	0.3187	0.1261	0.7170
CV(RMSE)	0.0174	0.0179	0.0663	0.0681	0.0177	0.0178	0.0755	0.0767
NRMSE	0.2439	0.1942	0.0975	0.0988	0.2475	0.1932	0.1111	0.1113

4.6 Relative Error

Relative error is calculated by taking the value considered to be the "actual" value, subtracting it from the "predicted" value, and dividing the resulting difference by the "actual" value. (Freedman 1998) (Equation 4.4):

$$\text{Relative error (\%)} = \frac{NDG_{VALUE} - EDG_{VALUE}}{NDG_{VALUE}} \times 100 \qquad (4.4)$$

The following section shows histograms of the relative error calculated for moist unit weight, weight of water per unit volume, dry unit weight, and moisture content for the DOVER and MDLTOWN soils. A cumulative distribution function (CDF) is displayed on each histogram as well.

4.6.1 Relative Error: DOVER Soil

Figure 4.10a is a histogram plot of relative error between $\gamma_{m\text{-}NDG}$ and $\gamma_{m\text{-}EDG}$ (TC ON & TC OFF). For the DOVER Soil (TC OFF), relative error values for γ_m range from -5.43% to 4.10%, and for the DOVER Soil (TC ON) relative error values for γ_m range from -4.43% to 3.98%.

Figure 4.10b is a histogram plot of relative error between $\gamma_{d\text{-}NDG}$ and $\gamma_{d\text{-}EDG}$ (TC ON & TC OFF). For the DOVER Soil (TC OFF), relative error values for γ_d

range from -5.48% to 4.62%, and for the DOVER Soil (TC ON) relative error values for γ_d range from -4.63% to 3.89%.

Figure 4.10c is a histogram plot of relative error between $W_{W\text{-}NDG}$ and $W_{W\text{-}EDG}$ (TC ON & TC OFF). For the DOVER Soil (TC OFF), relative error values for W_W range from -29.30% to 30.79%, and for the DOVER Soil (TC ON) relative error values for W_W range from -25.93% to 29.28%.

Figure 4.10d is a histogram plot of relative error between w_{NDG} and w_{EDG} (TC ON & TC OFF). For the DOVER Soil (TC OFF), relative percent error values for w range from -28.98% to 30.14%, and for the DOVER Soil (TC ON), relative percent error values for w range from -25.68% to 29.33%.

Table 4.7 provides a summary of the minimum, maximum, range, and mean of the relative error histograms for the DOVER Soil (TC ON & TC OFF).

Table 4.7 Summary Table of Relative Error (%) – DOVER Soil

	DOVER Soil							
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-5.43	-5.48	-29.30	-28.98	-4.43	-4.63	-25.93	-25.68
MAX	4.10	4.62	30.79	30.14	3.98	3.89	29.28	29.33
RANGE	9.53	10.10	60.09	59.12	8.40	8.52	55.21	55.01
MEAN	-0.08	-0.07	-2.00	-1.97	-0.05	-0.06	-1.71	-1.76

4.6.2 Relative Error: SM MDLTOWN

Figure 4.11a is a histogram plot of relative error between $\gamma_{m\text{-}NDG}$ and $\gamma_{m\text{-}EDG}$ (TC ON & TC OFF). For the MDLTOWN Soil (TC OFF), relative error values for γ_m range from -4.14% to 3.27%, and for the MDLTOWN Soil (TC ON) relative error values for γ_m range from -4.23% to 3.21%.

Figure 4.11b is a histogram plot of relative error between $\gamma_{d\text{-}NDG}$ and $\gamma_{d\text{-}EDG}$ (TC ON & TC OFF). For the MDLTOWN Soil (TC OFF), relative error values for γ_d range from -4.32% to 3.48%, and for the MDLTOWN Soil (TC ON) relative error values for γ_d range from -4.19% to 3.47%.

Figure 4.11c is a histogram plot of relative error between $W_{W\text{-}NDG}$ and $W_{W\text{-}EDG}$ (TC ON & TC OFF). For the MDLTOWN Soil (TC OFF), relative error values for W_W range from -16.50% to 12.97%, and for the MDLTOWN Soil (TC ON) relative error values for W_W range from -16.03% to 15.94%.

Figure 4.11d is a histogram plot of relative error between w_{NDG} and w_{EDG} (TC ON & TC OFF). For the MDLTOWN Soil (TC OFF), relative error values for w range from -13.58% to 13.19%, and for the MDLTOWN Soil (TC ON), relative error values for w range from -16.03% to 15.94%.

Table 4.8 provides a summary of the minimum, maximum, range, and mean of the relative error histograms for the MDLTOWN Soil (TC ON & TC OFF).

Table 4.8 Summary Table of Relative Error (%) – MDLTOWN Soil

	MDLTOWN Soil							
	(TC OFF)				**(TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-4.14	-4.32	-16.50	-13.58	-4.23	-4.19	-18.04	-16.03
MAX	3.27	3.48	12.97	13.19	3.21	3.47	15.77	15.94
RANGE	7.40	7.80	29.47	26.77	7.44	7.67	33.81	31.97
MEAN	-0.03	-0.03	-0.65	-0.64	-0.03	-0.03	-0.84	-0.83

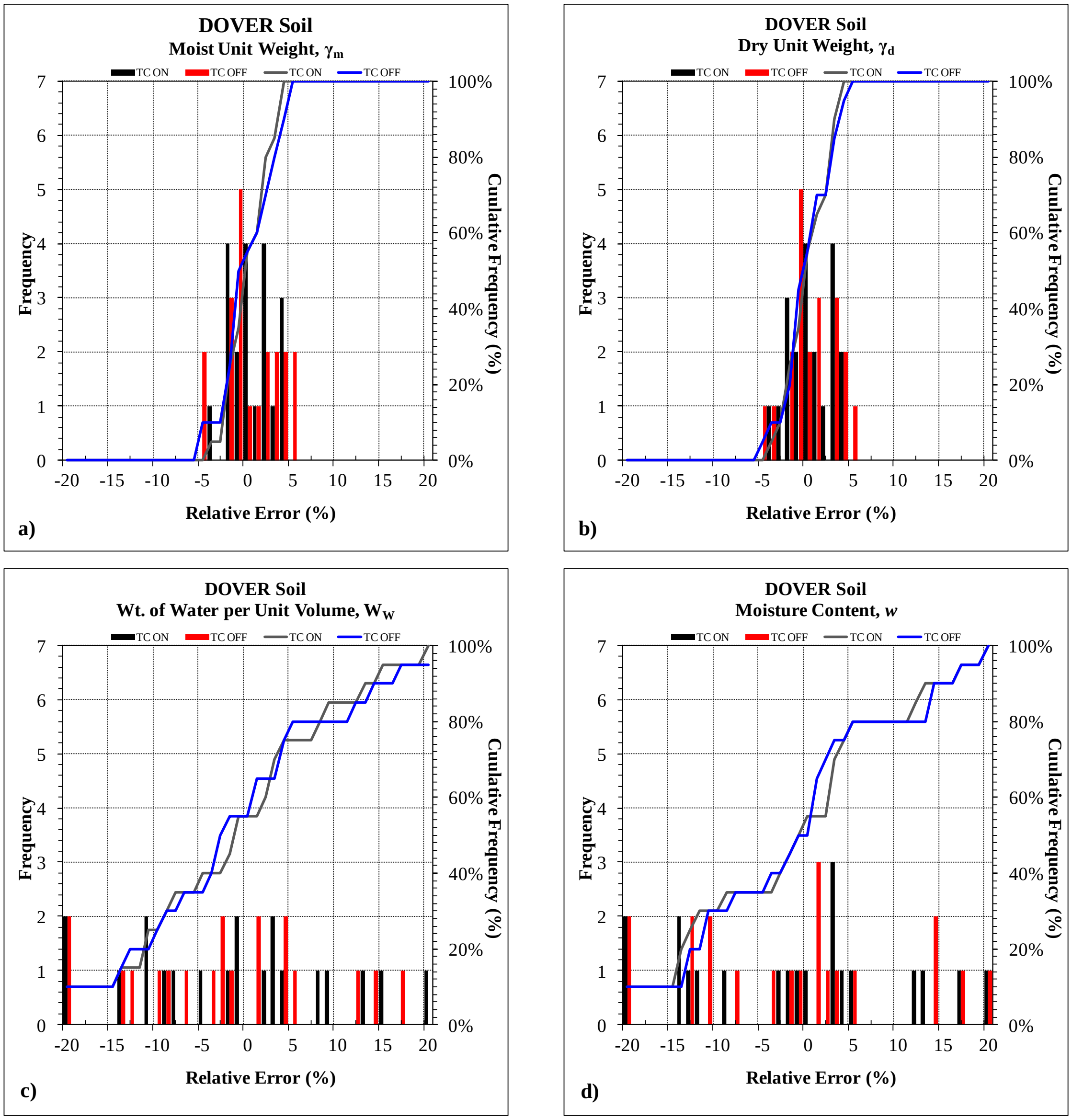


Figure 4.10 Relative Error Histograms and CDF Plots – DOVER Soil
a) Histogram & CDF – Moist Unit Weight (TC OFF & TC ON)
b) Histogram & CDF – Dry Unit Weight (TC OFF & TC ON)
c) Histogram & CDF – Wt. of Water per Unit Volume (TC OFF & TC ON)
d) Histogram & CDF - Moisture Content (TC OFF & TC ON)

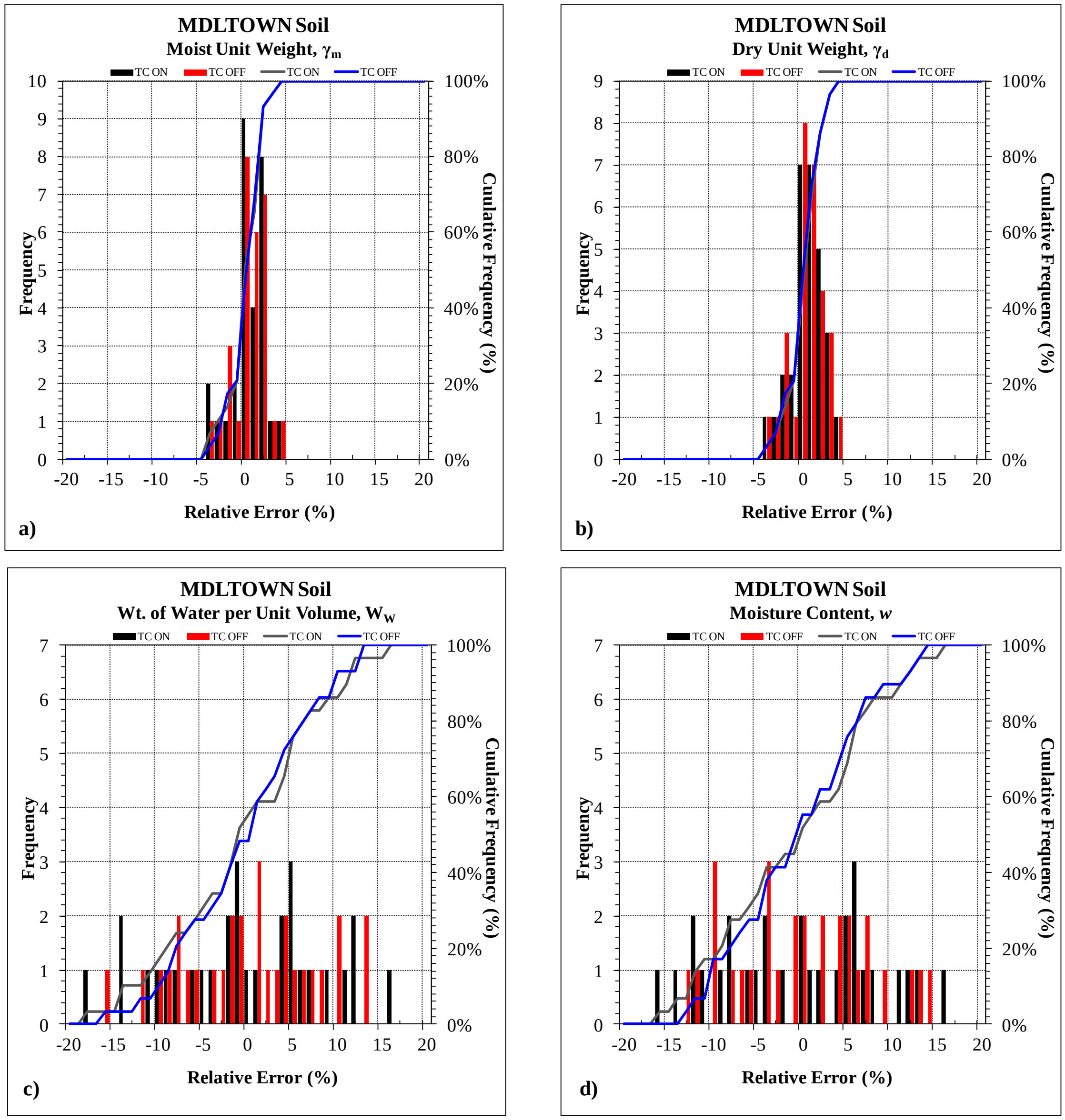


Figure 4.11 Relative Error Histograms and CDF Plots – MDLTOWN Soil
a) Histogram & CDF – Moist Unit Weight (TC OFF & TC ON)
b) Histogram & CDF – Dry Unit Weight (TC OFF & TC ON)
c) Histogram & CDF – Wt. of Water per Unit Volume (TC OFF & TC ON)
d) Histogram & CDF - Moisture Content (TC OFF & TC ON)

4.7 Summary of Results

4.7.1 Summary of DOVER Soil Results

The soil model created using the field calibration procedure at the Dover construction site had particularly low R^2 values for the calibration equations. The R^2 values for the temperature compensated calibration equations for all soil models were slightly higher in all cases (Table 4.1). Generally, the RMSE, CV(RMSE), and NRMSE values were greater when no EDG temperature correction algorithm was applied. Differences in relative error between the NDG and EDG predicted values for the calibration equations with and without the EDG temperature correction algorithm applied are generally minimal. In addition, the standard deviation from the average for each set of EDG predicted values (TC ON & TC OFF) is lower than the standard deviation from the average for the corresponding NDG measured values; this observation manifests itself as a smoothing effect, which can be observed on the moist unit weight and dry unit weight 1:1 plots for the DOVER Soil (Figure 4.8a, 4.8c). Table 4.9 provides a summary of the standard deviation values for the DOVER Soil.

Table 4.9 Summary Table of Standard Deviation values for the DOVER Soil

DOVER Soil: Standard Deviation, σ_d				
	γ_m	γ_d	W_w	w
NDG	0.57	0.50	0.26	1.49
EDG (TC OFF)	0.09	0.04	0.13	0.75
EDG (TC ON)	0.34	0.22	0.15	0.80

4.7.2 Summary of MDLTOWN Soil Results

The soil models created using the field calibration procedure at the Middletown construction site had higher R^2 values for the calibration equations than the Dover site. The R^2 values for the temperature compensated calibration equations for all soil models were basically the same as the R^2 values for the calibration equations with no temperature correction (Table 4.4). Generally, the RMSE, CV(RMSE), and NRMSE values were greater when the EDG temperature correction algorithm was applied. Differences in relative error between the NDG and EDG predicted values for the calibration equations with and without the EDG temperature correction algorithm applied are generally minimal. In addition, the standard deviation from the average for each set of EDG predicted density values (only dry unit weight and moist unit weight) is generally lower than the standard deviation from the average for the corresponding NDG measured values; this observation manifests itself as a smoothing effect, which can be observed on the moist unit weight and dry unit weight 1:1 plots for the MDLTOWN Soil (Figure 4.9a, 4.9c). Table 4.10 provides a summary of the standard deviation values for the MDLTOWN Soil.

Table 4.10 Summary Table of Standard Deviation values for the MDLTOWN Soil

MDLTOWN Soil: Standard Deviation, σ_d				
	γ_m	γ_d	W_w	w
NDG	0.38	0.39	0.38	2.19
EDG (TC OFF)	0.14	0.22	0.36	2.10
EDG (TC ON)	0.13	0.23	0.35	2.07

4.8 Discussion of Results and Conclusions

From the raw data and associated analysis that is presented in this chapter, it is clear that there are some limitations to creating a soil model using the field calibration process. In particular, for the data that was recorded during these two field studies, relatively poor agreement was observed between the NDG and EDG predicted values. This lack of agreement occurred even when the "assessment" data set was the same as the "calibration" data set, which is a much less rigorous test than a truly "blind" assessment (as discussed previously).

There are a number of possible causes for the general lack of agreement that was observed. Some of the more notable reasons that are believed to have been possible contributing factors in this field study include:

- Difficulties in constructing a soil model that is representative of the range of moisture contents and soil densities that will be encountered during the compaction process. In particular, on an active construction site, contractors try to maintain the same moisture content and reach the same density for the fill material they are compacting. This creates difficulty when trying to build a soil model that spans the range of densities and moisture contents that may be encountered in a fair and representative way. Getting the necessary field variability in moisture content can be particularly challenging under certain field conditions.

- Inherent uncertainties and sources of error in the tests that are used for the field calibration purposes themselves. In particular, the field calibration process requires the use of a NDG or other standard in-situ density test like the sand cone or rubber balloon test. These tests have their own uncertainty and sources of error in measurement, and consequently this error has the potential to become compounded when building a soil model.
- Soil variability on site. The EDG appears to be more sensitive than the NDG to variations in the soil borrow source. This effect is evident if the results from the Dover project are compared against those from the Middletown project. In particular, changes in the quantity or nature of the fines in a borrow soil are believed to have a significant effect on measured EDG results. This is because the electrical characteristics of a soil matrix are significantly affected by the characteristics of the finer particles in the matrix.
- Another observation captured by the preliminary field studies discussed in this chapter is that the EDG temperature correction algorithm can lower the R^2 values for the calibration equations, thus not improving the results. The EDG temperature correction algorithm does not seem to properly capture the effect of temperature on the soils that were tested in this field study. An assessment of the effectiveness of the EDG temperature correction algorithm will be described in more detail in a later chapter in this thesis.

After a considerable amount of time and effort trying to get the necessary data on active construction projects, it was determined that an alternative approach was needed to generate data that could be used to fairly assess the EDG. The wide range of moisture contents and densities needed to build proper calibration equations made obtaining a calibration soil model challenging on an active construction site, in part because of contractor demands, budget constraints, and compaction control requirements. Additionally, the somewhat non-uniform soil conditions at the Dover project yielded unusually poor calibration equations, and made deployment of the gauge on this project problematic.

The decision to stop utilizing a field calibration approach for the EDG also coincided with the development of a new type of "soil mold" laboratory calibration procedure that was developed by EDG, LLC, that could potentially be used to build superior soil models. This laboratory calibration procedure presents a desirable alternative to field calibration, and its implementation will be discussed in more detail in the following chapter (Chapter 5).

CHAPTER 5

MOLD CALIBRATION PROCEDURE

5.1 Introduction

During the progress of this research study, EDG, LLC. developed a new calibration procedure. This new calibration procedure still adheres to the same general principles of creating a soil model (See Chapter 3), but calibration test points are not gathered in the field and traditional in-situ compaction control tests (NDG, sand cone, etc.) are not used for correlation purposes. Instead, calibration test points are gathered by preparing soil at various moisture contents and densities using a large "Proctor"-type mold having an inside diameter of 378 mm (14.88 in.) diameter and 254 mm (10 in.) depth (Figure 5.1).

Figure 5.1 Large "Proctor" type mold and tamper

5.2 Soil Properties

The soil used for the soil model mold calibration tests was from a borrow pit at the Greggo & Ferrara facilities in Delaware. A truckload of soil was donated by Greggo & Ferrara and dumped at the DELDOT facility in Bear, Delaware for usage during this research study. Visual-manual classification of soil samples from the borrow pit indicated that this soil was generally a brown silty sand with trace amounts of fine gravel (ASTM D 2488-09a). Figure 5.2 is a photo of a portion of the stockpile that was used for testing, located at the DELDOT facility in Bear.

Figure 5.2 Soil Stockpile at DELDOT facility in Bear

Sieve analysis and hydrometer tests were conducted in general accordance with ASTM D 6913-04 and ASTM D422-63 on samples from all 12 of the mold tests that were conducted. From these tests, 10 of the soil samples classified as a silty sand

(SM) and 2 samples classified as poorly-graded sand with silt (SP-SM), according to the Unified Soil Classification System (ASTM D 2487-06). Table 5.1 provides overall gradation information for the soil, as determined from the 12 samples that were analyzed from the mold tests.

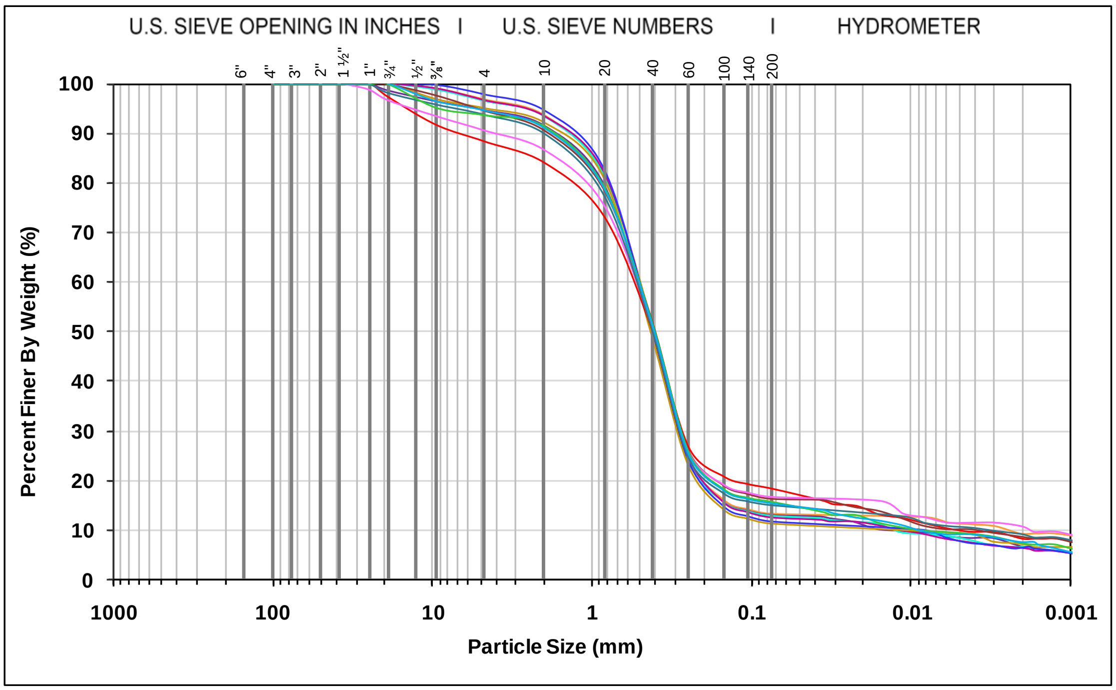


Figure 5.3 Gradation distributions for soil samples from mold tests

Table 5.1 General summary table of classification results – Mold Tests

	MIN	MAX	MEAN	STD	CV (%)
No. 4 (%)	88.28	97.70	94.42	2.69	2.85%
No. 10 (%)	83.96	94.47	91.02	3.04	3.34%
No. 40 (%)	49.45	52.77	51.25	0.91	1.77%
No. 200 (%)	14.29	20.65	17.01	1.98	11.62%
% gravel	2.30	11.72	5.58	2.69	48.24%
% sand	70.05	85.94	80.09	4.64	5.80%
% fines	11.44	18.22	14.33	2.14	14.94%
%silt	6.60	9.50	7.89	0.95	12.01%
%clay	6.30	10.70	7.89	1.35	17.07%
C_u	48.54	337.84	172.20	110.73	64.30%
C_c	14.16	85.76	43.82	23.96	54.69%

5.3 Mold Calibration Procedure

The outer frame of the mold is constructed from a section of 378 mm (14.88 in.) inside-diameter and 389 mm (15.32 in.) outside-diameter polyvinyl chloride (PVC) pipe. The base of the mold is constructed of a highly durable plastic material. Plastics are used for the mold construction because they are insulators and will not interfere with the electrical measurements carried out by the EDG in the same fashion that a metal (conductive) mold might.

It should be noted that this calibration procedure is relatively new and innovative, and consequently it is not included in the ASTM approved methodology for the EDG (ASTM D7698-11 – Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance).

The following procedure was utilized when performing mold calibration tests for this research study:

1) Prepare the soil at the desired moisture content and wait 24 hours for the moisture in the bulk sample to come to equilibrium (to help ensure moisture homogeneity). It should be noted that soil was mixed at the DELDOT facility in Bear with a concrete mixer. The soil was then placed in buckets and brought to the Soil Lab at the University of Delaware.
2) Weigh the dry empty mold and record its mass.
3) Place the soil in lifts in the mold (See Table 5.1 for the number of lifts that were used for each mold that was tested).
4) Compact the soil after each lift with a tamper by hand from a height of 16 to 18 inches.
5) Weigh the mold that is filled with the moist tamped soil and record its mass.
6) Setup the EDG and drive the EDG electrical probes and temperature probe into the soil in the mold (Figure 5.4).
7) Take electrical measurements with the EDG that can be used for the "soil model" calibration process (following the procedure outlined in Chapter 3).

Figure 5.4 Typical EDG setup in Mold

Twelve (12) mold calibration tests were conducted to build a soil model for the material being tested. In order to achieve a wide range of densities, various numbers of lifts and blows per lift were performed. Table 5.2 summarizes the number of lifts, blows per lift, and the calculated physical data that was used for correlation to the electrical measurements taken by the EDG to build a soil model.

Table 5.2 Physical Mold Calibration Data

	Mold #1	Mold #2	Mold #3
Lifts	10	5	2
Blows per Lift	100	100	50
γ_m (kN/m^3)	20.05	19.61	18.65
γ_d (kN/m^3)	18.44	17.96	17.11
W_w (kN/m^3)	1.62	1.65	1.54
w (%)	8.77	9.20	9.01

	Mold #4	Mold #5	Mold #6
Lifts	5	3	2
Blows per Lift	100	50	25
γ_m (kN/m^3)	21.04	19.68	18.87
γ_d (kN/m^3)	18.88	17.71	16.92
W_w (kN/m^3)	2.16	1.97	1.94
w (%)	11.47	11.15	11.47

	Mold #7	Mold #8	Mold #9
Lifts	5	3	2
Blows per Lift	100	50	25
γ_m (kN/m^3)	21.02	20.38	19.37
γ_d (kN/m^3)	18.47	17.87	17.03
W_w (kN/m^3)	2.55	2.51	2.34
w (%)	13.78	14.04	13.74

	Mold #10	Mold #11	Mold #12
Lifts	10	5	2
Blows per Lift	100	100	50
γ_m (kN/m^3)	20.59	19.18	18.35
γ_d (kN/m^3)	18.82	17.49	16.73
W_w (kN/m^3)	1.77	1.70	1.62
w (%)	9.41	9.70	9.67

5.4 Mold Calibration Results

The mold tests described in this section were conducted to create a soil model to use in making a “blind” assessment of the EDG’s effectiveness. A truly blind assessment of the type that is recommended is provided in Chapter 6.

Calibration equations for the soil model developed from the mold tests are presented in the following section. It should be noted that calibration equations are presented without the EDG temperature correction algorithm (TC OFF) and with the EDG temperature correction algorithm (TC ON).

As stated earlier in Chapter 4, it is not best practice to assess the effectiveness of the EDG when the calibration data set is the same as the assessment data set, but for research and understanding this method is presented again. Direct comparison of the EDG-predicted values with the measured physical data from the mold tests is presented in this section. 1:1 plots that compare MOLD measured values versus EDG predicted values are presented, along with relative error histogram plots between the measured and predicted values. The in-situ measured soil properties assessed in this study were: moist unit weight (γ_{m},), weight of water per unit volume (W_W), dry unit weight (γ_{d},), and moisture content (*w*).

5.4.1 Mold Soil Model: Calibration Equations

The associated calibration equations for the mold calibration soil model are presented in Figure 5.5. The coefficient of determination (R^2) values are presented on each graph in Figure 5.5 as well. It should be noted that the soil model calibration equations in Figure 5.5a for the Mold Soil Model (TC OFF & TC ON), show an increase in R^2 from 0.4931 to 0.5463 when the EDG temperature correction algorithm is applied. Table 5.3 provides a summary of the R^2 values, slopes, and intercepts of the calibration equations for the Mold Soil Model (TC OFF & TC ON).

Table 5.3 General summary table of calibration equations – Mold Soil Model

Mold Soil Model				
	Calibration Curve	**R^2**	**Slope**	**Intercept**
TC OFF	$\gamma_{m\text{-}MOLD}$ vs. Z	0.4953	-0.0086	26.1933
TC ON	$\gamma_{m\text{-}MOLD}$ vs. Z	0.5463	-0.0099	27.9314
TC OFF	$W_{w\text{-}MOLD}$ vs. C/R	0.7138	29.1141	0.8200
TC ON	$W_{w\text{-}MOLD}$ vs. C/R	0.6382	35.0837	0.7630

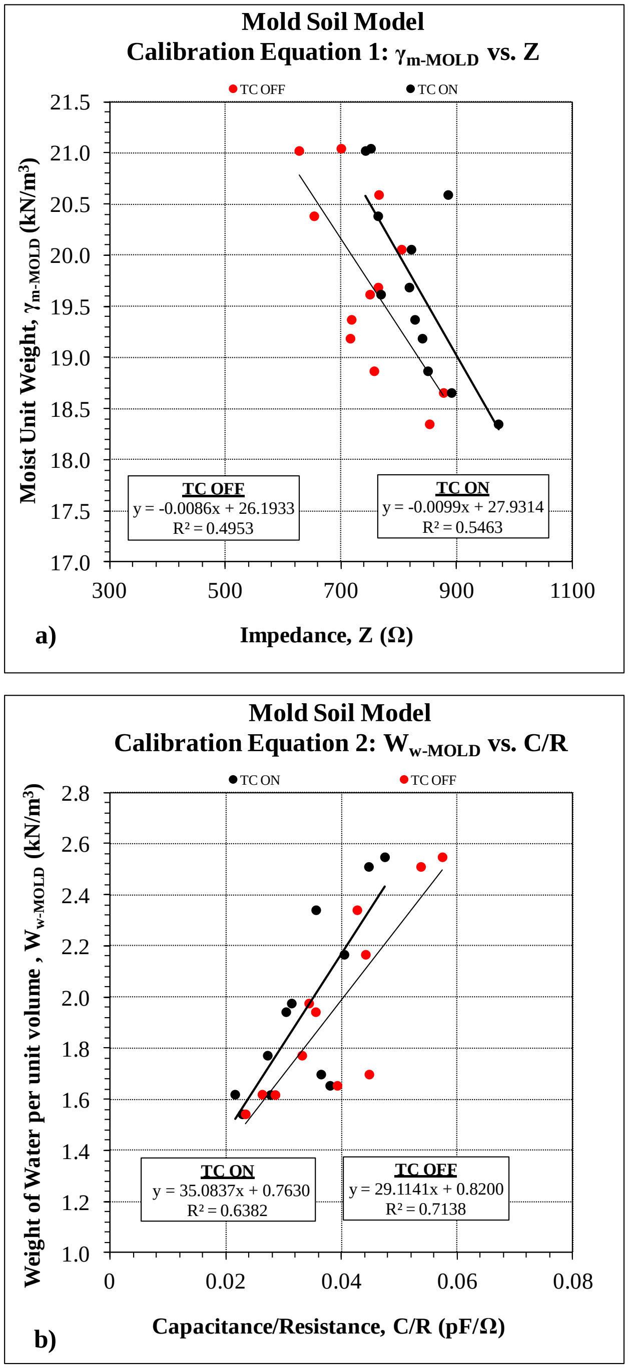


Figure 5.5 Calibration Equations – Mold Soil Model (TC OFF & TC ON)
a) Calibration Curve 1: $\gamma_{m\text{-}MOLD}$ vs. Z
b) Calibration Curve 2: $W_{w\text{-}MOLD}$ vs. C/R

5.4.2 Mold Soil: 1:1 Plots

It should be noted that the Mold Soil Model calibration equations were used to predict the EDG values presented in this section. Figure 5.6a shows MOLD measured moist unit weights ($\gamma_{m\text{-}MOLD}$) versus EDG predicted moist unit weights ($\gamma_{m\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). Figure 5.6b shows MOLD measured dry unit weights ($\gamma_{d\text{-}MOLD}$) versus EDG predicted dry unit weights ($\gamma_{d\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). Figure 5.6c shows MOLD measured weight of water per unit volume ($W_{W\text{-}MOLD}$) versus EDG predicted weight of water per unit volume ($W_{W\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). Figure 5.6d shows MOLD measured moisture content (w_{MOLD}) versus EDG predicted moisture content (w_{EDG}) with and without the EDG temperature correction algorithm applied (TC ON & TC OFF). It should be noted that the solid line in Figure 5.6a, 5.6b, 5.6c, and 5.6d is a 1:1 line, and the dashed lines are ±0.5 kN/m^3 in Figure 5.6a, 5.6b, and 5.6c, and ±0.5 % lines in Figure 5.4d for reference.

For the Mold Soil, the RMSE, CV(RMSE), and NRMSE values for moist unit weight and dry unit weight are slightly greater with no EDG temperature correction algorithm applied. The RMSE, CV(RMSE), and NRMSE values for weight of water per unit volume and moisture content are slightly greater with the EDG temperature correction algorithm applied. Table 5.4 summarizes the statistical values for the Mold Soil.

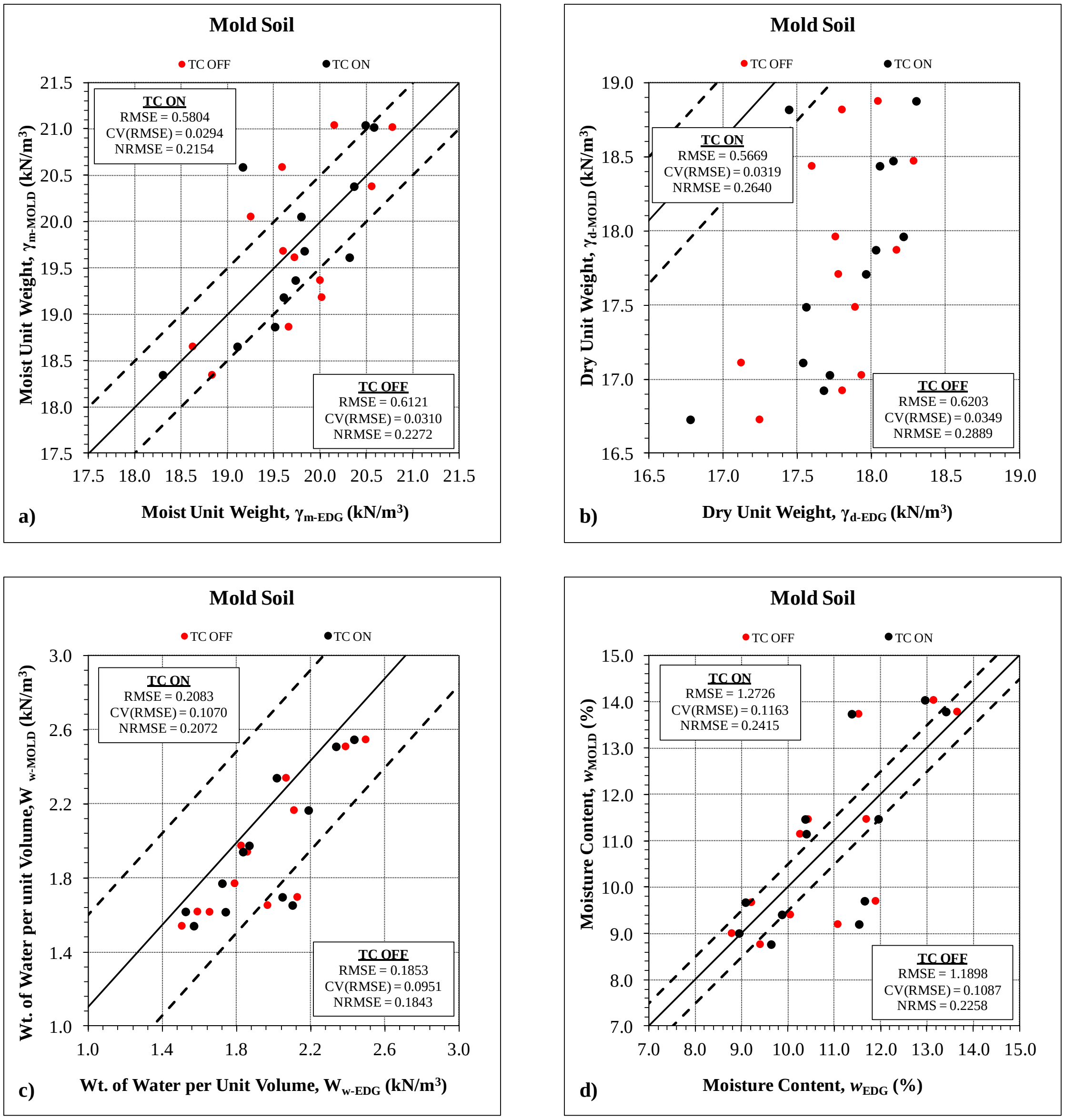


Figure 5.6 **1:1 Plots – Mold Soil (TC OFF & TC ON)**
a) 1:1 Plot – Moist Unit Weight
b) 1:1 Plot – Dry Unit Weight
c) 1:1 Plot – Wt. of Water per Unit Volume
d) 1:1 Plot – Moisture Content

Table 5.4 Summary of Statistical Measures – Mold Soil

	MOLD Soil							
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	0.6121	0.6203	0.1853	1.1898	0.5804	0.5669	0.2083	1.2726
CV(RMSE)	0.0310	0.0349	0.0951	0.1087	0.0294	0.0319	0.1070	0.1162
NRMSE	0.2272	0.2889	0.1843	0.2258	0.2154	0.2640	0.2072	0.2415

5.4.3 Relative Error

Relative error is calculated by taking the value considered to be the "actual" value, subtracting it from the "predicted" value, and dividing the resulting difference by the "actual" value (Freedman 1998). (Equation 5.1):

$$\text{Relative error (\%)} = \frac{MOLD_{VALUE} - EDG_{VALUE}}{MOLD_{VALUE}} \times 100 \qquad (5.1)$$

The following section shows histograms of the relative error calculated for moist unit weight, weight of water per unit volume, dry unit weight, and moisture content for the Mold Soil. A cumulative distribution function (CDF) is displayed on each histogram as well.

5.4.4 Relative Error Results: Mold Soil

Figure 5.7a is a histogram plot of relative error between $\gamma_{m\text{-}MOLD}$ and $\gamma_{m\text{-}EDG}$ (TC ON & TC OFF). For the Mold Soil with TC OFF, relative error values for γ_m range from -4.34% to 4.85%, and for the Mold Soil with TC ON relative error values for γ_m range from -3.58% to 6.92%.

Figure 5.7b is a histogram plot of relative error between $\gamma_{d\text{-MOLD}}$ and $\gamma_{d\text{-EDG}}$ (TC ON & TC OFF). For the Mold Soil (TC OFF), relative error values for γ_d range from -5.31% to 5.40%, and for the Mold Soil (TC ON) relative error values for γ_d range from -4.45% to 7.30%.

Figure 5.7c is a histogram plot of relative error between $W_{W\text{-MOLD}}$ and $W_{W\text{-EDG}}$ (TC ON & TC OFF). For the Mold Soil (TC OFF), relative error values for W_W range from -25.37% to 11.66%, and for the Mold Soil (TC ON) relative error values for W_W range from -27.09% to 13.85%.

Figure 5.7d is a histogram plot of relative error between w_{MOLD} and w_{EDG} (TC ON & TC OFF). For the Mold Soil (TC OFF), relative error values for *w* range from -22.55% to 16.11%, and for the Mold Soil (TC ON), relative percent error values for *w* range from -25.32% to 17.20%.

Table 5.5 provides a summary of the minimum, maximum, range, and mean of the relative error histograms for the Mold Soil (TC ON & TC OFF).

Table 5.5 Summary Table of Relative Error (%) – Mold Soil

MOLD Soil

	(TC OFF)				**(TC ON)**			
	γ_m	γ_d	W_w	*w*	γ_m	γ_d	W_w	*w*
MIN	-4.34	-5.31	-25.37	-22.55	-3.58	-4.45	-27.09	-25.32
MAX	4.85	5.40	11.66	16.11	6.92	7.30	13.85	17.20
RANGE	9.19	10.71	37.03	38.66	10.49	11.75	40.94	42.52
MEAN	-0.10	-0.12	-0.88	-0.93	-0.08	-0.10	-1.10	-1.13

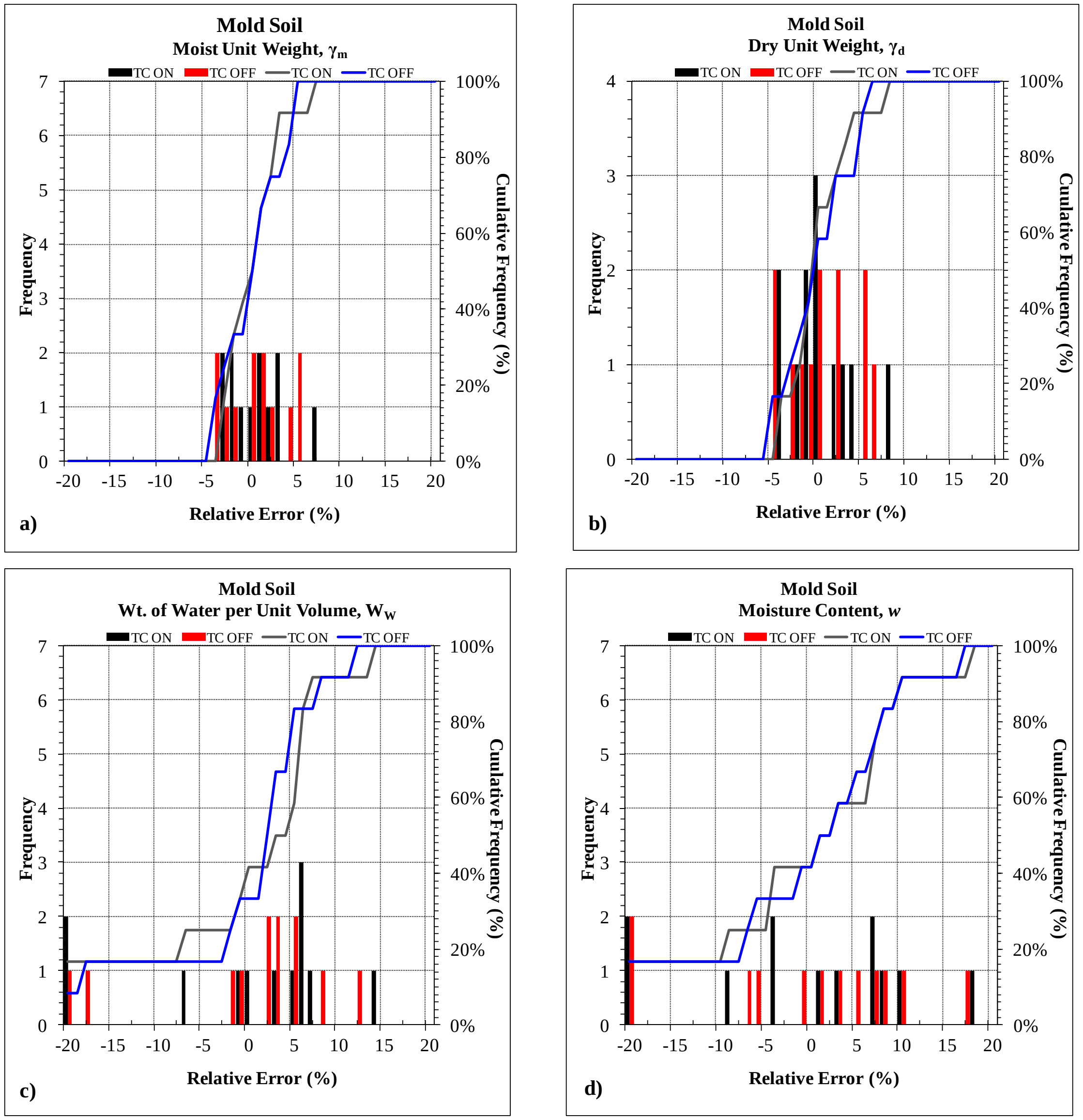


Figure 5.7 Relative Error Histograms and CDF Plots – Mold Soil
a) Histogram & CDF – Moist Unit Weight (TC OFF & TC ON)
b) Histogram & CDF – Dry Unit Weight (TC OFF & TC ON)
c) Histogram & CDF – Wt. of Water per Unit Volume (TC OFF & TC ON)
d) Histogram & CDF - Moisture Content (TC OFF & TC ON)

5.4.5 Summary of Mold Results

The soil model created using the mold calibration procedure has R^2 values for the calibration equations that range from .4953 to .7138. The R^2 values for the temperature compensated calibration equations for this soil model were higher in one case and lower in the other case (Table 5.3). The RMSE, CV(RMSE), and NRMSE values were greater when no EDG temperature correction algorithm was applied in some cases, and were less in other cases. Differences in relative percent error between the MOLD and EDG predicted values for the calibration equations with and without the EDG temperature correction algorithm applied are generally minimal. In addition, the standard deviation from the average for each set of EDG predicted values (TC ON & TC OFF) is lower than the standard deviation from the average for the corresponding MOLD measured values; this observation manifests itself as a smoothing effect, which can be observed on some of the 1:1 plots in this section. Table 5.6 provides a summary of the standard deviation values for the Mold Soil.

Table 5.6 Summary Table of Standard Deviation values for the Mold Soil

Mold Soil: Standard Deviation, σ_d				
	γ_m	γ_d	W_w	w
MOLD	0.90	0.75	0.36	1.98
EDG (TC OFF)	0.63	0.34	0.31	1.52
EDG (TC ON)	0.67	0.43	0.29	1.45

5.5 Discussion of Results and Conclusions

From the raw data and associated analysis that is presented in this chapter, it is inherently evident that the raw physical data gathered from the mold tests has considerably less error associated with the test than its counterpart, the nuclear density gauge test results using the field calibration method. Preparing molds for calibration tests in a controlled environment in a lab is a more reliable way to build a calibration data set and is considerably more trustworthy than physical data obtained from a nuclear density gauge or sand cone test. Generally, the agreement observed between the MOLD and EDG predicted values is relatively poor. This lack of agreement occurred even when the "assessment" data set was the same as the "calibration" data set, which is a much less rigorous test than a truly "blind" assessment (as discussed previously).

There are a number of possible causes for the general lack of agreement that was observed. Some of the more notable reasons that are believed to have been possible contributing factors in this mold calibration study include:

- The EDG electrical measurements of soil are believed to be very sensitive to the fines content of the soil. This is because the electrical characteristics of a soil matrix are significantly affected by the characteristics of the finer particles in the matrix. The fines content of the soil tested ranged from 11.44% to 18.22%, which is generally an acceptable variability in a given soil type, but may have a significant effect on the EDG electrical measurements.
- Once again, it is observed that the EDG temperature correction algorithm can lower the R^2 values for the calibration equations, thus not improving the results. The EDG temperature correction algorithm does not seem to properly capture the effect of temperature on the soil that was tested in this study. The assessment of the effectiveness of the EDG temperature correction algorithm will be explored in more detail in a later chapter in this thesis.

A true “blind” assessment of the EDG using the soil model developed in this chapter will be discussed in detail in Chapter 6.

CHAPTER 6

SIMULATED FIELD TESTING PROCEDURE AND RESULTS

6.1 Introduction

As stated earlier in Chapter 4, it was very difficult to gather a wide range of field testing data on an active construction project. After this realization, a way to gather simulated field data was developed. To accomplish this task, a large, relatively stiff wooden box having inside dimensions of 1.52 m (5 ft) (Length), 0.91 m (3 ft) (Width), and 0.30 m (1 ft) (Height) was constructed. For each series of "field box" tests soil was placed in the rigid box and compacted with a walk-behind vibratory plate compactor prior to running in situ tests (Figure 6.1). A truly "blind" assessment of the EDG is performed and assessed in this chapter.

Figure 6.1 Large Box used for simulated field conditions

6.2 Soil Properties

The soil used for the large box testing was the same as the soil that was used for the mold calibration tests. This soil was from a borrow pit at the Greggo & Ferrara facilities in Delaware. A truckload of soil was donated by Greggo & Ferrarra and dumped at the DELDOT facility in Bear, Delaware for usage during this research study. Soil samples from the borrow pit were generally a brown silty sand with trace amounts of fine gravel (ASTM D 2488-09a).

Sieve analysis tests were conducted in general accordance with ASTM D 6913-04 on samples from all 42 large box tests. From the results of these tests, thirty-four (34) soil samples were classified as silty sand (SM) and 8 soil samples were classified as poorly-graded sand with silt (SP-SM), according to the Unified Soil Classification System (ASTM D 2487-10). Table 6.1 provides overall gradation information for the soil, as determined from the 42 samples that were analyzed from the mold tests. It should also be noted that the samples from the box are generally the same as the samples tested in the mold tests discussed in Chapter 5 (as shown in Figure 6.2).

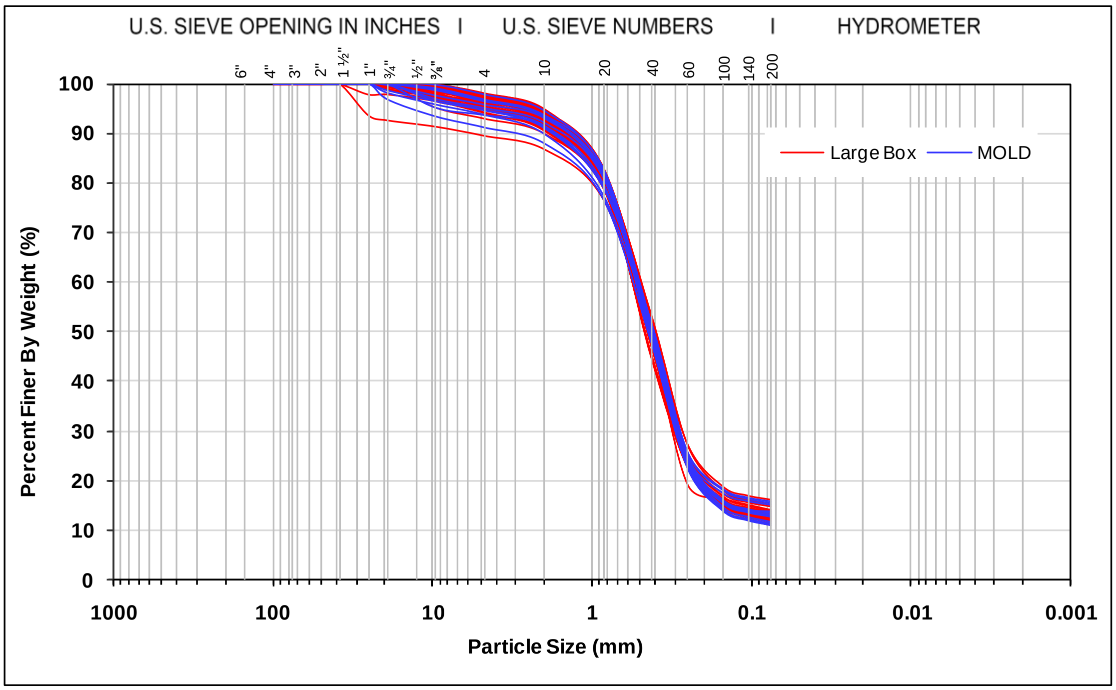


Figure 6.2 Gradation distributions for soil samples from large box and mold tests

Table 6.1 General summary table of classification results – Mold Tests

	MIN	MAX	MEAN	STD	CV (%)
No. 4 (%)	89.63	97.95	96.10	1.57	1.63%
No. 10 (%)	86.93	94.85	92.87	1.50	1.62%
No. 40 (%)	45.04	53.72	50.24	2.22	4.43%
No. 200 (%)	13.88	18.74	15.62	0.96	6.16%
% gravel	2.05	10.37	3.90	1.57	40.16%
% sand	77.69	86.45	83.13	1.78	2.14%
% fines	11.13	16.09	12.97	1.02	7.88%

6.3 Large Box Testing Procedure

The large wooden box used to simulate field conditions was 1.52 m (5 ft) (Length) by 0.91 m (3 ft) (Width) by 0.30 m (1 ft) (Height). Standard 38 x 89 mm (2x4 in.) lumber and 13 mm (1/2 in.) plywood were used to construct the large box (Figure 6.1)

The following test procedure was followed when performing large box tests for this research study:

1) Prepare soil at desired moisture content and wait 30 minutes for equilibration. Soil was mixed at the DELDOT facility in Bear with a concrete mixer (Figure 6.3).
2) The soil was then placed in buckets for volume control and then dumped into the large wooden box (Figure 6.4).
3) In order to vary density in the large wooden box, it was found that varying lift thickness was the best way to achieve desired densities (unit weights). Either 3 or 6 passes were performed using a walk-behind vibratory plate compactor. Soil was placed in uniform lift thicknesses ranging from 25 mm (1 in.) to 102

mm (4 in.) and compacted with a walk behind vibratory plate compactor (See Table 6.2 for lift thicknesses, total lifts, and total number of passes per lift). Large cobbles and gravel were removed during fill placement to avoid any possible effects that these materials might have on the test results. (Figure 6.5).

4) Four (4) in-situ density tests were performed in a given test location. It should be noted that there were 3 test locations in each large box (Figure 6.6).
5) An electrical density gauge (EDG) test was performed in general accordance with ASTM D 7698-11 (Figure 6.7).
6) A nuclear density gauge (NDG) test using a Troxler 3440 Gauge was performed in general accordance with ASTM D 6938-10 (Figure 6.8).
7) A sand cone (SC) test was performed in general accordance with ASTM D 1556-07 (Figure 6.9).
8) A drive cylinder test (DC) was performed in general accordance with ASTM D 2937-10 (Figure 6.10 and 6.11).

Figure 6.3 Concrete Mixer used to mix soil to different moisture contents

Figure 6.4 Soil Placed in buckets for volume control

Figure 6.5 Soil Compacted with walk-behind vibratory plate compactor

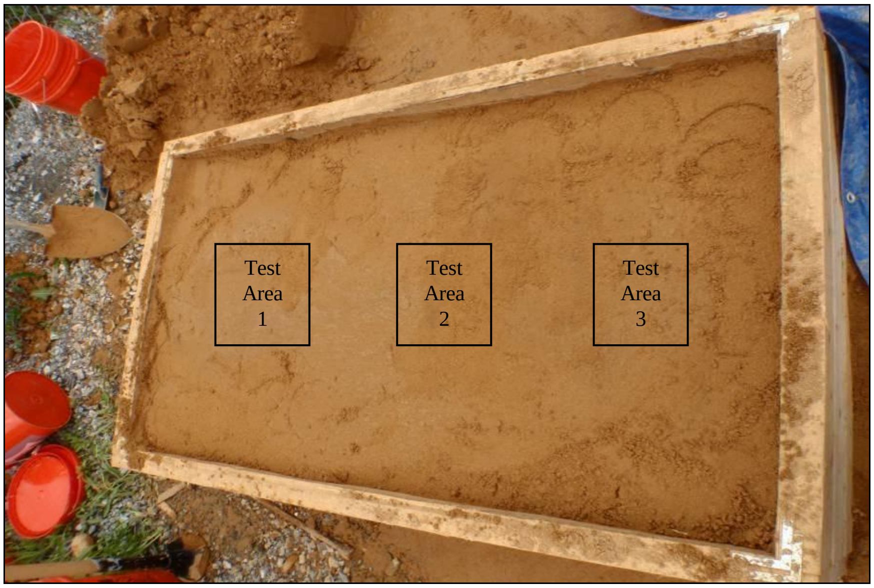


Figure 6.6 Large box before performing in-situ density tests

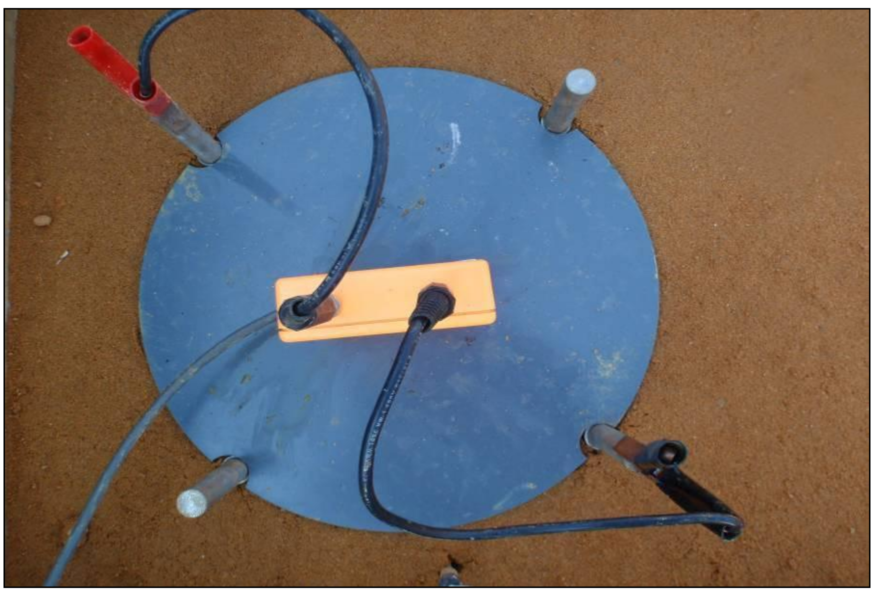


Figure 6.7 EDG test performed in Large Box

Figure 6.8 NDG test performed in Large Box

Figure 6.9 Sand Cone test performed in Large Box

Figure 6.10 Drive Cylinder test performed in Large Box

Figure 6.11 Drive Cylinder after excavation from hole

Table 6.2 Physical Mold Calibration Data

Box No.	Lift Thickness	Total Lifts	Passes
1	51 mm (2 in.)	6	3
2	38 mm (1.5 in.)	9	6
3	51 mm (2 in.)	6	6
4	51 mm (2 in.)	6	6
5	76 mm (3 in.)	4	6
6	102 mm (4 in.)	3	3
7	51 mm (2 in.)	6	3
8	25 mm (1 in.)	12	6
9	76 mm (3 in.)	4	3
10	76 mm (3 in.)	4	3
11	25 mm (1 in.)	12	6
12	51 mm (2 in.)	6	3
13	51 mm (2 in.)	6	3
14	38 mm (1.5 in.)	9	6

6.4 Simulated Field Test Results: Large Box Tests

In order to establish a benchmark for comparing EDG test results with the results for the three more traditionally utilized field density tests, the results from the nuclear density gauge (NDG), sand cone (SC), and drive cylinder (DC) tests are presented first. For purposes of this study, the DC is assumed to be the "actual" value when comparing to the NDG or SC, and the NDG is assumed to be the "actual" value when comparing to the SC (these assumptions are based on the general scatter that was observed in the unit weight values for each of these tests).

6.4.1 Standard Large Box Tests

Figure 6.12 shows comparisons of measured moist unit weight for each of the traditional in situ density tests, as follows: NDG versus SC, NDG versus DC, and

SC versus DC. It should be noted that the solid line in Figure 6.12a, 6.12b, and 6.12c is a 1:1 line, and the dashed lines are ±0.5 kN/m^3.

Figure 6.13 shows comparisons of measured weight of water per unit volume for each of the traditional in situ density tests, as follows: NDG versus SC, DC versus NDG, and DC versus SC. It should be noted that the solid line in Figure 6.13a, 6.13b, and 6.13c is a 1:1 line, and the dashed lines are ±0.5 kN/m^3.

Figure 6.14 shows comparisons of measured dry unit weight for each of the traditional in situ density tests, as follows: NDG versus SC, DC versus NDG, and DC versus SC. It should be noted that the solid line in Figure 6.14a, 6.14b, and 6.14c is a 1:1 line, and the dashed lines are ±0.5 kN/m^3.

Figure 6.15 shows comparisons of measured moisture content for each of the traditional in situ density tests, as follows: NDG versus SC, DC versus NDG, and DC versus SC. It should be noted that the solid line in Figure 6.15a, 6.15b, and 6.15c is a 1:1 line, and the dashed lines are ±0.5 % lines.

The RMSE, CV(RMSE), and NRMSE values for moist unit weight, weight of water per unit volume, and dry unit weight are the lowest when comparing the DC versus NDG. The RMSE, CV(RMSE), and NRMSE values for moisture content are the lowest when comparing the DC versus SC. Table 6.3, Table 6.4, and Table 6.5 summarize the statistical values for the large box test comparisons that are presented in this section.

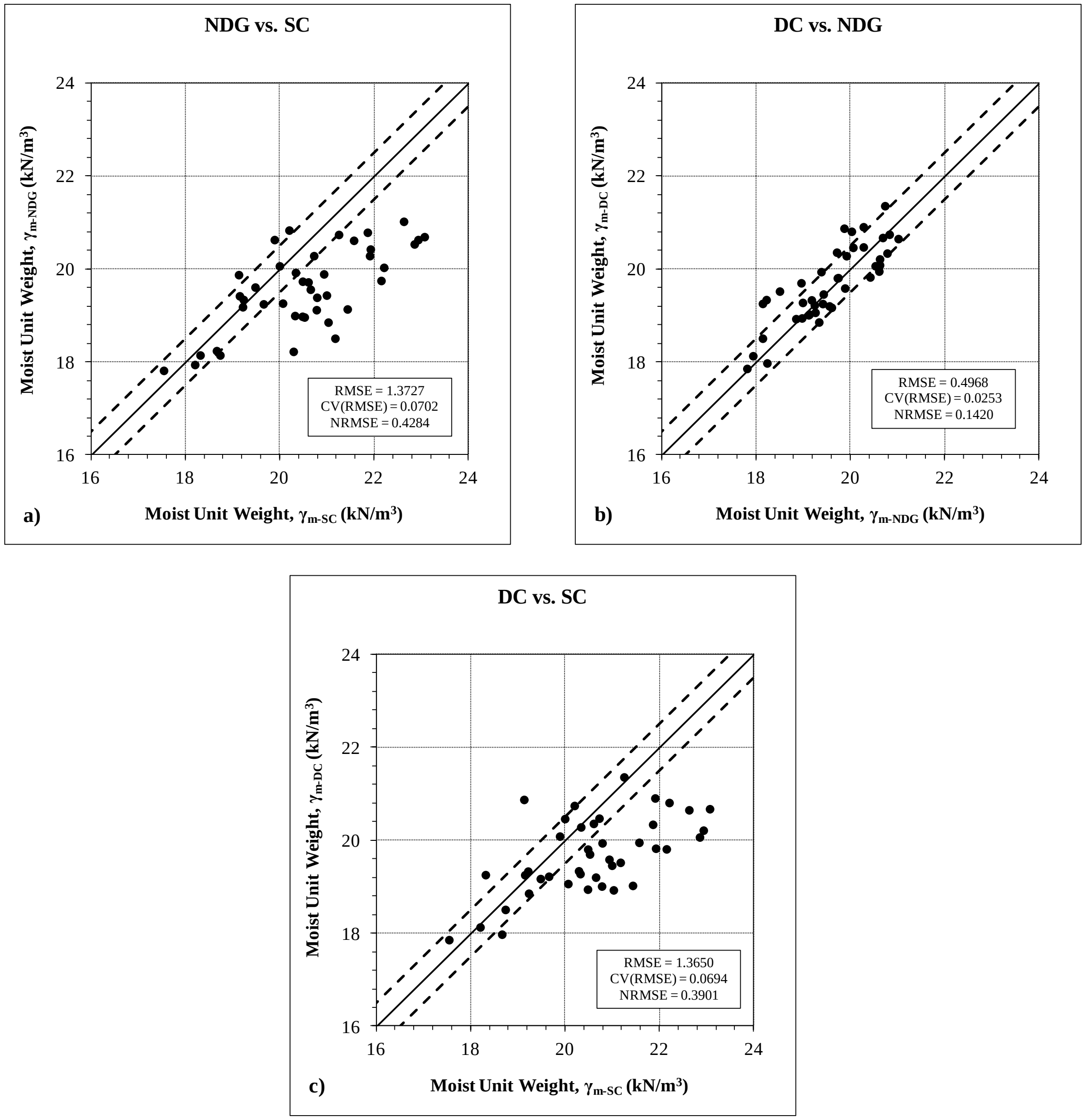


Figure 6.12 Standard Large Box Tests – Moist Unit Weight
a) NDG vs. SC: $\gamma_{m\text{-}NDG}$ vs. $\gamma_{m\text{-}SC}$
b) DC vs. NDG: $\gamma_{m\text{-}DC}$ vs. $\gamma_{m\text{-}NDG}$
c) DC vs. SC: $\gamma_{m\text{-}DC}$ vs. $\gamma_{m\text{-}SC}$

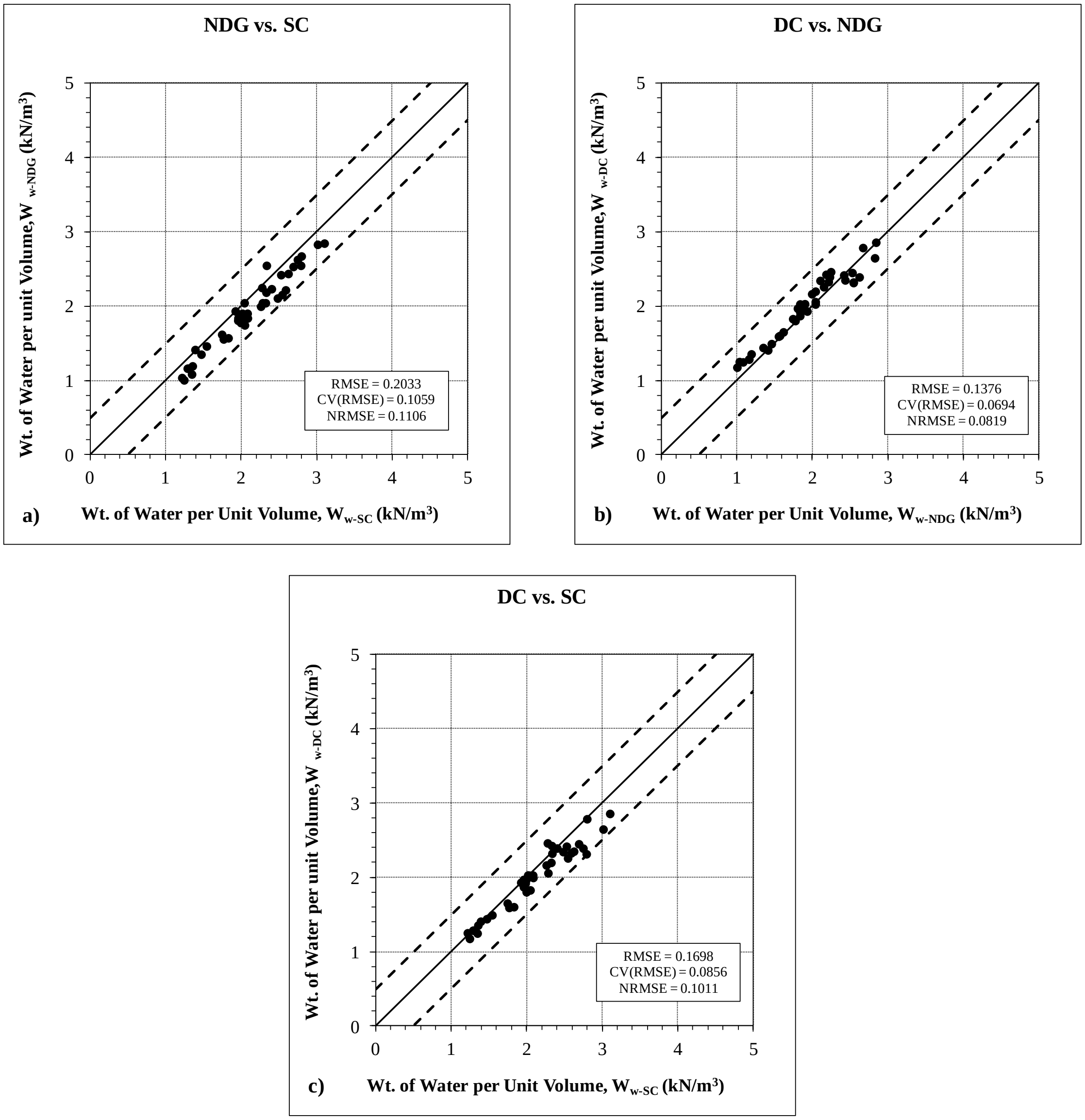


Figure 6.13 Standard Large Box Tests – Weight of Water per Unit Volume
a) NDG vs. SC: $W_{W\text{-}NDG}$ vs. $W_{W\text{-}SC}$
b) DC vs. NDG: $W_{W\text{-}DC}$ vs. $W_{W\text{-}NDG}$
c) DC vs. SC: $W_{W\text{-}DC}$ vs. $W_{W\text{-}SC}$

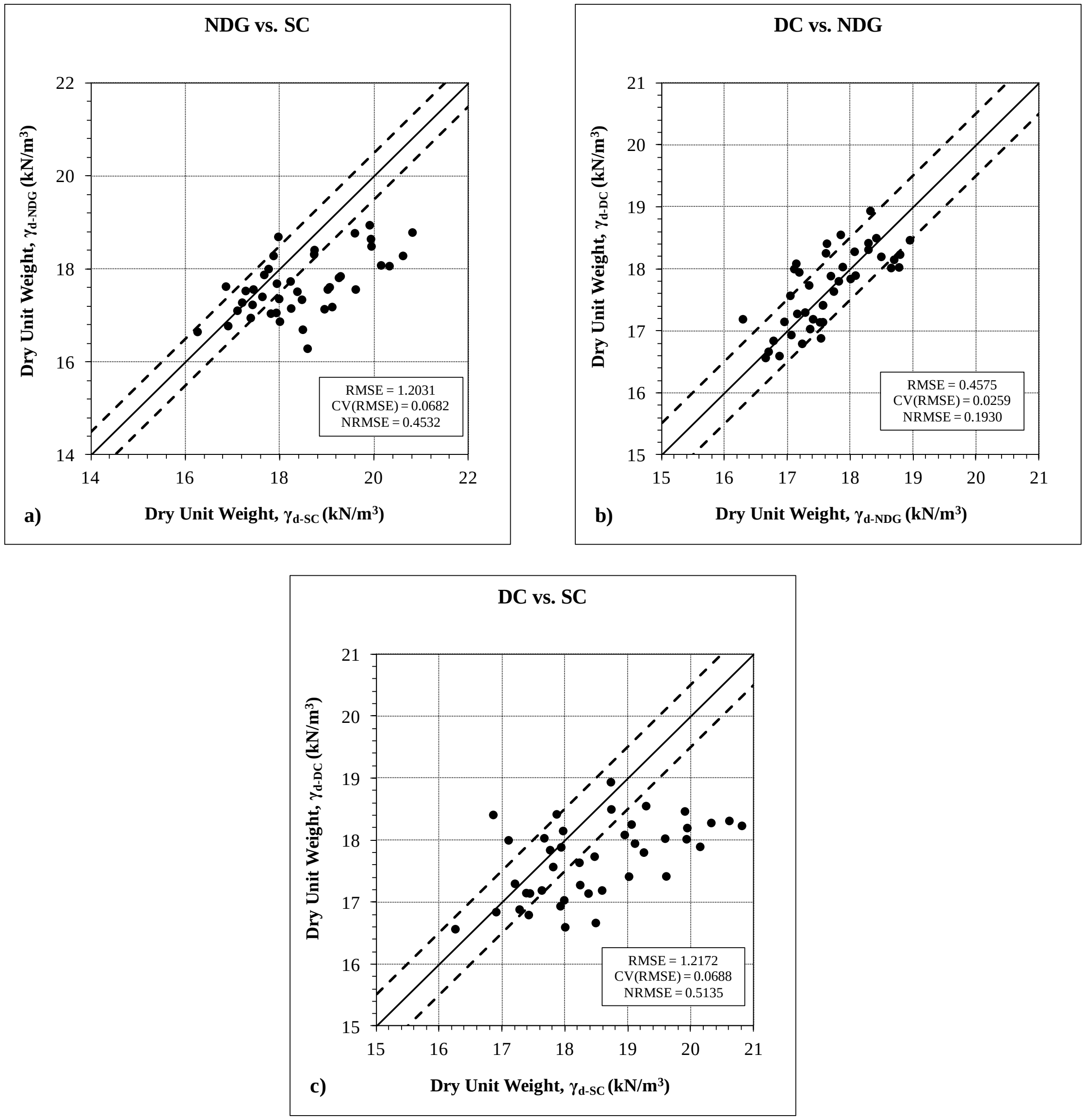


Figure 6.14 Standard Large Box Tests – Dry Unit Weight
a) NDG vs. SC: $\gamma_{d\text{-}NDG}$ vs. $\gamma_{d\text{-}SC}$
b) DC vs. NDG: $\gamma_{d\text{-}DC}$ vs. $\gamma_{d\text{-}NDG}$
c) DC vs. SC: $\gamma_{d\text{-}DC}$ vs. $\gamma_{d\text{-}SC}$

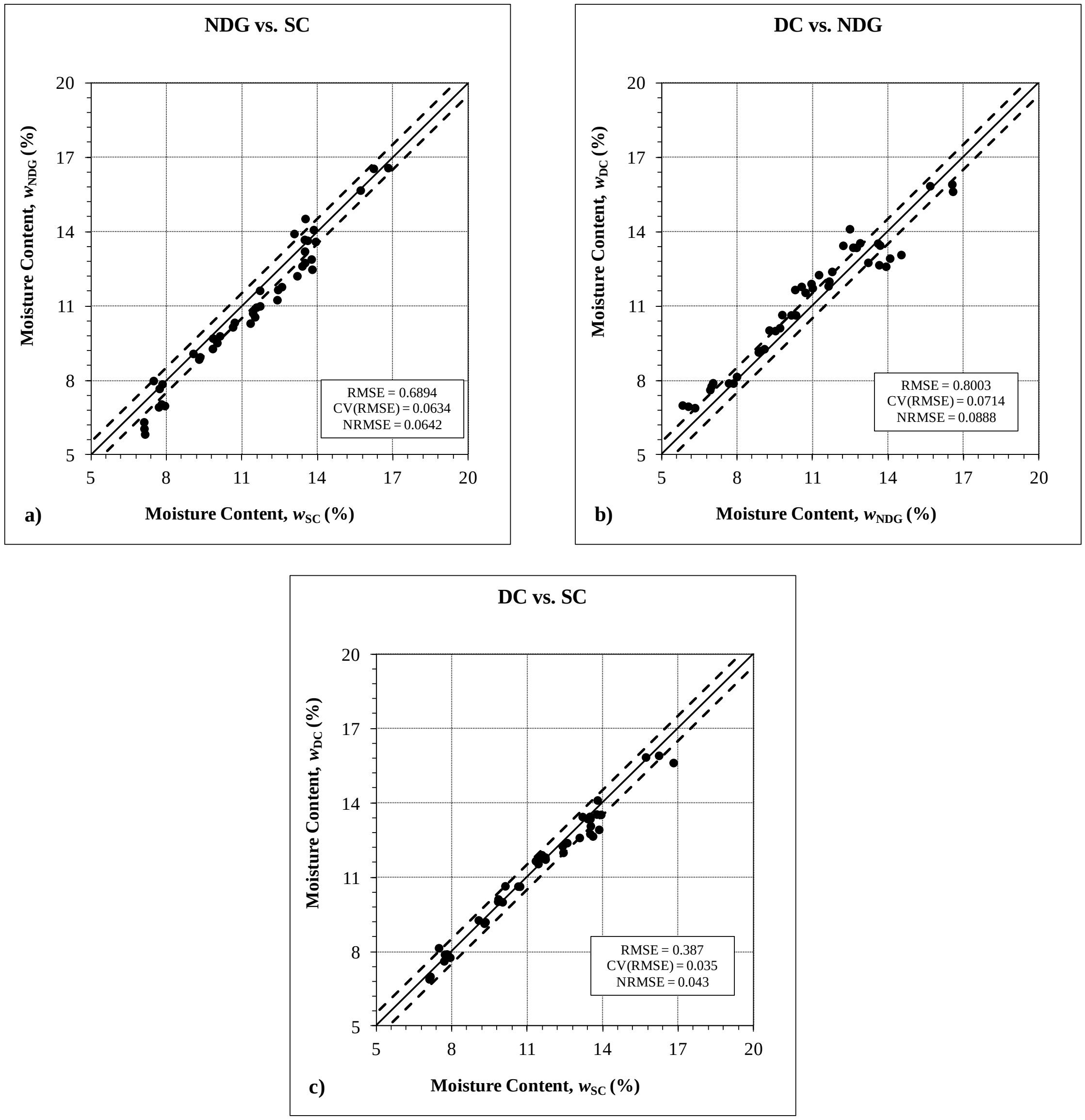


Figure 6.15 Standard Large Box Tests – Moisture Content
a) NDG vs. SC: w_{NDG} vs. w_{SC}
b) DC vs. NDG: w_{DC} vs. w_{NDG}
c) DC vs. SC: w_{DC} vs. w_{SC}

Table 6.3 Summary Table of Statistical Measures – NDG vs. SC

NDG vs. SC				
	γ_m	γ_d	W_w	w
RMSE	1.3727	1.2031	0.2033	0.6894
CV(RMSE)	0.0702	0.0682	0.1059	0.0634
NRMSE	0.4284	0.4532	0.1106	0.0642

Table 6.4 Summary Table of Statistical Measures – DC vs. NDG

DC vs. NDG				
	γ_m	γ_d	W_w	w
RMSE	0.4968	0.4575	0.1376	0.8003
CV(RMSE)	0.0253	0.0259	0.0694	0.0714
NRMSE	0.1420	0.1930	0.0819	0.0888

Table 6.5 Summary Table of Statistical Measures – DC vs. SC

DC vs. SC				
	γ_m	γ_d	W_w	w
RMSE	1.3650	1.2172	0.1698	0.3872
CV(RMSE)	0.0694	0.0688	0.0856	0.0345
NRMSE	0.3901	0.5135	0.1011	0.0430

6.4.2 Standard Field Tests: Relative Error

Relative error is calculated by taking the value considered to be the "actual" value, subtracting it from the "predicted" value, and dividing the resulting difference by the "actual" value (Freedman 1998). The following three equations show how relative error was calculated in this section (Equation 6.1, 6.2, 6.3):

$$\text{Relative error (\%)} = \frac{NDG_{VALUE} - SC_{VALUE}}{NDG_{VALUE}} \times 100 \tag{6.1}$$

$$\text{Relative error (\%)} = \frac{DC_{VALUE} - NDG_{VALUE}}{DC_{VALUE}} \times 100 \tag{6.2}$$

$$\text{Relative error (\%)} = \frac{DC_{VALUE} - SC_{VALUE}}{DC_{VALUE}} \times 100 \tag{6.3}$$

The following section shows histograms of the relative error that is calculated for moist unit weight, weight of water per unit volume, dry unit weight, and moisture content for all of the standard field tests. A cumulative distribution function (CDF) is displayed on each histogram as well.

6.4.3 Standard Field Tests: Relative Error Results

Figure 6.16a is a histogram plot of relative error between $\gamma_{m\text{-}NDG}$ and $\gamma_{m\text{-}SC}$, $\gamma_{m\text{-}DC}$ and $\gamma_{m\text{-}NDG}$, and $\gamma_{m\text{-}DC}$ and $\gamma_{m\text{-}SC}$. For NDG versus SC, relative error values for γ_m range from -14.43% to 3.72%. For DC vs. NDG, relative error values for γ_m range from -6.11% to 3.21%. For DC vs. SC, relative error values for γ_m range from -9.08% to 12.22%.

Figure 6.16b is a histogram plot of relative error between $\gamma_{d\text{-}NDG}$ and $\gamma_{d\text{-}SC}$, $\gamma_{d\text{-}DC}$ and $\gamma_{d\text{-}NDG}$, and $\gamma_{d\text{-}DC}$ and $\gamma_{d\text{-}SC}$. For NDG vs.SC, relative error values for γ_d range from -14.10% to 4.36%. For DC vs. NDG, relative error values for γ_d range from -5.54% to 3.96%. For DC vs. SC, relative error values for γ_d range from -9.22% to 12.37%.

Figure 6.16c is a histogram plot of relative error between $W_{W\text{-}NDG}$ and $W_{W\text{-}SC}$, $W_{W\text{-}DC}$ and $W_{W\text{-}NDG}$, and $W_{W\text{-}DC}$ and $W_{W\text{-}SC}$. For NDG vs. SC, relative error values for W_W range from -24.26% to 8.19%. For DC vs. NDG, relative error values for W_W range from -20.75% to 9.10%. For DC vs. SC, relative error values for W_W range from -8.06% to 17.09%.

Figure 6.16d is a histogram plot of relative error between w_{NDG} and w_{SC}, w_{DC} and w_{NDG}, and w_{DC} and w_{SC}. For NDG vs. SC, relative error values for w range from -22.49% to 6.91%. For DC vs. NDG, relative error values for w range from -20.03% to 10.00%. For DC vs. SC, relative error values for w range from -8.89% to 7.07%.

Table 6.6, Table 6.7, and Table 6.8 provide a summary of the minimum, maximum, range, and mean of the relative error for all of the standard field tests.

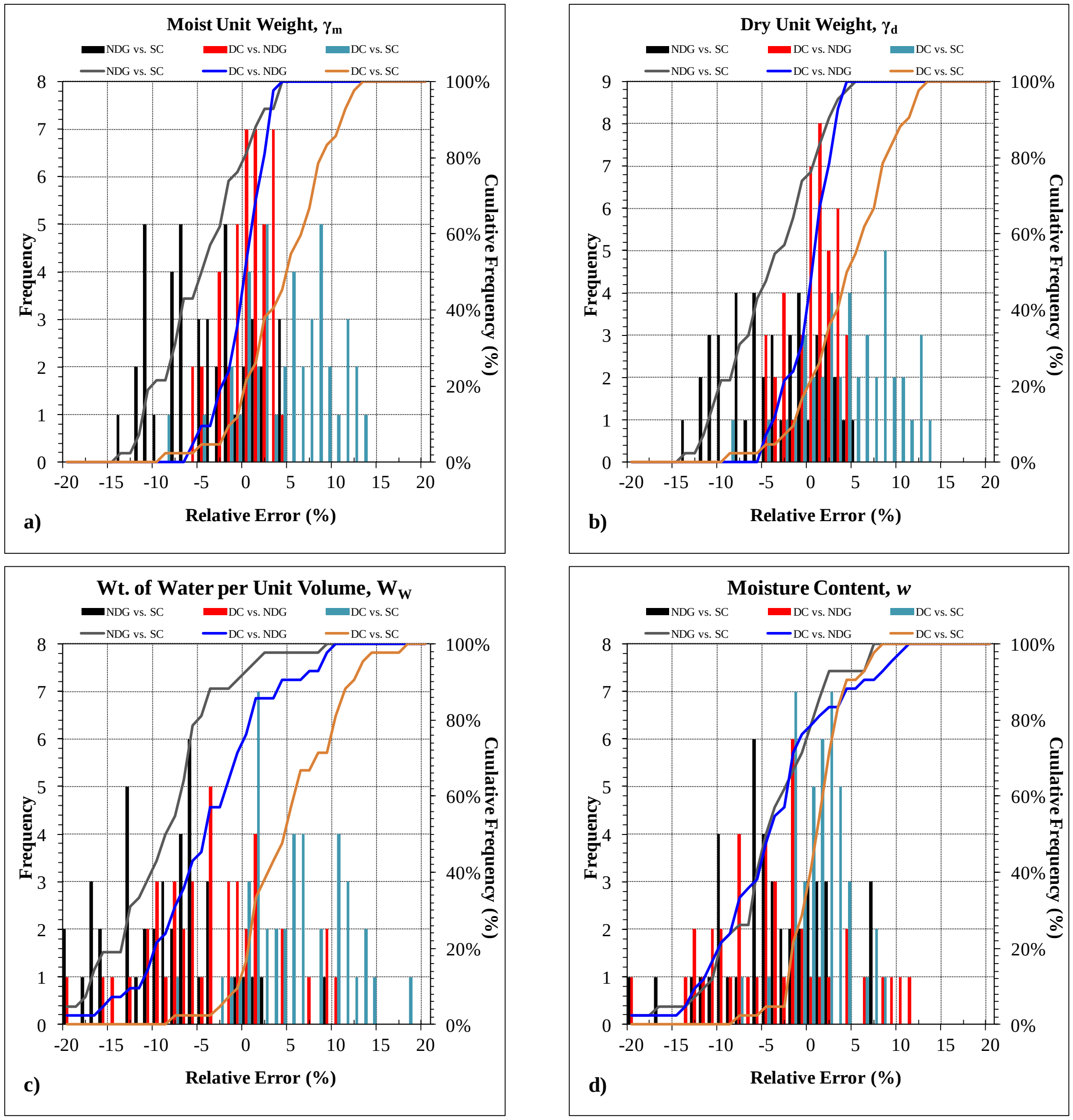


Figure 6.16 Relative Error Histograms and CDF Plots – Standard Field Tests
a) Histogram & CDF – Moist Unit Weight
b) Histogram & CDF – Dry Unit Weight
c) Histogram & CDF – Wt. of Water per Unit Volume
d) Histogram & CDF - Moisture Content

Table 6.6 Summary Table of Relative Error (%) – NDG vs. SC

NDG vs. SC				
	γ_m	W_w	γ_d	w
MIN	-14.43	-14.10	-24.26	-22.49
MAX	3.72	4.36	8.19	6.91
RANGE	18.15	18.46	32.45	29.41
MEAN	-5.06	-4.66	-9.62	-4.85

Table 6.7 Summary Table of Relative Error (%) – DC vs. NDG

DC vs. NDG				
	γ_m	W_w	γ_d	w
MIN	-6.11	-5.54	-20.75	-20.03
MAX	3.21	3.96	9.10	10.00
RANGE	9.33	9.50	29.85	30.03
MEAN	-0.56	-0.25	-4.53	-4.31

Table 6.8 Summary Table of Relative Error (%) – DC vs. SC

DC vs. SC				
	γ_m	W_w	γ_d	w
MIN	-9.08	-9.22	-8.06	-8.89
MAX	12.22	12.37	17.09	7.07
RANGE	21.30	21.59	25.15	15.96
MEAN	4.09	4.02	4.53	0.52

6.5 "Blind" Assessment of EDG: Mold Soil Model

The following section uses the calibration relationships developed using the large mold tests (see Chapter 5) as a Soil Model for the EDG tests run in the large box tests. The following assessment is a truly "blind" assessment of how well the EDG performs, and is the recommended way to assess the EDG's performance.

6.5.1 Large Box Test Results: Mold Soil Model

Figure 6.17 shows NDG versus EDG, SC versus EDG, and DC versus EDG measured moist unit weight with and without the EDG temperature correction applied (TC ON & TC OFF). It should be noted that the solid line in Figure 6.17a, 6.17b, and 6.17c is a 1:1 line, and the dashed lines are ±0.5 kN/m^3.

Figure 6.13 shows NDG versus EDG, SC versus EDG, and DC versus EDG measured weight of water per unit volume with and without the EDG temperature correction applied (TC ON & TC OFF). It should be noted that the solid line in Figure 6.13a, 6.13b, and 6.13c is a 1:1 line, and the dashed lines are ±0.5 kN/m^3.

Figure 6.14 shows NDG versus EDG, SC versus EDG, and DC versus EDG measured dry unit weight with and without the EDG temperature correction applied (TC ON & TC OFF). It should be noted that the solid line in Figure 6.14a, 6.14b, and 6.14c is a 1:1 line, and the dashed lines are ±0.5 kN/m^3.

Figure 6.15 shows NDG versus EDG, SC versus EDG, and DC versus EDG measured moisture content with and without the EDG temperature correction applied (TC ON & TC OFF). It should be noted that the solid line in Figure 6.15a, 6.15b, and 6.15c is a 1:1 line, and the dashed lines are ±0.5 %. The RMSE, CV(RMSE), and NRMSE values for moist unit weight, weight of water per unit volume, and moisture content generally become lower when the EDG temperature correction is applied when comparing the EDG to all 3 standard field tests. The RMSE, CV(RMSE), and NRMSE values for dry unit weight generally become higher when the EDG temperature correction is applied when comparing the EDG to all 3 standard field tests. Table 6.9, Table 6.10, and Table 6.11 summarize the statistical values for all of the large box test comparisons that are presented in this section.

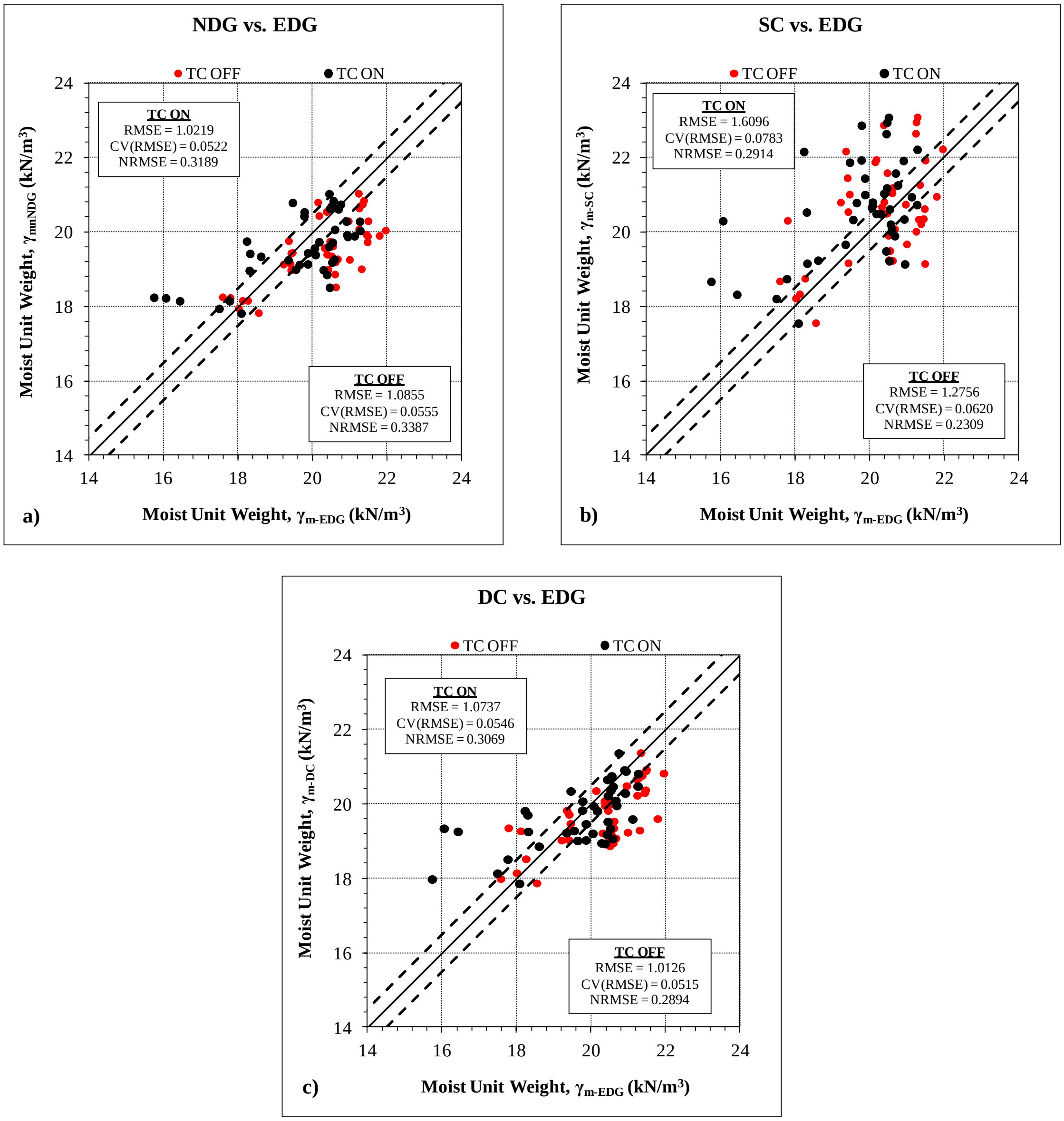


Figure 6.17 Large Box Test Results: Mold Soil Model – Moist Unit Weight
a) NDG vs. EDG: $\gamma_{m\text{-}NDG}$ vs. $\gamma_{m\text{-}EDG}$
b) SC vs. EDG: $\gamma_{m\text{-}SC}$ vs. $\gamma_{m\text{-}EDG}$
c) DC vs. EDG: $\gamma_{m\text{-}DC}$ vs. $\gamma_{m\text{-}EDG}$

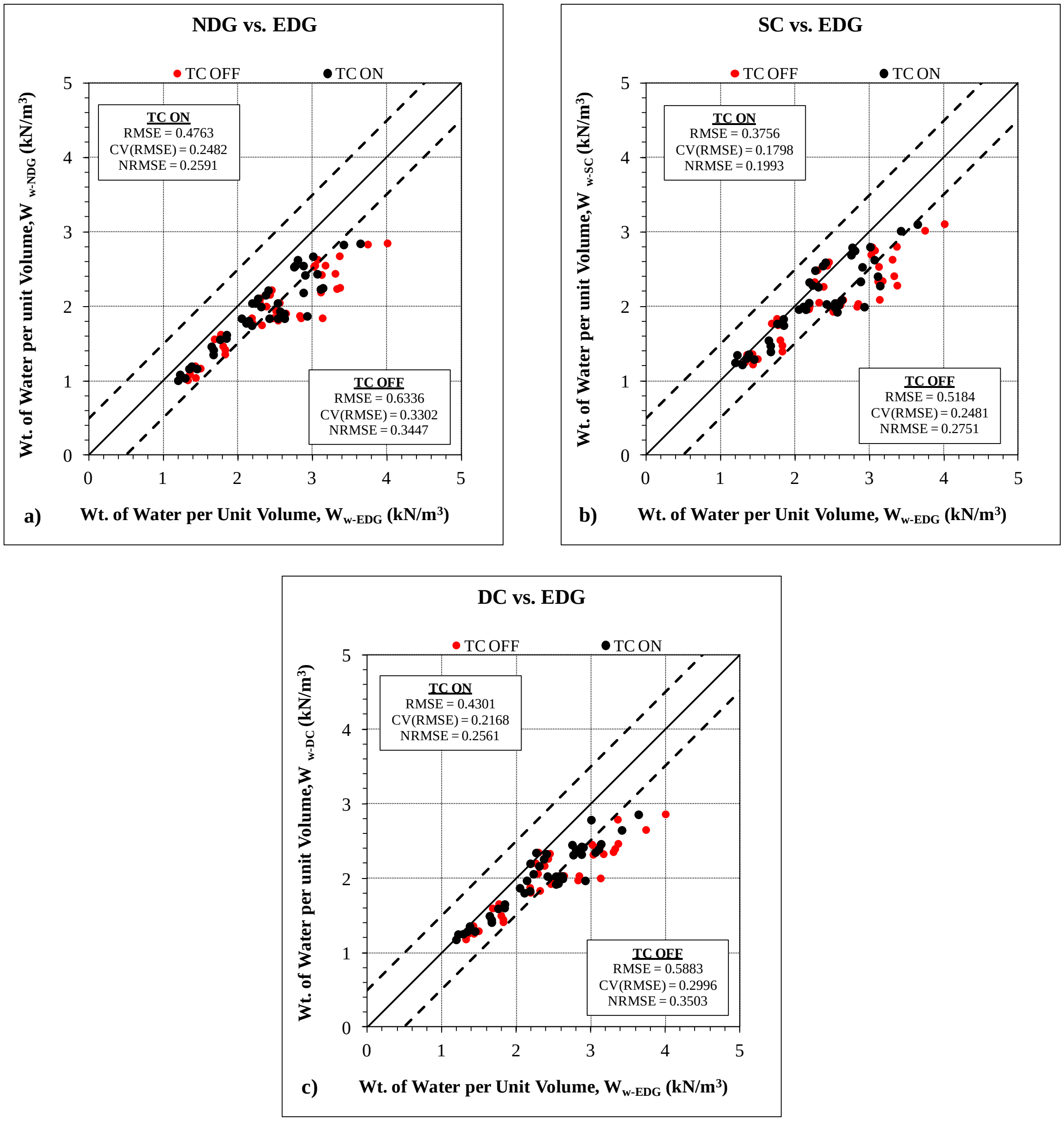


Figure 6.18 Large Box Test Results: Mold Soil Model – Weight of Water per Unit Volume
a) NDG vs. EDG: $W_{W\text{-}NDG}$ vs. $W_{W\text{-}EDG}$
b) SC vs. EDG: $W_{W\text{-}SC}$ vs. $W_{W\text{-}EDG}$
c) DC vs. EDG: $W_{W\text{-}DC}$ vs. $W_{W\text{-}EDG}$

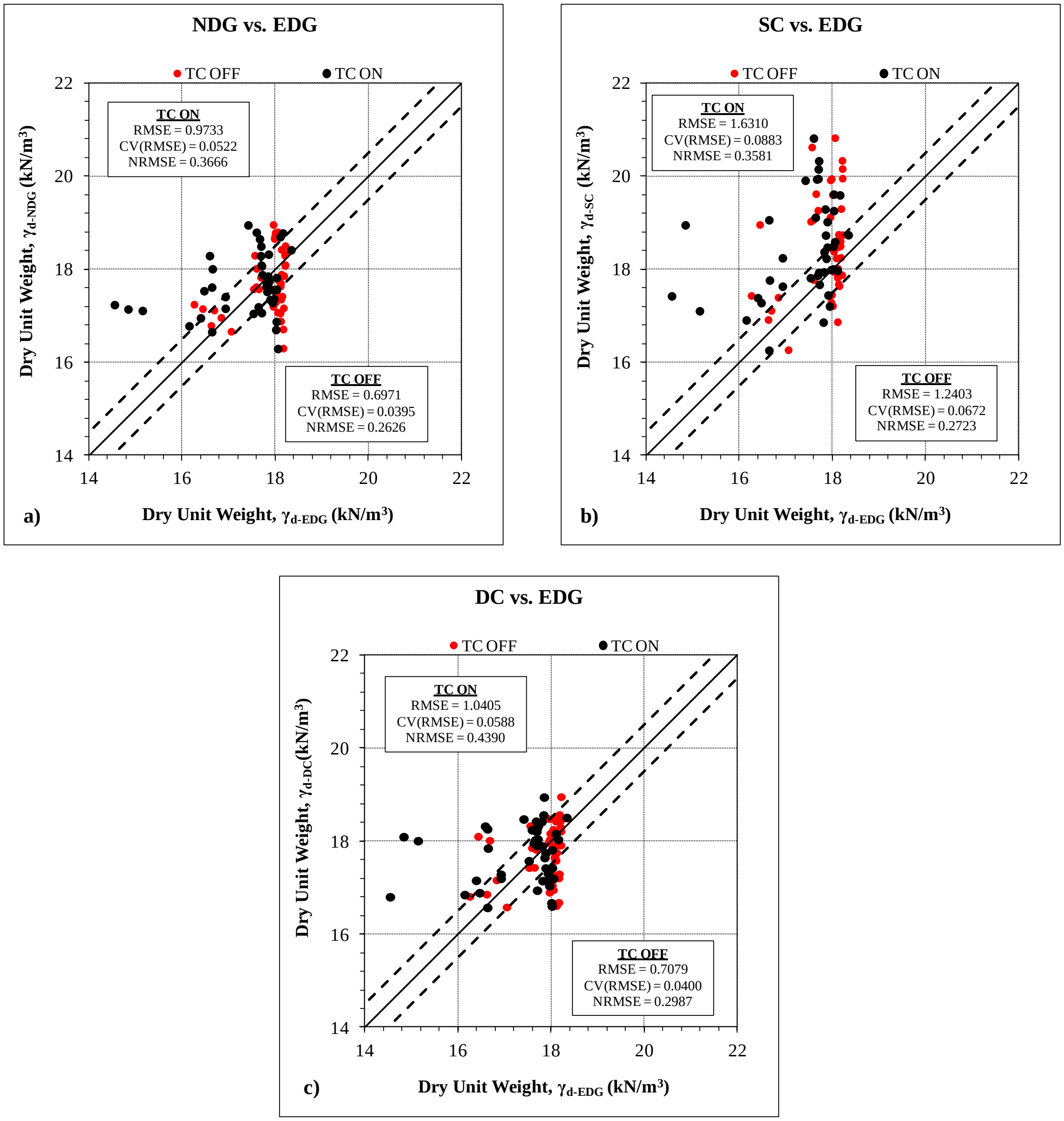


Figure 6.19 Large Box Test Results: Mold Soil Model – Dry Unit Weight
a) NDG vs. EDG: $\gamma_{d\text{-}NDG}$ vs. $\gamma_{d\text{-}EDG}$
b) SC vs. EDG: $\gamma_{d\text{-}SC}$ vs. $\gamma_{d\text{-}EDG}$
c) DC vs. EDG: $\gamma_{d\text{-}DC}$ vs. $\gamma_{d\text{-}EDG}$

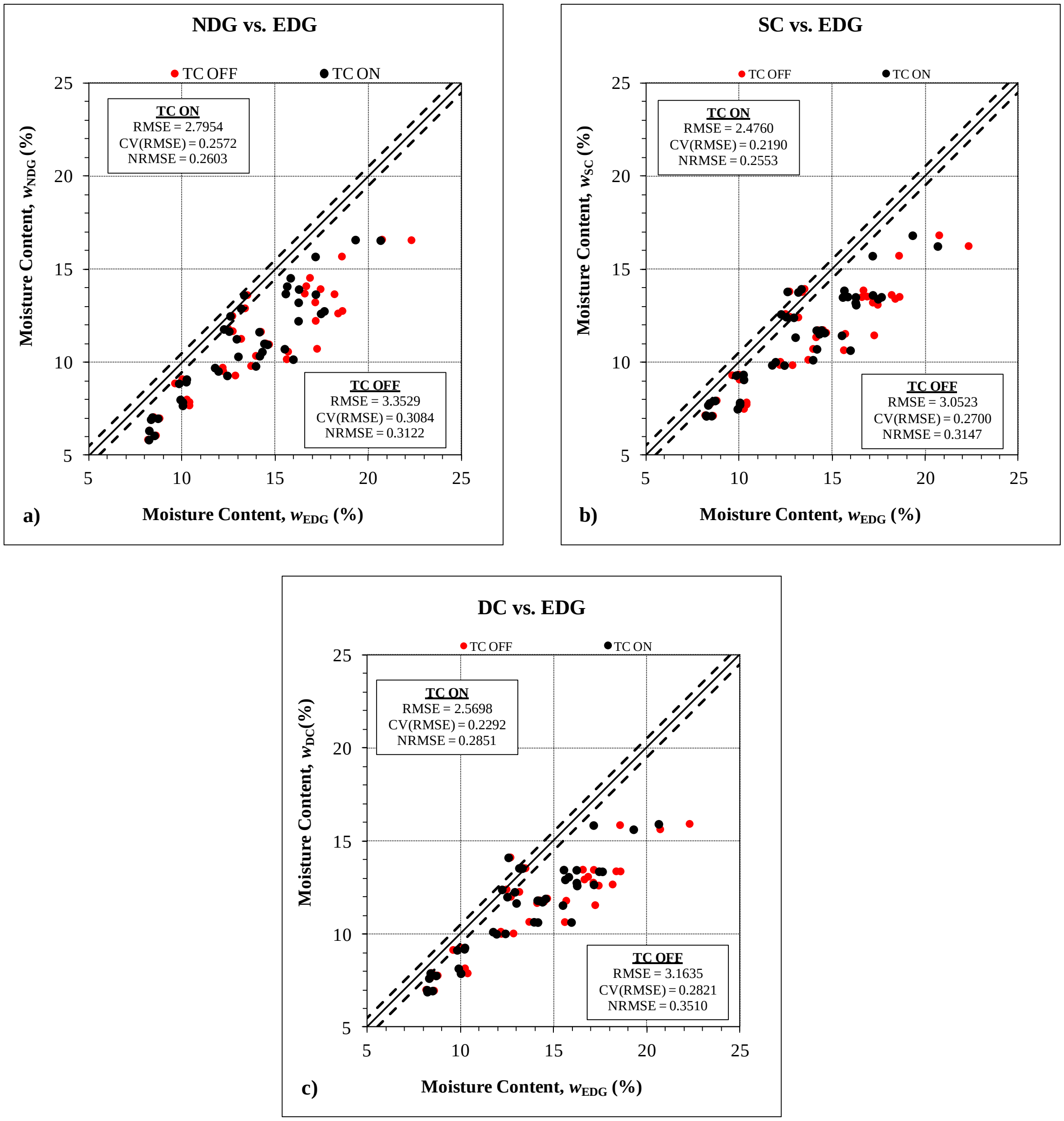


Figure 6.20 Large Box Test Results: Mold Soil Model – Moisture Content
a) NDG vs. EDG: w_{NDG} vs. w_{EDG}
b) SC vs. EDG: w_{SC} vs. w_{EDG}
c) DC vs. EDG: w_{DC} vs. w_{EDG}

Table 6.9 Summary Table of Statistical Measures – NDG vs. EDG (Mold Soil Model)

NDG vs. EDG	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	1.0855	0.6971	0.6336	3.3529	1.0219	0.9733	0.4763	2.7954
CV(RMSE)	0.0555	0.0395	0.3302	0.3084	0.0522	0.0552	0.2482	0.2572
NRMSE	0.3387	0.2626	0.3447	0.3122	0.3189	0.3666	0.2591	0.2603

Table 6.10 Summary Table of Statistical Measures – SC vs. EDG (Mold Soil Model)

SC vs. EDG	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	1.2756	1.2403	0.5184	3.0523	1.6096	1.6310	0.3756	2.4760
CV(RMSE)	0.0620	0.0672	0.2481	0.2700	0.0783	0.0883	0.1798	0.2190
NRMSE	0.2309	0.2723	0.2751	0.3147	0.2914	0.3581	0.1993	0.2553

Table 6.11 Summary Table of Statistical Measures – DC vs. EDG (Mold Soil Model)

DC vs. EDG	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	1.0126	0.7079	0.5883	3.1635	1.0737	1.0405	0.4301	2.5698
CV(RMSE)	0.0515	0.0400	0.2966	0.2821	0.0546	0.0588	0.2168	0.2292
NRMSE	0.2894	0.2987	0.3503	0.3510	0.3069	0.4390	0.2561	0.2851

6.5.2 Large Box Tests: Mold Soil Model - Relative Error

Relative error is calculated by taking the value considered to be the "actual" value, subtracting it from the "predicted" value, and dividing the resulting difference by the "actual" value (Freedman 1998). The following three equations show how relative error was calculated in this section (Equation 6.4, 6.5, 6.6):

$$\text{Relative error (\%)} = \frac{NDG_{VALUE} - EDG_{VALUE}}{NDG_{VALUE}} \times 100 \qquad (6.4)$$

$$\text{Relative error (\%)} = \frac{SC_{VALUE} - EDG_{VALUE}}{SC_{VALUE}} \times 100 \qquad (6.5)$$

$$\text{Relative error (\%)} = \frac{DC_{VALUE} - EDG_{VALUE}}{DC_{VALUE}} \times 100 \qquad (6.6)$$

The following section shows histograms of the relative error calculated for moist unit weight, weight of water per unit volume, dry unit weight, and moisture content for all of the EDG large box tests. A cumulative distribution function (CDF) is displayed on each histogram as well.

6.5.3 Large Box Tests: Mold Soil Model - Relative Error Results

Figure 6.16a is a histogram plot of relative error between $\gamma_{m\text{-}NDG}$ and $\gamma_{m\text{-}EDG}$ (TC ON and TC OFF). For NDG vs. EDG (TC OFF), relative error values for γ_m range from -12.28% to 3.52% and for NDG vs. EDG (TC ON), relative error values for γ_m range from -10.56% to 13.68%.

Figure 6.16b is a histogram plot of relative error between $\gamma_{d\text{-}NDG}$ and $\gamma_{d\text{-}EDG}$ (TC ON and TC OFF). For NDG vs. EDG (TC OFF), relative error values for γ_d range from -11.59% to 5.61% and for NDG vs. EDG (TC ON), relative error values for γ_d range from -10.83% to 15.57%.

Figure 6.16c is a histogram plot of relative error between $W_{W\text{-}NDG}$ and $W_{W\text{-}EDG}$ (TC ON and TC OFF). For NDG VS. EDG (TC OFF), relative error values for W_W range from -70.68% to -8.53% and for NDG VS. EDG (TC ON), relative error values for W_W range from -56.54% to -6.73%.

Figure 6.16d is a histogram plot of relative error between w_{NDG} and w_{EDG} (TC ON and TC OFF). For NDG vs. EDG (TC OFF), relative error values for *w* range from -60.99% to 0.66% and for NDG vs. EDG (TC ON), relative error values for *w* range from -57.14% to 2.02%.

Figure 6.17a is a histogram plot of relative error between $\gamma_{m\text{-}SC}$ and $\gamma_{m\text{-}EDG}$ (TC ON and TC OFF). For SC vs. EDG (TC OFF), relative error values for γ_m range from -12.33% to 12.56% and for SC vs. EDG (TC ON), relative error values for γ_m range from -9.46% to 20.85%.

Figure 6.17b is a histogram plot of relative error between $\gamma_{d\text{-}SC}$ and $\gamma_{d\text{-}EDG}$ (TC ON and TC OFF). For SC vs. EDG (TC OFF), relative error values for γ_d range from -7.49% to 14.76% and for SC vs. EDG (TC ON), relative error values for γ_d range from -5.62% to 21.67%.

Figure 6.17c is a histogram plot of relative error between $W_{W\text{-}SC}$ and $W_{W\text{-}EDG}$ (TC ON and TC OFF). For SC vs. EDG (TC OFF), relative error values for W_W range from -50.41% to 7.26% and for SC vs. EDG (TC ON), relative error values for W_W range from -46.83% to 9.40%.

Figure 6.17d is a histogram plot of relative error between w_{SC} and w_{EDG} (TC ON and TC OFF). For SC vs. EDG (TC OFF), relative error values for *w* range from -50.84% to 7.9% and for SC vs. EDG (TC ON), relative error values for *w* range from -49.97% to 8.79%.

Figure 6.18a is a histogram plot of relative error between $\gamma_{m\text{-}DC}$ and $\gamma_{m\text{-}EDG}$ (TC ON and TC OFF). For DC vs. EDG (TC OFF), relative error values for γ_m range from -11.35% to 7.92% and for DC vs. EDG (TC ON), relative error values for γ_m range from -8.01% to 16.93%.

Figure 6.18b is a histogram plot of relative error between $\gamma_{d\text{-}DC}$ and $\gamma_{d\text{-}EDG}$ (TC ON and TC OFF). For DC vs. EDG (TC OFF), relative error values for γ_d range from -9.21% to 9.06% and for DC vs. EDG (TC ON), relative error values for γ_d range from -8.58% to 17.95%.

Figure 6.18c is a histogram plot of relative error between $W_{W\text{-}DC}$ and $W_{W\text{-}EDG}$ (TC ON and TC OFF). For DC vs. EDG (TC OFF), relative error values for W_W range from -57.24% to 1.69% and for DC vs. EDG (TC ON), relative error values for W_W range from -48.7% to 3.19%

Figure 6.18d is a histogram plot of relative error between w_{DC} and w_{EDG} (TC ON and TC OFF). For DC vs. EDG (TC OFF), relative error values for *w* range from -49.87% to 10.21% and for DC vs. EDG (TC ON), relative error values for *w* range from -49.99% to 11.09%.

Table 6.12, Table 6.13, and Table 6.14 provide a summary of the minimum, maximum, range, and mean of the relative error for all of the EDG large box tests.

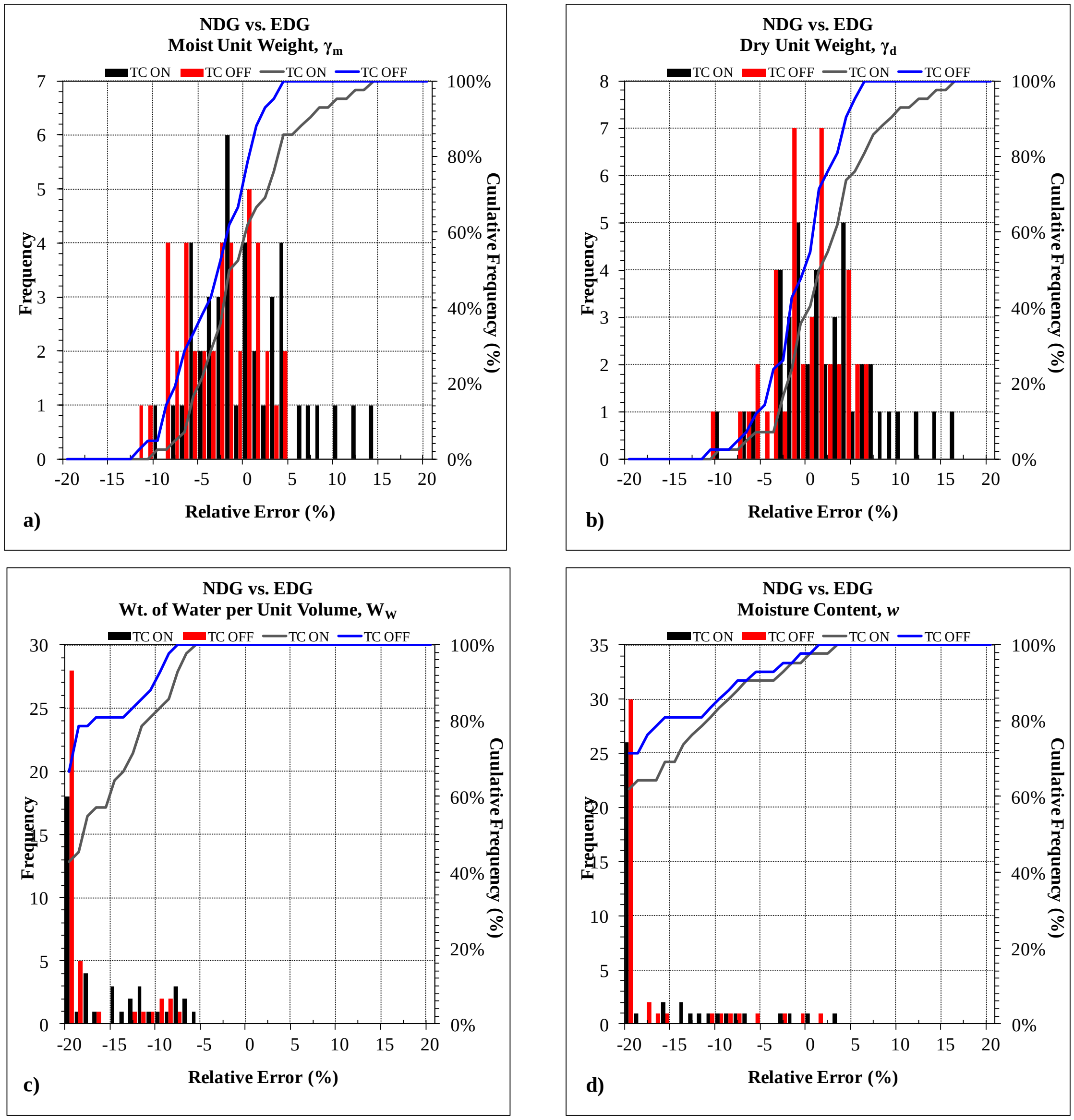


Figure 6.21 Relative Error Histograms and CDF Plots – NDG vs. EDG (Mold Soil Model)
a) Histogram & CDF – Moist Unit Weight
b) Histogram & CDF – Dry Unit Weight
c) Histogram & CDF – Wt. of Water per Unit Volume
d) Histogram & CDF - Moisture Content

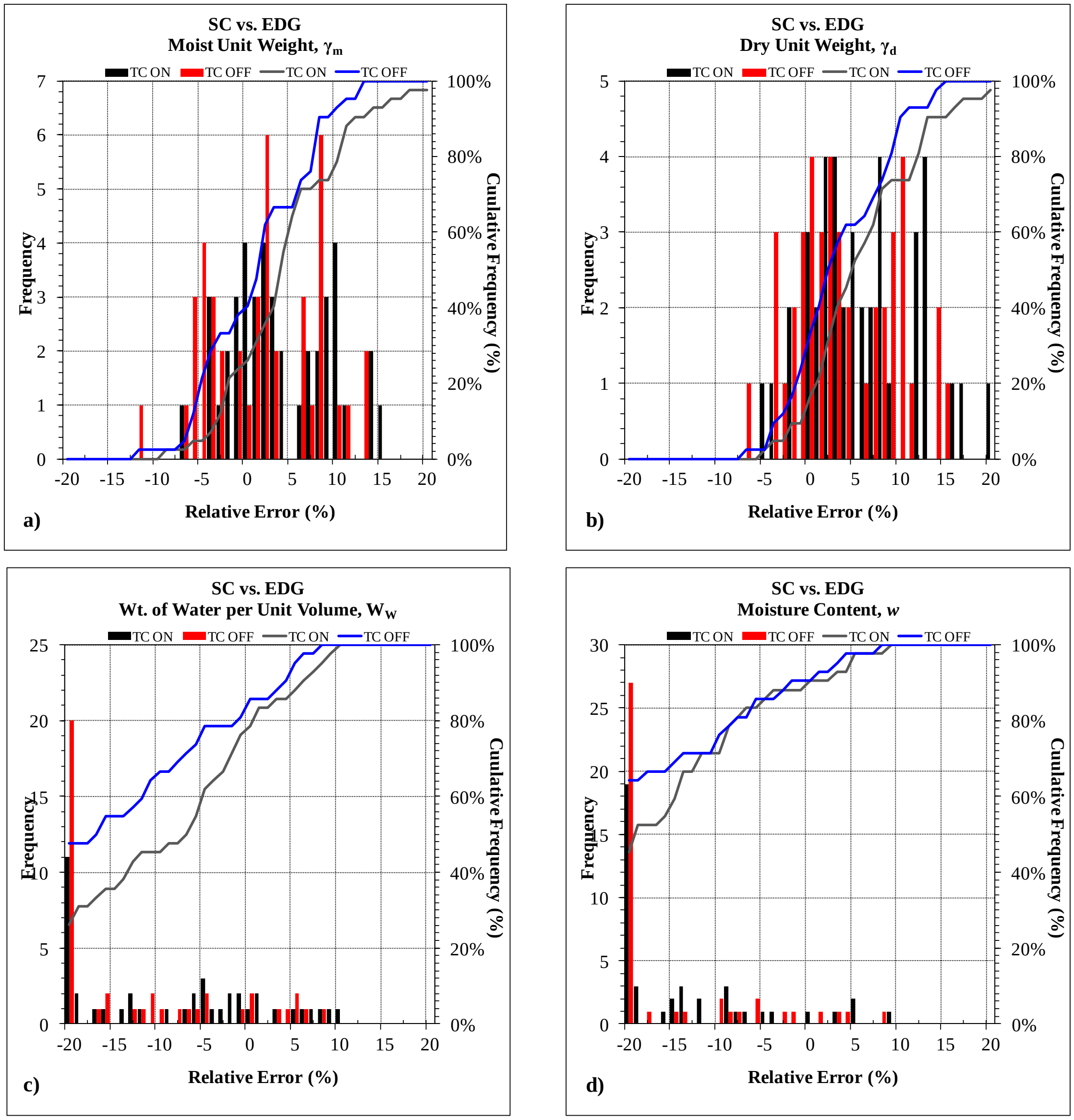


Figure 6.22 Relative Error Histograms and CDF Plots – SC vs. EDG (Mold Soil Model)
a) Histogram & CDF – Moist Unit Weight
b) Histogram & CDF – Dry Unit Weight
c) Histogram & CDF – Wt. of Water per Unit Volume
d) Histogram & CDF - Moisture Content

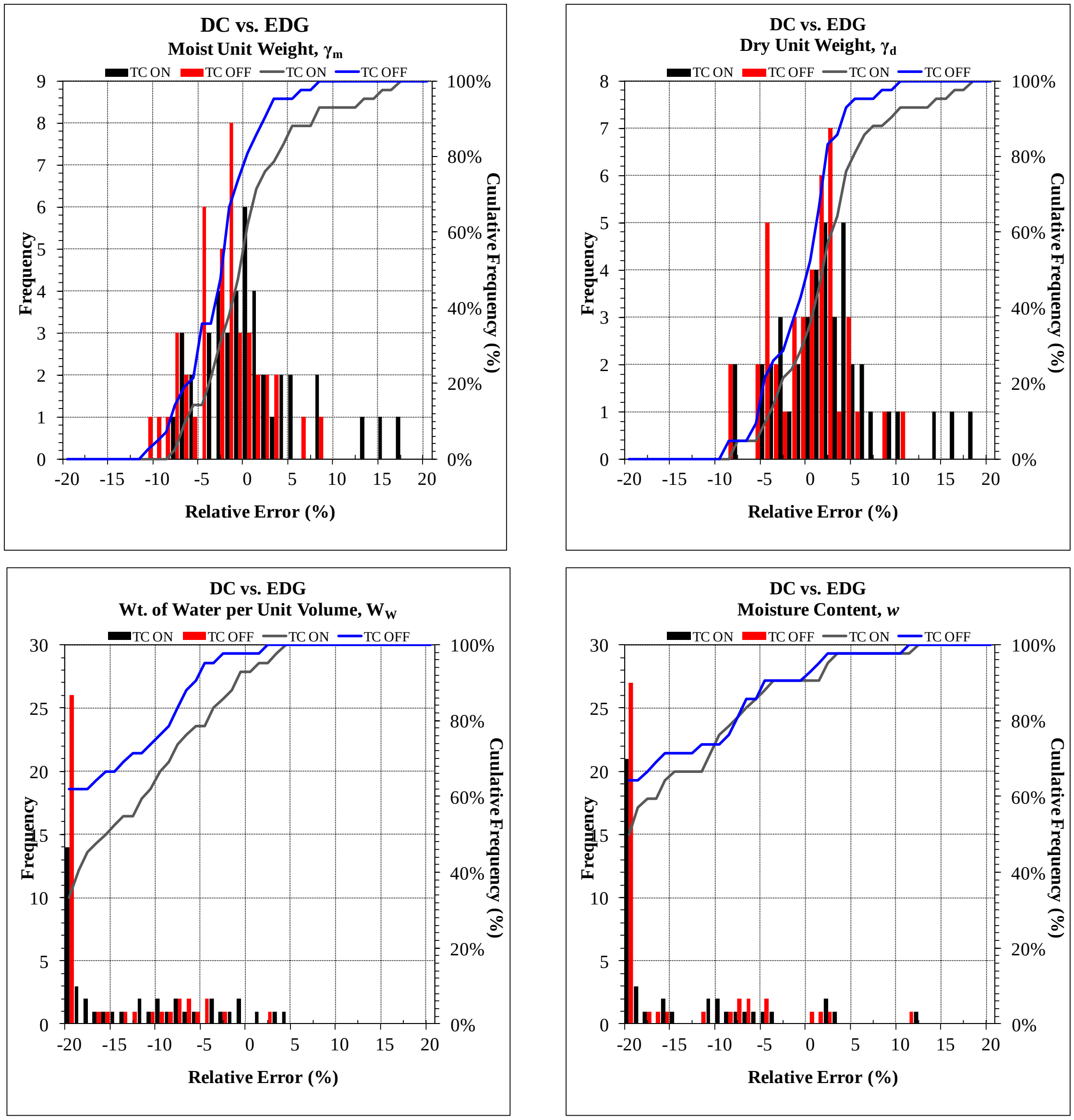


Figure 6.23 Relative Error Histograms and CDF Plots – DC vs. EDG (Mold Soil Model)
a) Histogram & CDF – Moist Unit Weight
b) Histogram & CDF – Dry Unit Weight
c) Histogram & CDF – Wt. of Water per Unit Volume
d) Histogram & CDF - Moisture Content

Table 6.12 **Summary Table of Relative Error (%) – NDG vs. EDG (Mold Soil Model)**

NDG vs. EDG

	(TC OFF)				**(TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-12.28	-11.59	-70.68	-60.99	-10.56	-10.83	-56.54	-57.14
MAX	3.52	5.61	-8.53	0.66	13.68	15.57	-6.73	2.02
RANGE	15.80	17.20	62.16	61.65	24.24	26.40	49.82	59.16
MEAN	-3.75	-1.10	-28.74	-27.51	-0.61	1.53	-21.32	-23.56

Table 6.13 Summary Table of Relative Error (%) – SC vs. EDG (Mold Soil Model)

SC vs. EDG

	(TC OFF)				**(TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-12.33	-7.49	-50.41	-50.84	-9.46	-5.62	-46.83	-49.97
MAX	12.56	14.76	7.26	7.91	20.85	21.67	9.40	8.79
RANGE	24.89	22.25	57.67	58.74	30.31	27.29	56.23	58.76
MEAN	1.04	3.20	-17.98	-21.87	4.05	5.74	-11.18	-18.02

Table 6.14 Summary Table of Relative Error (%) – DC vs. EDG (Mold Soil Model)

DC vs. EDG

	(TC OFF)				**(TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-11.35	-9.21	-57.24	-49.87	-8.01	-8.58	-48.71	-49.99
MAX	7.92	9.06	1.69	10.21	16.93	17.95	3.19	11.09
RANGE	19.26	18.27	58.94	60.08	24.95	26.54	51.90	61.08
MEAN	-3.20	-0.89	-23.44	-22.38	-0.10	1.72	-16.37	-18.54

6.6 Large Box Test Data Subset

It should be noted that 12 of the 42 large box tests that were performed fell outside of the data set that was used for mold calibration. In general, it is not best practice to use calibration equations to predict test points outside of the range of data that is used for calibration. Consequently, the same analyses that are described in the previous sections were performed excluding the points that fell outside of the calibration range; the results yielded no significant differences in the EDG's performance than what is generally described in the previous sections. For general comparison purposes, summary tables of statistical measures and relative error (%) values are provided in Tables 6.15 through Table 6.20.

Table 6.15 Summary Table of Statistical Measures (Mold Soil Model:All Data Within Calibration Range) – NDG vs. EDG

NDG vs. EDG								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	1.1162	0.7119	0.6607	3.5161	0.8556	0.7365	0.5154	2.9779
CV(RMSE)	0.0562	0.0400	0.3230	0.3057	0.0431	0.0414	0.2520	0.2589
NRMSE	0.4441	0.2681	0.6185	0.6205	0.3404	0.2774	0.4825	0.5255

Table 6.16 Summary Table of Statistical Measures (Mold Soil Model: All Data Within Calibration Range) – SC vs. EDG

SC vs. EDG								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	1.2792	1.1979	0.5508	3.1776	1.3566	1.3616	0.4184	2.6347
CV(RMSE)	0.0613	0.0642	0.2478	0.2661	0.0650	0.0730	0.1883	0.2207
NRMSE	0.3250	0.3031	0.5270	0.6532	0.3447	0.3446	0.4004	0.5416

Table 6.17 Summary Table of Statistical Measures (Mold Soil Model: All Data Within Calibration Range) – DC vs. EDG

DC vs. EDG								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	1.0148	0.6682	0.6083	3.2695	0.7281	0.6580	0.4596	2.7104
CV(RMSE)	0.0511	0.0376	0.2893	0.2759	0.0367	0.0371	0.2186	0.2287
NRMSE	0.4058	0.2856	0.7013	0.6583	0.2912	0.2812	0.5298	0.5457

Table 6.18 Summary Table of Relative Error (%) (Mold Soil Model: All Data Within Calibration Range) – NDG vs. EDG

NDG vs. EDG								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-12.28	-11.59	-70.68	-60.99	-10.56	-10.83	-56.54	-57.14
MAX	3.02	5.17	-8.53	0.66	6.34	8.06	-6.73	2.02
RANGE	15.30	16.76	62.16	61.65	16.90	18.89	49.82	59.16
MEAN	-4.30	-1.56	-28.48	-26.68	-2.12	0.12	-22.31	-22.73

Table 6.19 Summary Table of Relative Error (%) (Mold Soil Model: All Data Within Calibration Range) – SC vs. EDG

SC vs. EDG								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-12.33	-7.49	-50.41	-50.84	-9.46	-5.62	-46.83	-49.97
MAX	10.81	13.20	7.26	7.91	13.46	15.44	8.67	8.79
RANGE	23.14	20.69	57.67	58.74	22.91	21.06	55.50	58.76
MEAN	0.60	2.86	-18.47	-21.83	2.69	4.49	-12.74	-18.02

Table 6.20 Summary Table of Relative Error (%) (Mold Soil Model: All Data Within Calibration Range) – DC vs. EDG

DC vs. EDG								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-10.64	-9.21	-57.24	-49.87	-8.01	-8.58	-48.71	-49.99
MAX	0.89	3.75	1.69	10.21	4.28	5.72	3.19	11.09
RANGE	11.52	12.96	58.94	60.08	12.30	14.31	51.90	61.08
MEAN	-4.28	-1.87	-24.56	-22.37	-2.10	-0.18	-18.58	-18.56

6.7 Large Box Soil Model Calibration Procedure

The large box calibration equations presented in this section were developed by using the drive cylinder tests and EDG tests conducted in the large box. It is possible to use other data sets for field calibration of the EDG, such as the NDG or sand cone data sets; however, these data sets were not selected since they exhibited more scatter than the drive cylinder data set, and also because it was particularly desirable to have side-by-side comparisons of the EDG, NDG, and sand cone results. The procedure for calibration in this section was conducted in accordance with ASTM D 7698, Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance.

6.8 Large Box Soil Model Calibration Results

Calibration equations for the soil model developed from the drive cylinder tests in the large box are presented in the following section. It should be noted that calibration equations are presented without the EDG temperature correction algorithm (TC OFF) and with the EDG temperature correction algorithm (TC ON).

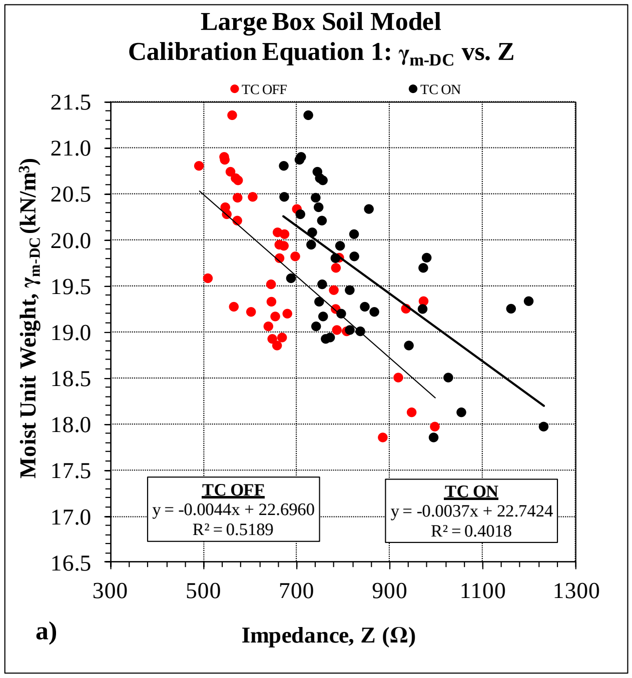
As stated earlier in Chapter 4, it is not best practice to assess the effectiveness of the EDG using an approach where the calibration data set (in this case the drive cylinder data set) is the same as the assessment data set; however, for comparison purposes with the mold calibration approach this method is presented again (See Figure 6.25c, 6.26c, 6.27c, 628c). In addition, direct comparison of the EDG-predicted values with the nuclear density gauge and sand cone tests from the large box are presented in this section. A series of 1:1 plots that compare NDG, SC, and DC values versus EDG predicted values are presented, along with relative error histogram plots between the measured and predicted values. The in-situ measured soil properties assessed in this study were: moist unit weight (γ_m), weight of water per unit volume (W_W), dry unit weight (γ_d,), and moisture content (w).

6.8.1 Large Box Soil Model: Calibration Equations

The associated calibration equations for the large box calibration soil model are presented in Figure 6.24. The coefficient of determination (R^2) values are presented on each graph and in Figure 6.24 as well. It should be noted that the soil model calibration equations in Figure 6.24a for the Large Box Soil Model (TC OFF & TC ON), show a decrease in R^2 from 0.5189 to 0.4018 when the EDG temperature correction algorithm is applied. Table 6.21 provides a summary of the R^2 values, slopes, and intercepts of the calibration equations for the Mold Soil Model (TC OFF & TC ON).

Table 6.21 General summary table of calibration equations – Large Box Soil Model

Large Box Soil Model				
	Calibration Equation	**R^2**	**Slope**	**Intercept**
TC OFF	$\gamma_{m\text{-}DC}$ vs. Z	0.5189	-0.0044	22.6960
TC ON	$\gamma_{m\text{-}DC}$ vs. Z	0.4018	-0.0037	22.7424
TC OFF	$W_{w\text{-}DC}$ vs. C/R	0.8576	17.2211	1.0065
TC ON	$W_{w\text{-}DC}$ vs. C/R	0.8690	23.4028	0.9412



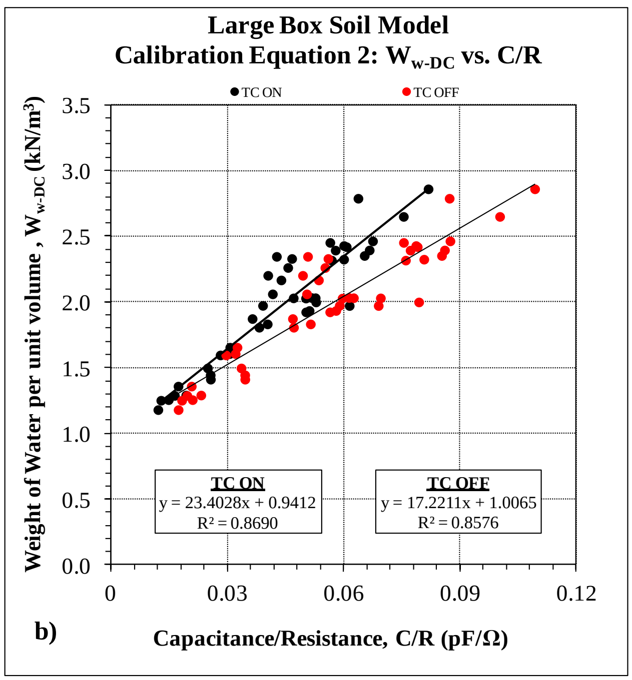


Figure 6.24 Calibration Equations – Large Box Soil Model (TC OFF & TC ON)
a) Calibration Equation 1: γ_{m-DC} vs. Z
b) Calibration Equation 2: W_{w-DC} vs. C/R

6.8.2 Large Box Soil Results: 1:1 Plots

It should be noted that the Large Box Soil Model calibration equations were used to predict the EDG values presented in this section.

Figure 6.25 shows NDG versus EDG, SC versus EDG, and DC versus EDG measured moist unit weight with and without the EDG temperature correction applied (TC ON & TC OFF). It should be noted that the solid line in Figure 6.25a, 6.25b, and 6.25c is a 1:1 line, and the dashed lines are ±0.5 kN/m^3.

Figure 6.26 shows NDG versus EDG, SC versus EDG, and DC versus EDG measured weight of water per unit volume with and without the EDG temperature correction applied (TC ON & TC OFF). It should be noted that the solid line in Figure 6.26a, 6.26b, and 6.26c is a 1:1 line, and the dashed lines are ±0.5 kN/m^3.

Figure 6.27 shows NDG versus EDG, SC versus EDG, and DC versus EDG measured dry unit weight with and without the EDG temperature correction applied (TC ON & TC OFF). It should be noted that the solid line in Figure 6.27a, 6.27b, and 6.27c is a 1:1 line, and the dashed lines are ±0.5 kN/m^3.

Figure 6.28 shows NDG versus EDG, SC versus EDG, and DC versus EDG measured moisture content with and without the EDG temperature correction applied (TC ON & TC OFF). It should be noted that the solid line in Figure 6.28a, 6.28b, and 6.28c is a 1:1 line, and the dashed lines are ±0.5 %.

The RMSE, CV(RMSE), and NRMSE values for moist unit weight, dry unit weight, and moisture content generally become higher when the EDG temperature correction is applied when comparing the EDG to the NDG and SC tests. The RMSE, CV(RMSE), and NRMSE values for weight of water per unit volume generally become lower when the EDG temperature correction is applied when comparing the

EDG to all 3 standard field tests (NDG, SC, DC). Table 6.22, Table 6.23, and Table 6.24 summarize the statistical values for all of the large box test comparisons that are presented in this section.

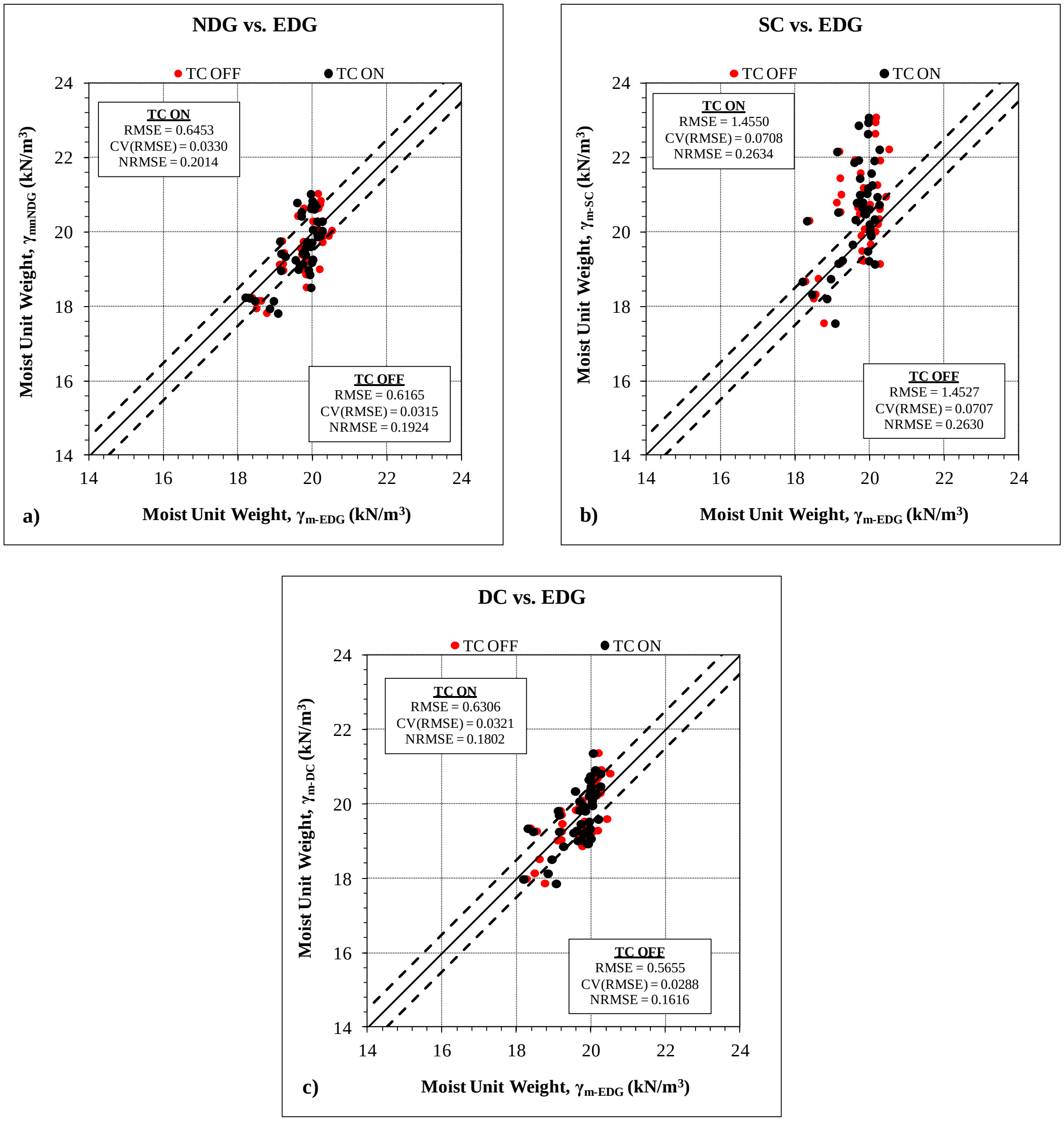


Figure 6.25 Large Box Soil Model Results – Moist Unit Weight
a) NDG vs. EDG: $\gamma_{m\text{-}NDG}$ vs. $\gamma_{m\text{-}EDG}$
b) SC vs. EDG: $\gamma_{m\text{-}SC}$ vs. $\gamma_{m\text{-}EDG}$
c) DC vs. EDG: $\gamma_{m\text{-}DC}$ vs. $\gamma_{m\text{-}EDG}$

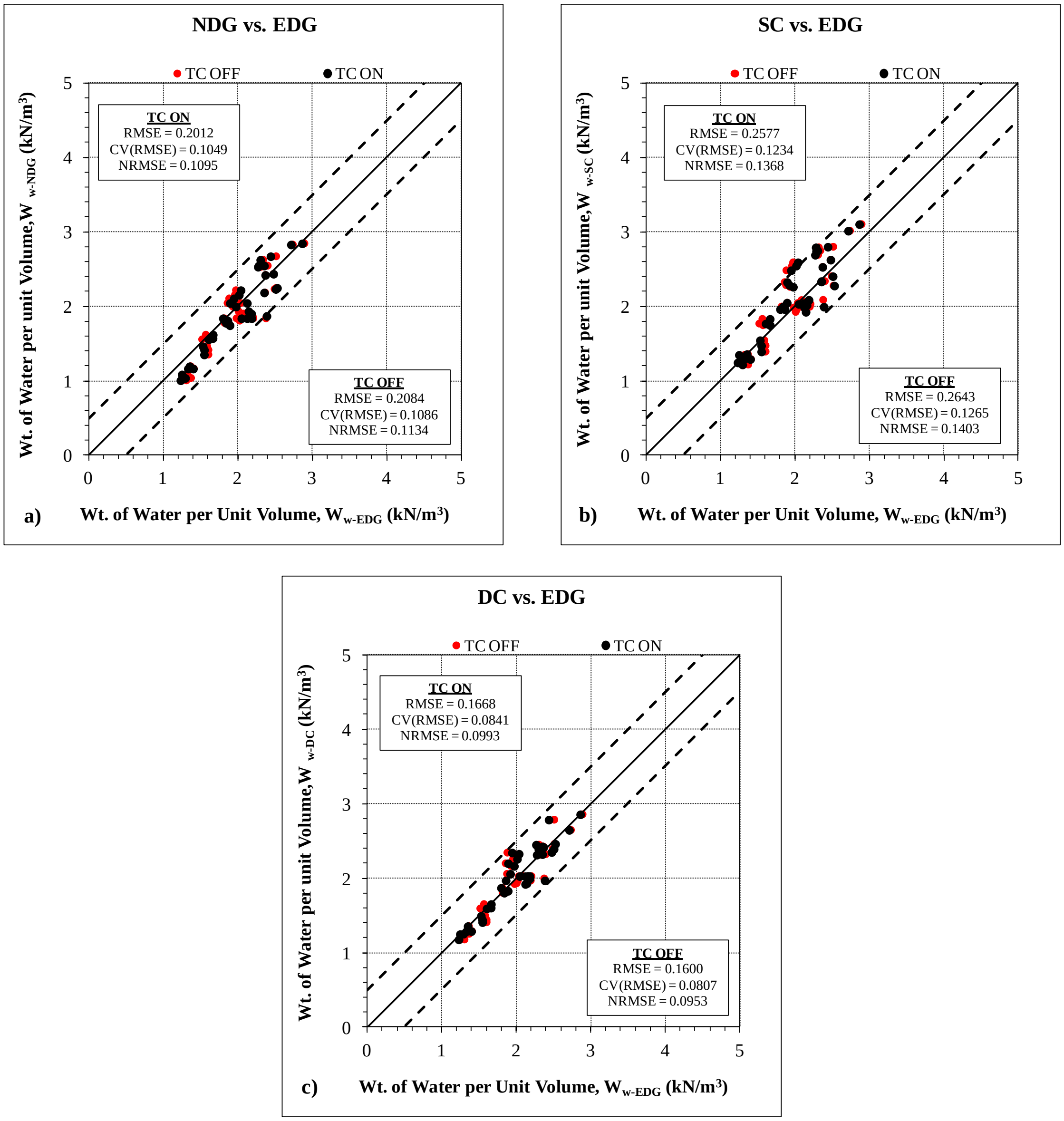


Figure 6.26 Large Box Soil Model Results – Weight of Water per Unit Volume
a) NDG vs. EDG: $W_{W\text{-}NDG}$ vs. $W_{W\text{-}EDG}$
b) SC vs. EDG: $W_{W\text{-}SC}$ vs. $W_{W\text{-}EDG}$
c) DC vs. EDG: $W_{W\text{-}DC}$ vs. $W_{W\text{-}EDG}$

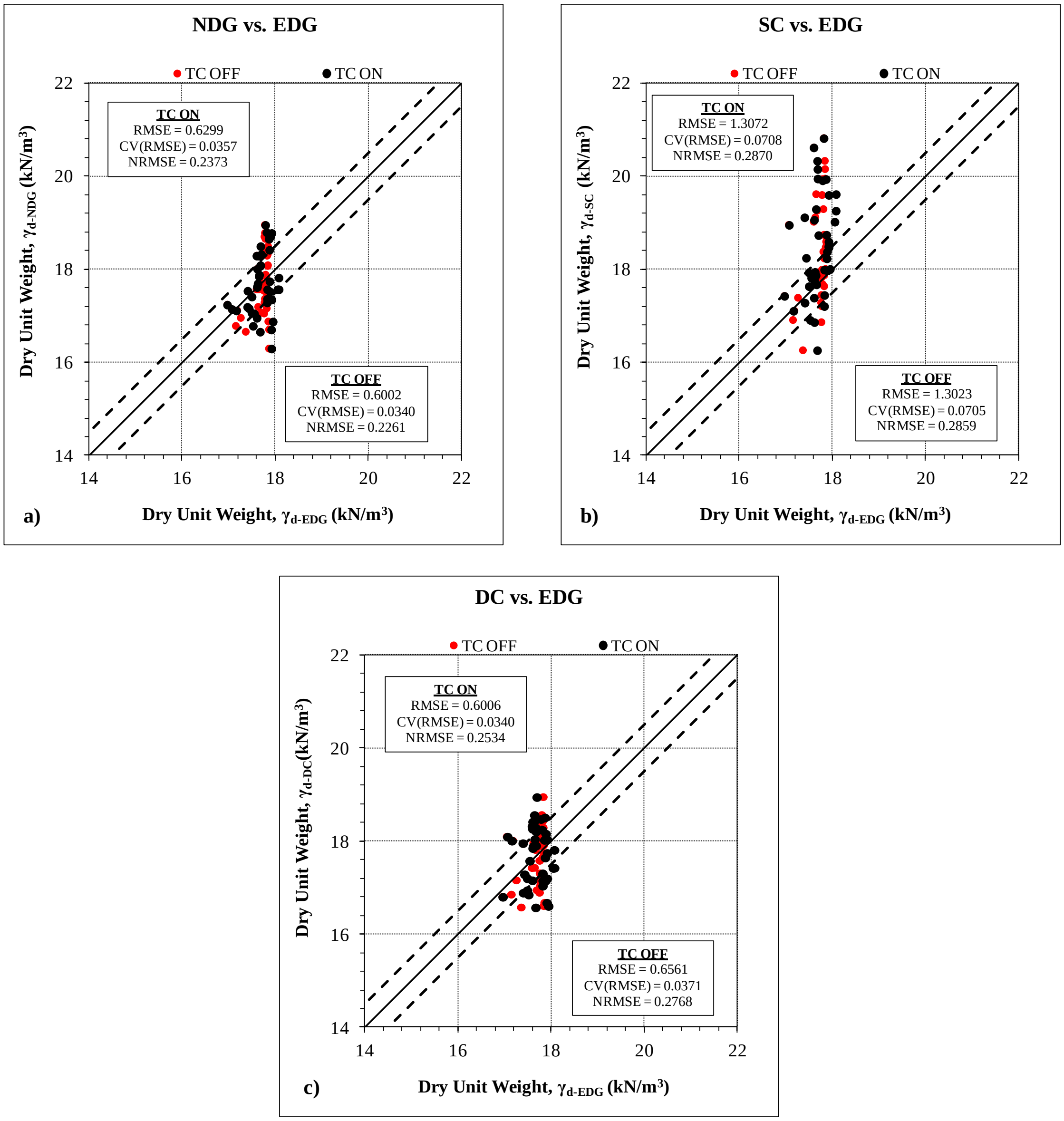


Figure 6.27 Large Box Soil Model Results – Dry Unit Weight
a) NDG vs. EDG: $\gamma_{d\text{-}NDG}$ vs. $\gamma_{d\text{-}EDG}$
b) SC vs. EDG: $\gamma_{d\text{-}SC}$ vs. $\gamma_{d\text{-}EDG}$
c) DC vs. EDG: $\gamma_{d\text{-}DC}$ vs. $\gamma_{d\text{-}EDG}$

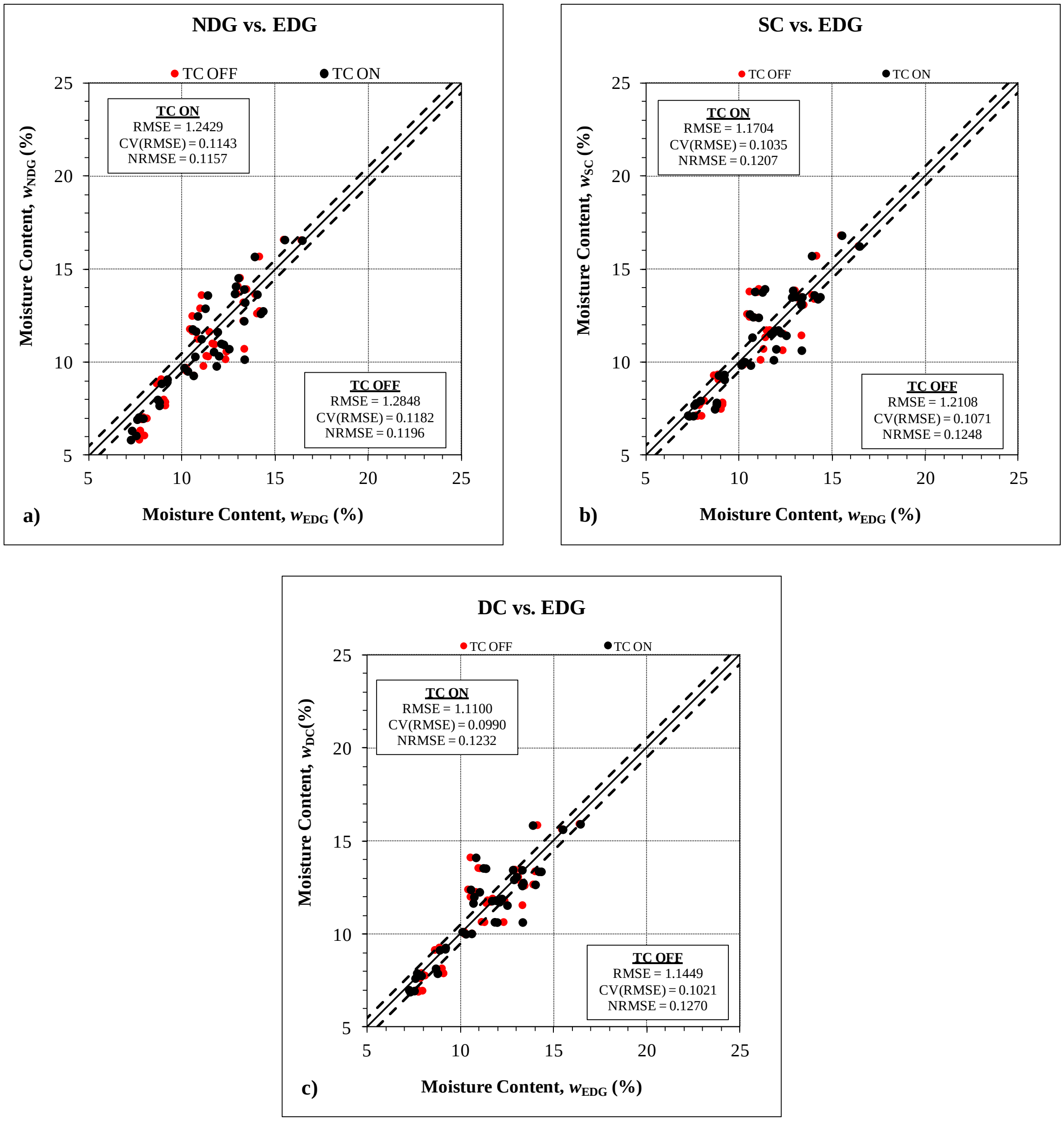


Figure 6.28 Large Box Soil Model Results – Moisture Content
a) NDG vs. EDG: w_{NDG} vs. w_{EDG}
b) SC vs. EDG: w_{SC} vs. w_{EDG}
c) DC vs. EDG: w_{DC} vs. w_{EDG}

Table 6.22 Summary Table of Statistical Measures – NDG vs. EDG

NDG vs. EDG	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	0.6165	0.6002	0.2084	1.2848	0.6453	0.6299	0.2012	1.2429
CV(RMSE)	0.0315	0.0340	0.1086	0.1182	0.0330	0.0357	0.1049	0.1143
NRMSE	0.1924	0.2261	0.1134	0.1196	0.2014	0.2373	0.1095	0.1157

Table 6.23 Summary Table of Statistical Measures – SC vs. EDG

SC vs. EDG	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	1.4527	1.3023	0.2643	1.2108	1.4550	1.3072	0.2577	1.1704
CV(RMSE)	0.0707	0.0705	0.1265	0.1071	0.0708	0.0708	0.1234	0.1035
NRMSE	0.2630	0.2859	0.1403	0.1248	0.2634	0.2870	0.1368	0.1207

Table 6.24 Summary Table of Statistical Measures – DC vs. EDG

DC vs. EDG	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	0.5655	0.6006	0.1668	1.1449	0.6306	0.6561	0.1600	1.1100
CV(RMSE)	0.0288	0.0340	0.0841	0.1021	0.0321	0.0371	0.0807	0.0990
NRMSE	0.1616	0.2534	0.0993	0.1270	0.1802	0.2768	0.0953	0.1232

6.8.3 Large Box Soil Model Tests: Relative Error

Relative error is calculated by taking the value considered to be the "actual" value, subtracting it from the "predicted" value, and dividing the resulting difference by the "actual" value (Freedman 1998). The following three equations show how relative error was calculated in this section (Equation 6.7, 6.8, 6.9):

$$\text{Relative error (\%)} = \frac{NDG_{VALUE} - EDG_{VALUE}}{NDG_{VALUE}} \times 100 \tag{6.7}$$

$$\text{Relative error (\%)} = \frac{SC_{VALUE} - EDG_{VALUE}}{SC_{VALUE}} \times 100 \tag{6.8}$$

$$\text{Relative error (\%)} = \frac{DC_{VALUE} - EDG_{VALUE}}{DC_{VALUE}} \times 100 \tag{6.9}$$

The following section shows histograms of the relative error calculated for moist unit weight, weight of water per unit volume, dry unit weight, and moisture content for all of the EDG large box tests using the large box soil model. A cumulative distribution function (CDF) is displayed on each histogram as well.

6.8.4 Large Box Soil Model Tests: Relative Error Results

Figure 6.29a is a histogram plot of relative error between $\gamma_{m\text{-}NDG}$ and $\gamma_{m\text{-}EDG}$ (TC ON and TC OFF). For NDG vs. EDG (TC OFF), relative error values for γ_m range from -7.22% to 5.71% and for NDG vs. EDG (TC ON), relative error values for γ_m range from -7.84% to 5.77%.

Figure 6.29b is a histogram plot of relative error between $\gamma_{d\text{-}NDG}$ and $\gamma_{d\text{-}EDG}$ (TC ON and TC OFF). For NDG vs. EDG (TC OFF), relative error values for γ_d range from -9.68% to 6.15% and for NDG vs. EDG (TC ON), relative error values for γ_d range from -10.00% to 6.11%.

Figure 6.29c is a histogram plot of relative error between $W_{W\text{-}NDG}$ and $W_{W\text{-}EDG}$ (TC ON and TC OFF). For NDG VS. EDG (TC OFF), relative error values for W_W range from -32.21% to 10.88% and for NDG VS. EDG (TC ON), relative error values for W_W range from -27.54% to 12.34%.

Figure 6.29d is a histogram plot of relative error between w_{NDG} and w_{EDG} (TC ON and TC OFF). For NDG vs. EDG (TC OFF), relative error values for *w* range from -32.09% to 18.75% and for NDG vs. EDG (TC ON), relative error values for *w* range from -31.38% to 16.41%.

Figure 6.30a is a histogram plot of relative error between $\gamma_{m\text{-}SC}$ and $\gamma_{m\text{-}EDG}$ (TC ON and TC OFF). For SC vs. EDG (TC OFF), relative error values for γ_m range from -7.03% to 13.75% and for SC vs. EDG (TC ON), relative error values for γ_m range from -8.70% to 13.80%.

Figure 6.30b is a histogram plot of relative error between $\gamma_{d\text{-}SC}$ and $\gamma_{d\text{-}EDG}$ (TC ON and TC OFF). For SC vs. EDG (TC OFF), relative error values for γ_d range from -6.85% to 14.58% and for SC vs. EDG (TC ON), relative error values for γ_d range from -8.73% to 14.61%.

Figure 6.30c is a histogram plot of relative error between $W_{W\text{-}SC}$ and $W_{W\text{-}EDG}$ (TC ON and TC OFF). For SC vs. EDG (TC OFF), relative error values for W_W range from -15.30% to 24.13% and for SC vs. EDG (TC ON), relative error values for W_W range from -19.63% to 21.67%.

Figure 6.30d is a histogram plot of relative error between w_{SC} and w_{EDG} (TC ON and TC OFF). For SC vs. EDG (TC OFF), relative error values for *w* range from -20.46% to 23.51% and for SC vs. EDG (TC ON), relative error values for w range from -25.39% to 21.44%.

Figure 6.31a is a histogram plot of relative error between $\gamma_{m\text{-}DC}$ and $\gamma_{m\text{-}EDG}$ (TC ON and TC OFF). For DC vs. EDG (TC OFF), relative error values for γ_m range from -5.17% to 5.35% and for DC vs. EDG (TC ON), relative error values for γ_m range from -6.81% to 6.03%.

Figure 6.31b is a histogram plot of relative error between $\gamma_{d\text{-}DC}$ and $\gamma_{d\text{-}EDG}$ (TC ON and TC OFF). For DC vs. EDG (TC OFF), relative error values for γ_d range from -7.56% to 5.80% and for DC vs. EDG (TC ON), relative error values for γ_d range from -8.13% to 6.54%.

Figure 6.31c is a histogram plot of relative error between $W_{W\text{-}DC}$ and $W_{W\text{-}EDG}$ (TC ON and TC OFF). For DC vs. EDG (TC OFF), relative error values for W_W range from -19.15% to 19.58% and for DC vs. EDG (TC ON), relative error values for W_W range from -21.16% to 16.97%

Figure 6.31d is a histogram plot of relative error between w_{DC} and w_{EDG} (TC ON and TC OFF). For DC vs. EDG (TC OFF), relative error values for w range from -15.94% to 25.81% and for DC vs. EDG (TC ON), relative error values for w range from -25.41% to 23.75%.

Table 6.25, Table 6.26, and Table 6.27 provide a summary of the minimum, maximum, range, and mean of the relative error for all of the EDG large box tests.

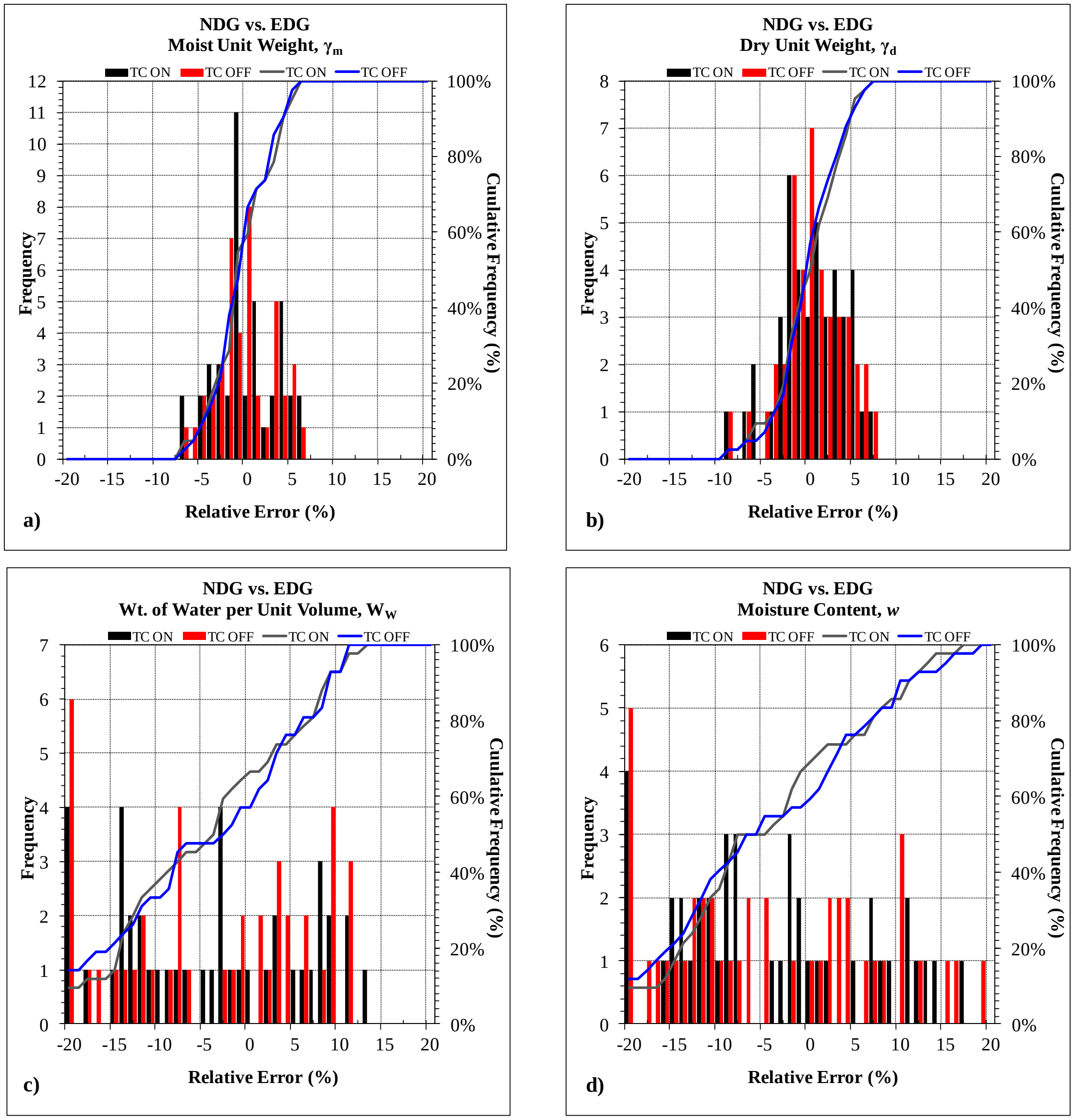


Figure 6.29 Relative Error Histograms and CDF Plots – NDG vs. EDG
a) Histogram & CDF – Moist Unit Weight
b) Histogram & CDF – Dry Unit Weight
c) Histogram & CDF – Wt. of Water per Unit Volume
d) Histogram & CDF - Moisture Content

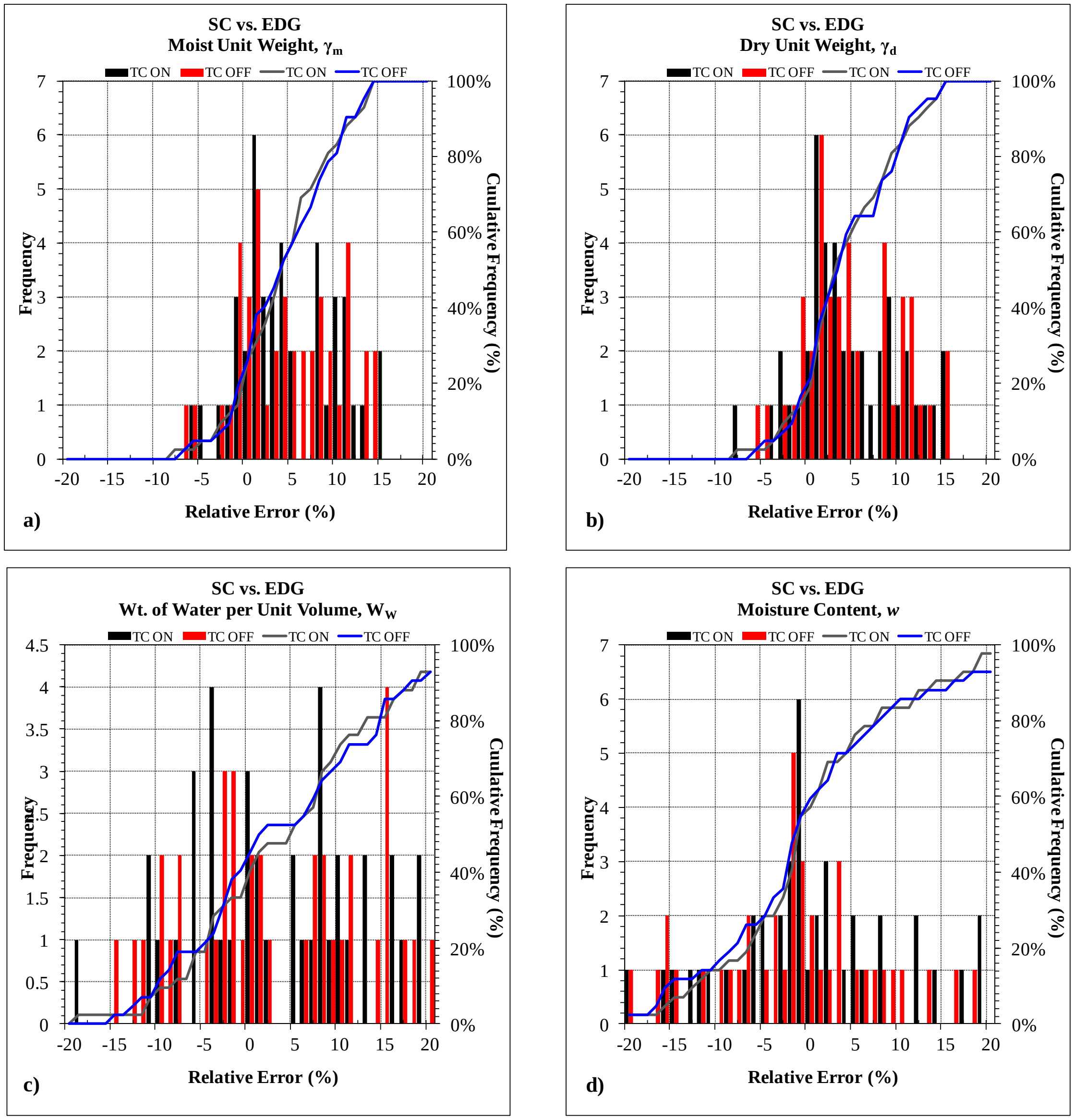


Figure 6.30 Relative Error Histograms and CDF Plots – SC vs. EDG
a) Histogram & CDF – Moist Unit Weight
b) Histogram & CDF – Dry Unit Weight
c) Histogram & CDF – Wt. of Water per Unit Volume
d) Histogram & CDF - Moisture Content

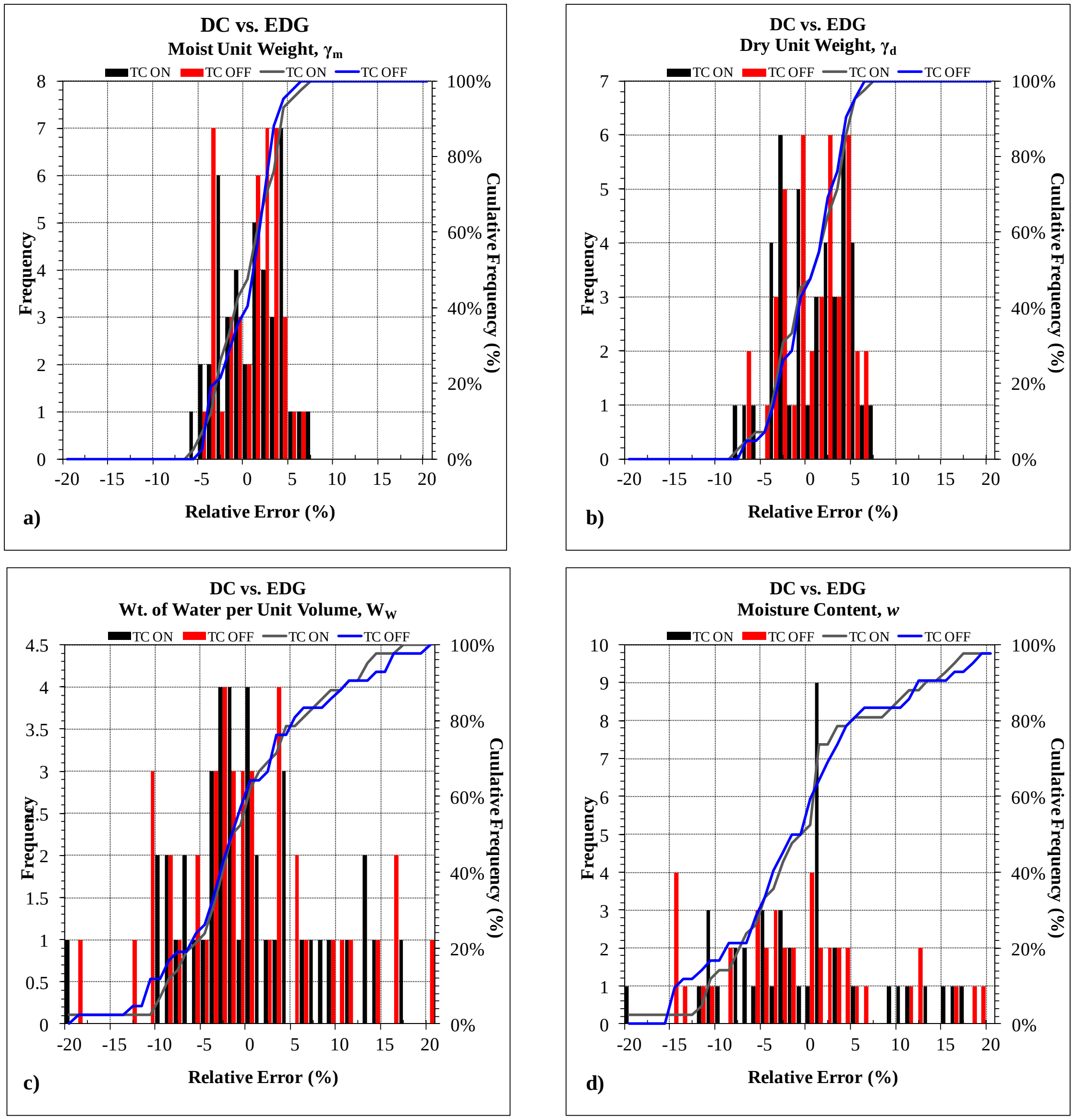


Figure 6.31 Relative Error Histograms and CDF Plots – DC vs. EDG
a) Histogram & CDF – Moist Unit Weight
b) Histogram & CDF – Dry Unit Weight
c) Histogram & CDF – Wt. of Water per Unit Volume
d) Histogram & CDF - Moisture Content

Table 6.25 Summary Table of Relative Error (%) – NDG vs. EDG (Large Box Soil Model)

NDG vs. EDG								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-7.22	-9.68	-32.21	-32.09	-7.84	-10.00	-27.54	-31.38
MAX	5.71	6.15	10.88	18.75	5.77	6.11	12.34	16.41
RANGE	12.94	15.84	43.10	50.84	13.61	16.11	39.88	47.79
MEAN	-0.62	-0.32	-5.48	-5.29	-0.64	-0.33	-5.23	-5.05

Table 6.26 Summary Table of Relative Error (%) – SC vs. EDG (Large Box Soil Model)

SC vs. EDG								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-7.03	-6.85	-15.30	-20.46	-8.70	-8.73	-19.63	-25.39
MAX	13.75	14.58	24.13	23.51	13.80	14.61	21.67	21.44
RANGE	20.78	21.43	39.44	43.96	22.50	23.34	41.30	46.83
MEAN	4.02	3.94	3.59	-0.43	4.01	3.94	3.77	-0.26

Table 6.27 Summary Table of Relative Error (%) – DC vs. EDG (Large Box Soil Model)

DC vs. EDG								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-5.17	-7.56	-19.15	-15.94	-6.81	-8.13	-21.16	-25.41
MAX	5.35	5.80	19.58	25.81	6.03	6.54	16.97	23.75
RANGE	10.52	13.35	38.73	41.75	12.84	14.67	38.13	49.15
MEAN	-0.08	-0.11	-0.83	-0.95	-0.10	-0.12	-0.67	-0.77

6.8.5 Summary of Large Box Test Results

The nuclear density gauge and drive cylinder tests generally have the best agreement out of all of the tests for moist unit weight, weight of water per unit volume, and dry unit weight. The moisture content determined from the sand cone test and the drive cylinder test had the best agreement. Generally, the "blind" assessment tests (mold soil model) that were conducted using the EDG showed relatively poor agreement between the EDG-predicted values and the NDG, SC, or DC tests (worse than the results obtained from some of the more traditional density-based tests such as the NDG or DC), for EDG tests that were conducted using the soil model determined from the mold calibration process. It should be noted that the minimum, maximum, and mean relative error (%) for weight of water per unit volume and moisture content are extremely high, which indicates that the calibration equation that was established to determine the weight of water per unit volume and moisture content for the EDG tests from the molds did not do a good job of capturing the in situ soil properties in the large box. However, the calibration equations developed from the large box tests using the drive cylinder method (large box soil model) had significantly better agreement with the standard field tests conducted in the large box than the mold soil model results.

6.9 Discussion of Results and Conclusions

From the raw data and associated analysis that are presented in this chapter, it is inherently evident that the truly "blind" assessment (mold soil model) of the electrical density gauge (EDG) provides results with higher RMSE, CV(RMSE), NRMSE, and relative error (%) values than its comparable in situ density-based testing counterparts, particularly the nuclear density gauge (NDG) and drive cylinder (DC) tests. However, the EDG results using the large box soil model provide results with considerably lower RMSE, CV(RMSE), NRMSE, and relative error (%) values than the mold soil model results. Further, the temperature correction algorithm tends not to produce a significantly marked improvement in the EDG test results. However on the plus side, from the results that are provided, the EDG may yield better predictions of moist unit weight and dry unit weight than those that can be obtained from the sand cone (SC) test. It should be noted that these conclusions were made using the default on-board calibration relationships, and the default temperature correction algorithm. It may be possible to significantly improve the results from EDG tests if alternative calibration procedures, calibration relationships, or temperature correction algorithms are used. The effect of alternative temperature correction algorithms and calibration relationships will be the focus of Chapter 8 and Chapter 9 in this thesis.

CHAPTER 7

TEMPERATURE TESTING: PROCEDURE & RESULTS

7.1 Introduction

During the progress of this research study, it was observed that the proprietary temperature correction algorithm developed by EDG, LLC. may not accurately capture the effect of temperature on the electrical properties of the Delaware soils that were tested. As was shown in previous chapters, the proprietary temperature correction algorithm did not significantly improve the results, and sometimes even lowered the RMSE for the measured values of interest. This chapter describes a test procedure that was developed to further study the effect that temperature has on EDG-measured electrical properties for the Delaware soils that were tested in this study. A large volume of test results from this phase of the study are presented in this chapter and in Appendices A-D.

7.2 Temperature Testing Procedure

The 12 soil molds that were used to build a soil model following the mold calibration procedure (a process that is described in Chapter 5) were also used for the temperature testing experiments that are discussed in this chapter. The following procedure was utilized when performing the temperature testing experiments on the 12 molds that were prepared during this research study (see Chapter 5 for more details regarding the mold construction procedure and associated soil properties):

1) During the placement of soil for lifts in each mold, three moisture content samples were taken to see the effects of temperature cycling on moisture migration within the molds.
2) After initial EDG measurements were taken for the mold calibration procedure (see Chapter 5), plastic was wrapped around the molds to prevent any loss (or gain) of moisture during the temperature cycling phase of the study (as shown in Figure 7.1 and Figure 7.2). During the temperature cycling phase of the mold testing program, the EDG soil probes were left continuously in the molds, to help ensure more consistent EDG measurements.
3) For each compacted soil mold that was prepared, the covered soil mold was placed in a temperature-controlled laboratory room in the Department of Civil & Environmental Engineering (CEE) at the University of Delaware campus, which was set to a constant temperature of 37°C for 24 hours to allow for temperature equilibrium to occur in the mold.
4) Cooling Cycle: After 24 hours, each soil mold was then placed in a different temperature-controlled room in the CEE laboratory, which was set at 4°C for 24 hours. EDG Readings were taken to capture the electrical properties of the soil every 10 to 15 minutes for the first 12 to 16 hours and at 24 hours.
5) Heating Cycle: After the 24-hour reading had been taken in the temperature-controlled room in the lab set at 4°C, molds were placed in a temperature-controlled room in the lab set at 37°C for 24 hours. Readings were taken to capture electrical properties of the soil every 10 to 15 minutes for the first 12 to 16 hours and at 24 hours with the EDG.

6) Constant Temperature Room at 15°C: After the 24-hour reading was taken in the temperature-controlled room in the lab set at 37°C, molds were placed in a temperature-controlled room in the lab set at 15°C for 24 hours. After waiting 24 hours for the soil to come to equilibrium, a reading was taken to capture the electrical properties of the soil using the EDG.
7) Constant Temperature Room at 12°C: After the 24-hour reading was taken in the temperature-controlled room in the lab set at 15°C, the temperature of the room was set to 12°C. After waiting 24 hours for the soil to come to equilibrium, a reading was taken to capture the electrical properties of the soil using the EDG.
8) Constant Temperature Room at 9°C: After the 24-hour reading was taken in the temperature-controlled room in the lab set at 12°C, the temperature of the room was set to 9°C. After waiting 24 hours for the soil to come to equilibrium, a reading was taken to capture the electrical properties of the soil using the EDG.
9) Constant Temperature Room at 6.5°C: After the 24-hour reading was taken in the temperature-controlled room in the lab set at 9 °C, the temperature of the room was set to 6.5°C. After waiting 24 hours for the soil to come to equilibrium, a reading was taken to capture the electrical properties of the soil using the EDG.
10) Constant Temperature Room at 4°C: After the 24-hour reading was taken in the temperature-controlled room in the lab set at 6.5°C, the temperature of the room was set to 4°C. After waiting 24 hours for the soil to come to

equilibrium, a reading was taken to capture the electrical properties of the soil using the EDG.

11) After the temperature testing experiments were completed, 3 moisture content samples were taken from the top, middle, and bottom of the molds to assess any changes in moisture content that may have occurred during the temperature testing experiments (Table 7.1, 7.2, & 7.3). From the data shown in these tables, it can be reasonably concluded that a significant change in overall moisture content in the molds during the temperature testing experiments did not occur. Also, significant localized moisture content redistribution was not observed to occur within the molds.

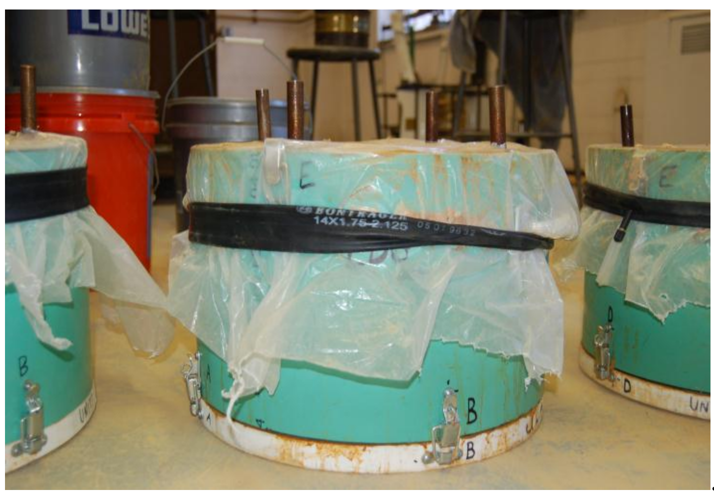


Figure 7.1 A plastic sealing layer tightly secured to the compacted soil molds using rubber bicycle tire tubes

Figure 7.2 Compacted soil molds wrapped in plastic for temperature testing experiments

Table 7.1 Moisture Contents Measured in Compacted Soil Molds – Before Temperature Testing

	BEFORE TEMP TESTING				
	Top	**Middle**	**Bottom**	**AVG**	**STDEV**
Mold #1	8.62%	8.87%	8.81%	8.77%	0.13%
Mold #2	9.11%	9.23%	9.22%	9.19%	0.07%
Mold #3	9.04%	8.97%	8.98%	9.00%	0.04%
Mold #4	11.56%	11.45%	11.43%	11.48%	0.07%
Mold #5	11.09%	11.23%	11.12%	11.15%	0.07%
Mold #6	11.45%	11.55%	11.42%	11.47%	0.07%
Mold #7	13.91%	13.63%	13.79%	13.78%	0.14%
Mold #8	13.98%	14.14%	14.01%	14.04%	0.09%
Mold #9	13.84%	13.65%	13.74%	13.74%	0.10%
Mold #10	9.48%	9.51%	9.26%	9.42%	0.14%
Mold #11	9.83%	9.67%	9.61%	9.70%	0.11%
Mold #12	9.57%	9.71%	9.74%	9.67%	0.09%

Table 7.2 Moisture Contents Measured in Compacted Soil Molds – After Temperature Testing

	BEFORE TEMP TESTING				
	Top	**Middle**	**Bottom**	**AVG**	**STDEV**
Mold #1	9.01%	8.82%	9.03%	8.95%	0.12%
Mold #2	9.02%	8.86%	8.96%	8.95%	0.08%
Mold #3	9.11%	8.82%	9.18%	9.04%	0.19%
Mold #4	11.25%	11.05%	11.02%	11.11%	0.13%
Mold #5	11.08%	11.19%	11.25%	11.17%	0.09%
Mold #6	11.24%	11.15%	11.01%	11.13%	0.12%
Mold #7	13.58%	13.45%	13.22%	13.42%	0.18%
Mold #8	13.87%	13.74%	13.54%	13.72%	0.17%
Mold #9	14.11%	13.88%	13.78%	13.92%	0.17%
Mold #10	9.51%	9.62%	9.47%	9.53%	0.08%
Mold #11	9.45%	9.54%	9.57%	9.52%	0.06%
Mold #12	9.66%	9.43%	9.35%	9.48%	0.16%

Table 7.3 Summary of Moisture Content Data – Net Change Before & After Temperature Testing

	ΔTop	ΔMiddle	ΔBottom	ΔAVG	ΔSTDEV
Mold #1	0.39%	-0.05%	0.22%	0.19%	0.22%
Mold #2	-0.09%	-0.37%	-0.26%	-0.24%	0.14%
Mold #3	0.07%	-0.15%	0.20%	0.04%	0.18%
Mold #4	-0.31%	-0.40%	-0.41%	-0.37%	0.06%
Mold #5	-0.01%	-0.04%	0.13%	0.03%	0.09%
Mold #6	-0.21%	-0.40%	-0.41%	-0.34%	0.11%
Mold #7	-0.33%	-0.18%	-0.57%	-0.36%	0.20%
Mold #8	-0.11%	-0.40%	-0.47%	-0.33%	0.19%
Mold #9	0.27%	0.23%	0.04%	0.18%	0.12%
Mold #10	0.03%	0.11%	0.21%	0.12%	0.09%
Mold #11	-0.38%	-0.13%	-0.04%	-0.18%	0.18%
Mold #12	0.09%	-0.28%	-0.39%	-0.19%	0.25%
MAX	-0.39%	-0.23%	-0.22%	-0.19%	-0.25%
MIN	-0.38%	-0.40%	-0.57%	-0.37%	0.06%
MEAN	-0.05%	-0.17%	-0.15%	-0.12%	0.15%

7.3 Temperature Testing Results

In order to illustrate how the proprietary temperature correction algorithm performs when the soil is subjected to different temperature conditions, calibration equations using the “Constant Temperature Room” data and the “Cooling/Heating Cycles” data are presented in the following section. For purposes of this research study, the cooling cycle data and heating cycle data have been combined into one data set in an attempt to compensate for the effects of temperature gradients (i.e., non-uniform temperature distributions) throughout the mold as the temperature in the mold changes as the soil is being heated or cooled. Each data point from the cooling cycle and the heating cycle is considered to be of the same type and has been combined into a combination of the two data sets for analysis in this research.

The resulting calibration equations are presented without the EDG temperature correction algorithm (TC OFF) and with the default EDG temperature correction algorithm (TC ON). 1:1 plots that compare MOLD measured values versus EDG predicted values are presented, along with relative error histogram plots between the measured and predicted values. The in-situ measured soil properties assessed in this study were: moist unit weight (γ_m), weight of water per unit volume (W_W), dry unit weight (γ_d), and moisture content (*w*).

7.3.1 Mold Calibration Equations

The associated mold calibration equations for the "Constant Temperature Room" data, and the combined "Cooling/Heating Cycles" data are presented in Figures 7.3 and 7.4. The coefficient of determination (R^2) values are presented on each graph as well. Tables 7.4 and 7.5 provide a summary of the R^2 values, slopes, and intercepts of the calibration equations that are presented in this section.

It should be noted that the data points in the soil model calibration equation that relate moist unit weight to impedance (Calibration Equation 1) all shift away from the best fit line when applying the EDG temperature correction and appear more scattered (Compare Figure 7.3a vs. 7.3b and Figure 7.4a vs. 7.4b). This observation supports the conclusion that the EDG temperature correction for impedance did not properly capture the effects of temperature for the soil that was tested in this study. In addition, it should be noted that the data points in the soil model calibration equations that relate capacitance over resistance (C/R) to weight of water per unit volume (Calibration Equation 2) all shift toward the best fit line when applying the EDG temperature correction, and appear less scattered (Compare Figure

7.3c vs. 7.3d and Figure 7.4c vs. 7.4d). This signifies that the EDG temperature correction for C/R did improve the results for the soil that was tested in this study.

Table 7.4 General Summary Table of Calibration Equations: Constant Temperature Room Soil Model

Constant Temperature Room Soil Model

	Calibration Equation	**R^2**	**Slope**	**Intercept**
TC OFF	$\gamma_{m\text{-}MOLD}$ vs. Z	0.2895	-0.0058	24.3385
TC ON	$\gamma_{m\text{-}MOLD}$ vs. Z	0.0653	-0.0012	20.6299
TC OFF	$W_{w\text{-}MOLD}$ vs. C/R	0.2376	14.5865	1.4981
TC ON	$W_{w\text{-}MOLD}$ vs. C/R	0.6581	36.5364	0.7101

Table 7.5 General Summary Table of Calibration Equations: Cooling/Heating Cycles Soil Model

Cooling/Heating Cycle Soil Model

	Calibration Equation	**R^2**	**Slope**	**Intercept**
TC OFF	$\gamma_{m\text{-}MOLD}$ vs. Z	0.3847	-0.0070	25.0379
TC ON	$\gamma_{m\text{-}MOLD}$ vs. Z	0.0826	-0.0017	21.1262
TC OFF	$W_{w\text{-}MOLD}$ vs. C/R	0.4081	19.2554	1.2171
TC ON	$W_{w\text{-}MOLD}$ vs. C/R	0.6099	33.5366	0.8300

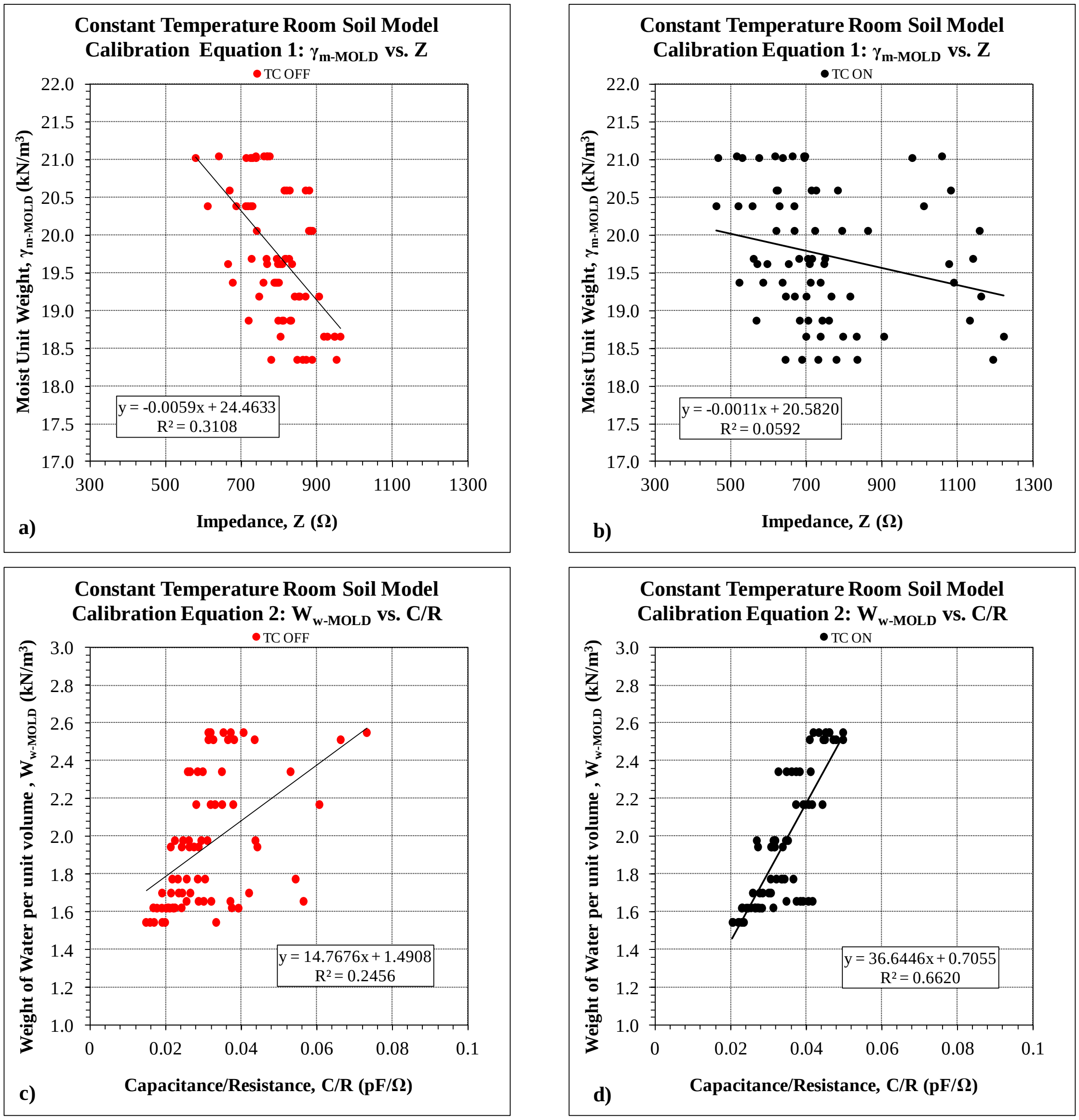


Figure 7.3 Calibration Equations – Constant Temperature Room Soil Model
a) Calibration Equation 1: $\gamma_{m\text{-}MOLD}$ vs. Z (TC OFF)
b) Calibration Equation 1: $\gamma_{m\text{-}MOLD}$ vs. Z (TC ON)
c) Calibration Equation 2: $W_{w\text{-}MOLD}$ vs. C/R (TC OFF)
d) Calibration Equation 2: $W_{w\text{-}MOLD}$ vs. C/R (TC ON)

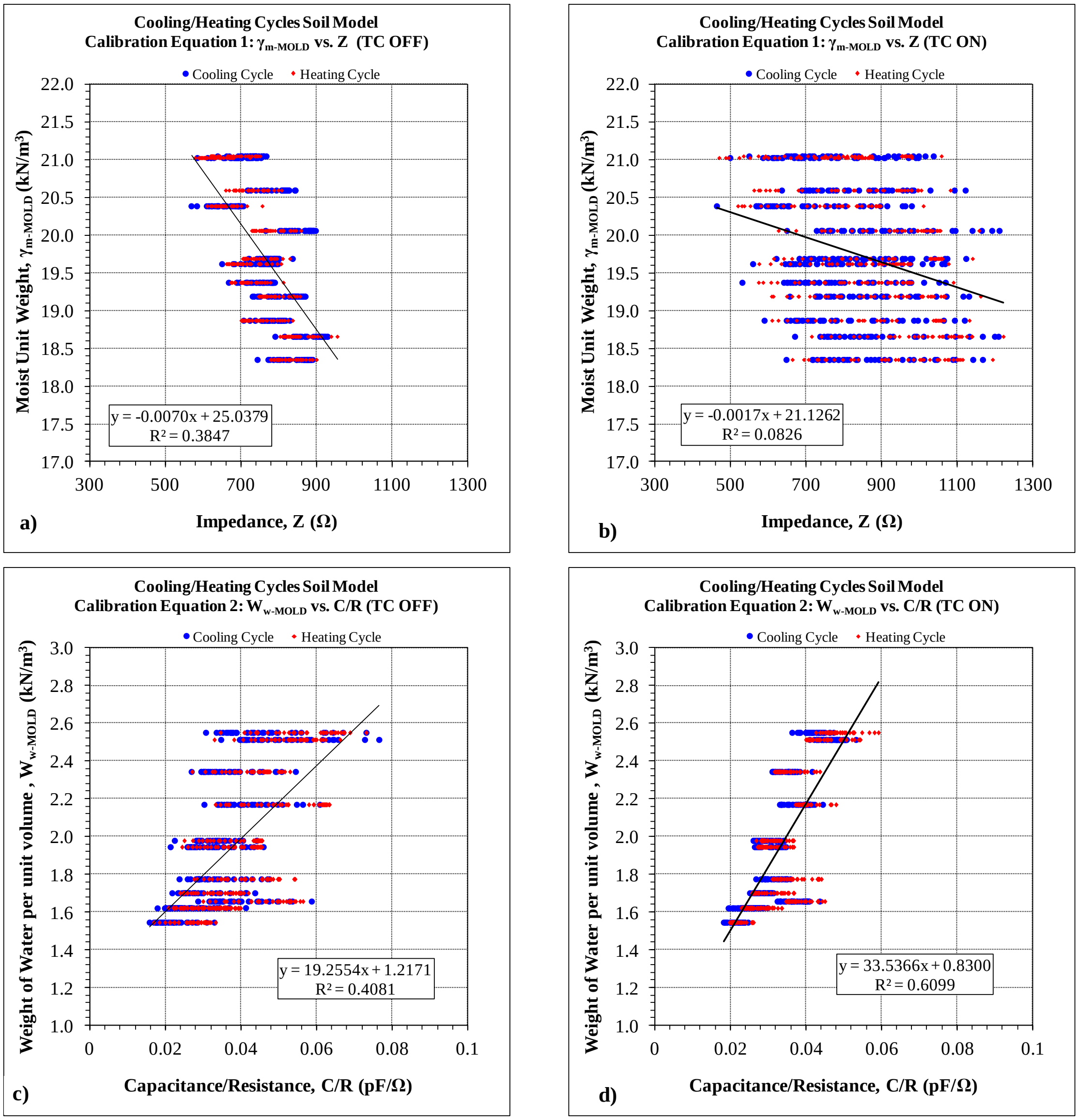


Figure 7.4 Calibration Equations – Cooling/Heating Cycles Soil Model
a) Calibration Equation 1: $\gamma_{m\text{-MOLD}}$ vs. Z (TC OFF)
b) Calibration Equation 1: $\gamma_{m\text{-MOLD}}$ vs. Z (TC ON)
c) Calibration Equation 2: $W_{w\text{-MOLD}}$ vs. C/R (TC OFF)
d) Calibration Equation 2: $W_{w\text{-MOLD}}$ vs. C/R (TC ON)

7.3.2 Temperature Testing Soil Models: Calibration Equations

It should be noted that the Constant Temperature Room Soil Model and the Cooling/Heating Cycles Soil Model calibration equations were used to predict the EDG values that are presented in this section. Figure 7.5a, 7.5b, 7.7a, and 7.7b show MOLD measured moist unit weights ($\gamma_{m\text{-}MOLD}$) versus EDG predicted moist unit weights ($\gamma_{m\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON). Figure 7.5c, 7.5d, 7.7c, and 7.7d show MOLD measured weight of water per unit volume ($W_{W\text{-}MOLD}$) versus EDG predicted weight of water per unit volume ($W_{W\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON). Figure 7.6a, 7.6b, 7.8a, and 7.8b show MOLD measured dry unit weights ($\gamma_{d\text{-}MOLD}$) versus EDG predicted dry unit weights ($\gamma_{d\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON). Figure 7.6c, 7.6d, 7.8c, and 7.8d show MOLD measured moisture content (w_{MOLD}) versus EDG predicted moisture content (w_{EDG}) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON). It should be noted that the solid line in all figures is a 1:1 line, and the dashed lines are ±0.5 kN/m^3 or ±0.5 % reference lines.

Table 7.6 and Table 7.7 summarize error measurements of interest for the EDG values that are predicted for the Constant Temperature Room Soil Model and the Cooling/Heating Cycles Soil Model. For the Constant Temperature Room Soil Model, the RMSE, CV(RMSE), and NRMSE values for moist unit weight and dry unit weight are greater with the EDG temperature correction algorithm applied. In contrast, the RMSE, CV(RMSE), and NRMSE values for weight of water per unit volume and moisture content are smaller with the EDG temperature correction applied. For the Cooling/Heating Cycles Soil Model, the RMSE, CV(RMSE), and NRMSE values for dry unit weight are greater with the EDG temperature correction algorithm applied. In contrast, the RMSE, CV(RMSE), and NRMSE values for moist unit weight, weight of water per unit volume, and moisture content are smaller with the EDG temperature correction applied.

Table 7.6 Summary of Statistical Measures: Constant Temperature Room Soil Model

Constant Temperature Room Soil Model								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	0.7153	0.6812	0.3008	1.7751	0.8357	0.8405	0.2013	1.3082
CV(RMSE)	0.0362	0.0383	0.1545	0.1621	0.0424	0.0473	0.1034	0.1195
NRMSE	0.2655	0.3173	0.2992	0.3369	0.3102	0.3915	0.2003	0.2483

Table 7.7 Summary of Statistical Measures: Cooling/Heating Cycles Soil Model

Cooling/Heating Cycles Soil Model								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	0.6759	0.6602	0.2664	1.6025	0.8253	0.8151	0.2163	1.3542
CV(RMSE)	0.0343	0.0371	0.1368	0.1464	0.0418	0.0458	0.1111	0.1237
NRMSE	0.2509	0.3075	0.2651	0.3042	0.3064	0.3796	0.2152	0.2570

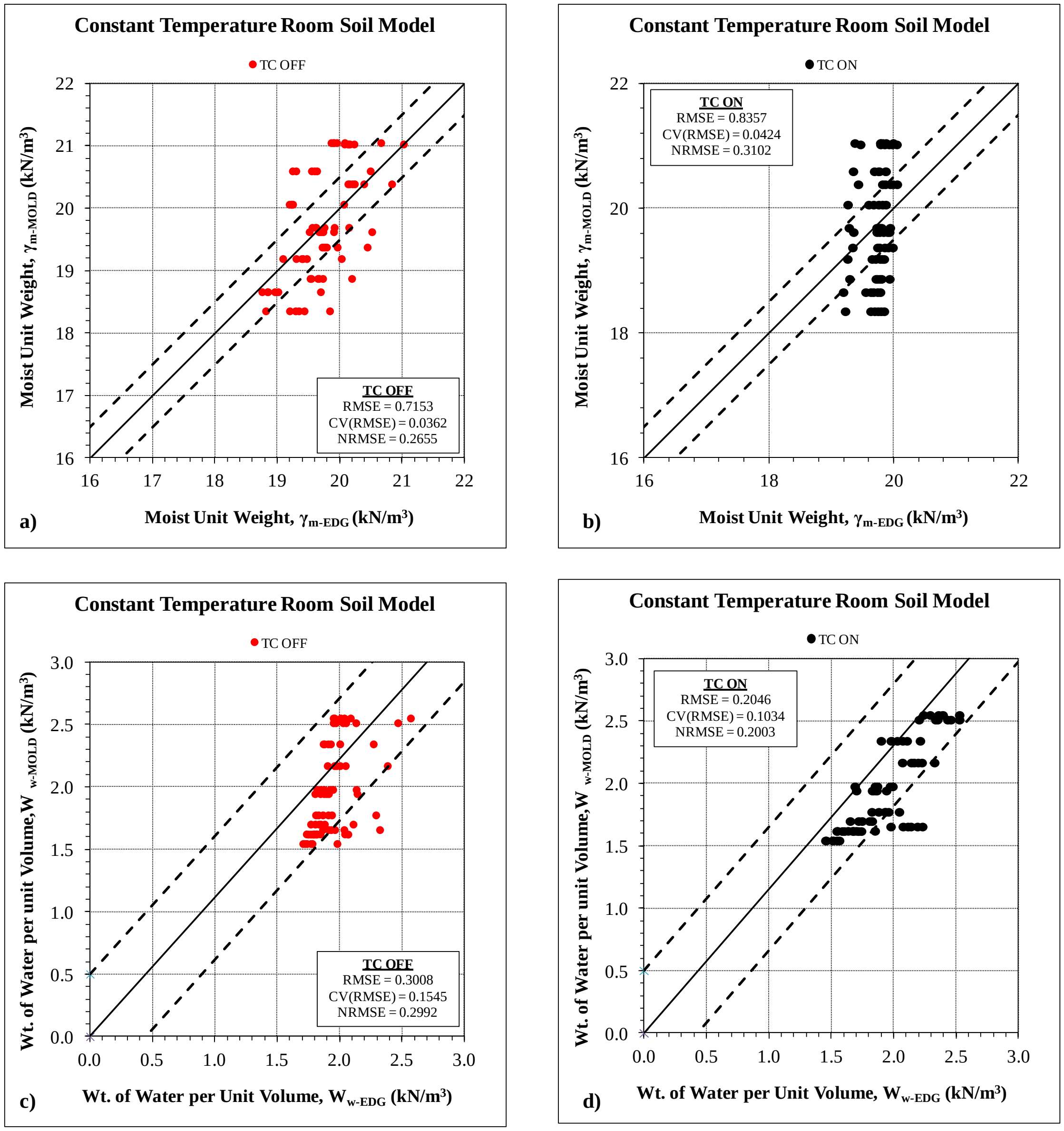


Figure 7.5 1:1 Plots – Constant Temperature Room Soil Model (TC OFF & TC ON)
a) 1:1 Plot – Moist Unit Weight (TC OFF)
b) 1:1 Plot – Moist Unit Weight (TC ON)
c) 1:1 Plot – Wt. of Water per Unit Volume (TC OFF)
d) 1:1 Plot – Wt. of Water per Unit Volume (TC ON)

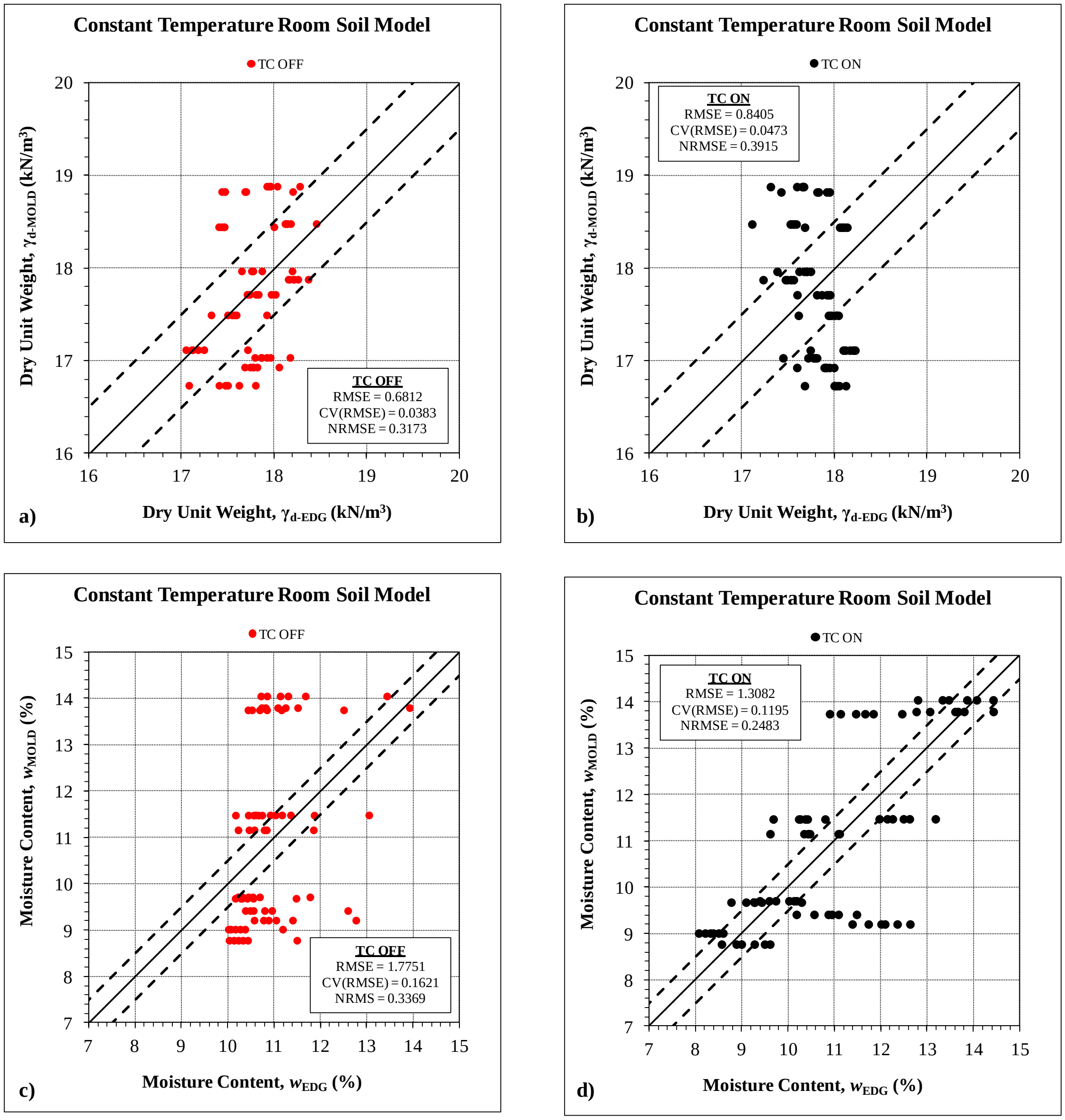


Figure 7.6 1:1 Plots – Constant temperature Room Soil Model (TC OFF & TC ON)
a) 1:1 Plot – Dry Unit Weight (TC OFF)
b) 1:1 Plot – Dry Unit Weight (TC ON)
c) 1:1 Plot – Moisture Content (TC OFF)
d) 1:1 Plot – Moisture Content (TC ON)

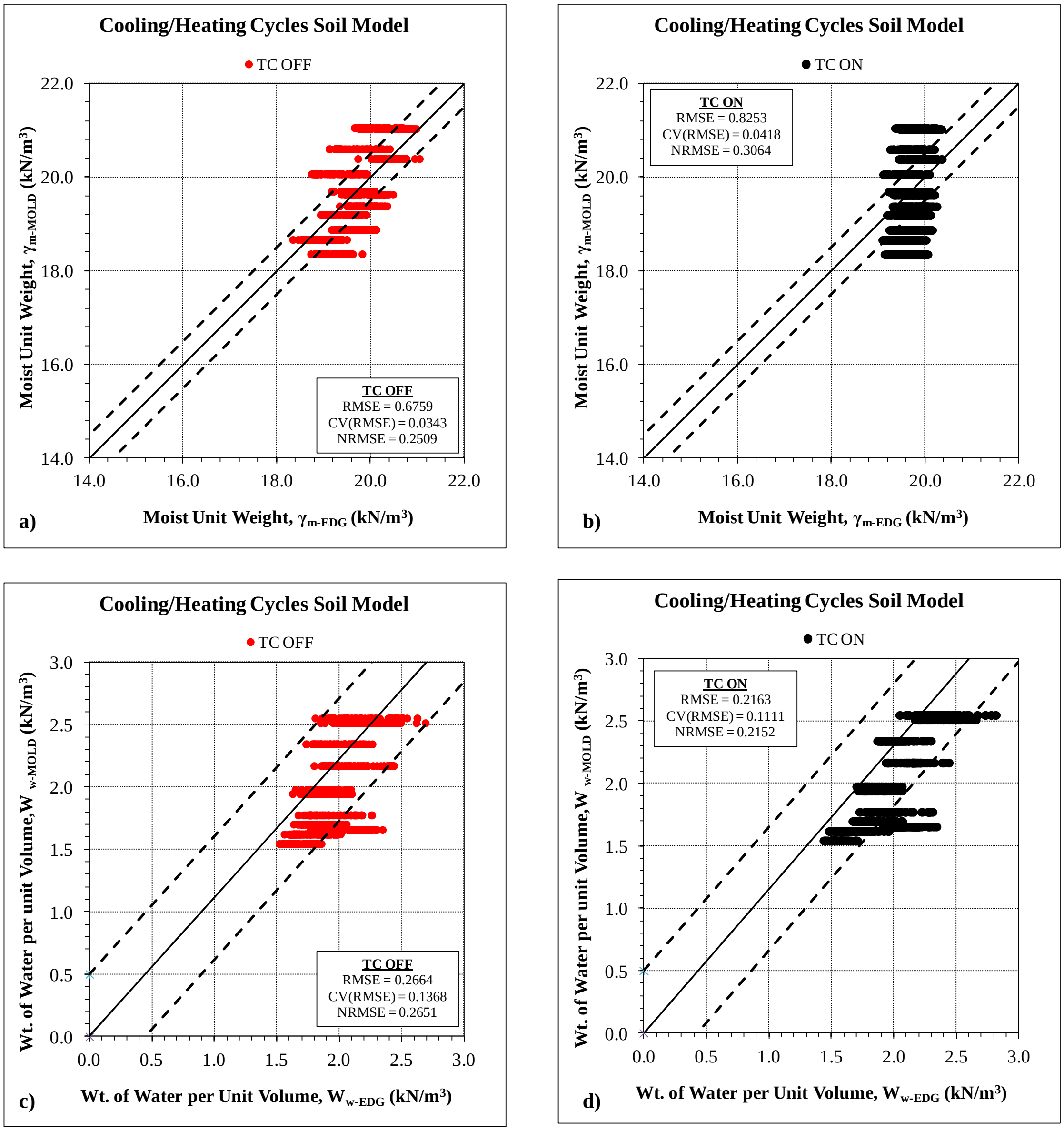


Figure 7.7 1:1 Plots – Cooling/Heating Cycles Soil Model (TC OFF & TC ON)
a) 1:1 Plot – Moist Unit Weight (TC OFF)
b) 1:1 Plot – Moist Unit Weight (TC ON)
c) 1:1 Plot – Wt. of Water per Unit Volume (TC OFF)
d) 1:1 Plot – Wt. of Water per Unit Volume (TC ON)

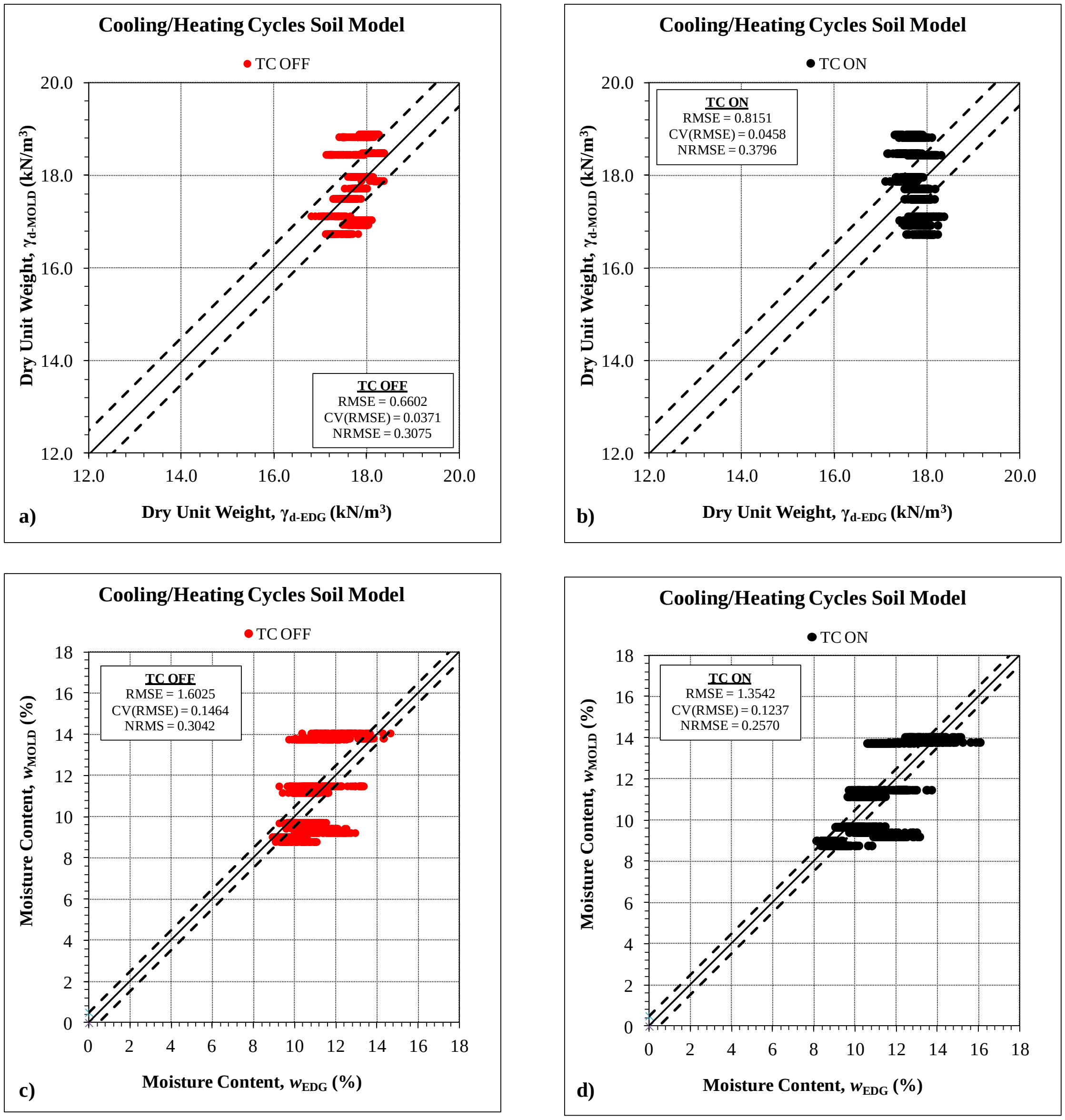


Figure 7.8 1:1 Plots – Cooling/Heating Cycle Soil Model (TC OFF & TC ON)
a) 1:1 Plot – Dry Unit Weight (TC OFF)
b) 1:1 Plot – Dry Unit Weight (TC ON)
c) 1:1 Plot – Moisture Content (TC OFF)
d) 1:1 Plot – Moisture Content (TC ON)

7.3.3 Relative Error

The following section shows histograms of the relative error calculated for moist unit weight, weight of water per unit volume, dry unit weight, and moisture content for the constant temperature room soil model and the cooling/heating cycles soil model. A cumulative distribution function (CDF) is displayed on each histogram as well. Relative error values are calculated using Equation 5.1 in Chapter 5.

7.3.4 Relative Error Results: Constant Temperature Room Soil Model and Cooling/Heating Cycles Soil Model

Figure 7.9a and 7.10a are histogram plots of relative error between $\gamma_{m\text{-}MOLD}$ and $\gamma_{m\text{-}EDG}$ (TC OFF & TC ON). For the constant temperature room soil model with TC OFF, relative error values for γ_m range from -8.19% to 6.49%, and for the constant temperature room soil model with TC ON, relative error values for γ_m range from -8.20% to 7.88%. For the cooling/heating cycle soil model with TC OFF, relative error values for γ_m range from -8.09% to 7.09%, and for the cooling/heating cycles soil model with TC ON, relative error values for γ_m range from -9.31% to 7.91%.

Figure 7.9b and 7.10b are histogram plots of relative error between $\gamma_{d\text{-}MOLD}$ and $\gamma_{d\text{-}EDG}$ (TC OFF & TC ON). For the constant temperature room soil model (TC OFF), relative error values for γ_d range from -6.74% to 7.32%, and for the constant temperature room soil model (TC ON), relative error values for γ_d range from -8.33% to 8.29%. For the cooling/heating cycle soil model (TC OFF), relative error values for γ_d range from -6.57% to 7.50%, and for the cooling/heating cycle soil model (TC ON), relative error values for γ_d range from -8.94% to 8.37%.

Figure 7.9c and 7.10c are histogram plots of relative error between $W_{W\text{-}MOLD}$ and $W_{W\text{-}EDG}$ (TC OFF & TC ON). For the constant temperature room soil model

(TC OFF), relative error values for W_W range from -40.69% to 23.30%, and for the constant temperature room soil model (TC ON), relative error values for W_W range from -35.10% to 18.72%. For the cooling/heating cycle soil model (TC OFF), relative error values for W_W range from -42.11% to 28.93%, and for the cooling/heating cycle soil model (TC ON), relative error values for W_W range from -41.71% to 19.88%.

Figure 7.9d and 7.10d are histogram plots of relative error between w_{MOLD} and w_{EDG} (TC OFF & TC ON). For the constant temperature room soil model (TC OFF), relative error values for *w* range from -38.85% to 23.95%, and for the constant temperature room soil model (TC ON), relative percent error values for *w* range from -37.30% to 20.66%. For the cooling/heating cycle soil model (TC OFF), relative error values for *w* range from -40.73% to 29.17%, and for the cooling/heating cycle soil model (TC ON), relative percent error values for *w* range from -41.74% to 22.93%.

Table 7.8 and Table 7.9 provide a summary of the minimum, maximum, range, and mean of the relative error histograms for the constant temperature room soil model and the cooling/heating cycle soil model.

Table 7.8 Summary Table of Relative Error (%) – Constant Temperature Room Soil Model

Constant Temperature Room Soil Model								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-8.19	-6.74	-40.69	-38.85	-8.20	-8.22	-35.10	-37.30
MAX	6.49	7.32	23.30	23.95	7.88	8.29	18.72	20.66
RANGE	14.68	14.06	63.99	62.80	16.08	16.62	53.82	57.96
MEAN	-0.13	-0.14	-2.27	-2.33	-0.18	-0.18	-1.01	-1.13

Table 7.9 Summary Table of Relative Error (%) – Cooling/Heating Cycles Soil Model

Cooling/Heating Cycles Soil Model								
	(TC OFF)				(TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-8.09	-6.57	-42.11	-40.73	-9.31	-8.94	-41.71	-42.74
MAX	7.09	7.50	28.93	29.17	7.91	8.37	19.88	22.93
RANGE	15.18	14.07	71.05	69.90	17.22	17.30	61.59	65.67
MEAN	-0.12	-0.13	-1.78	-1.84	-0.18	-0.18	-1.18	-1.26

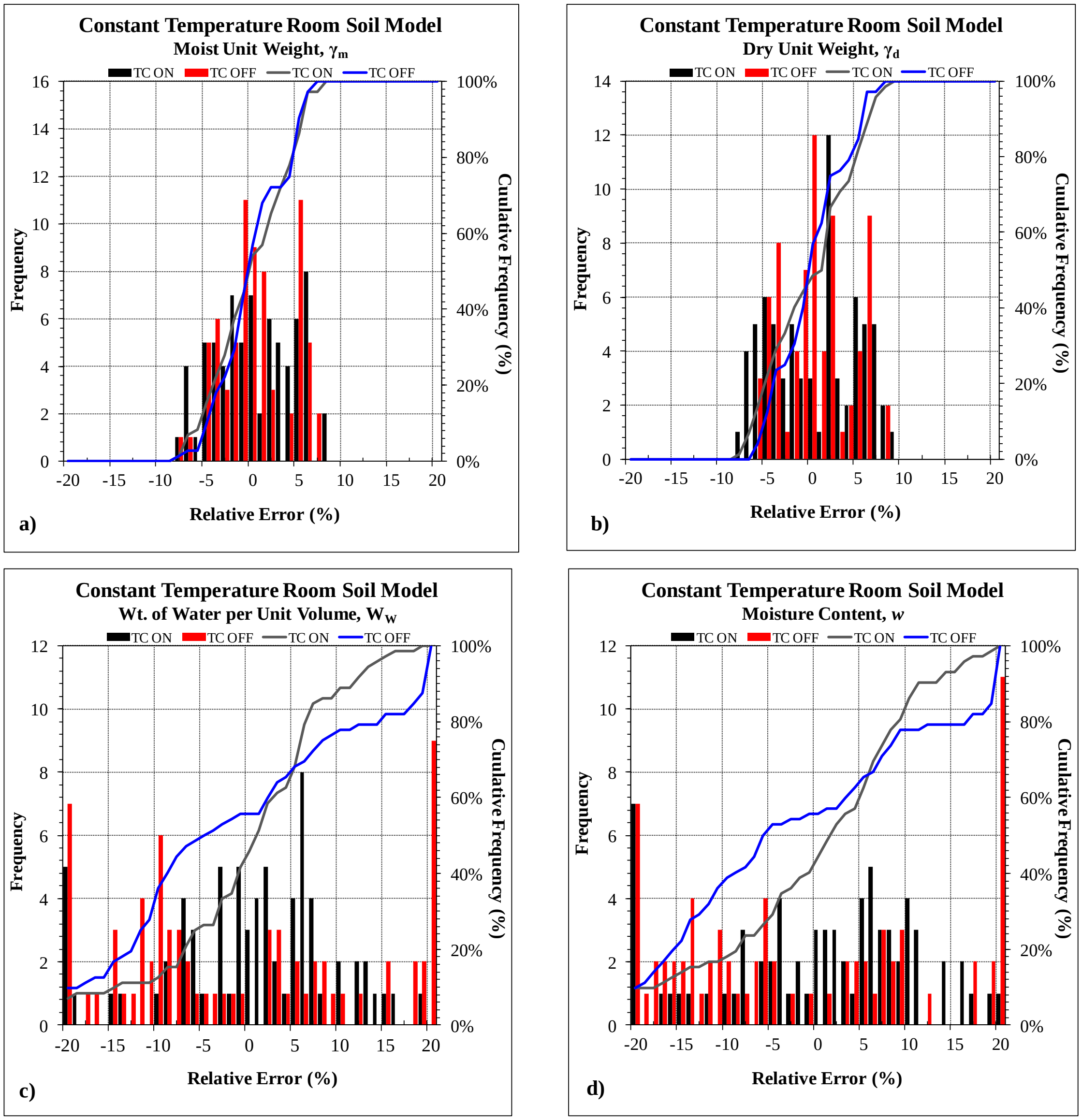


Figure 7.9 Relative Error Histograms and CDF Plots – Constant Temperature Room Soil Model
a) Histogram & CDF – Moist Unit Weight (TC OFF & TC ON)
b) Histogram & CDF – Dry Unit Weight (TC OFF & TC ON)
c) Histogram & CDF – Wt. of Water per Unit Volume (TC OFF & TC ON)
d) Histogram & CDF - Moisture Content (TC OFF & TC ON)

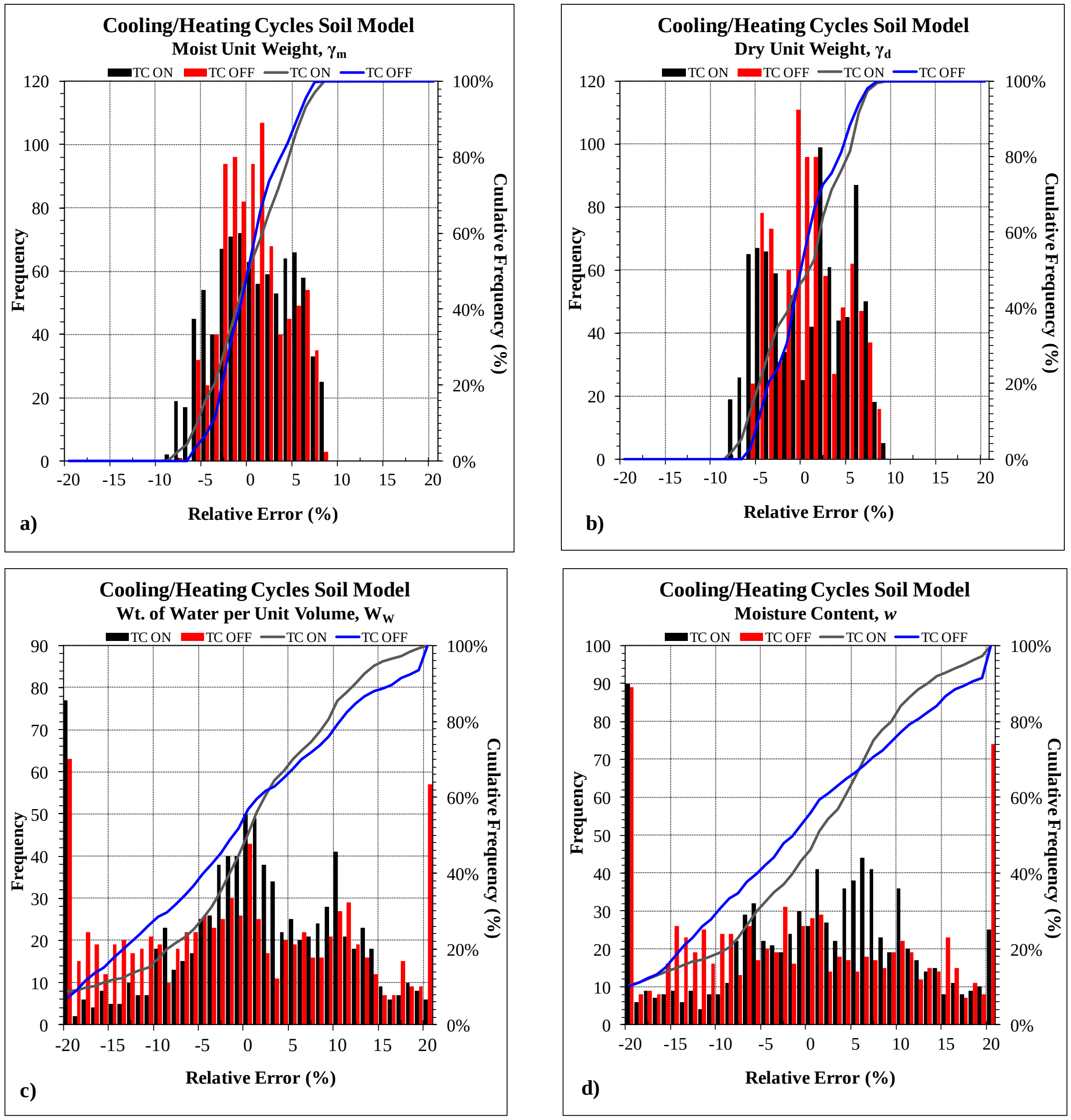


Figure 7.10 Relative Error Histograms and CDF Plots – Cooling/Heating Cycles Soil Model
a) Histogram & CDF – Moist Unit Weight (TC OFF & TC ON)
b) Histogram & CDF – Dry Unit Weight (TC OFF & TC ON)
c) Histogram & CDF – Wt. of Water per Unit Volume (TC OFF & TC ON)
d) Histogram & CDF - Moisture Content (TC OFF & TC ON)

7.3.5 Summary of Constant Room Temperature and Cooling/Heating Cycles Model Results

The coefficient of determination (R^2) values for the calibration equations created using the Constant Room Soil Model and the Cooling/Heating Cycles Soil Model are lower than the R^2 values for the calibration equations that are created using the initial readings before any temperature cycles were induced on the molds (see the results for the Mold Soil Model presented in Chapter 5). The associated RMSE, CV(RMSE), and NRMSE values for the EDG-predicted soil properties (γ_m, γ_d, W_w, w) for the Constant Temperature Room Soil Model and the Cooling/Heating Cycles Soil Model are all greater than the RMSE, CV(RMSE), and NRMSE values for the EDG-predicted soil properties using the Mold Soil Model presented in Chapter 5.

The RMSE, CV(RMSE), and NRMSE values for moist unit weight and dry unit weight for both the Constant Temperature Room Soil Model and the Cooling/Heating Cycles Soil Model increased when applying the EDG temperature correction algorithm. However, the RMSE, CV(RMSE), and NRMSE values for weight of water per unit volume and moisture content for both the Constant Temperature Room Soil Model and the Cooling/Heating Cycles Soil Model decreased when applying the EDG temperature correction algorithm. This indicates that the EDG temperature correction is improving the values for weight of water per unit volume and moisture content, and reducing the quality of the predictions for the moist unit weight and dry unit weight.

Differences in relative percent error between the MOLD and EDG predicted values for the calibration equations presented in this section with and without the EDG temperature correction algorithm applied are generally minimal. In addition, the standard deviation from the average for each set of EDG predicted values

(TC OFF & TC ON) is lower than the standard deviation from the average for the corresponding EDG predicted values presented in Chapter 5; this observation manifests itself as an even more significant smoothing effect, which can be observed on some of the 1:1 plots in this section. Table 7.10 and Table 7.11 provide a summary of the standard deviation values for the Constant Temperature Room Soil Model and Cooling/Heating Cycles Soil Model.

Table 7.10 Summary Table of Standard Deviation Values – Constant Temperature Room Soil Model

	Standard Deviation, σ_d			
	γ_m	γ_d	W_w	w
MOLD	0.90	0.75	0.36	1.98
EDG (TC OFF)	0.48	0.33	0.17	0.80
EDG (TC ON)	0.21	0.25	0.28	1.71

Table 7.11 Summary Table of Standard Deviation Values – Cooling/Heating Cycles Soil Model

	Standard Deviation, σ_d			
	γ_m	γ_d	W_w	w
MOLD	0.86	0.72	0.35	1.90
EDG (TC OFF)	0.46	0.27	0.20	0.98
EDG (TC ON)	0.16	0.21	0.27	1.63

7.4 Analysis of Temperature Cycle Data

From the raw data and associated analysis that is presented in this chapter, it is apparent that the EDG temperature correction does not improve the results that are yielded by the EDG calibration equations under varying temperature conditions. In order to further understand the relationships between soil properties, temperature, and the electrical properties measured by the EDG, various plots comparing temperature versus electrical properties are presented. Appendices A through D contain plots of electrical properties measured by the EDG versus temperature grouped by various soil properties to help explain the effect of temperature change on the electrical properties measured in the soil molds. It should be noted that the data presented in these plots is all the of same data set, but is presented in different plots for clarity and understanding.

Figure 7.11 is a plot displaying the electrical properties recorded by the EDG versus temperature during the cooling cycle, heating cycle, and constant temperature room testing for Mold 7, which is a representative case for the molds tested in this research study. Similar plots for the other molds that were tested are presented in Appendix A. As shown in this figure, there are variations in the electrical properties recorded by the EDG during each temperature cycle. The constant temperature room data appears to be closer to the values obtained during the cooling cycle. Despite the variation in measured electrical values, the same general trends due to temperature variation are displayed during each of the temperature loading cycles.

Table 7.12 shows the average percent change in the various electrical properties measured by the EDG during each different temperature cycle, and displays the absolute value of the average percent change of all three temperature cycles. The percent change is calculated by the following formula:

$$\text{Percent Change (\%)} = \frac{\text{Elec.Prop}_{T_O} - \text{Elec.Prop}_{T_F}}{\text{Elec.Prop}_{T_O}} \times 100 \tag{7.1}$$

where $Elec.Prop_{T_O}$= Electrical Property measured at the initial temperature of a temperature cycle (heating, cooling, or constant room), and $Elec.Prop_{T_F}$ = Electrical Property measured at the final temperature of a temperature cycle (heating, cooling, or constant room). It should be noted that a positive percent change values indicate the electrical property of interest increased, and negative percent change values indicate the electrical property of interest decreased.

As shown in Table 7.12, a temperature change of about 30°C has relatively minimal effects on variation in voltage and capacitance with absolute values of percent change ranging from 1.79% to 7.81%, with an average of 5.80%. However, a temperature change of about 30°C has more significant effects on current, phase, and impedance. Absolute values of percent change for these three electrical properties ranged from 11.37% to 23.31%, with an average of 17.30%. A temperature change of about 30°C had the most significant effect on resistance with absolute values of percent change ranging from 42.52% to 102.96%, with an average of 79.76%. From these observations, it can be concluded that temperature has a first-order effect on resistance, second-order effects on current, phase, and impedance, and minimal effects on voltage and capacitance.

Table 7.12 Summary Table of Average Percent Change in Electrical Property during Temperature Cycles of Molds

	Cooling	**Heating**	**Constant Room**	**|Average|**
Voltage, V	5.69%	-5.56%	-1.79%	4.35%
Current, I	-11.37%	11.94%	15.63%	12.98%
Phase, Θ	22.10%	-15.67%	-23.31%	20.36%
Resistance, R	93.81%	-42.52%	-102.96%	79.76%
Capacitance, C	-6.63%	7.81%	7.29%	7.25%
Impedance, Z	19.30%	-15.57%	-20.79%	18.55%
ΔTemp. (°C), T	29.15°**C**	-29.20°**C**	30.69°**C**	

Figure 7.12 is a plot displaying impedance versus temperature during the heating cycle. Each individual plot displays 3 molds with the same approximate moisture content and varying unit weights. Similar plots of EDG electrical properties versus temperature, grouped by moisture content for the cooling cycle, heating cycle, and constant temperature room testing, are presented in Appendix B. As shown in Figure 7.12c and Figure 7.12d, molds with similar moisture contents and varying unit weight generally have impedance values that are greater with a lower unit weight and lower with a higher unit weight. This indicates that soils with the same moisture content and varying unit weights do display differences in their electrical properties and that this trend exists at varying temperatures as well. The trend is not quite as clear in Figure 7.12a and 7.12b, however this trend is generally the same for all electrical properties, as shown in the other similar plots that are presented in Appendix B.

Figure 7.13 is a plot displaying resistance versus temperature during the heating cycle. Each individual plot displays 4 molds with the same approximate dry unit weights and varying moisture contents. Similar plots of EDG electrical properties versus temperature, grouped by dry unit weight for the cooling cycle, heating cycle, and constant temperature room testing, are presented in Appendix C. As shown in Figure 7.13c, molds with similar dry unit weight and varying moisture contents generally have resistance values that are greater with a lower moisture content and lower with a higher moisture content. This indicates that soils with the same dry unit weight and varying moisture contents do display differences in their electrical properties and that this trend exists at varying temperatures as well. The trend is not quite as clear in Figure 7.12a and 7.12b, however this trend is generally the same for all electrical properties, as shown in the other similar plots that are presented in Appendix C.

Figure 7.14 is a plot displaying impedance versus temperature during all of the temperature cycles with all 12 molds. Similar plots of EDG-measured properties versus temperature for all of the temperature cycles that were recorded with each mold are presented in Appendix D. These plots make it very clear how moisture content has a significant effect on the measured EDG electrical properties, as is indicated by the various bands that are grouped by moisture content.

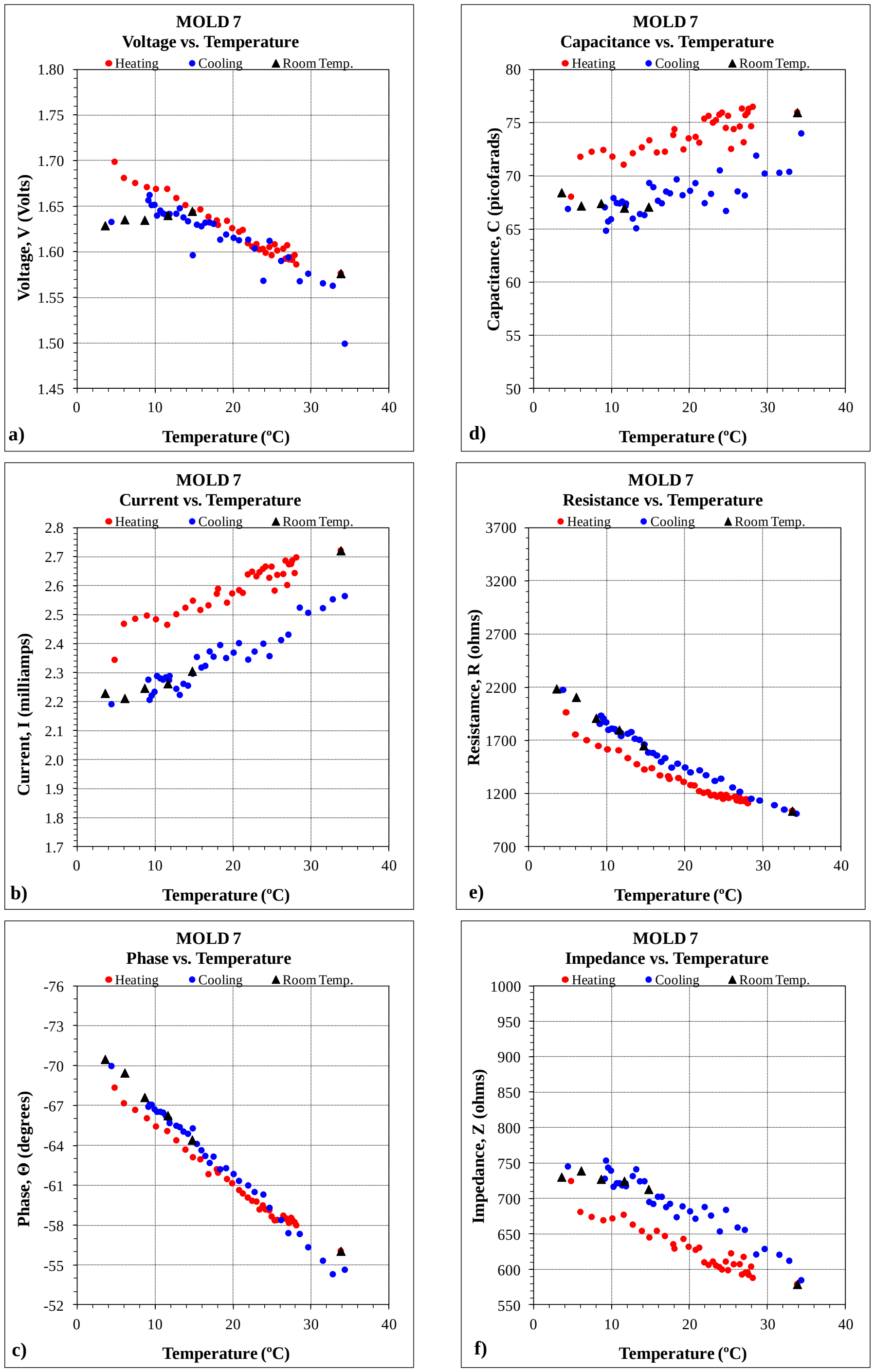


Figure 7.11 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 7)

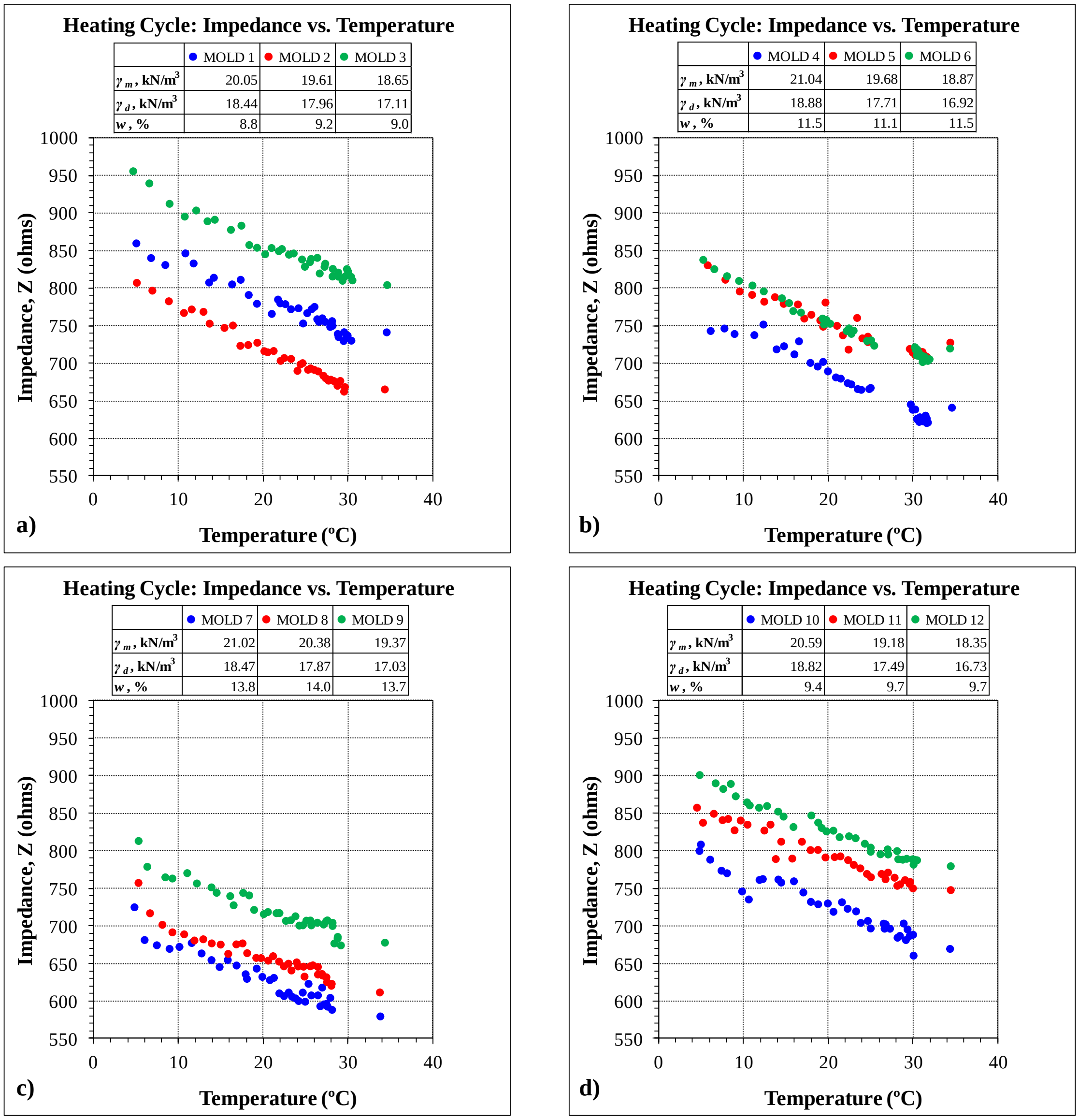


Figure 7.12 Heating Cycle: Impedance vs. Temperature

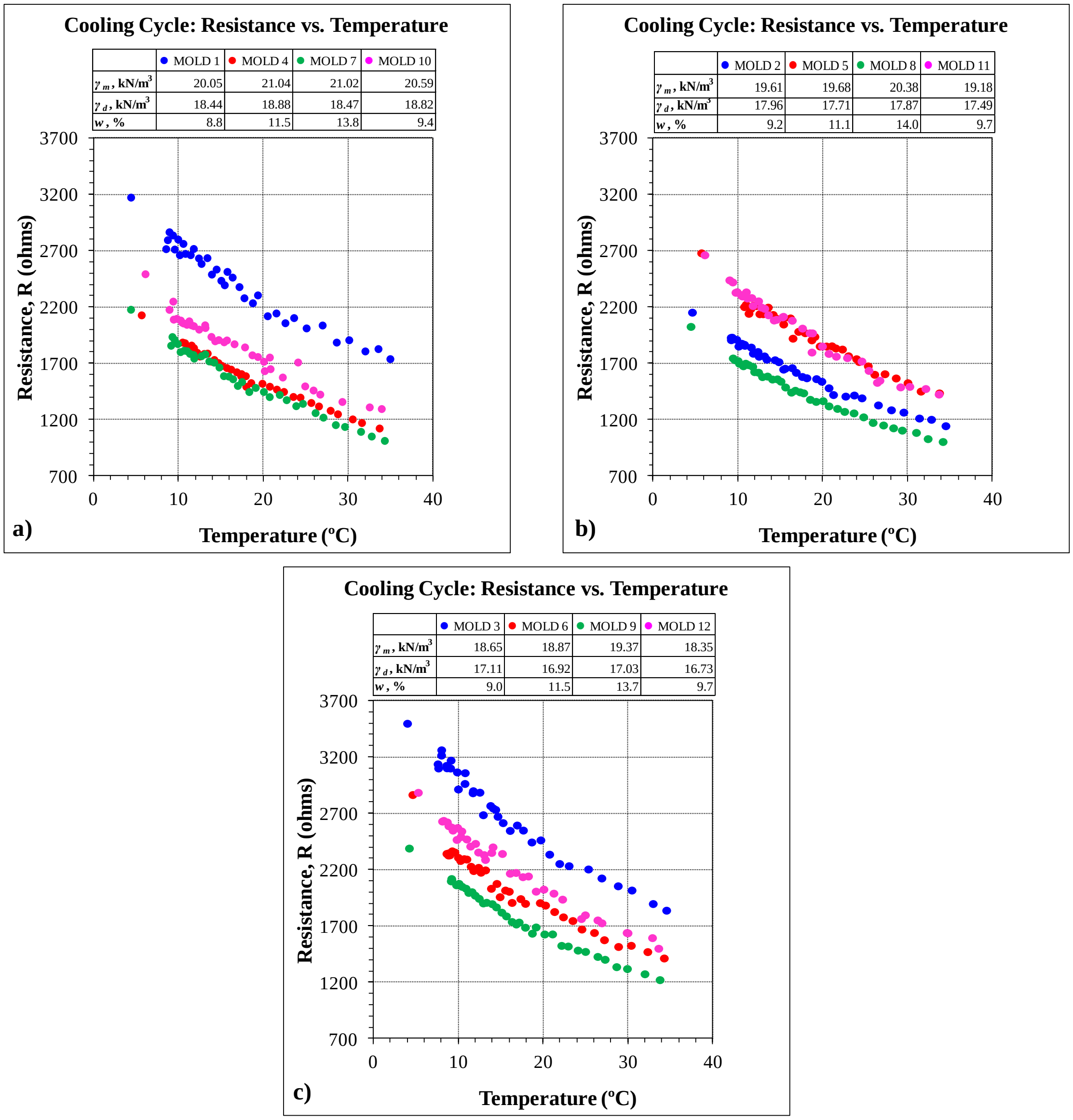


Figure 7.13 Cooling Cycle: Resistance vs. Temperature

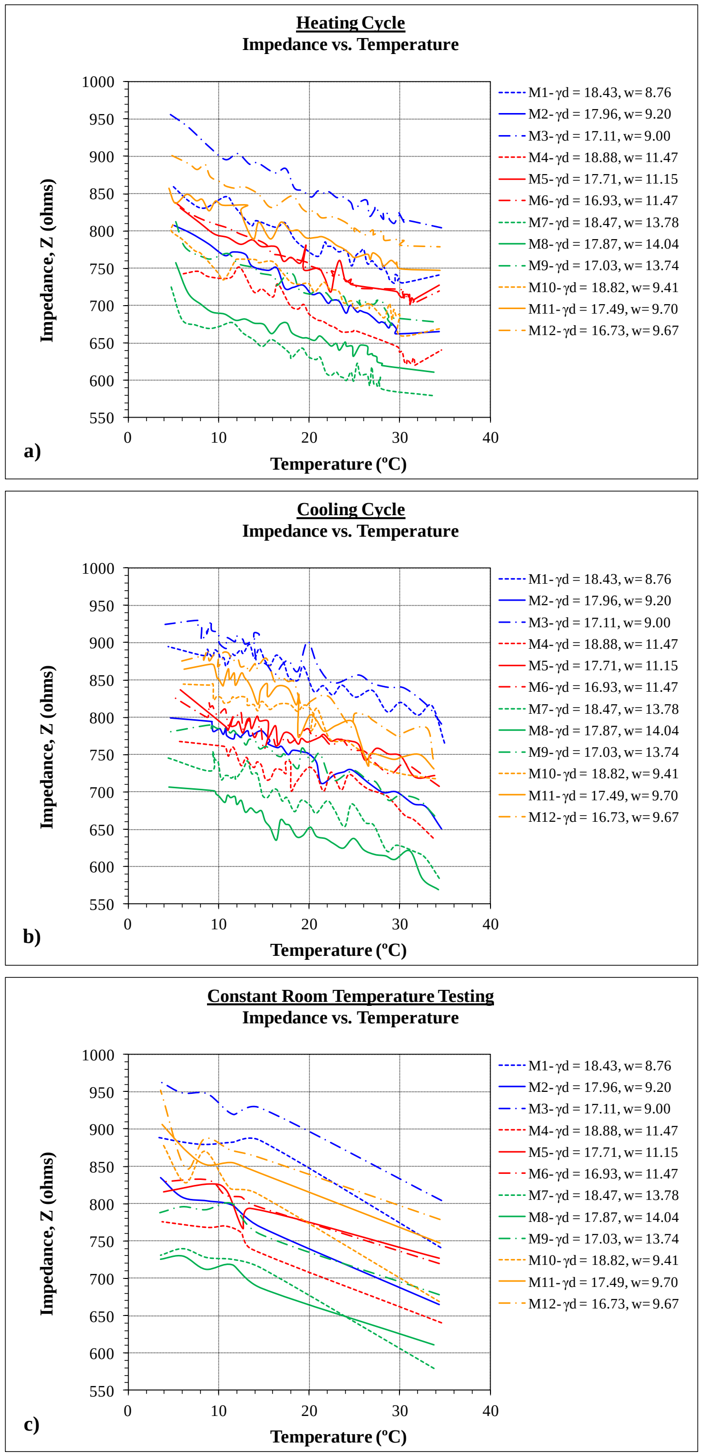


Figure 7.14 Impedance vs. Temperature (All Molds)

7.5 Conclusions

From the data that is presented in this chapter, it is quite evident that temperature has a significant effect on the electrical properties that are recorded by the EDG. Trends relating unit weight, moisture content, and the measured electrical properties were identified although they are not always strikingly clear. In addition, it was reiterated that the proprietary EDG temperature correction does not improve the overall results that were observed in the current study to a significant degree.

The next chapter will explore the creation of new temperature corrections aimed at improving the overall results that can be achieved via temperature correction of EDG results.

CHAPTER 8

NEW TEMPERATURE CORRECTION ALGORITHM

8.1 Introduction

As shown in previous chapters, the EDG proprietary temperature correction algorithm did not significantly improve the results in this research study. Based on the data obtained in the temperature testing study discussed in detail in Chapter 7, a new empirical temperature correction model has been developed. This chapter describes the methodology used to develop the new temperature correction model and evaluates the overall effectiveness of the temperature correction model on the data sets acquired during this research study.

8.2 New Temperature Correction Algorithm (TC 1)

The “Constant Temperature Room” data and the “Cooling/Heating Cycles” data were used to develop the new temperature correction model. When analyzing the data presented in Chapter 7, it is quite evident that temperature effects the raw electrical properties (voltage, current, and phase) measured by the EDG. The new temperature correction model uses the slopes of voltage, current, and phase versus temperature to correct the electrical property to the expected value that would be observed at a temperature of 15°C. New values of capacitance, resistance, and impedance are then calculated from the new temperature corrected raw values (See

Chapter 3 for formulas). The functional form of the temperature correction is shown in Equations 8.1 to 8.3:

$$\text{Voltage}_{\text{TC1}} = \text{Voltage}_{\text{MEAS}} - \text{Voltage}_{T.SLOPE} \times \left(\text{T}_{\text{MEAS}} - 15\,°\right) \tag{8.1}$$

$$\text{Current}_{\text{TC1}} = \text{Current}_{\text{MEAS}} - \text{Current}_{T.SLOPE} \times \left(\text{T}_{\text{MEAS}} - 15\,°\right) \tag{8.2}$$

$$\text{Phase}_{\text{TC1}} = \text{Phase}_{\text{MEAS}} - \text{Phase}_{T.SLOPE} \times \left(\text{T}_{\text{MEAS}} - 15\,°\right) \tag{8.3}$$

where the subscript $_{\text{TC1}}$ refers to the new temperature corrected electrical property value, the subscript $_{\text{MEAS}}$ refers to the electrical property value measured by the EDG, and the subscript $_{\text{T.SLOPE}}$ refers to the average slope value computed from the linear regression of voltage, current, and phase versus temperature. The $_{\text{T.SLOPE}}$ value of each of the individual 12 molds was calculated for the heating/cooling cycle data and for the constant temperature room data. The average $_{\text{T.SLOPE}}$ value of the 12 molds for each raw electrical property is used as the empirical coefficient. Table 8.1 displays the empirical coefficients calculated from the two data sets.

Table 8.1 Empirical Temperature Correction Algorithm Constants

	Voltage$_{\text{T.SLOPE}}$	**Current$_{\text{T.SLOPE}}$**	**Phase$_{\text{T.SLOPE}}$**
Cooling/Heating Cycle	-0.00094	0.012362	0.439423
Constant Temperature Room	-0.00305	0.008949	0.405828

8.3 New Temperature Correction Algorithm (TC 1) Results

In order to illustrate how the new temperature correction model performs when the soil is subjected to different temperature conditions, calibration equations using the “Constant Temperature Room” data and the “Cooling/Heating Cycles” data with the new temperature correction (TC 1) applied are presented in the following section. It should be noted that the empirical coefficients calculated from the “Constant Temperature Room” data are applied to the “Constant Temperature Room” data, and that the empirical coefficients from the “Cooling/Heating Cycles” data are applied to the “Cooling/Heating Cycle” data for analysis in this chapter. The resulting calibration equations are presented with the new temperature correction algorithm (TC 1), in addition to the standard EDG calibration equations (TC OFF & TC ON) which have already been presented in Chapter 7. 1:1 plots that compare MOLD measured values versus EDG predicted values are presented, along with relative error histogram plots between the measured and predicted values. The in-situ measured soil properties assessed in this study were: moist unit weight (γ_m), weight of water per unit volume (W_W), dry unit weight (γ_d), and moisture content (w).

8.3.1 Mold Calibration Equations (TC 1 Applied)

The associated mold calibration equations for the “Constant Temperature Room” data, and the combined “Cooling/Heating Cycles” data with the new temperature correction (TC 1) applied are presented in Figures 8.1 through 8.4. The coefficient of determination (R^2) values are presented on each graph as well. Table 8.2 and Table 8.3 provide a summary of the R^2 values, slopes, and intercepts of the calibration equations that are presented in this section. It should be noted that the coefficient of determination (R^2) values when the new temperature correction (TC 1)

Table 8.2 General Summary Table of Calibration Equations: Constant Temperature Room Soil Model

Constant Temperature Room Soil Model				
	Calibration Equation	**R^2**	**Slope**	**Intercept**
TC 1	$\gamma_{m\text{-MOLD}}$ vs. Z	0.4724	-0.0091	26.8954
TC OFF	$\gamma_{m\text{-MOLD}}$ vs. Z	0.2895	-0.0058	24.3385
TC ON	$\gamma_{m\text{-MOLD}}$ vs. Z	0.0653	-0.0012	20.6299
TC 1	$W_{w\text{-MOLD}}$ vs. C/R	0.6870	40.3428	0.6555
TC OFF	$W_{w\text{-MOLD}}$ vs. C/R	0.2376	14.5865	1.4981
TC ON	$W_{w\text{-MOLD}}$ vs. C/R	0.6581	36.5364	0.7101

Table 8.3 General Summary Table of Calibration Equations: Cooling/Heating Cycles Soil Model

Cooling/Heating Cycle Soil Model				
	Calibration Equation	**R^2**	**Slope**	**Intercept**
TC 1	$\gamma_{m\text{-MOLD}}$ vs. Z	0.4965	-0.0089	26.6164
TC OFF	$\gamma_{m\text{-MOLD}}$ vs. Z	0.3847	-0.0070	25.0379
TC ON	$\gamma_{m\text{-MOLD}}$ vs. Z	0.0826	-0.0017	21.1262
TC 1	$W_{w\text{-MOLD}}$ vs. C/R	0.6619	33.8241	0.7975
TC OFF	$W_{w\text{-MOLD}}$ vs. C/R	0.4081	19.2554	1.2171
TC ON	$W_{w\text{-MOLD}}$ vs. C/R	0.6099	33.5366	0.8300

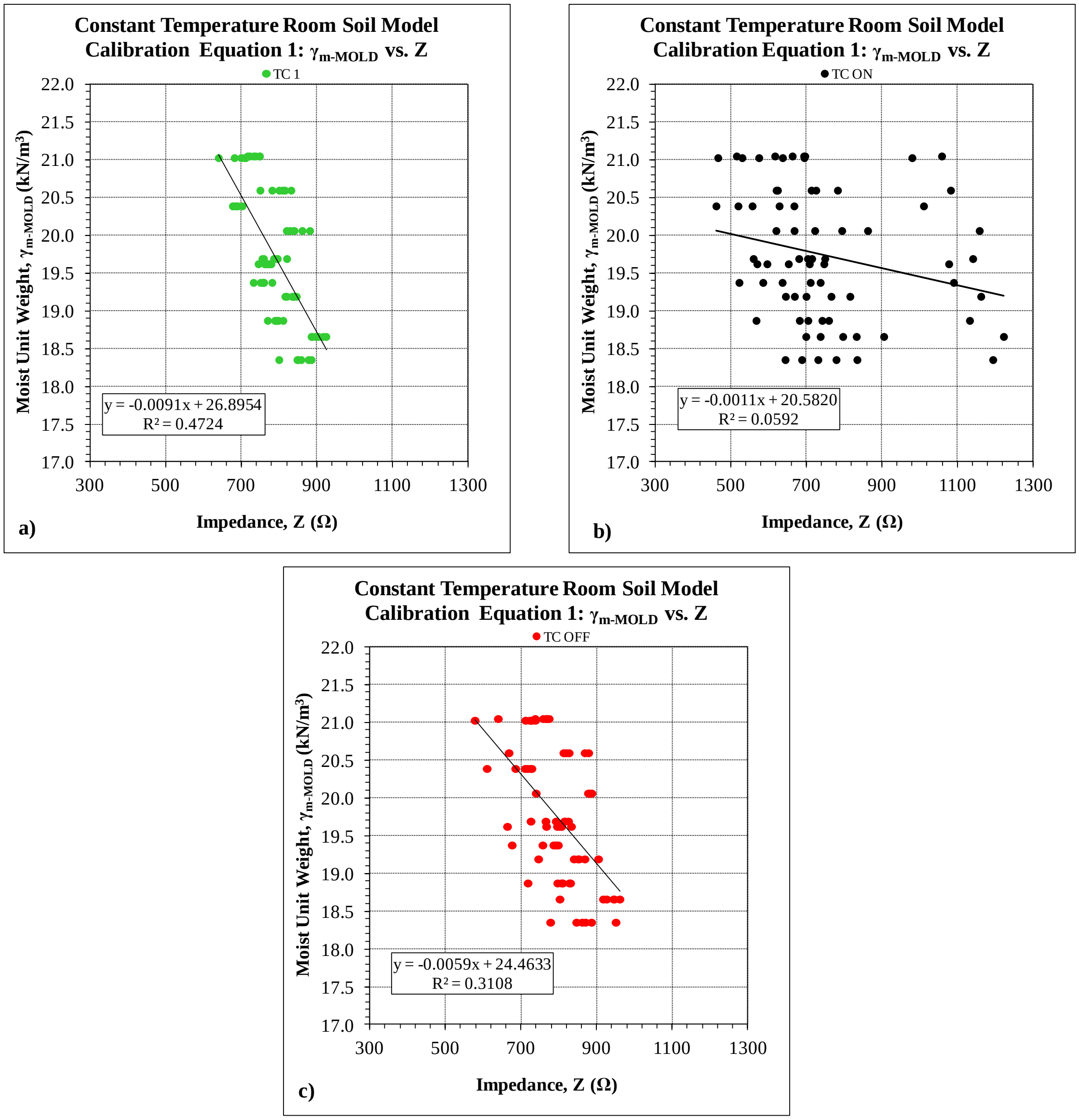
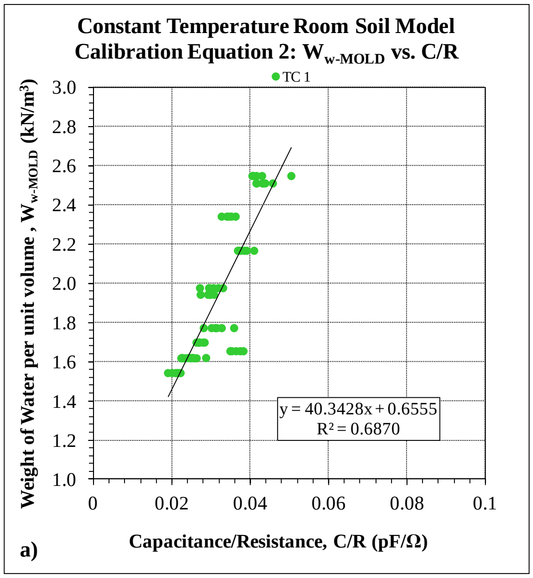
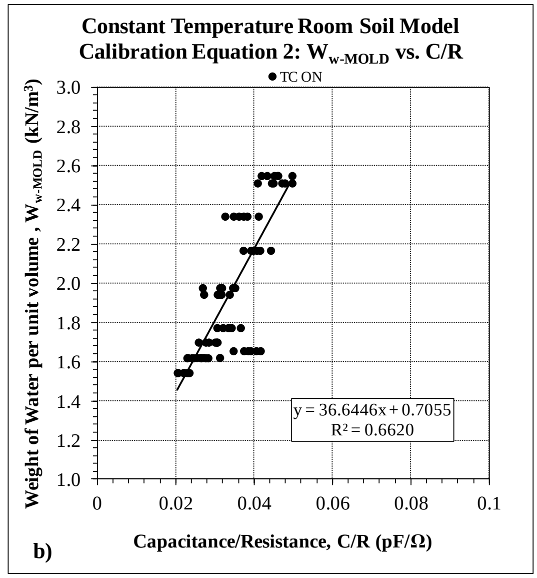


Figure 8.1 Calibration Equations – Constant Temperature Room Soil Model
a) Calibration Equation 1: $\gamma_{m\text{-}MOLD}$ vs. Z (TC 1)
b) Calibration Equation 1: $\gamma_{m\text{-}MOLD}$ vs. Z (TC ON)
c) Calibration Equation 1: $\gamma_{m\text{-}MOLD}$ vs. Z (TC OFF)





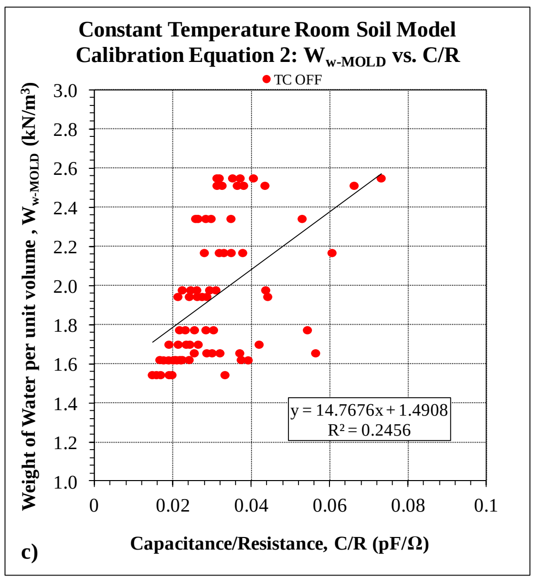


Figure 8.2 Calibration Equations – Constant Temperature Room Soil Model
a) Calibration Equation 2: $W_{w\text{-}MOLD}$ vs. C/R (TC 1)
b) Calibration Equation 2: $W_{w\text{-}MOLD}$ vs. C/R (TC ON)
c) Calibration Equation 2: $W_{w\text{-}MOLD}$ vs. C/R (TC OFF)

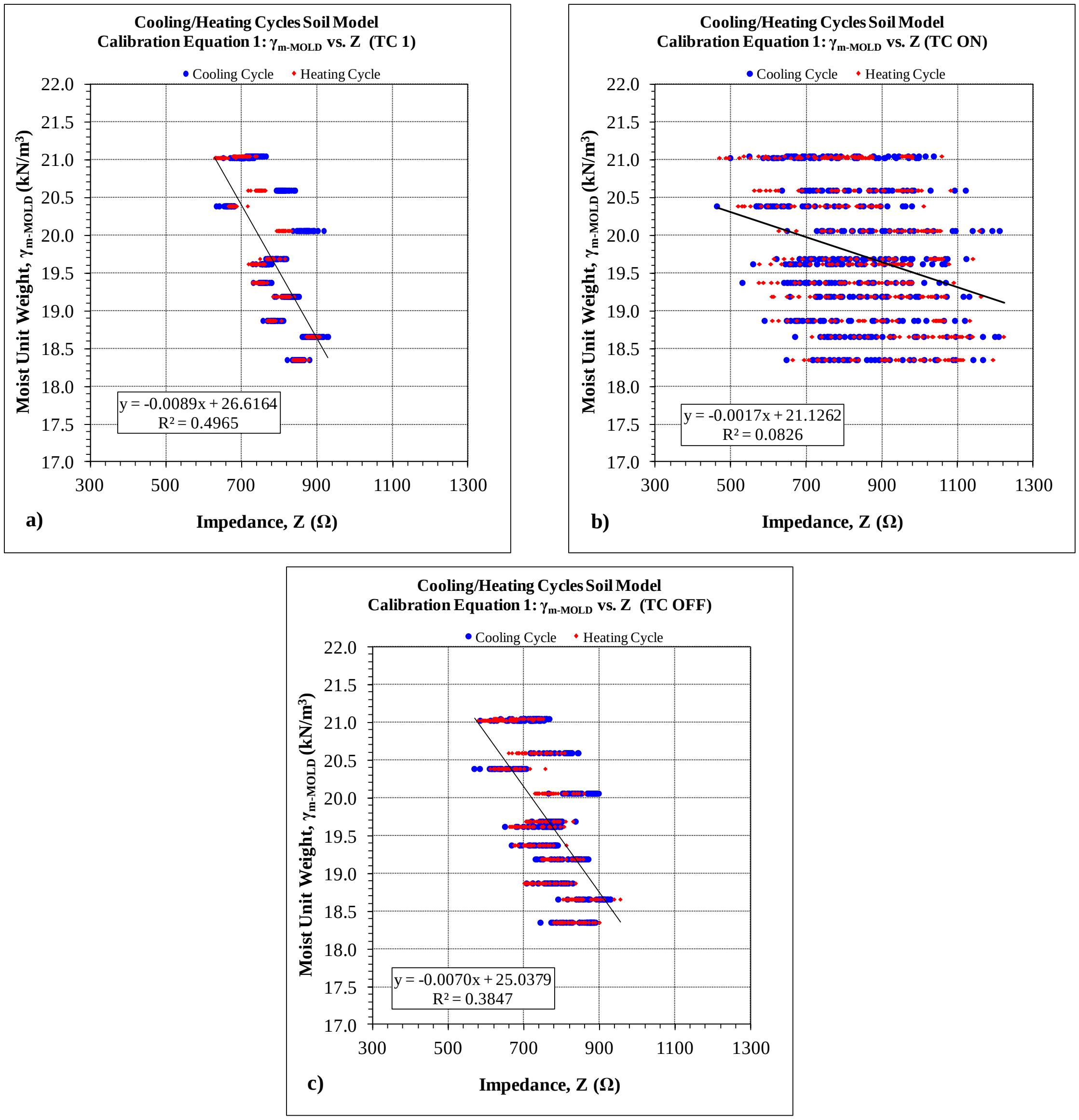


Figure 8.3 Calibration Equations – Cooling/Heating Cycles Soil Model
a) Calibration Equation 1: $\gamma_{m\text{-}MOLD}$ vs. Z (TC 1)
b) Calibration Equation 1: $\gamma_{m\text{-}MOLD}$ vs. Z (TC ON)
c) Calibration Equation 1: $\gamma_{m\text{-}MOLD}$ vs. Z (TC OFF)

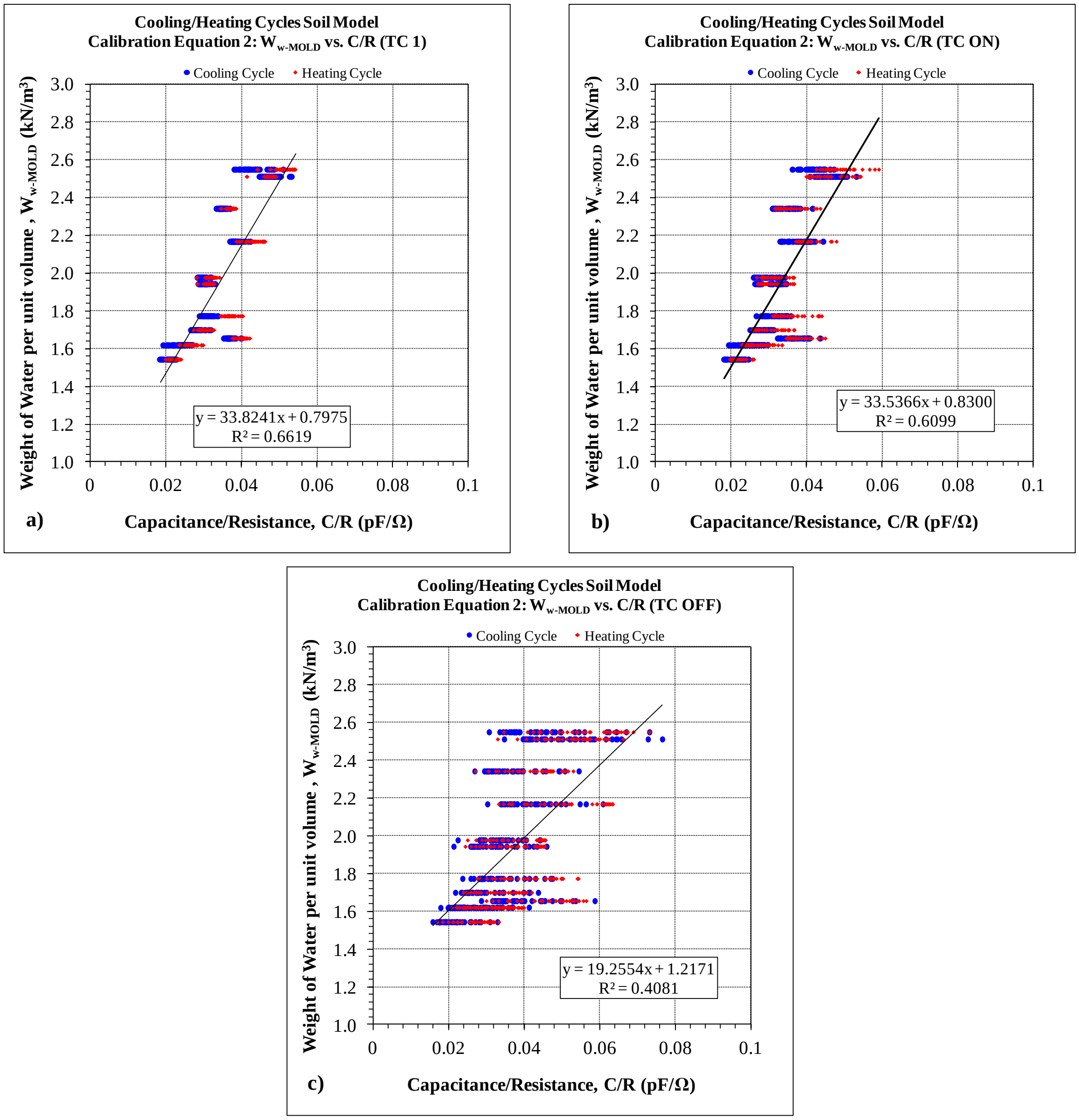


Figure 8.4 Calibration Equations – Cooling/Heating Cycles Soil Model
a) Calibration Equation 2: $W_{w\text{-}MOLD}$ vs. C/R (TC 1)
b) Calibration Equation 2: $W_{w\text{-}MOLD}$ vs. C/R (TC ON)
c) Calibration Equation 2: $W_{w\text{-}MOLD}$ vs. C/R (TC OFF)

8.3.2 Temperature Testing Soil Models: 1:1 Plots

The Constant Temperature Room Soil Model and the Cooling/Heating Cycles Soil Model calibration equations were used to predict the EDG values that are presented in this section. Figure 8.5 and Figure 8.9 show MOLD measured moist unit weights ($\gamma_{m\text{-}MOLD}$) versus EDG predicted moist unit weights ($\gamma_{m\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON), and with the new temperature correction algorithm applied (TC 1). Figure 8.6 and Figure 8.10 show MOLD measured weight of water per unit volume ($W_{W\text{-}MOLD}$) versus EDG predicted weight of water per unit volume ($W_{W\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON), and with the new temperature correction algorithm applied (TC 1). Figure 8.7 and Figure 8.11 show MOLD measured dry unit weights ($\gamma_{d\text{-}MOLD}$) versus EDG predicted dry unit weights ($\gamma_{d\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON), and with the new temperature correction algorithm applied (TC 1). Figure 8.8 and Figure 8.12 show MOLD measured moisture content (w_{MOLD}) versus EDG predicted moisture content (w_{EDG}) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON), and with the new temperature correction algorithm applied (TC 1). It should be noted that the solid line in all figures is a 1:1 line, and the dashed lines are ±0.5 kN/m^3 or ±0.5 % reference lines.

Table 8.4 and Table 8.5 summarize statistical error measurements of interest for the EDG values that are predicted for the Constant Temperature Room Soil Model and the Cooling/Heating Cycles Soil Model with the new temperature correction (TC 1) applied.

Table 8.6 and Table 8.7 summarize the net difference in statistical error measurements of interest when the new temperature correction algorithm is applied compared to the standard EDG error measurements of interest (TC OFF & TC ON).

Table 8.8 and Table 8.9 summarize the net percent difference in error measurements of interest when the new temperature correction algorithm is applied compared to the standard EDG error measurements of interest (TC OFF & TC ON).

For both the Constant Temperature Room Soil Model and the Cooling/Heating Cycles Soil Model, the RMSE, CV(RMSE), and NRMSE for all predicted values (moist unit weight, weight of water per unit volume, dry unit weight, and moisture content) are smaller with the new temperature correction applied (TC 1). The levels of improvement for each respective soil property vary, but overall the new temperature correction algorithm has a positive impact on the predicted results.

With TC1 applied, the RMSE, CV(RMSE), and NRMSE values for moist unit weight decrease significantly (-25.1% to -25.9%) compared to the EDG proprietary temperature correction algorithm (TC ON). However, the RMSE, CV(RMSE), and NRMSE values for moist unit weight decrease slightly less (-9.5% to -12.5%) compared to the standard EDG calibration method with no temperature correction algorithm applied (TC OFF).

With TC1 applied, the RMSE, CV(RMSE), and NRMSE values for dry unit weight decrease significantly (-20.1% to -20.3%) compared to the EDG proprietary temperature correction algorithm (TC ON). However, the RMSE, CV(RMSE), and NRMSE values for dry unit weight decrease minimally (-1.4% to -1.7%) compared to the standard EDG calibration method with no temperature correction algorithm applied (TC OFF).

With TC1 applied, the RMSE, CV(RMSE), and NRMSE values for weight of water per unit volume decrease minimally (-3.8% to -6.9%) compared to the EDG proprietary temperature correction algorithm (TC ON). However, the RMSE, CV(RMSE), and NRMSE values for weight of water per unit volume decrease significantly (-24.4% to -35.6%) compared to the standard EDG calibration method with no temperature correction algorithm applied (TC OFF).

With TC1 applied, the RMSE, CV(RMSE), and NRMSE values for moisture content decrease minimally (-0.6% to -2.1%) compared to the EDG proprietary temperature correction algorithm (TC ON). However, the RMSE, CV(RMSE), and NRMSE values for dry unit weight decrease significantly (-17.3% to -26.7%) compared to the standard EDG calibration method with no temperature correction algorithm applied (TC OFF).

Overall the new temperature correction (TC 1) improves the results from those presented in previous chapters in the following manner:

- Relatively significant improvement in the RMSE, CV(RMSE), and NRMSE values for moist unit weight and dry unit weight when comparing to the EDG temperature correction (TC ON).
- Relatively minimal improvement in the RMSE, CV(RMSE), and NRMSE values for weight of water per unit volume and moisture content when comparing to the EDG temperature correction (TC ON).
- Relatively significant improvement in the RMSE, CV(RMSE), and NRMSE values for weight of water per unit volume and moisture content when comparing to the EDG without the temperature correction applied (TC OFF).

- Relatively minimal improvement in the RMSE, CV(RMSE), and NRMSE values for moist unit weight and dry unit weight when comparing to the EDG without the temperature correction applied (TC OFF).

Table 8.4 Summary of Statistical Measures: Constant Temperature Room Soil Model (TC 1)

Constant Temperature Room Soil Model (TC 1)				
	γ_m	γ_d	W_w	w
RMSE	0.6258	0.6699	0.1937	1.3006
CV(RMSE)	0.0317	0.0377	0.0995	0.1188
NRMSE	0.2323	0.3120	0.1927	0.2469

Table 8.5 Summary of Statistical Measures: Cooling/Heating Cycles Soil Model (TC 1)

Cooling/Heating Cycles Soil Model (TC 1)				
	γ_m	γ_d	W_w	w
RMSE	0.6114	0.6509	0.2014	1.3260
CV(RMSE)	0.0310	0.0366	0.1034	0.1211
NRMSE	0.2270	0.3032	0.2003	0.2517

Table 8.6 Summary of Statistical Measures: Net Difference between TC 1 and TC OFF/TC ON - Constant Temperature Room Soil Model

Cooling/Heating Cycles Soil Model

	(TC1 - TC OFF)				**(TC 1 - TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-0.0895	-0.0113	-0.1071	-0.4745	-0.2099	-0.1706	-0.0076	-0.0076
CV(RMSE)	-0.0045	-0.0006	-0.0550	-0.0433	-0.0107	-0.0096	-0.0039	-0.0007
NRMSE	-0.0332	-0.0053	-0.1065	-0.0900	-0.0779	-0.0795	-0.0076	-0.0014

Table 8.7 Summary of Statistical Measures: Net Difference between TC 1 and TC OFF/TC ON - Cooling/Heating Cycles Soil Model

Cooling/Heating Cycles Soil Model

	(TC 1 - TC OFF)				**(TC 1 - TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-0.0645	-0.0093	-0.0650	-0.2765	-0.2139	-0.1642	-0.0149	-0.0282
CV(RMSE)	-0.0033	-0.0005	-0.0334	-0.0253	-0.0108	-0.0092	-0.0077	-0.0026
NRMSE	-0.0239	-0.0043	-0.0648	-0.0525	-0.0794	-0.0764	-0.0149	-0.0053

Table 8.8 Summary of Statistical Measures: Net Percent Change between TC 1 and TC OFF/TC ON - Constant Temperature Room Soil Model

Cooling/Heating Cycles Soil Model								
	(TC 1 - TC OFF)				**(TC 1 - TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	·12.5%	-1.7%	-35.6%	-26.7%	-25.1%	-20.3%	-3.8%	-0.6%
CV(RMSE)	·12.4%	-1.7%	-35.6%	-26.7%	-25.2%	-20.4%	-3.8%	-0.6%
NRMSE	·12.5%	-1.7%	-35.6%	-26.7%	-25.1%	-20.3%	-3.8%	-0.6%

Table 8.9 Summary of Statistical Measures: Net Percent Change between TC 1 and TC OFF/TC ON - Constant Temperature Room Soil Model

Cooling/Heating Cycles Soil Model								
	(TC 1 - TC OFF)				**(TC 1 - TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-9.5%	-1.4%	-24.4%	-17.3%	-25.9%	-20.1%	-6.9%	-2.1%
CV(RMSE)	-9.7%	-1.4%	-24.4%	-17.3%	-25.9%	-20.1%	-6.9%	-2.1%
NRMSE	-9.5%	-1.4%	-24.4%	-17.3%	-25.9%	-20.1%	-6.9%	-2.1%

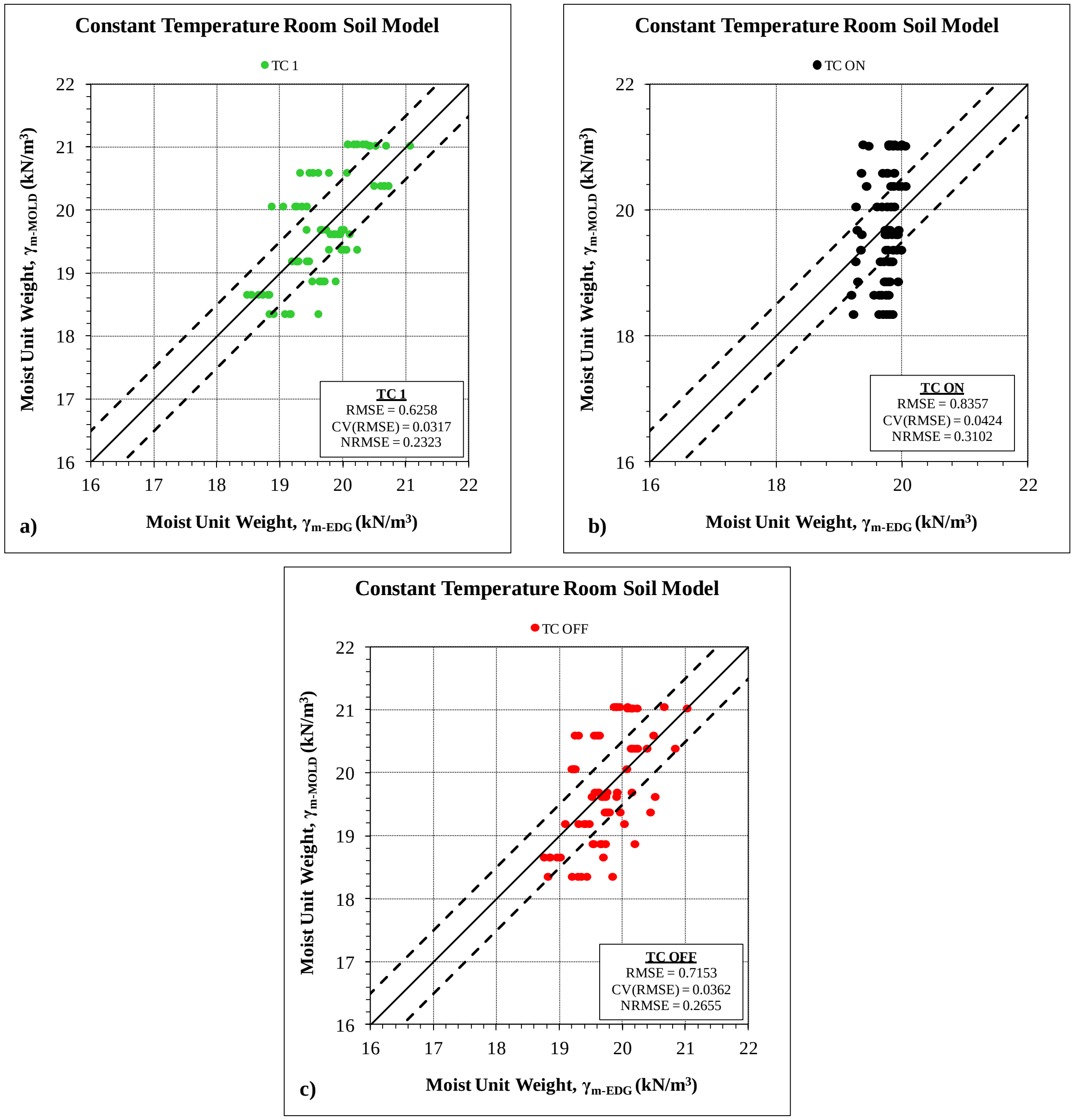


Figure 8.5 **1:1 Plots – Constant Temperature Room Soil Model**
a) 1:1 Plot – Moist Unit Weight (TC 1)
b) 1:1 Plot – Moist Unit Weight (TC ON)
c) 1:1 Plot – Moist Unit Weight (TC OFF)

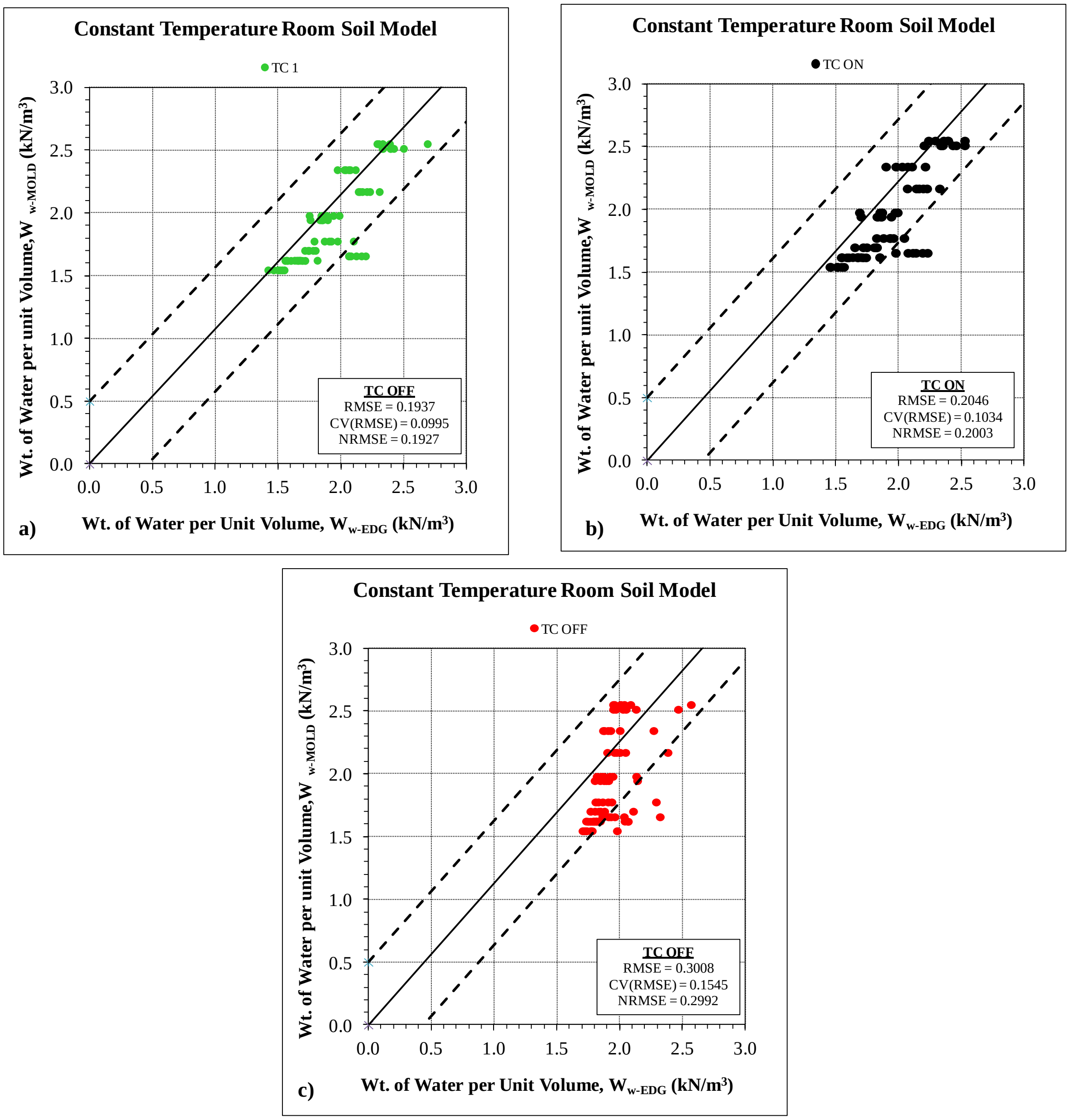


Figure 8.6 1:1 Plots – Constant Temperature Room Soil Model
a) 1:1 Plot – Wt. of Water per Unit Volume (TC 1)
b) 1:1 Plot – Wt. of Water per Unit Volume (TC ON)
c) 1:1 Plot – Wt. of Water per Unit Volume (TC OFF)

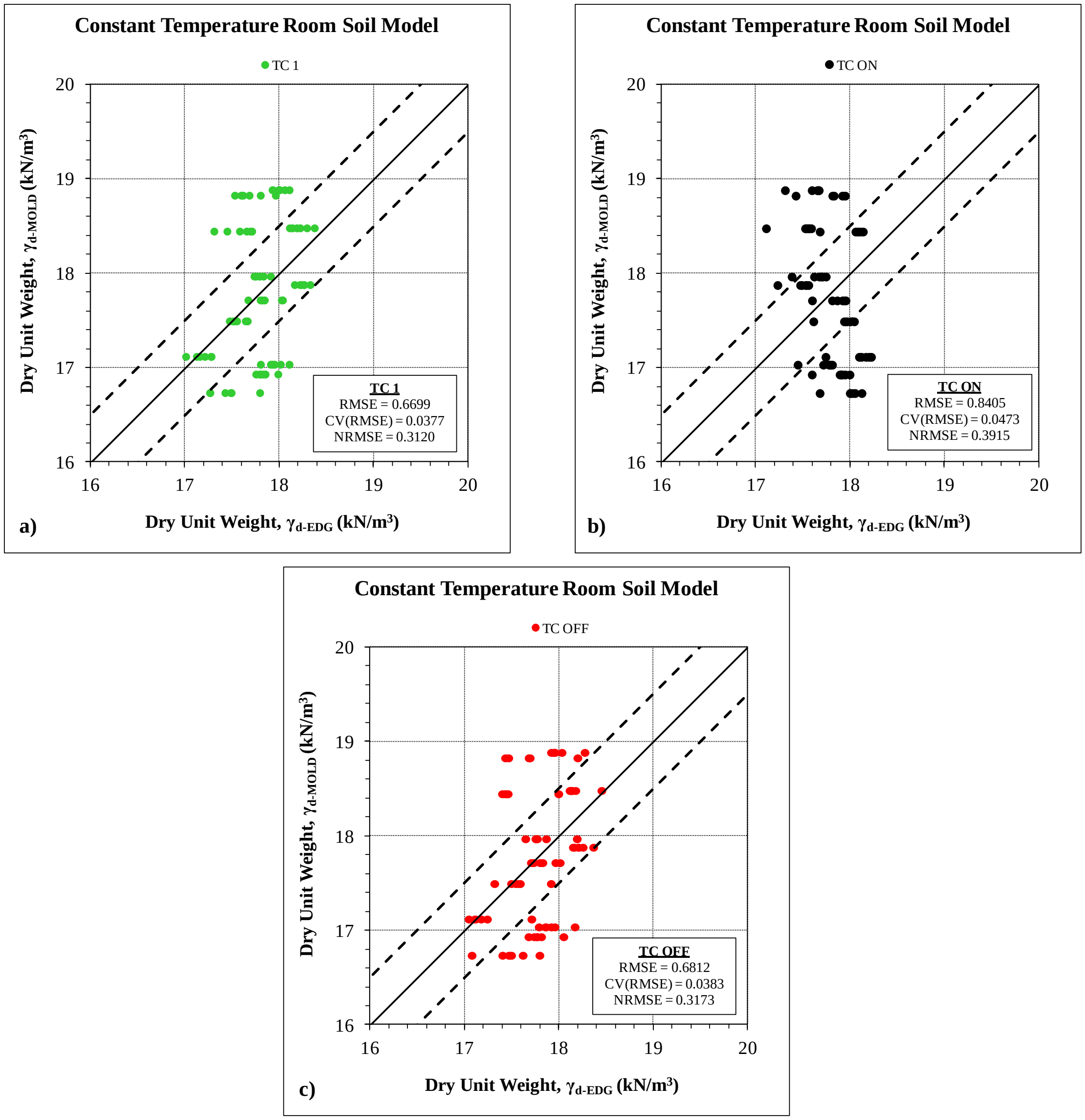


Figure 8.7 1:1 Plots – Constant Temperature Room Soil Model
a) 1:1 Plot – Dry Unit Weight (TC 1)
b) 1:1 Plot – Dry Unit Weight (TC ON)
c) 1:1 Plot – Dry Unit Weight (TC OFF)

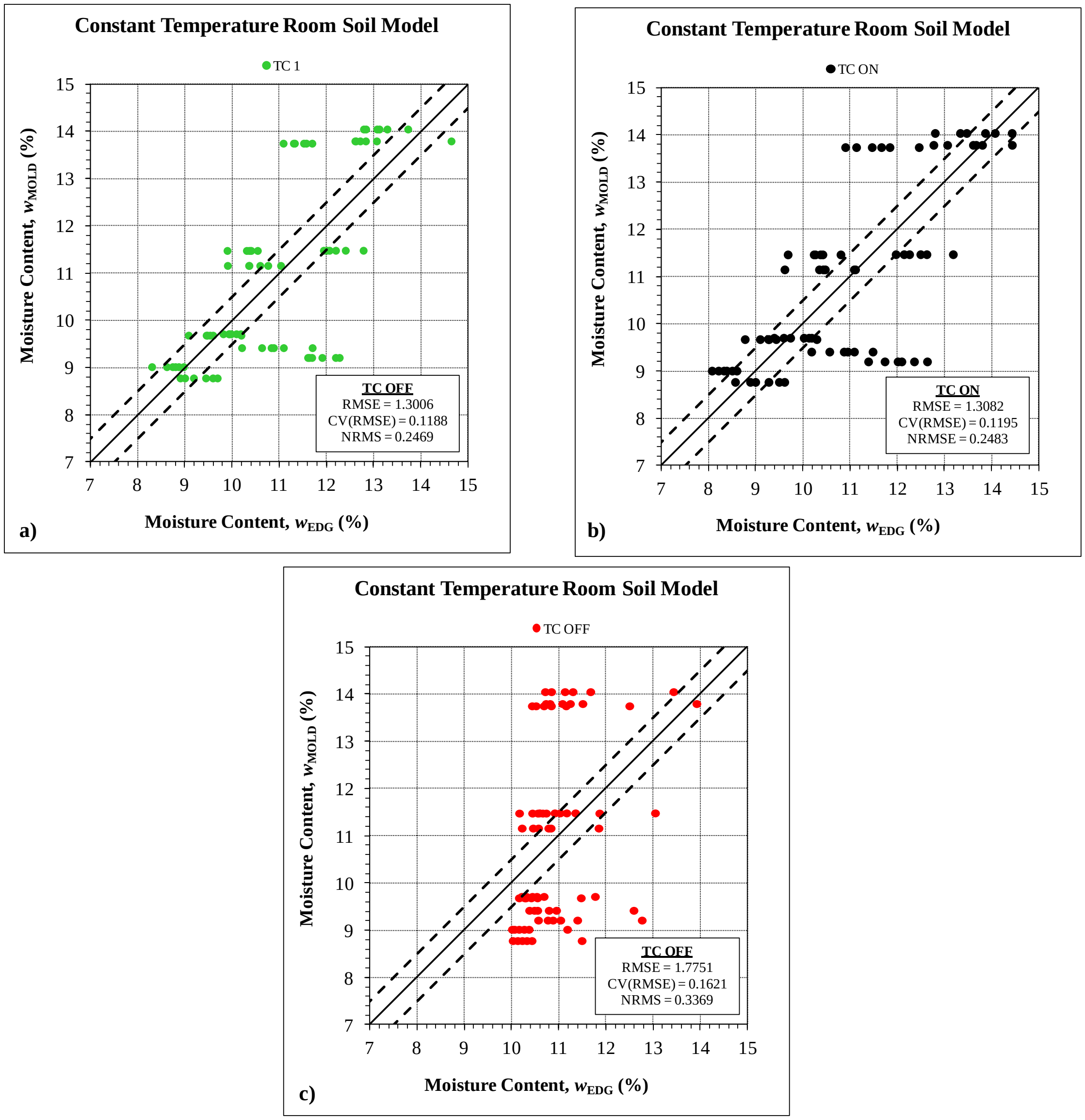


Figure 8.8 1:1 Plots – Constant Temperature Room Soil Model
a) 1:1 Plot – Moisture Content (TC 1)
b) 1:1 Plot – Moisture Content (TC ON)
c) 1:1 Plot – Moisture Content (TC OFF)

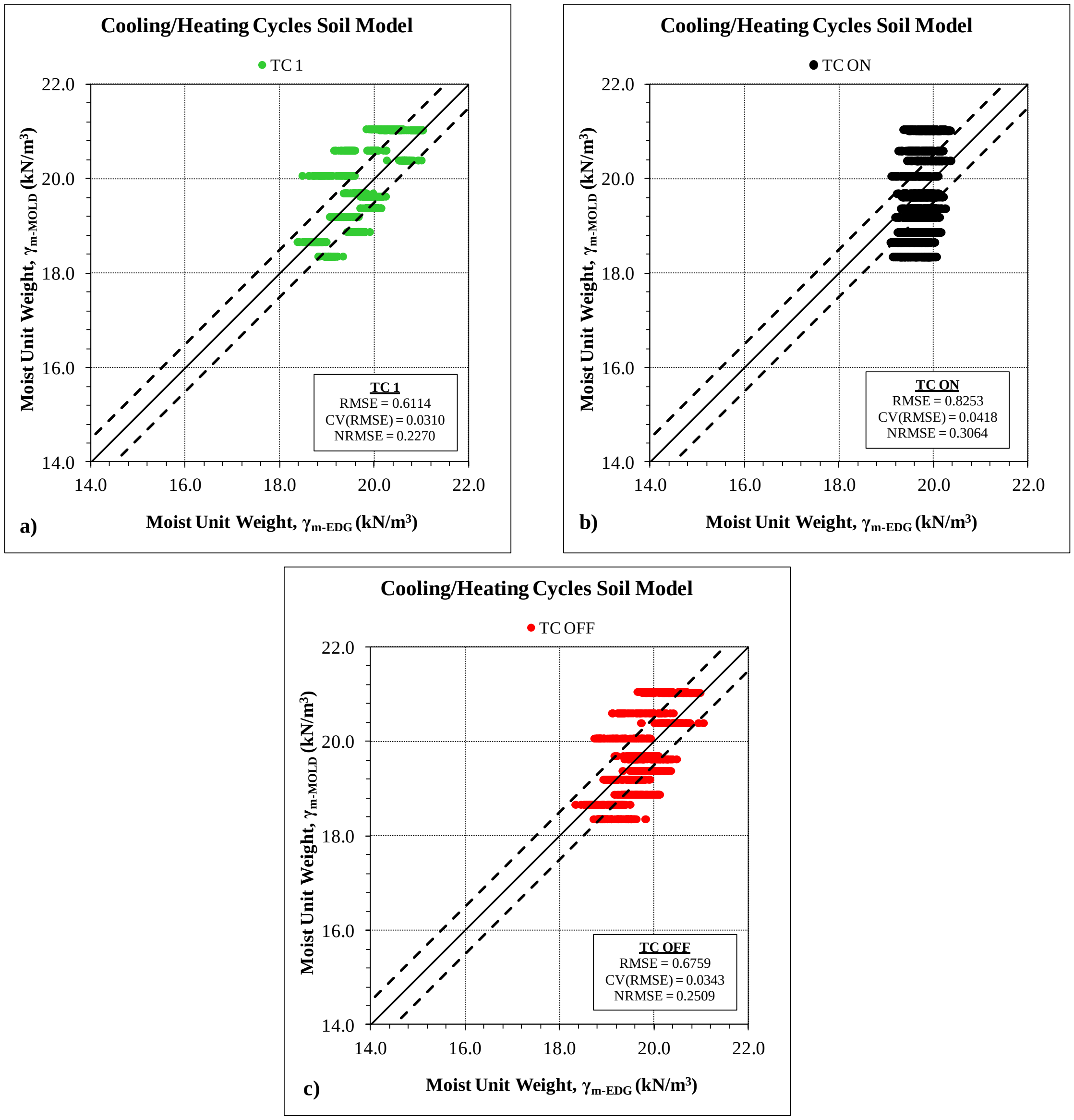


Figure 8.9 1:1 Plots – Cooling/Heating Cycles Soil Model
a) 1:1 Plot – Moist Unit Weight (TC 1)
b) 1:1 Plot – Moist Unit Weight (TC ON)
c) 1:1 Plot – Moist Unit Weight (TC OFF)

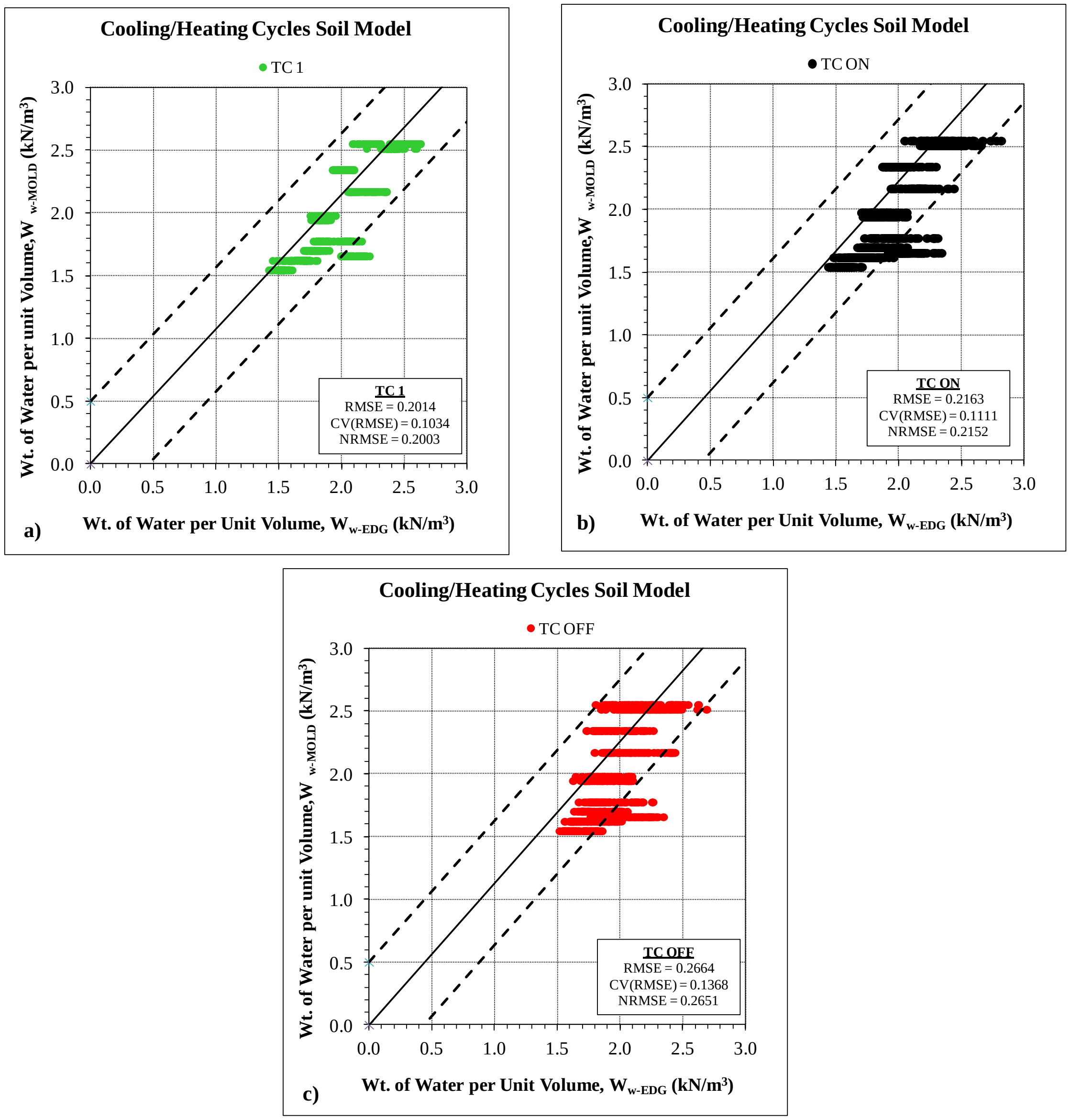


Figure 8.10 1:1 Plots – Cooling/Heating Cycles Soil Model
a) 1:1 Plot – Wt. of Water per Unit Volume (TC 1)
b) 1:1 Plot – Wt. of Water per Unit Volume (TC ON)
c) 1:1 Plot – Wt. of Water per Unit Volume (TC OFF)

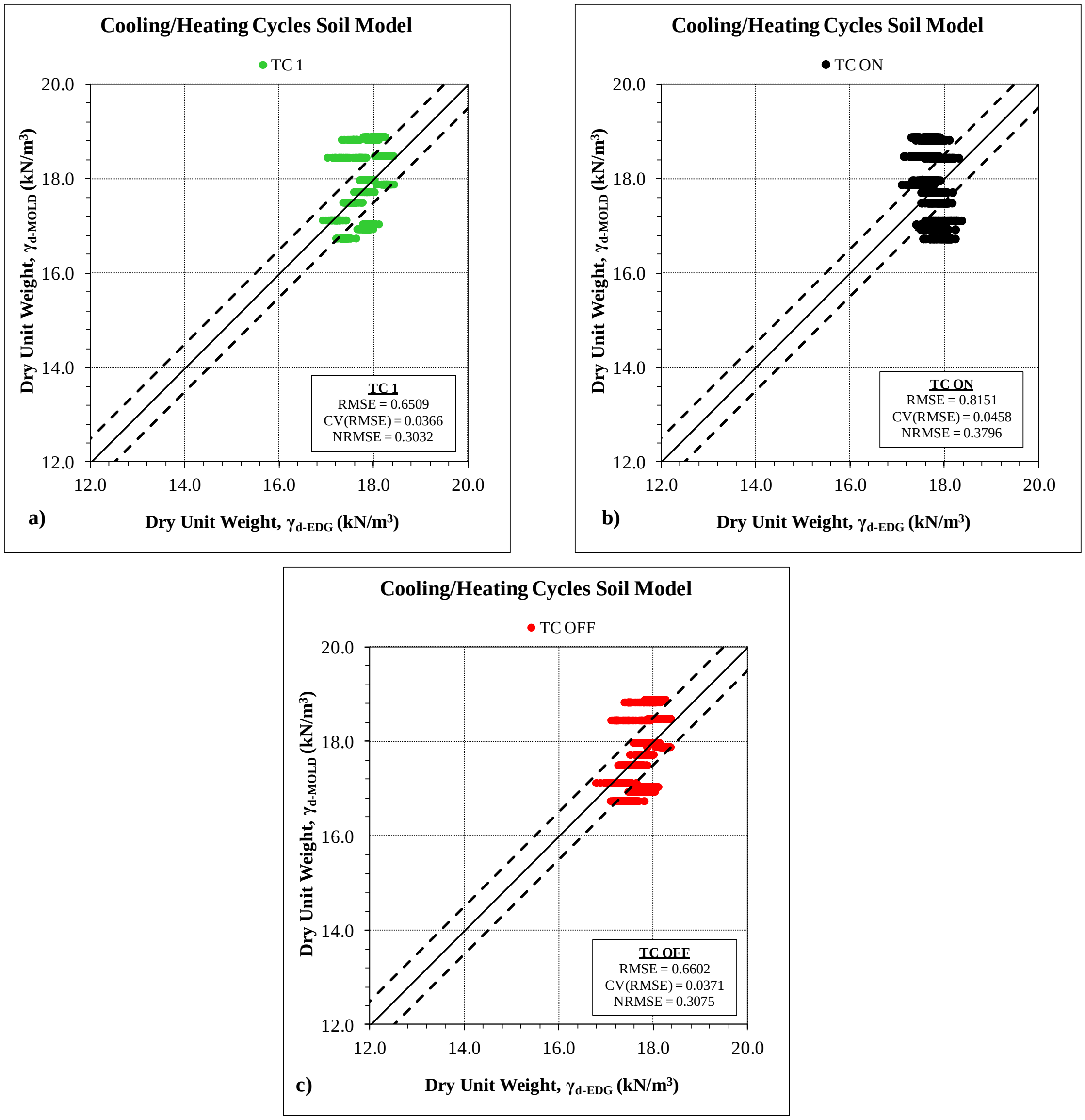


Figure 8.11 1:1 Plots – Cooling/Heating Cycles Soil Model
a) 1:1 Plot – Dry Unit Weight (TC 1)
b) 1:1 Plot – Dry Unit Weight (TC ON)
c) 1:1 Plot – Dry Unit Weight (TC OFF)

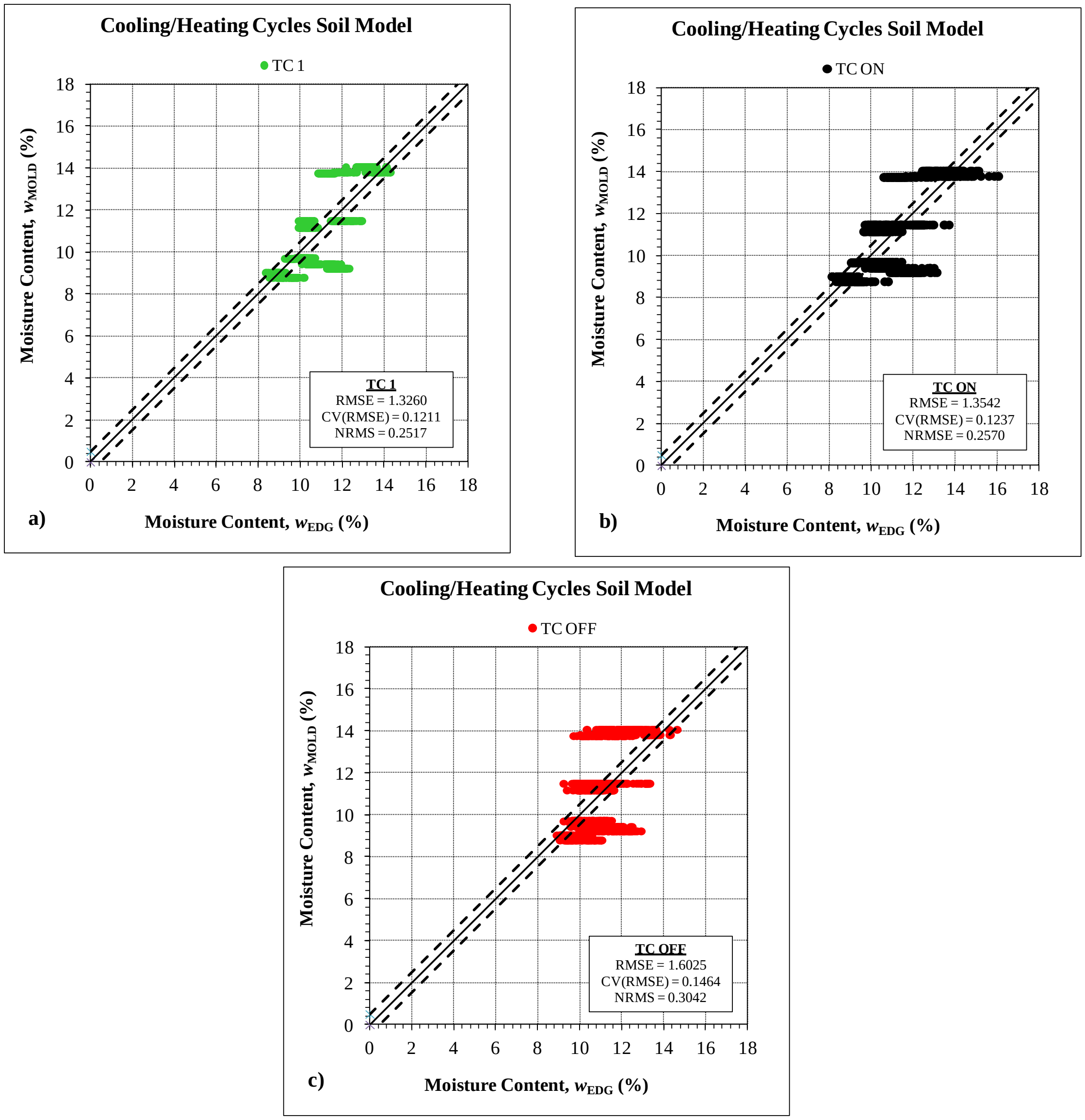


Figure 8.12 1:1 Plots – Cooling/Heating Cycles Soil Model
a) 1:1 Plot – Moisture Content (TC 1)
b) 1:1 Plot – Moisture Content (TC ON)
c) 1:1 Plot – Moisture Content (TC OFF)

8.3.3 Relative Error

The following section shows histograms of the relative error calculated for moist unit weight, weight of water per unit volume, dry unit weight, and moisture content for the constant-temperature room soil model and the cooling/heating cycles soil model (TC OFF, TC ON, and TC 1). A cumulative distribution function (CDF) is displayed on each histogram as well. Relative error values are calculated using Equation 5.1 in Chapter 5.

The results for relative error analysis for the constant temperature room soil model and the cooling/heating cycles soil model (TC OFF & TC ON) are discussed in detail in Chapter 7 for reference. The following section will provide details for the relative error analysis only for the constant temperature room soil model and the cooling/heating cycles soil model (TC 1).

8.3.4 Relative Error Results: Constant Temperature Room Soil Model and Cooling/Heating Cycles Soil Model (TC 1 Applied)

Table 8.10 and Table 8.11 provide a summary of the minimum, maximum, range, and mean of the relative error histograms of the Constant Temperature Room Soil Model and the Cooling/Heating Cycles Soil Model with the new temperature correction (TC 1) applied.

Table 8.12 and Table 8.13 provide a summary of the net percent difference of the minimum, maximum, range, and mean of the relative error histograms when the new temperature correction algorithm is applied (TC 1) compared to the standard EDG relative error measurements (TC OFF & TC ON).

It should be noted that the following terminology is used to rate the significance of improvement on the results in this section:

- No change (Decrease from 0% to 2%)
- Relatively minimal (Decrease from 2% to 10%)
- Moderately significant (Decrease from 10% to 40%)
- Extremely significant (Decrease greater than 40%)

Figure 8.13 and Figure 8.17 are histogram plots of relative error between $\gamma_{m\text{-}MOLD}$ and $\gamma_{m\text{-}EDG}$ (TC 1, TC OFF, & TC ON).

For the constant temperature room soil model (TC 1), relative error values for γ_m range from -6.91% to 6.14%. For the constant temperature room soil model, the net percent change in the mean relative error between TC 1 and TC ON is -80.0% and between TC 1 and TC OFF is -30.0%. This corresponds to a highly significant decrease from TC ON, and a moderately significant decrease from TC OFF.

For the cooling/heating cycles soil model (TC 1), relative error values for γ_m range from -5.54% to 7.84%. For the cooling/heating cycles soil model, the net percent change in the mean relative error between TC 1 and TC ON is -87.7% and between TC 1 and TC OFF is -25.4%. This corresponds to a highly significant decrease from TC ON, and a moderately significant decrease from TC OFF.

Figure 8.14 and Figure 8.18 are histogram plots of relative error between $\gamma_{d\text{-}MOLD}$ and $\gamma_{d\text{-}EDG}$ (TC1, TC OFF & TC ON).

For the constant-temperature room soil model (TC 1), relative error values for γ_d range from -6.40% to 6.83%. For the constant-temperature room soil model, the net percent change in the mean relative error between TC 1 and TC ON is -28.6% and between TC 1 and TC OFF is 0.0%. This corresponds to a moderately significant decrease from TC ON, and no change from TC OFF.

For the cooling/heating cycles soil model (TC 1), relative error values for γ_d range from -6.38% to 7.92%. For the cooling/heating cycles soil model, the net percent change in the mean relative error between TC 1 and TC ON is -38.6% and between TC 1 and TC OFF is -0.1%. This corresponds to a moderately significant decrease from TC ON, and no change from TC OFF.

Figure 8.15 and Figure 8.19 are histogram plots of relative error between $W_{W\text{-}MOLD}$ and $W_{W\text{-}EDG}$ (TC1, TC OFF & TC ON).

For the constant-temperature room soil model (TC 1), relative error values for W_W range from -33.10% to 15.55%.

For the constant-temperature room soil model, the net percent change in the mean relative error between TC 1 and TC ON is -7.4% and between TC 1 and TC OFF is -141.5%. This corresponds to a relatively minimal decrease from TC ON, and an extremely significant decrease from TC OFF.

For the cooling/heating cycles soil model (TC 1), relative error values for W_W range from -34.72% to 17.92%. For the cooling/heating cycles soil model, the net percent change in the mean relative error between TC 1 and TC ON is -15.4% and between TC 1 and TC OFF is -74.1%. This corresponds to a relatively significant decrease from TC ON, and an extremely significant decrease from TC OFF.

Figure 8.16 and Figure 8.20 are histogram plots of relative error between w_{MOLD} and w_{EDG} (TC1, TC OFF & TC ON).

For the constant-temperature room soil model (TC 1), relative error values for w range from -33.50% to 19.24%. For the constant-temperature room soil model, the net percent change in the mean relative error between TC 1 and TC ON is -5.6%

and between TC 1 and TC OFF is -117.8%. This corresponds to a relatively minimal decrease from TC ON, and a highly significant decrease from TC OFF.

For the cooling/heating cycles soil model (TC 1), relative error values for *w* range from -34.26% to 20.95%. For the cooling/heating cycles soil model, the net percent change in the mean relative error between TC 1 and TC ON is -9.7% and between TC 1 and TC OFF is -60.2%. This corresponds to a relatively significant decrease from TC ON, and a highly significant decrease from TC OFF.

Overall, the new temperature correction (TC 1) improves the relative error results presented in this section in the following manner:

- Highly to moderately significant improvement of the mean relative error for moist unit weight, dry unit weight, and weight of water per unit volume when compared to the EDG temperature correction (TC ON).
- Relatively minimal improvement of the mean relative error for moisture content when compared to the EDG temperature correction (TC ON).
- Highly significant improvement of the mean relative error for weight of water per unit volume and moisture content when compared to the EDG without the temperature correction applied (TC OFF).
- Moderately significant improvement of the mean relative error for moist unit weight when compared to the EDG without the temperature correction applied (TC OFF).
- Relatively minimal improvement of the mean relative error for dry unit weight when compared to the EDG without the temperature correction applied (TC OFF).

- Varying levels of improvement (Highly, moderately, and relatively minimal) of the minimum, maximum, and range of relative error for moist unit weight, dry unit weight, weight of water per unit volume, and moisture content. This signifies that the new temperature correction (TC 1) has an overall positive effect on all of the relative error results.

Table 8.10 Summary of Relative Error (%) – Constant Temperature Room Soil Model (TC 1)

Cooling/Heating Cycles Soil Model (TC 1)				
	γ_m	γ_d	W_w	w
MIN	-5.54	-6.38	-34.72	-34.26
MAX	7.84	7.92	17.92	20.95
RANGE	13.38	14.30	52.64	55.21
MEAN	-0.10	-0.13	-1.02	-1.15

Table 8.11 Summary of Relative Error (%) – Cooling/Heating Cycles Soil Model (TC 1)

Constant Temperature Room Soil Model (TC 1)				
	γ_m	γ_d	W_w	w
MIN	-6.91	-6.4	-33.1	-33.5
MAX	6.14	6.83	15.55	19.24
RANGE	13.1	13.23	48.68	52.73
MEAN	-0.1	-0.14	-0.94	-1.07

Table 8.12 Summary of Relative Error (%): Net Percent Change between TC 1 and TC OFF/TC ON - Constant Temperature Room Soil Model

Constant Temperature Room Soil Model

(TC 1 - TC OFF)

	γ_m	γ_d	W_w	w
MIN	-18.5%	-5.3%	-22.9%	-16.0%
MAX	-5.7%	-7.2%	-49.8%	-24.5%
RANGE	-12.5%	-6.3%	-31.5%	-19.1%
MEAN	-30.0%	0.0%	-141.5%	-117.8%

(TC1 - TC ON)

	γ_m	γ_d	W_w	w
MIN	-18.7%	-28.4%	-6.0%	-11.4%
MAX	-28.3%	-21.4%	-20.4%	-7.4%
RANGE	-23.2%	-25.6%	-10.6%	-9.9%
MEAN	-80.0%	-28.6%	-7.4%	-5.6%

Table 8.13 Summary of Relative Error (%): Net Percent Change between TC 1 and TC OFF/TC ON – Cooling/Heating Cycles Soil Model

Cooling/Heating Cycles Soil Model

(TC 1 - TC OFF)

	γ_m	γ_d	W_w	w
MIN	-46.0%	-3.0%	-21.3%	-18.9%
MAX	9.6%	5.3%	-61.4%	-39.2%
RANGE	-13.4%	1.6%	-35.0%	-26.6%
MEAN	-25.2%	-0.1%	-74.1%	-60.2%

(TC1 - TC ON)

	γ_m	γ_d	W_w	w
MIN	-18.7%	-28.4%	-6.0%	-11.4%
MAX	-28.3%	-21.4%	-20.4%	-7.4%
RANGE	-23.2%	-25.6%	-10.6%	-9.9%
MEAN	-80.0%	-28.6%	-7.4%	-5.6%

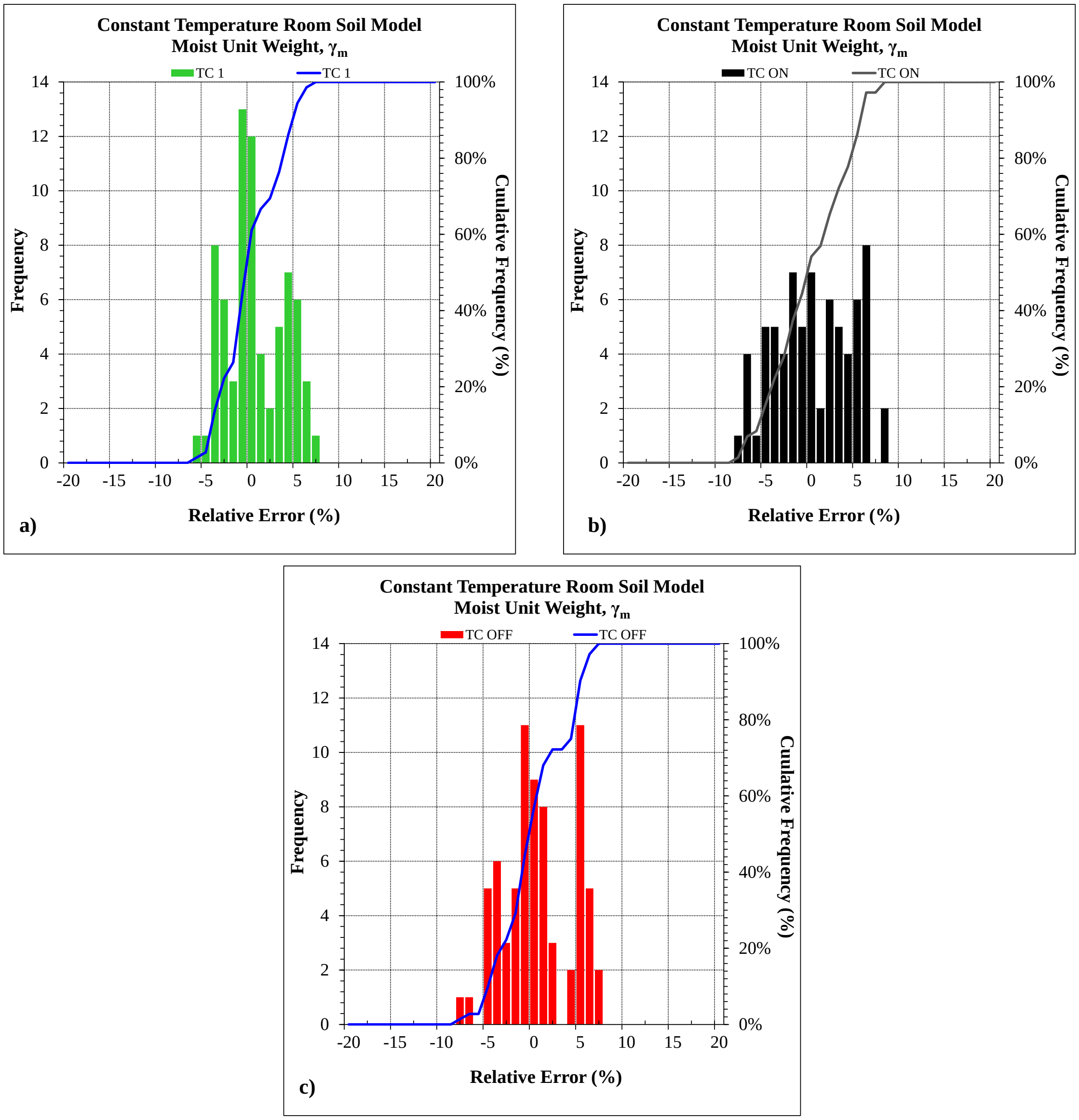
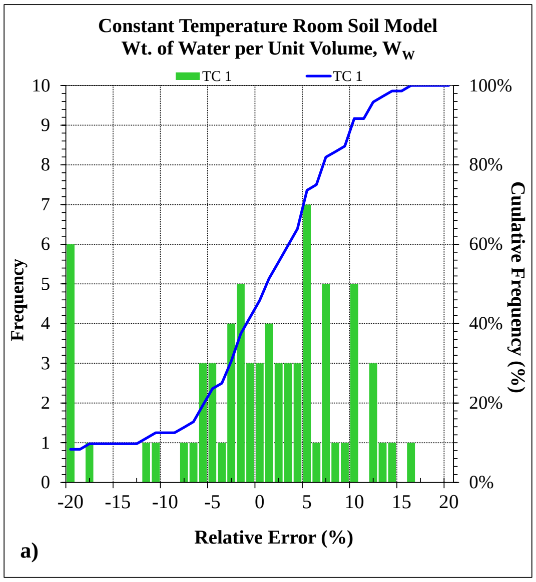
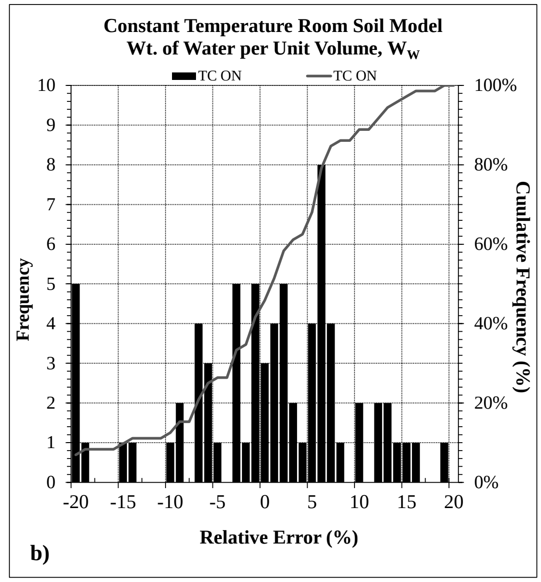


Figure 8.13 Relative Error Histograms and CDF Plots – Constant Temperature Room Soil Model
a) Histogram & CDF – Moist Unit Weight (TC 1)
b) Histogram & CDF – Moist Unit Weight (TC ON)
c) Histogram & CDF – Moist Unit Weight (TC OFF)





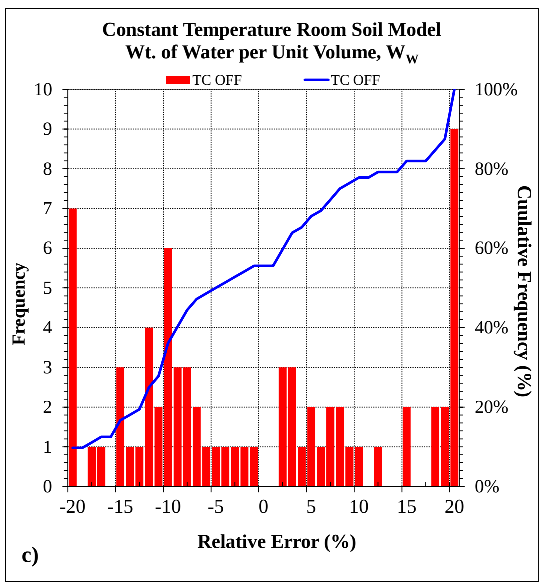


Figure 8.14 Relative Error Histograms and CDF Plots – Constant Temperature Room Soil Model
a) Histogram & CDF – Wt. of Water per Unit Volume (TC 1)
b) Histogram & CDF – Wt. of Water per Unit Volume (TC ON)
c) Histogram & CDF – Wt. of Water per Unit Volume (TC OFF)

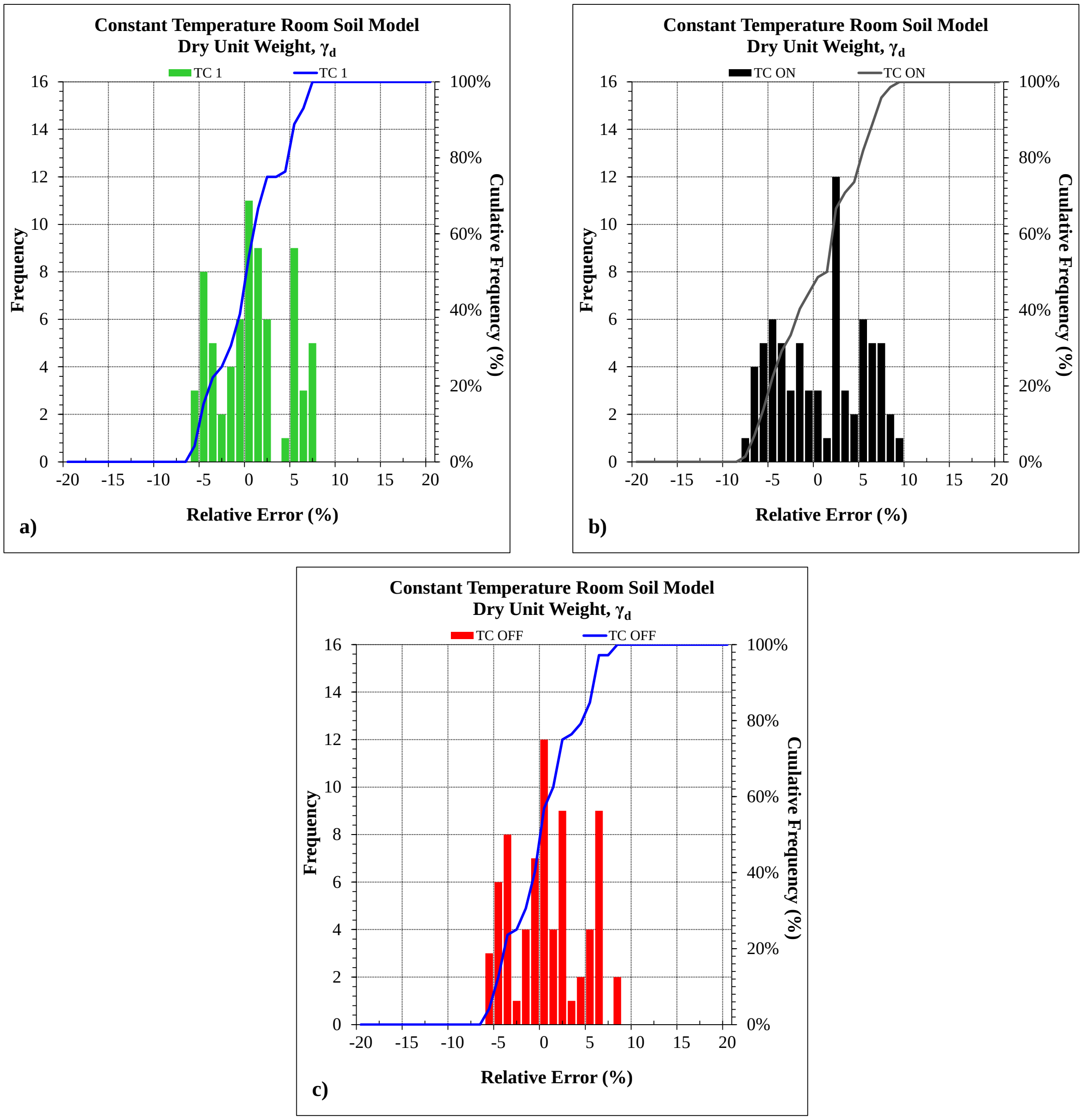


Figure 8.15 Relative Error Histograms and CDF Plots – Constant Temperature Room Soil Model
a) Histogram & CDF – Dry Unit Weight (TC 1)
b) Histogram & CDF – Dry Unit Weight (TC ON)
c) Histogram & CDF – Dry Unit Weight (TC OFF)

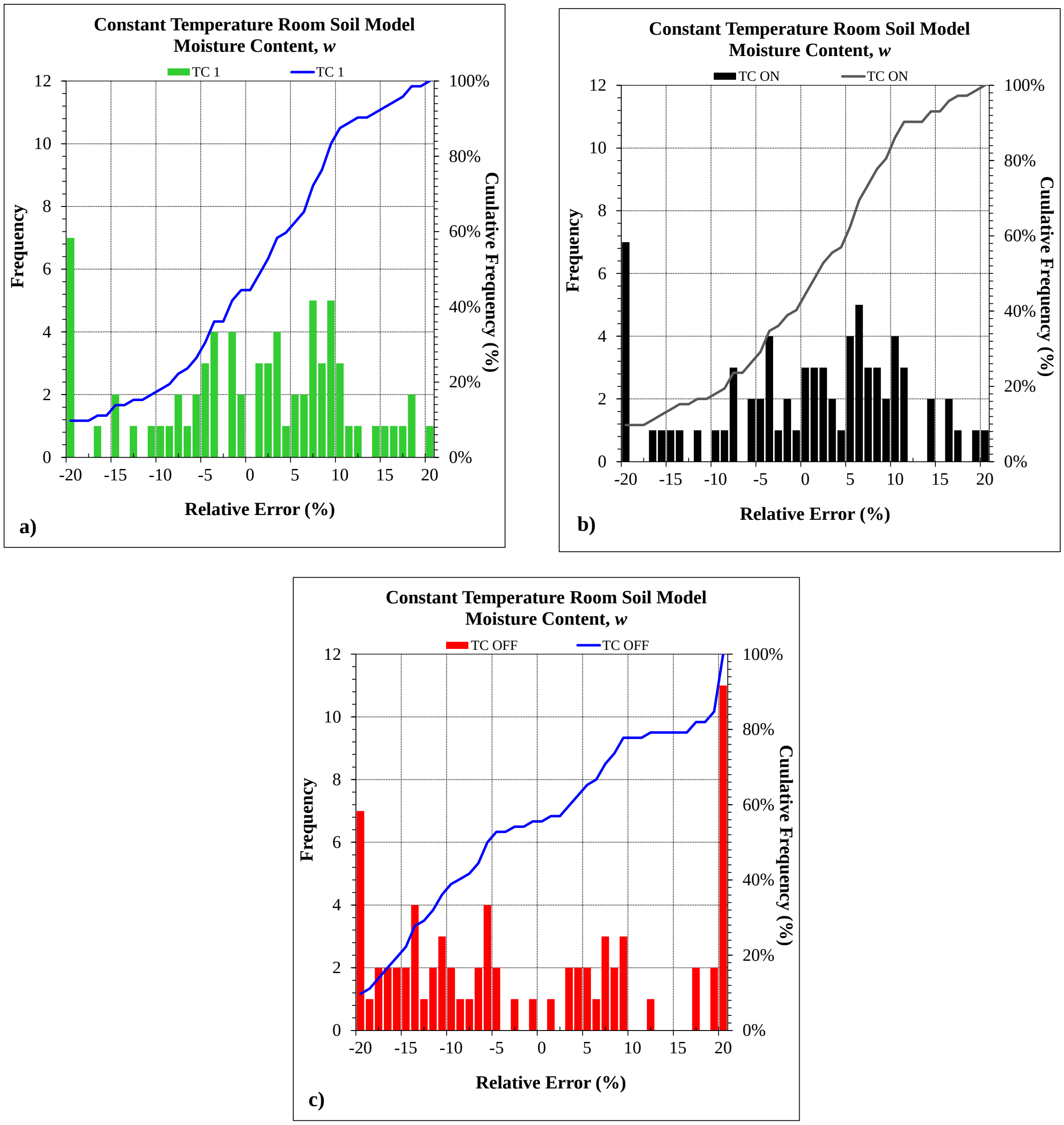


Figure 8.16 Relative Error Histograms and CDF Plots – Constant Temperature Room Soil Model
a) Histogram & CDF – Moisture Content (TC 1)
b) Histogram & CDF – Moisture Content (TC ON)
c) Histogram & CDF – Moisture Content (TC OFF)

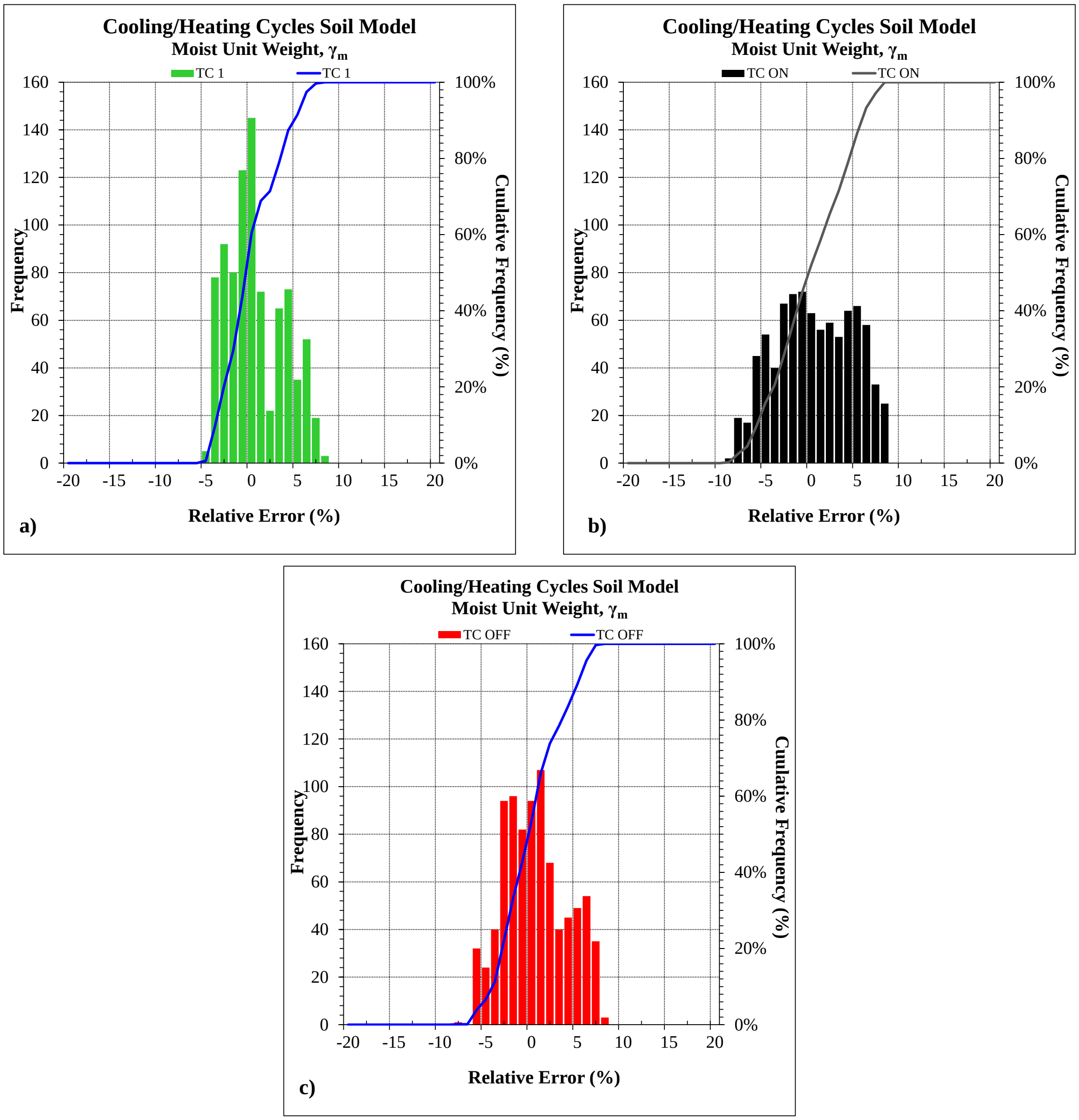


Figure 8.17 Relative Error Histograms and CDF Plots – Cooling/Heating Cycles Soil Model
a) Histogram & CDF – Moist Unit Weight (TC 1)
b) Histogram & CDF – Moist Unit Weight (TC ON)
c) Histogram & CDF – Moist Unit Weight (TC OFF)

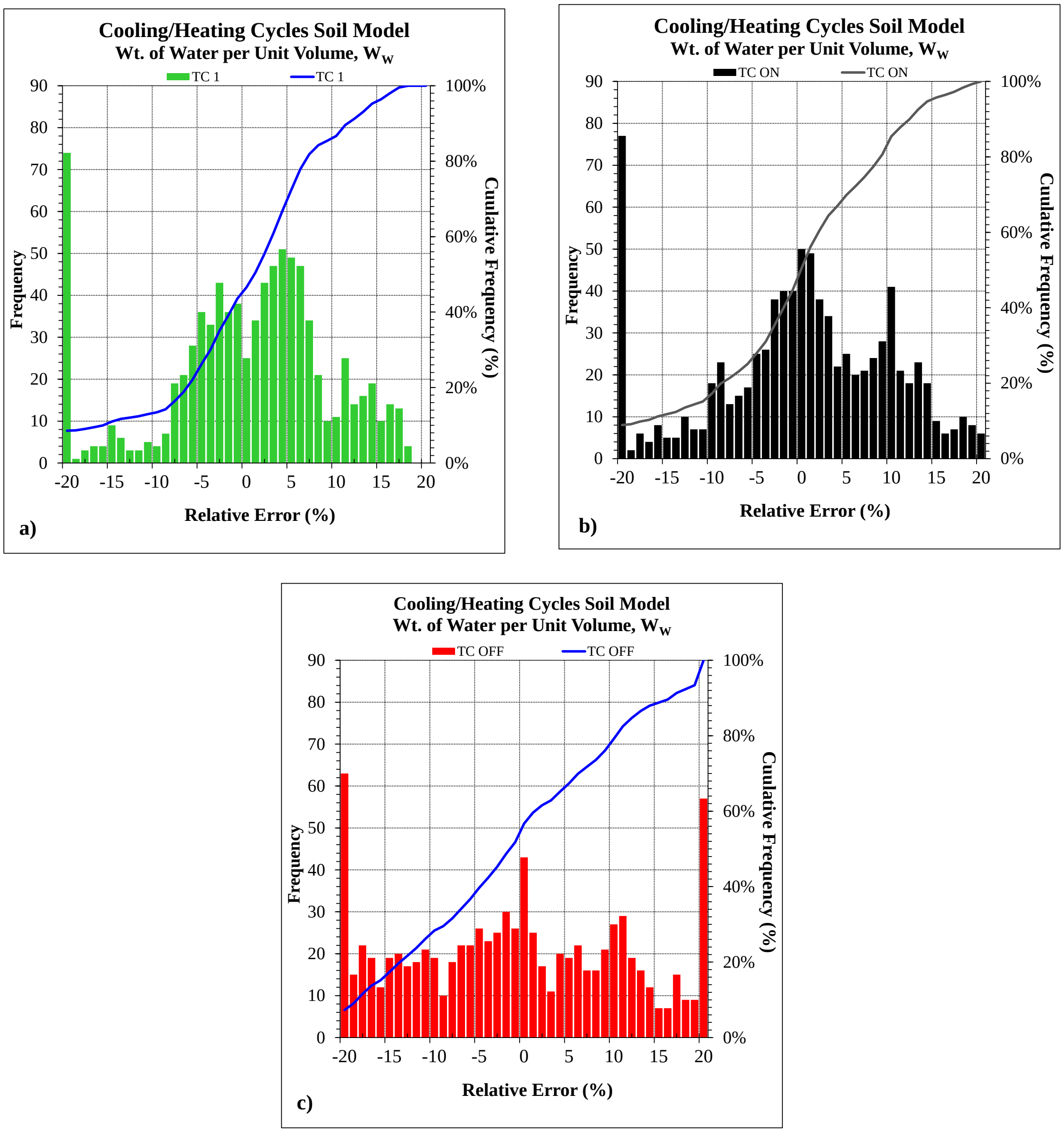


Figure 8.18 Relative Error Histograms and CDF Plots – Cooling/Heating Cycles Soil Model
a) Histogram & CDF – Wt. of Water per Unit Volume (TC 1)
b) Histogram & CDF – Wt. of Water per Unit Volume (TC ON)
c) Histogram & CDF – Wt. of Water per Unit Volume (TC OFF)

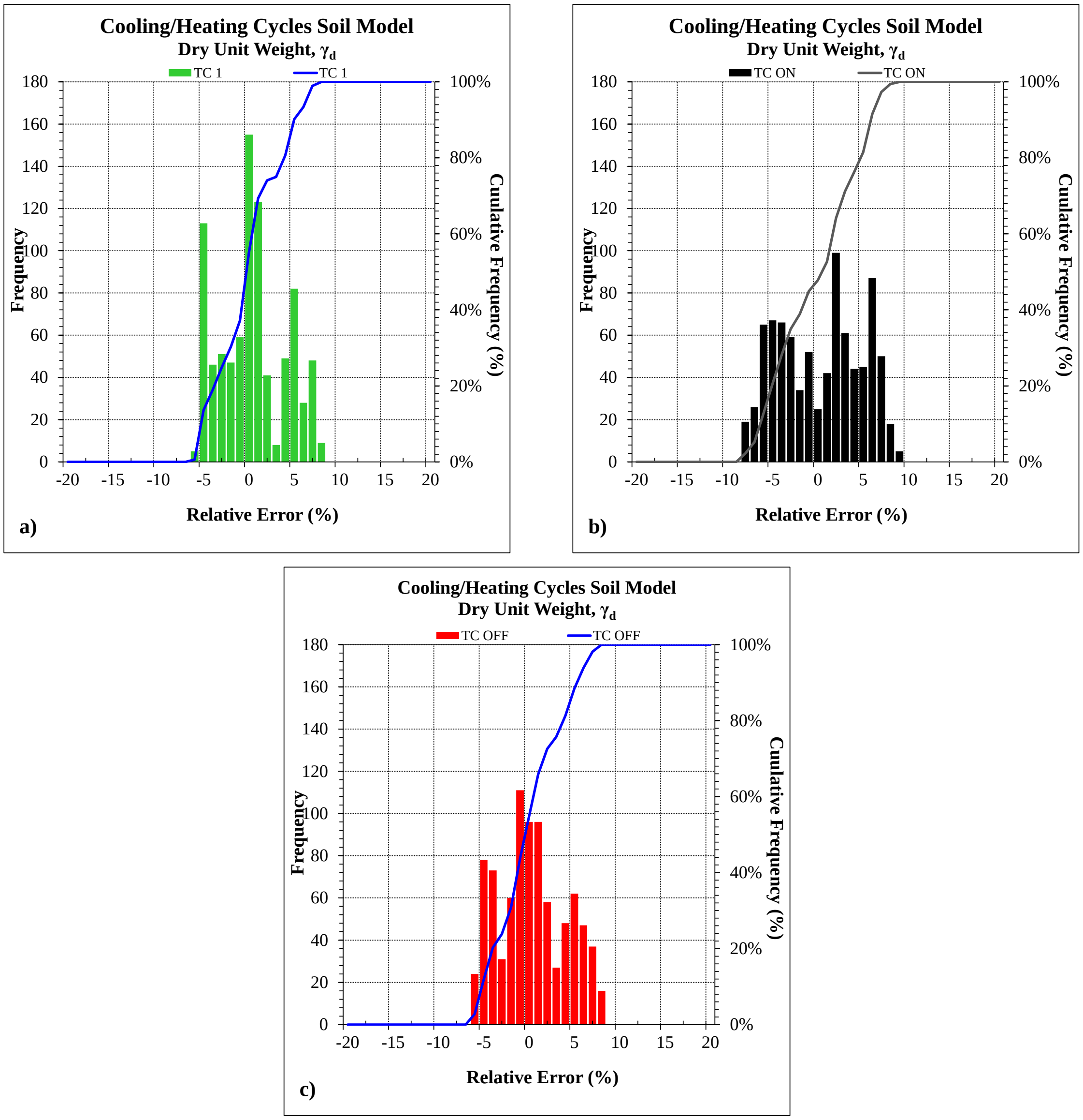


Figure 8.19 Relative Error Histograms and CDF Plots – Cooling/Heating Cycles Soil Model
a) Histogram & CDF – Dry Unit Weight (TC 1)
b) Histogram & CDF – Dry Unit Weight (TC ON)
c) Histogram & CDF – Dry Unit Weight (TC OFF)

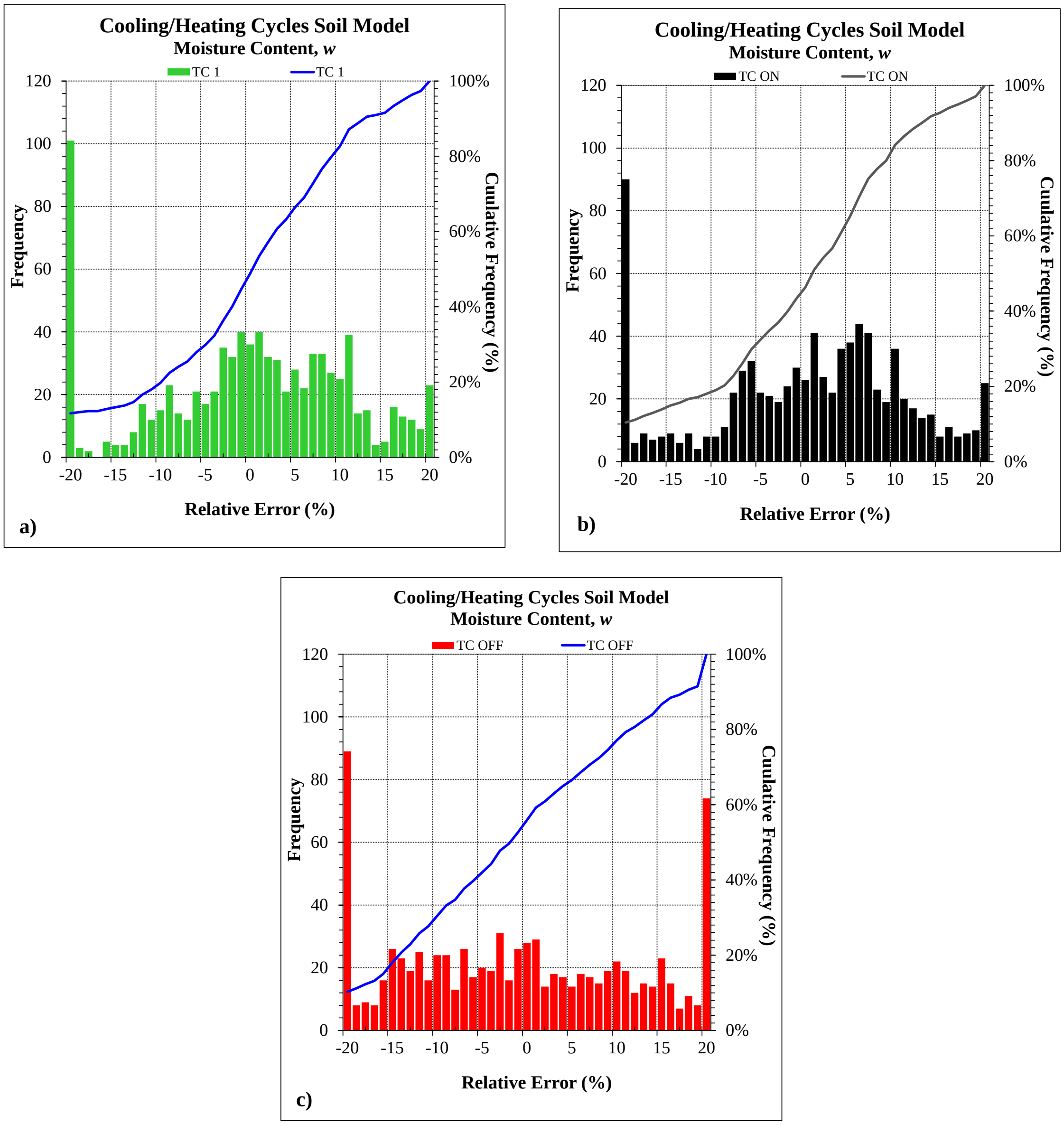


Figure 8.20 Relative Error Histograms and CDF Plots – Cooling/Heating Cycles Soil Model
a) Histogram & CDF – Moisture Content (TC 1)
b) Histogram & CDF – Moisture Content (TC ON)
c) Histogram & CDF – Moisture Content (TC OFF)

8.3.5 Summary of Constant Room Temperature and Cooling/Heating Cycles Model Results (TC 1 Applied)

The coefficient of determination (R^2) values for the calibration equations created using the Constant Room Soil Model and the Cooling/Heating Cycles Soil Model with the new temperature correction applied (TC 1) are all higher than the R^2 values for the calibration equations with both the EDG temperature correction applied (TC ON) and without the EDG temperature correction applied (TC OFF).

The associated RMSE, CV(RMSE), and NRMSE values for the EDG predicted soil properties (γ_m, γ_d, W_w, w) for the Constant Temperature Room Soil Model and the Cooling/Heating Cycles Soil Model with the new temperature correction applied (TC 1) are all lower than the RMSE, CV(RMSE), and NRMSE values for the EDG-predicted soil properties using the Constant Temperature Room Soil Model (TC OFF & TC ON) and the Cooling/Heating Cycles Soil Mode (TC OFF & TC ON).

In addition, the minimum, maximum, range, and mean of the relative error for the EDG predicted soil properties (γ_m, γ_d, W_w, w) for the Constant Temperature Room Soil Model and the Cooling/Heating Cycles Soil Model with the new temperature correction applied (TC 1) are all lower than the (TC OFF & TC ON) and the Cooling/Heating Cycles Soil Mode (TC OFF & TC ON).

The following list summarizes the results from the analysis performed in this chapter:

- The new temperature correction (TC 1) produces a highly to moderately significant improvement of the statistical error measurements of interest (RMSE, CV(RMSE), and NRMSE), and mean relative error for moist unit and dry unit weight when comparing to the EDG temperature correction (TC ON).

- However, the new temperature correction (TC 1) produces a relatively minimal improvement of the statistical error measurements of interest, and mean relative error for weight of water per unit volume and moisture content when comparing to the EDG temperature correction (TC ON).
- The new temperature correction (TC 1) produces a highly to moderately significant improvement of the statistical error measurements of interest and mean relative error for moist unit weight, weight of water per unit volume, and moisture content when comparing to the EDG without the temperature correction applied (TC OFF).
- However, the new temperature correction (TC 1) produces a relatively minimal improvement of the statistical error measurements of interest, and mean relative error for dry unit weight when comparing to the EDG without the temperature correction applied (TC OFF).

8.4 Discussion of Results and Conclusions

From the raw data and associated analysis presented in this chapter, it is evident that the new temperature correction (TC 1) improves the results of the "Constant Temperature Room" data and the "Cooling/Heating Cycles" data. The results from this section also reiterate that the EDG temperature correction (TC ON) does not properly capture the effects of temperature on the soil molds tested in this research study. The effect of the new temperature correction algorithm developed combined with alternative calibration relationships will be explored in Chapter 9 in this thesis.

CHAPTER 9

NEW CALIBRATION RELATIONSHIPS

9.1 Introduction

Throughout all the previous chapters of this thesis, the default-on board linear calibration relationships provided by the manufacturer of the EDG have been used to assess its accuracy. In this final chapter, alternative calibration relationships coupled with the new temperature correction approach developed in Chapter 8 are explored to further evaluate the performance of the EDG. The data analyzed in this chapter will focus on the Mold Soil Model data set (Chapter 5) and the Large Box Soil Model data set (Chapter 6) with the new temperature correction (TC1) developed in Chapter 8 applied to both of these data sets. It should be noted that analyzing the Mold Soil Model data set and Large Box Soil Model data set with the new temperature correction algorithm is a slightly more rigorous approach then the analysis performed in Chapter 8, and it is a more rigorous test for the newly developed temperature correction algorithm. For purposes of this chapter, a true "blind" assessment in which one data set is used for calibration and another is used for assessment was not performed, however it can be assumed that the results from such a study would be slightly more scattered. This chapter describes the methodology that was used to develop alternative calibration relationships, and the overall effectiveness of the new calibration relationships on the data sets that were acquired during this research study.

It should be noted that the following terminology is used in this chapter to rate the significance of improvement of the EDG test results for the different data analysis algorithms that were developed

- No change (Decrease from 0% to 2%)
- Relatively minimal (Decrease from 2% to 10%)
- Moderately significant (Decrease from 10% to 40%)
- Extremely significant (Decrease greater than 40%)

It should be noted that the term "decrease from" refers to a decrease in compared value from the results obtained using the standard default EDG calibration relationships with the proprietary temperature compensation algorithm applied (TC ON).

9.2 Correlation Analysis of Linear Relationships Between Electrical Values Measured by EDG and Physical Soil Properties

Prior to deciding what parameters to use to develop new calibration relationships, Pearson product-moment correlation coefficients between electrical values measured by the EDG and physical soil properties (i.e, moist unit weight, dry unit weight, moisture content, weight of water per unit volume) were determined. A Pearson-product moment correlation coefficient (Pearson's *r*) is a measure of the linear correlation or dependence between two variables (Freedman 1998).

Pearson's *r* values range from 1 to -1, in which the following are denoted:

- a positive value indicates a direct or positive correlation
- zero indicates no correlation
- a negative value indicates an indirect or negative correlation

It should be noted that this method was used solely to help identify trends and linear relationships that exist between measured electrical values and measured physical soil properties.

The Pearson product-moment correlation coefficient, *r*, can be calculated using the following formula:

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}} \tag{9.1}$$

where $\bar{x}$ is the mean of *x*, $\bar{y}$ is the mean of *y*, and *n* is the total number of samples. In this analysis, all *x*-variables are the electrical parameters measured by the EDG, and all *y*-variables are the physical soil properties measured by the Mold tests (See Chapter 5) or the drive cylinder tests (See Chapter 6). Tables 9.1 through 9.6 display the Pearson product-moment correlation coefficients. The "TC 1.R" notation refers to the use of the empirical temperature correction algorithm using the constants developed with the "Constant Temperature Room" data. The "TC 1.CH" notation refers to the use of the empirical temperature correction algorithm using the constants developed with the "Cooling/Heating Cycles" data.

Table 9.1 Pearson Correlation Coefficients: Mold Soil Model Data (TC 1.R)

	$\gamma_{m\text{-}MOLD}$	$\gamma_{d\text{-}MOLD}$	$W_{w\text{-}MOLD}$	w_{MOLD}
Voltage, V	-0.6219	-0.3494	-0.8239	-0.7611
Current, I	0.7634	0.5031	0.8577	0.7610
Phase, Θ	0.4049	0.2053	0.5824	0.5470
Resistance, R	-0.5814	-0.3472	-0.7277	-0.6658
Capacitance, C	0.7817	0.5121	0.8845	0.7862
Impedance, Z	-0.7343	-0.4782	-0.8369	-0.7475
Cap./Res., C/R	0.6533	0.3894	0.8192	0.7450

Table 9.2 Pearson Correlation Coefficients: Mold Soil Model Data (TC 1.CH)

	$\gamma_{m\text{-}MOLD}$	$\gamma_{d\text{-}MOLD}$	$W_{w\text{-}MOLD}$	w_{MOLD}
Voltage, V	-0.6429	-0.3811	-0.8105	-0.7399
Current, I	0.7549	0.4896	0.8647	0.7712
Phase, Θ	0.4043	0.2007	0.5904	0.5563
Resistance, R	-0.5800	-0.3436	-0.7316	-0.6707
Capacitance, C	0.7824	0.5129	0.8848	0.7864
Impedance, Z	-0.7330	-0.4762	-0.8380	-0.7491
Cap./Res., C/R	0.6517	0.3864	0.8214	0.7480

Table 9.3 Pearson Correlation Coefficients: Mold Soil Model Data (TC OFF)

	$\gamma_{m\text{-}MOLD}$	$\gamma_{d\text{-}MOLD}$	$W_{w\text{-}MOLD}$	w_{MOLD}
Voltage, V	-0.6112	-0.3350	-0.8270	-0.7677
Current, I	0.7284	0.4525	0.8756	0.7912
Phase, Θ	0.3825	0.1428	0.6559	0.6371
Resistance, R	-0.5505	-0.2929	-0.7633	-0.7152
Capacitance, C	0.7723	0.4976	0.8913	0.7967
Impedance, Z	-0.7038	-0.4348	-0.8508	-0.7719
Cap./Res., C/R	0.6240	0.3418	0.8449	0.7826

Table 9.4 Pearson Correlation Coefficients: Large Box Data (TC 1.R)

	$\gamma_{m\text{-}DC}$	$\gamma_{d\text{-}DC}$	$W_{w\text{-}DC}$	w_{DC}
Voltage, V	-0.6994	-0.2551	-0.9365	-0.9103
Current, I	0.7359	0.2961	0.9470	0.9132
Phase, Θ	0.6280	0.2192	0.8545	0.8329
Resistance, R	-0.6484	-0.2409	-0.8621	-0.8398
Capacitance, C	0.7362	0.3004	0.9416	0.9073
Impedance, Z	-0.7081	-0.2740	-0.9263	-0.8978
Cap./Res., C/R	0.7142	0.2769	0.9335	0.9011

Table 9.5 Pearson Correlation Coefficients: Large Box Data (TC 1.CH)

	$\gamma_{m\text{-}DC}$	$\gamma_{d\text{-}DC}$	$W_{w\text{-}DC}$	w_{DC}
Voltage, V	-0.6949	-0.2504	-0.9348	-0.9093
Current, I	0.7371	0.2977	0.9469	0.9128
Phase, Θ	0.6297	0.2205	0.8559	0.8341
Resistance, R	-0.6529	-0.2444	-0.8655	-0.8428
Capacitance, C	0.7377	0.3024	0.9416	0.9070
Impedance, Z	-0.7099	-0.2756	-0.9274	-0.8987
Cap./Res., C/R	0.7147	0.2776	0.9336	0.9010

Table 9.6 Pearson Correlation Coefficients: Large Box Data (TC OFF)

	$\gamma_{m\text{-}DC}$	$\gamma_{d\text{-}DC}$	$W_{w\text{-}DC}$	w_{DC}
Voltage, V	-0.7002	-0.2568	-0.9356	-0.9092
Current, I	0.7368	0.3007	0.9424	0.9078
Phase, Θ	0.6379	0.2314	0.8558	0.8324
Resistance, R	-0.6899	-0.2785	-0.8867	-0.8594
Capacitance, C	0.7436	0.3134	0.9373	0.9012
Impedance, Z	-0.7204	-0.2865	-0.9317	-0.9015
Cap./Res., C/R	0.7113	0.2785	0.9261	0.8934

9.2.1 Correlation Analysis Results

From the correlation analysis results presented in Tables 9.1 through 9.6, it is extremely clear that dry unit weight has the weakest linear correlation to any of the electrical properties measured by the EDG.

For the Mold Soil Model data, the absolute value of Pearson correlation coefficients comparing dry unit weight to any of the electrical properties measured by the EDG range from about 0.1428 to 0.5129, indicating very weak to moderate linear relationships. For the Large Box Soil Model data, the absolute value of Pearson correlation coefficients comparing dry unit weight to any of the measured electrical properties by the EDG range from about 0.2192 to 0.3134, indicating a weak linear relationship. When observing scatter plots of dry unit weight versus any of the electrical properties measured by the EDG, it is clear there is no distinct relationship.

For the Mold Soil Model data, the absolute value of Pearson correlation coefficients comparing moist unit weight to any of the measured electrical properties by the EDG range from about 0.3825 to 0.7824, indicating a weak to moderately strong linear relationship. For the Large Box Soil Model data, the absolute value of Pearson correlation coefficients comparing moist unit weight to any of the measured electrical properties by the EDG range from about 0.6280 to 0.7436, indicating a moderately strong relationship.

For the Mold Soil Model data, the absolute value of Pearson correlation coefficients comparing weight of water per unit volume to any of the measured electrical properties by the EDG range from about 0.5824 to 0.8913, indicating a moderately strong to strong linear relationship. For the Large Box Soil Model data, the absolute value of Pearson correlation coefficients comparing weight of water per unit volume to any of the measured electrical properties by the EDG range from about 0.8545 to 0.9470, indicating a strong to very strong relationship.

For the Mold Soil Model data, the absolute value of Pearson correlation coefficients comparing moisture content to any of the measured electrical properties by the EDG range from about 0.5470 to 0.7967, indicating a moderately strong to strong linear relationship. For the Large Box Soil Model data, the absolute value of Pearson correlation coefficients comparing moisture content to any of the measured electrical properties by the EDG range from about 0.8324 to 0.9132, indicating a strong to very strong linear relationship.

This analysis was performed to aid in the understanding of the relationships between physical soil properties and electrical values measured by the EDG.

9.3 New Calibration Relationships (Method A and Method B)

Based on the results from the correlation analysis, and a rigorous trial-and-error analysis of different linear and non-linear regression techniques, the following two calibration relationships were found to have slightly improved results than the default-on board calibration relationships proposed by the manufacturer.

<u>Method A</u>

$$\gamma_m = a_1 \times C^{b_1} \tag{9.2}$$

$$W_w = a_2 \times C^{b_2} \tag{9.3}$$

where a_1, b_1, a_2, and b_2 are constants, and *C* is the Capacitance measured by the EDG in picofarads (pF).

Method B

$$w(\%) = d_2 \times I^{e_2} \tag{9.4}$$

$$W_w = d_1 \times I^{e_1} \tag{9.5}$$

where d_1, e_1, d_2, and e_2 are constants, and I is the Current measured by the EDG in milliamps (mA).

9.3.1 New Calibration Relationship Results (Method A and Method B)

In order to illustrate how the new calibration relationships perform, the Mold Soil Model (see Chapter 5) and the Large Box Soil Model (See Chapter 6, Section 6.8) data sets are used. The new calibration relationships are analyzed with the new temperature correction (TC 1) developed in Chapter 8 applied to the Mold Soil Model and Large Box Soil Model data sets. The results presented in this chapter are compared to the results presented in Chapter 5 and Chapter 6 with the default manufacturer calibration relationships.

Calibration equations using Method A and Method B with the new temperature correction (TC 1) applied are presented in the following section. The resulting calibration equations are presented with the new temperature correction algorithm (TC 1). The notation “TC 1.R” signifies that the temperature correction algorithm using the empirical coefficients developed using the Constant Temperature Room data is applied, and the notation “TC1.CH” signifies that the temperature correction algorithm using the empirical coefficients developed using the Cooling/Heating Cycles data is applied.

The resulting calibration equations are presented with the new temperature correction algorithms (TC 1.R/TC1.CH), in addition to the standard EDG calibration equations (TC OFF & TC ON) which have already been presented in Chapter 5 and Chapter 6. 1:1 plots that compare Mold values or Drive cylinder (DC) values (from the Large Box tests) versus EDG predicted values are presented, along with relative error histogram plots between the measured and predicted values. The in-situ measured soil properties assessed in this study were: moist unit weight (γ_m), weight of water per unit volume (W_W), dry unit weight (γ_d), and moisture content (*w*).

9.3.2 Calibration Equations (Method A and Method B)

The associated calibration equations developed using Method A and Method B for the Mold Soil Model and Large Box Soil Model datasets, with the new temperature corrections (TC 1.R/TC 1.CH) applied are presented in Figures 9.1 through 9.4. The coefficient of determination (R^2) values are presented on each graph as well. Table 9.7 through Table 9.10 provide a summary of the R^2 values, slopes, and intercepts of the calibration equations that are presented in this section.

Table 9.7 General Summary Table of Calibration Equations: Mold Soil Model (Method A)

Mold Soil Model				
	Calibration Equation	**R^2**	**a_1/a_2**	**b_1/b_2**
TC 1.R	$\gamma_{m\text{-}MOLD}$ vs. C	0.6188	2.8980	0.4626
TC 1.CH	$\gamma_{m\text{-}MOLD}$ vs. C	0.6198	2.8427	0.4672
TC 1.R	$W_{w\text{-}MOLD}$ vs. C	0.7718	0.0004	2.0408
TC 1.CH	$W_{w\text{-}MOLD}$ vs. C	0.7727	0.0004	2.0609

Table 9.8 General Summary Table of Calibration Equations: Mold Soil Model (Method B)

Mold Soil Model				
	Calibration Equation	**R^2**	**d_1/d_2**	**e_1/e_2**
TC 1.R	w_{MOLD} vs. I	0.5610	2.5168	1.8312
TC 1.CH	w_{MOLD} vs. I	0.5778	2.4583	1.8461
TC 1.CH	$W_{w\text{-}MOLD}$ vs. I	0.7225	0.3520	2.1324
TC 1.R	$W_{w\text{-}MOLD}$ vs. I	0.7356	0.3459	2.1373

Table 9.9 General Summary Table of Calibration Equations: Large Box Soil Model (Method A)

Large Box Soil Model				
	Calibration Equation	**R^2**	**a_1/a_2**	**b_1/b_2**
TC 1.R	$\gamma_{m\text{-}MOLD}$ vs. C	0.5352	7.9609	0.2156
TC 1.CH	$\gamma_{m\text{-}MOLD}$ vs. C	0.5376	7.7917	0.2208
TC 1.R	$W_{w\text{-}MOLD}$ vs. C	0.9070	0.0023	1.6031
TC 1.CH	$W_{w\text{-}MOLD}$ vs. C	0.9072	0.0020	1.6380

Table 9.10 General Summary Table of Calibration Equations: Large Box Soil Model (Method B)

Large Box Soil Model				
	Calibration Equation	**R^2**	**d_1/d_2**	**e_1/e_2**
TC 1.R	w_{MOLD} vs. I	0.9172	0.4903	1.6223
TC 1.CH	w_{MOLD} vs. I	0.9170	0.4742	1.6410
TC 1.R	$W_{w\text{-}MOLD}$ vs. I	0.8661	2.9468	1.5507
TC 1.CH	$W_{w\text{-}MOLD}$ vs. I	0.8650	2.8560	1.5678

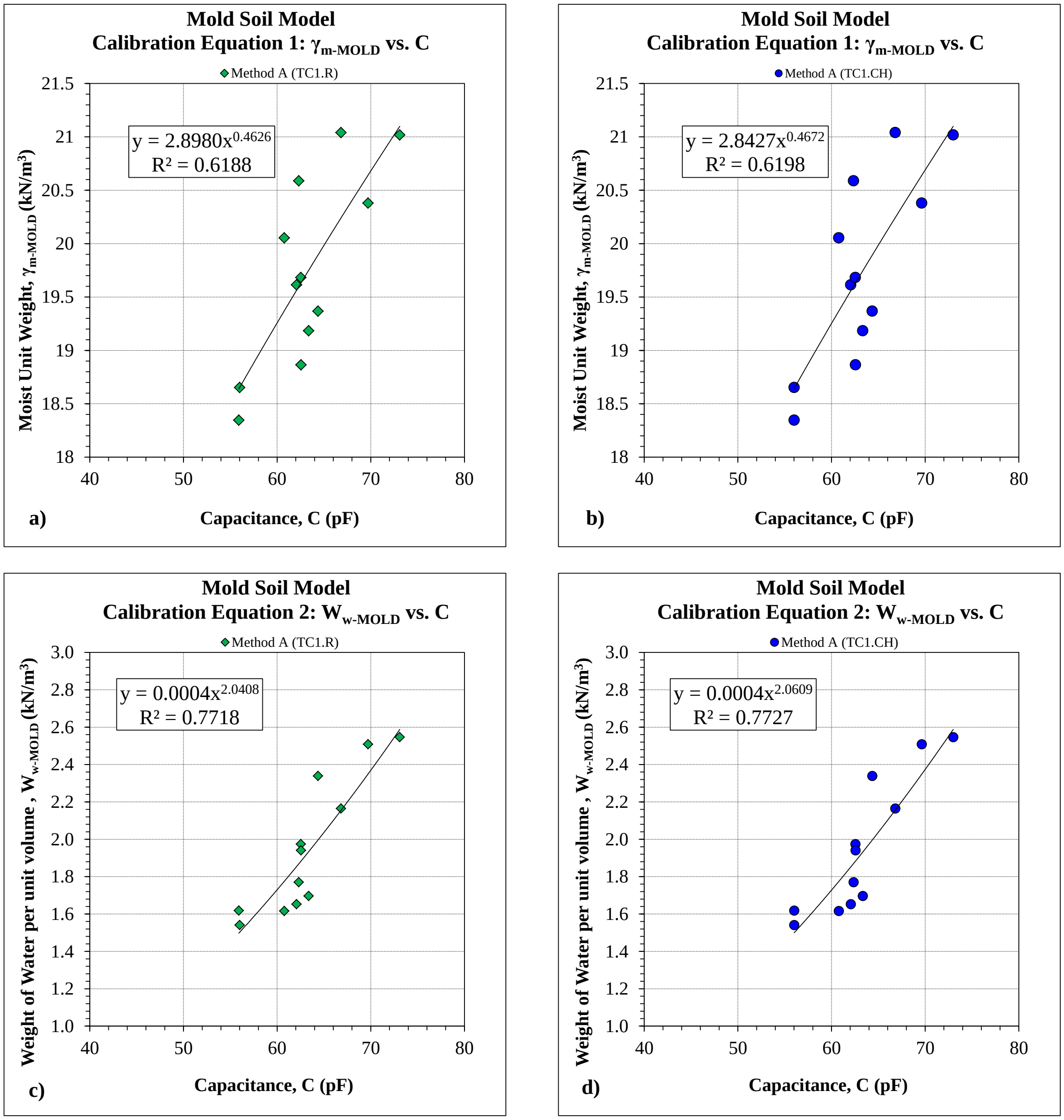


Figure 9.1 Calibration Equations – Mold Soil Model (Method A)
a) Calibration Equation 1 (Method A): $\gamma_{m\text{-}MOLD}$ vs. C (TC 1.R)
b) Calibration Equation 1 (Method A): $\gamma_{m\text{-}MOLD}$ vs. C (TC 1.CH)
c) Calibration Equation 2 (Method A): $W_{w\text{-}MOLD}$ vs. C (TC 1.R)
d) Calibration Equation 2 (Method A): $W_{w\text{-}MOLD}$ vs. C (TC 1.CH)

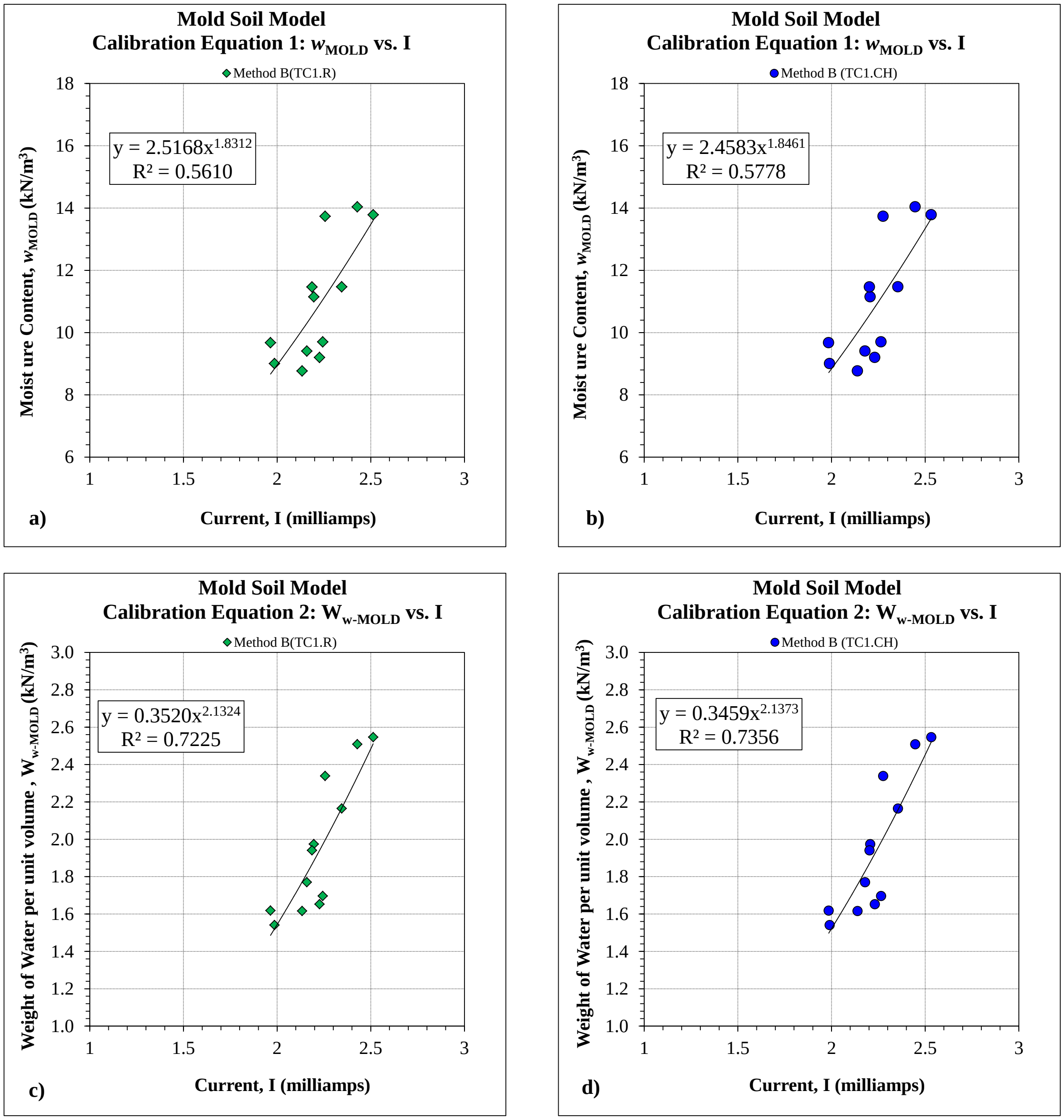


Figure 9.2 Calibration Equations – Mold Soil Model (Method B)
a) Calibration Equation 1 (Method B): w_{MOLD} vs. I (TC 1.R)
b) Calibration Equation 1 (Method B): w_{MOLD} vs. I (TC 1.CH)
c) Calibration Equation 2 (Method B): $W_{w\text{-}MOLD}$ vs. I (TC 1.R)
d) Calibration Equation 2 (Method B): $W_{w\text{-}MOLD}$ vs. I (TC 1.CH)

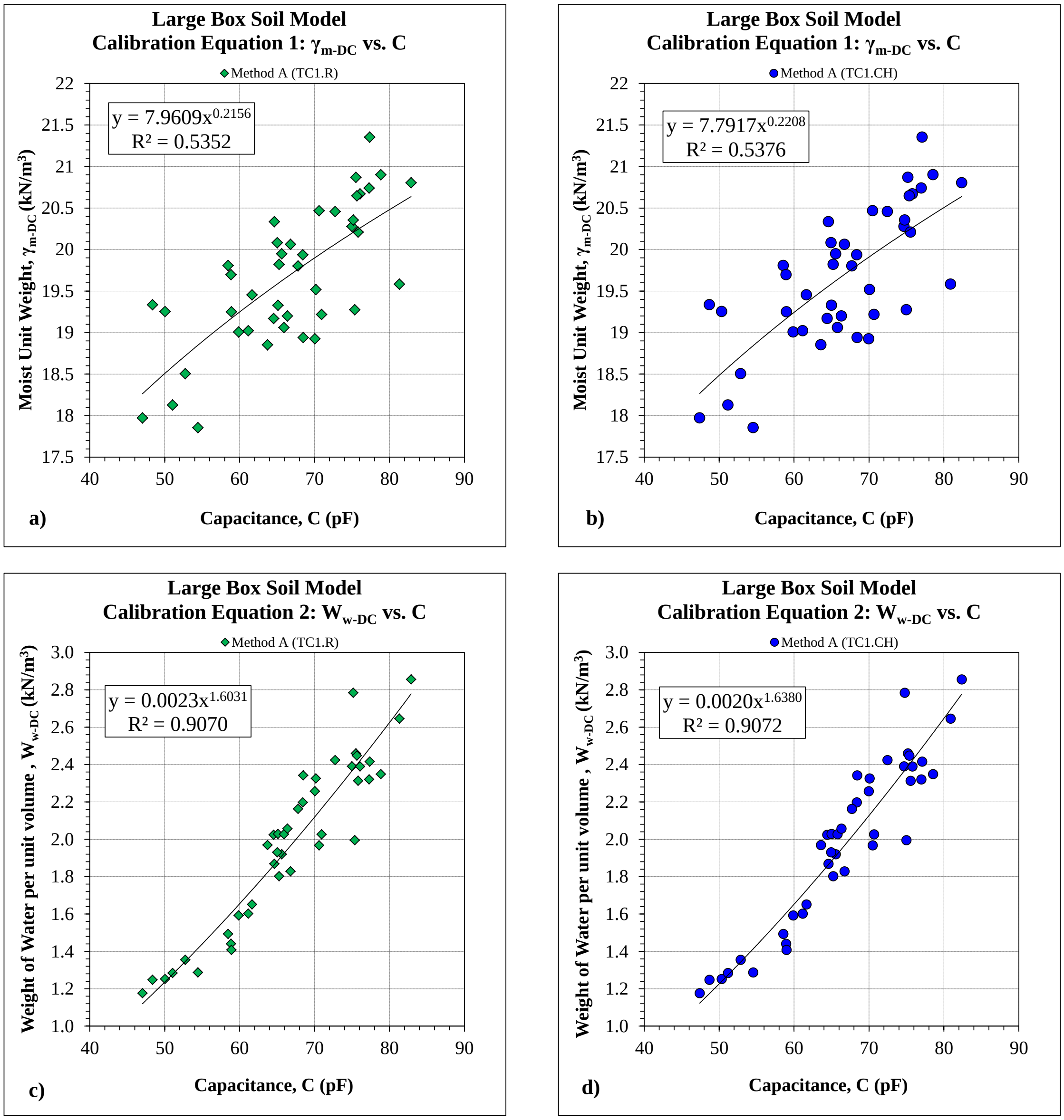


Figure 9.3 Calibration Equations – Large Box Soil Model (Method A)
a) Calibration Equation 1 (Method A): $\gamma_{m\text{-}MOLD}$ vs. Z (TC 1.R)
b) Calibration Equation 1 (Method A): $\gamma_{m\text{-}MOLD}$ vs. Z (TC 1.CH)
c) Calibration Equation 2 (Method A): $\gamma_{m\text{-}MOLD}$ vs. Z (TC 1.R)
d) Calibration Equation 2 (Method A): $\gamma_{m\text{-}MOLD}$ vs. Z (TC 1.CH)

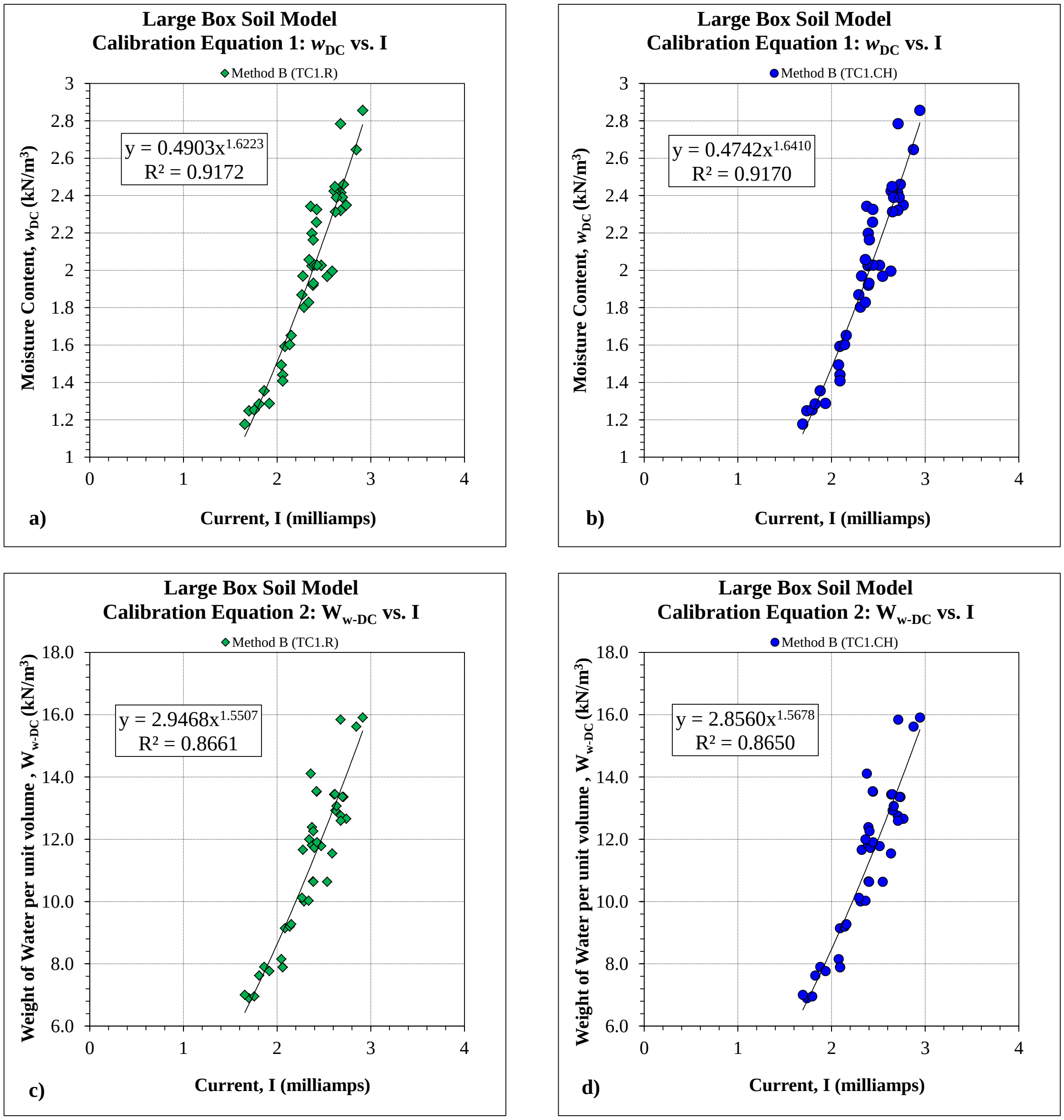


Figure 9.4 Calibration Equations – Large Box Soil Model (Method B)
a) Calibration Equation 1 (Method B): w_{DC} vs. I (TC 1.R)
b) Calibration Equation 1 (Method B): w_{DC} vs. I (TC 1.CH)
c) Calibration Equation 2 (Method B): $W_{w\text{-}DC}$ vs. I (TC 1.R)
d) Calibration Equation 2 (Method B): $W_{w\text{-}DC}$ vs. I (TC 1.CH)

9.4 Mold Soil and Large Box Soil: 1:1 Plots (Method A/Method B)

The Mold Soil Model (Method A and Method B) and the Large Box Soil Model (Method A and Method B) calibration equations were used to predict the EDG values that are presented in this section.

Figure 9.5 to Figure 9.8 show Mold or drive cylinder measured moist unit weights ($\gamma_{m\text{-}MOLD}$ or $\gamma_{m\text{-}DC}$) versus EDG predicted moist unit weights ($\gamma_{m\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON), and with the new temperature correction algorithm applied (TC 1) using the new calibration relationships (Method A and Method B).

Figure 9.9 to Figure 9.12 show Mold or drive cylinder measured weight of water per unit volume ($W_{W\text{-}MOLD}/W_{W\text{-}DC}$) versus EDG predicted weight of water per unit volume ($W_{W\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON), and with the new temperature correction algorithm applied (TC 1) using the new calibration relationships (Method A and Method B).

Figure 9.13 to Figure 9.16 show Mold or drive cylinder measured dry unit weights ($\gamma_{d\text{-}MOLD}$ / $\gamma_{d\text{-}DC}$) versus EDG predicted dry unit weights ($\gamma_{d\text{-}EDG}$) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON), and with the new temperature correction algorithm applied (TC 1) using the new calibration relationships (Method A and Method B).

Figure 9.17 to Figure 9.20 show Mold or drive cylinder measured moisture content (w_{MOLD}/w_{DC}) versus EDG predicted moisture content (w_{EDG}) with and without the EDG temperature correction algorithm applied (TC OFF & TC ON), and with the new temperature correction algorithm applied (TC 1) using the new calibration relationships (Method A and Method B).

It should be noted that the solid line shown in all figures is a 1:1 line, and the dashed lines are ±0.5 kN/m^3 or ±0.5 % reference lines.

Table 9.11 to Table 9.18 summarize statistical error measurements of interest for the EDG values that are predicted for the Mold Soil Model and Large Box Soil Model with the new temperature correction (TC 1) applied using the new calibration relationships (Method A and Method B).

Table 9.19 to Table 9.26 summarize the net difference in statistical error measurements of interest when the new temperature correction (TC 1) and the new calibration relationships (Method A and Method B) are applied compared to the standard EDG error measurements of interest (TC OFF & TC ON).

Table 9.27 to Table 9.34 summarize the net percent difference in error measurements of interest when the new temperature correction (TC 1) and the new calibration relationships (Method A and Method B) are applied compared to the standard EDG error measurements of interest (TC OFF & TC ON).

For the Mold Soil Model and Large Box Soil Model the RMSE, CV(RMSE), and NRMSE for all predicted values (moist unit weight, weight of water per unit volume, dry unit weight, and moisture content) are smaller with the combination of the new temperature correction (TC 1) and the new calibration relationships (Method A and Method B) applied. The levels of improvement for each respective soil property vary, but overall the combination of the new temperature correction algorithm combined with either of the new calibration relationships has a positive impact on the predicted results.

The following list summarizes the general trends and observations made from the data presented in this section:

- Mold Soil Model (Method A and Method B)
    - RMSE, CV(RMSE), and NRMSE values for moist unit weight had a relatively minimal decrease (-2.56% to -7.93%) when compared to the EDG proprietary temperature correction algorithm (TC ON).
    - RMSE, CV(RMSE), and NRMSE values for weight of water per unit volume had a moderately significant decrease (-16.23% to -23.60%) when compared to the EDG proprietary temperature correction algorithm (TC ON).
    - RMSE, CV(RMSE), and NRMSE values for moisture content had a relatively minimal decrease (-4.11% to -8.56%) when compared to the EDG proprietary temperature correction algorithm (TC ON).
    - RMSE, CV(RMSE), and NRMSE values for dry unit weight had a relatively minimal increase (7.69% to 10.01%) when compared to the EDG proprietary temperature correction algorithm (TC ON).

- Large Box Soil Model (Method A and Method B)
    - RMSE, CV(RMSE), and NRMSE values for moist unit weight had a moderately significant decrease (-11.89% to -12.68%) when compared to the EDG proprietary temperature correction algorithm (TC ON).
    - RMSE, CV(RMSE), and NRMSE values for weight of water per unit volume had a relatively minimal to moderately significant decrease

(-6.46% to -12.25%) when compared to the EDG proprietary temperature correction algorithm (TC ON).

- RMSE, CV(RMSE), and NRMSE values for moisture content had a relatively minimal decrease (-4.97% to -9.15%) when compared to the EDG proprietary temperature correction algorithm (TC ON).
- RMSE, CV(RMSE), and NRMSE values for dry unit weight had a moderately significant decrease (-10.11% to 10.77%) when compared to the EDG proprietary temperature correction algorithm (TC ON).

Generally, the combination of the new temperature correction (TC 1) and either of the new calibration relationships proposed (Method A or Method B) improves the results from those presented in previous chapters by lowering the RMSE values for all measured soil properties of interest.

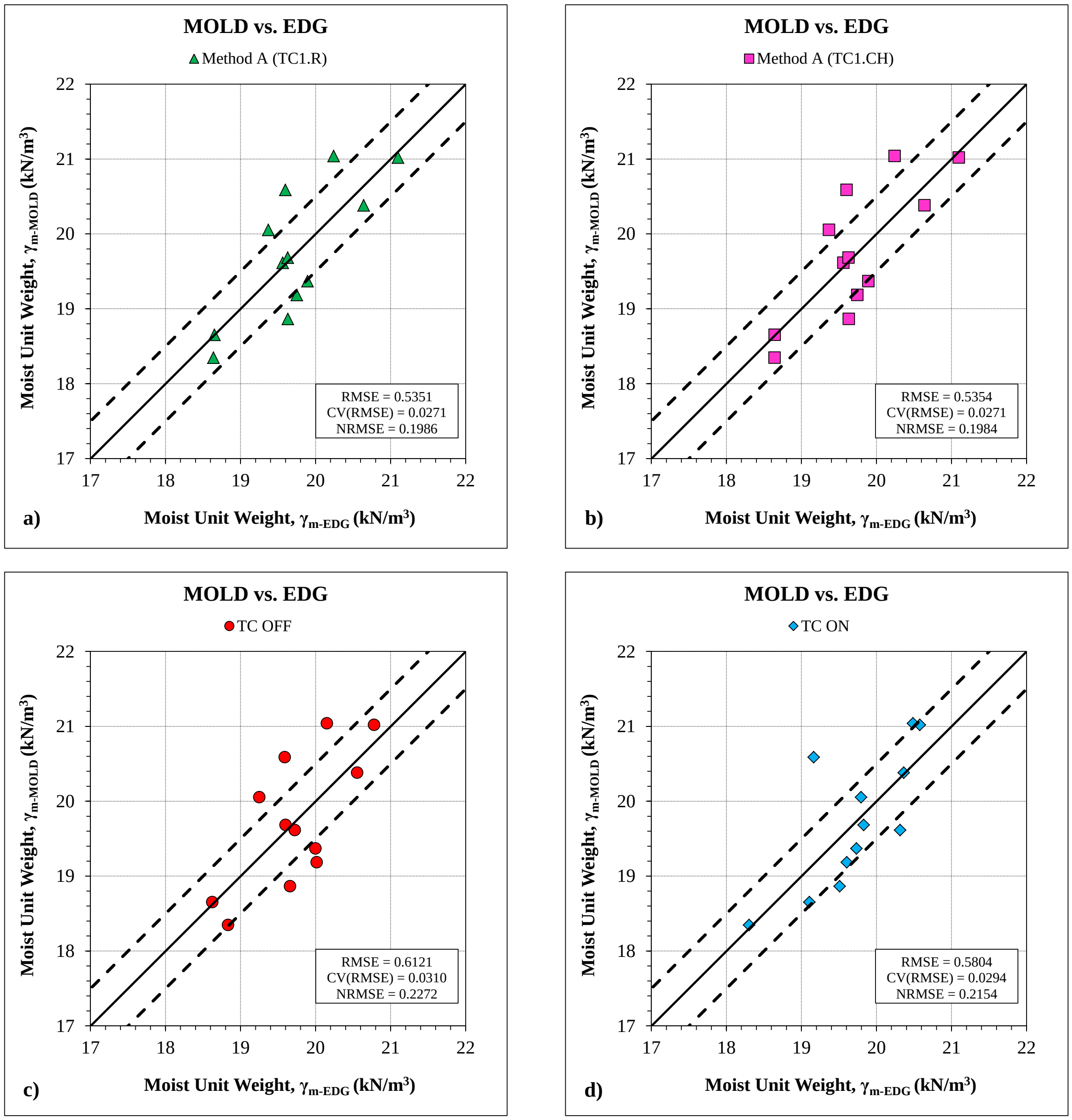


Figure 9.5 1:1 Plots – Mold Soil Model (Method A)
a) 1:1 Plot – Moist Unit Weight (TC 1.R)
b) 1:1 Plot – Moist Unit Weight (TC 1.CH)
c) 1:1 Plot – Moist Unit Weight (TC OFF)
d) 1:1 Plot – Moist Unit Weight (TC ON)

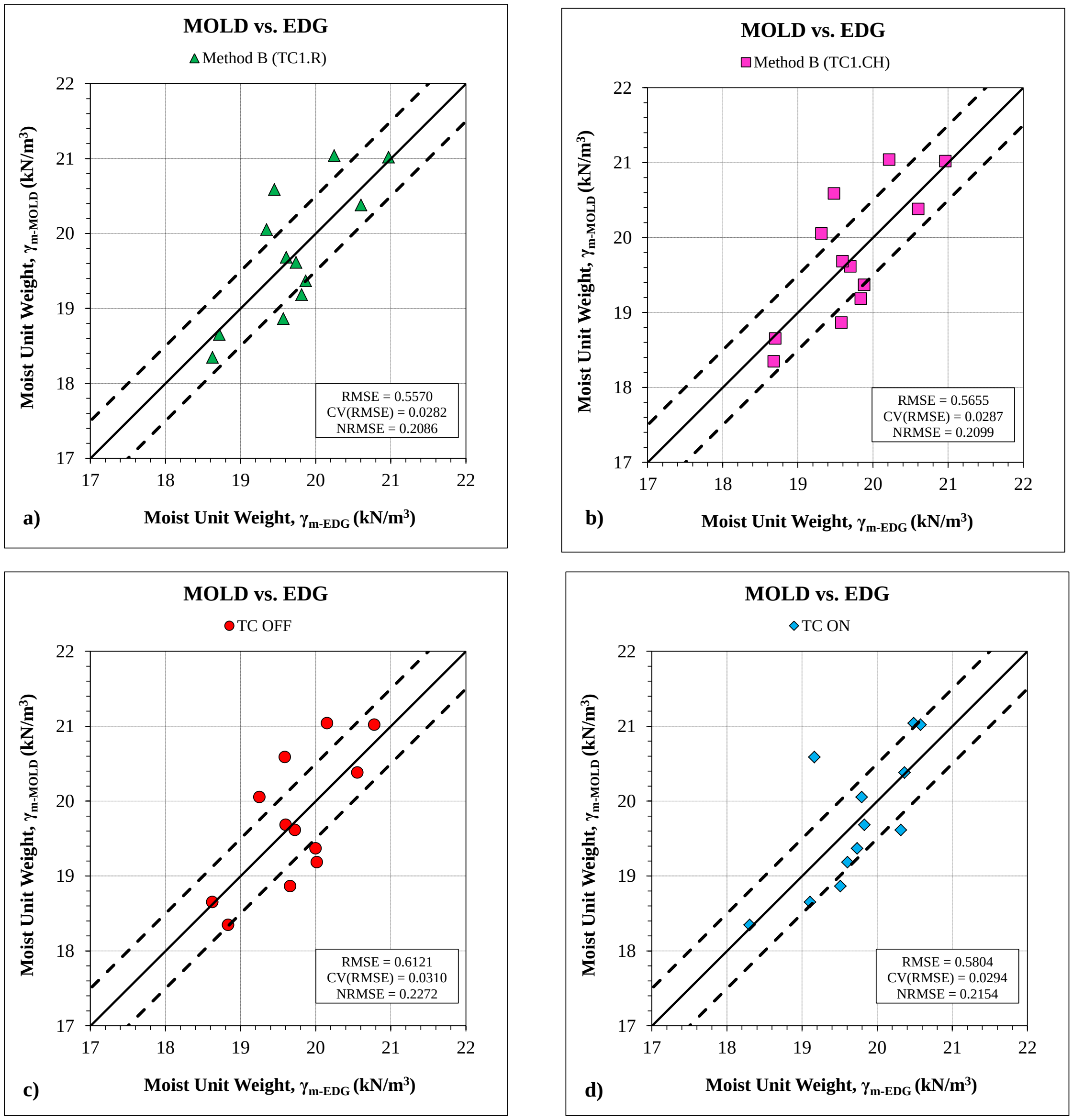


Figure 9.6 1:1 Plots – Mold Soil Model (Method B)
a) 1:1 Plot – Moist Unit Weight (TC 1.R)
b) 1:1 Plot – Moist Unit Weight (TC 1.CH)
c) 1:1 Plot – Moist Unit Weight (TC OFF)
d) 1:1 Plot – Moist Unit Weight (TC ON)

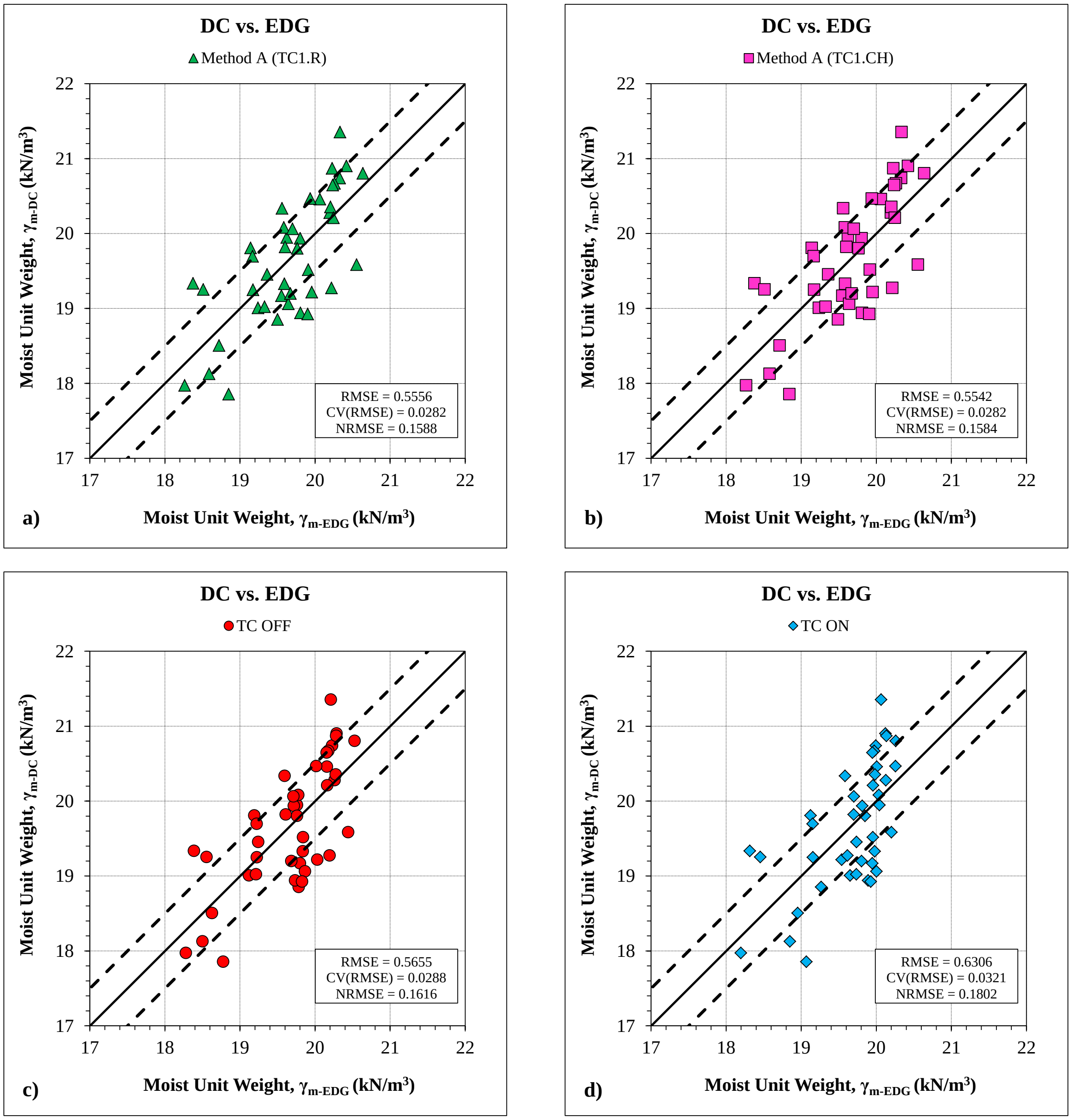


Figure 9.7 1:1 Plots – Large Box Soil Model (Method A)
a) 1:1 Plot – Moist Unit Weight (TC 1.R)
b) 1:1 Plot – Moist Unit Weight (TC 1.CH)
c) 1:1 Plot – Moist Unit Weight (TC OFF)
d) 1:1 Plot – Moist Unit Weight (TC ON)

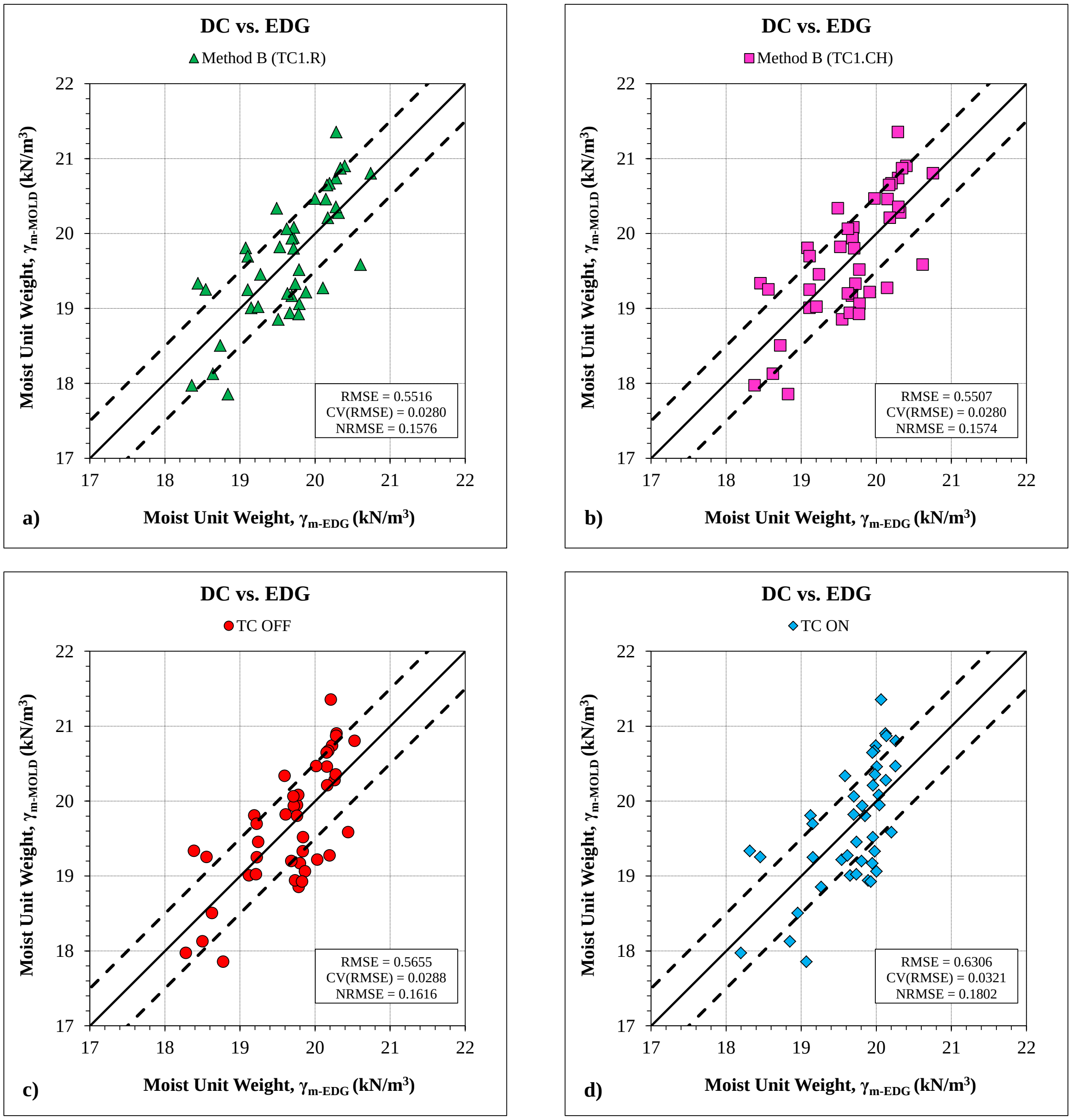


Figure 9.8 **1:1 Plots – Large Box Soil Model (Method B)**
a) 1:1 Plot – Moist Unit Weight (TC 1.R)
b) 1:1 Plot – Moist Unit Weight (TC 1.CH)
c) 1:1 Plot – Moist Unit Weight (TC OFF)
d) 1:1 Plot – Moist Unit Weight (TC ON)

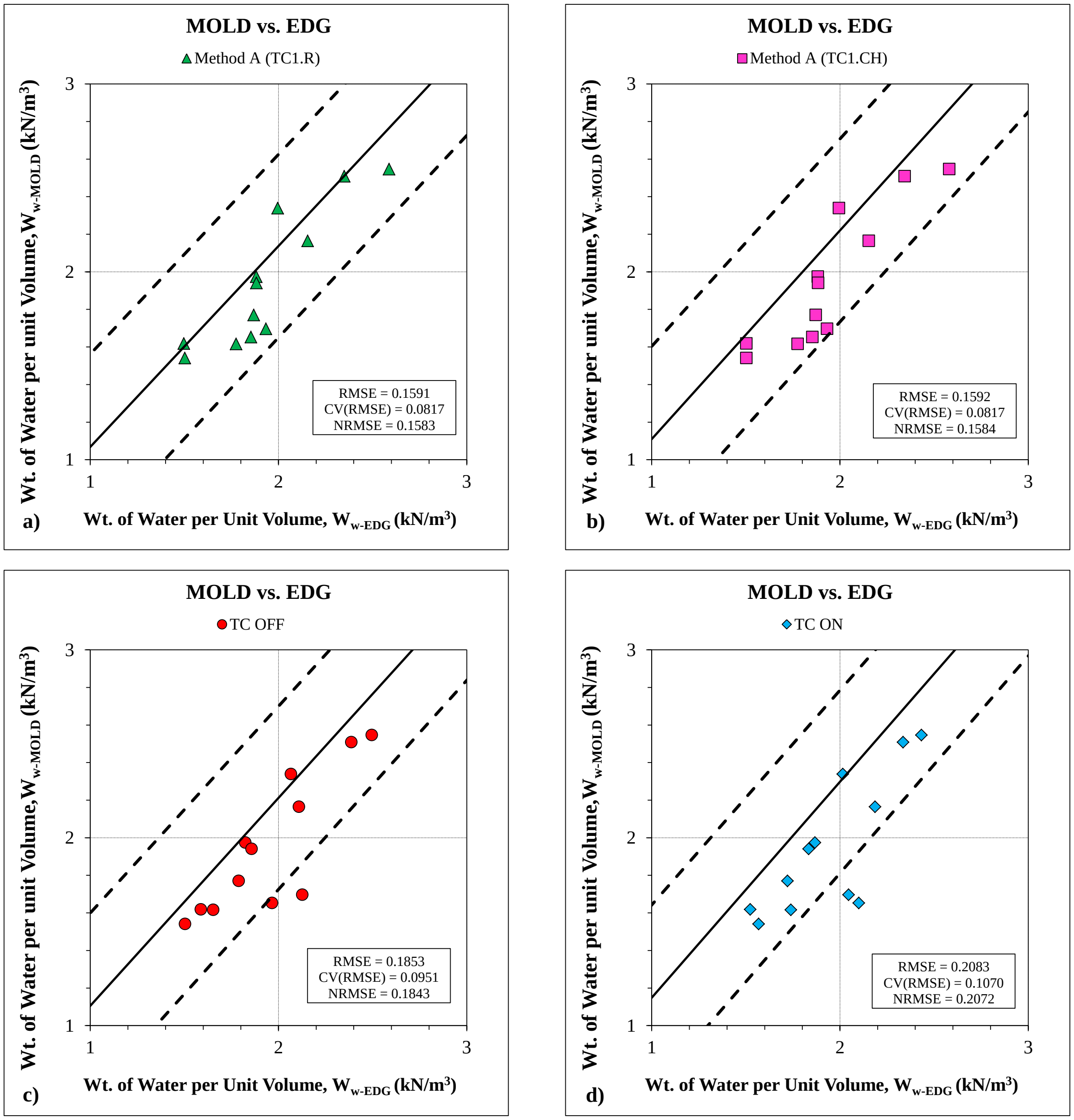


Figure 9.9 **1:1 Plots Mold Soil Model (Method A)**
a) 1:1 Plot – Wt. of Water per Unit Volume (TC 1.R)
b) 1:1 Plot – Wt. of Water per Unit Volume (TC 1.CH)
c) 1:1 Plot – Wt. of Water per Unit Volume (TC OFF)
d) 1:1 Plot – Wt. of Water per Unit Volume (TC ON)

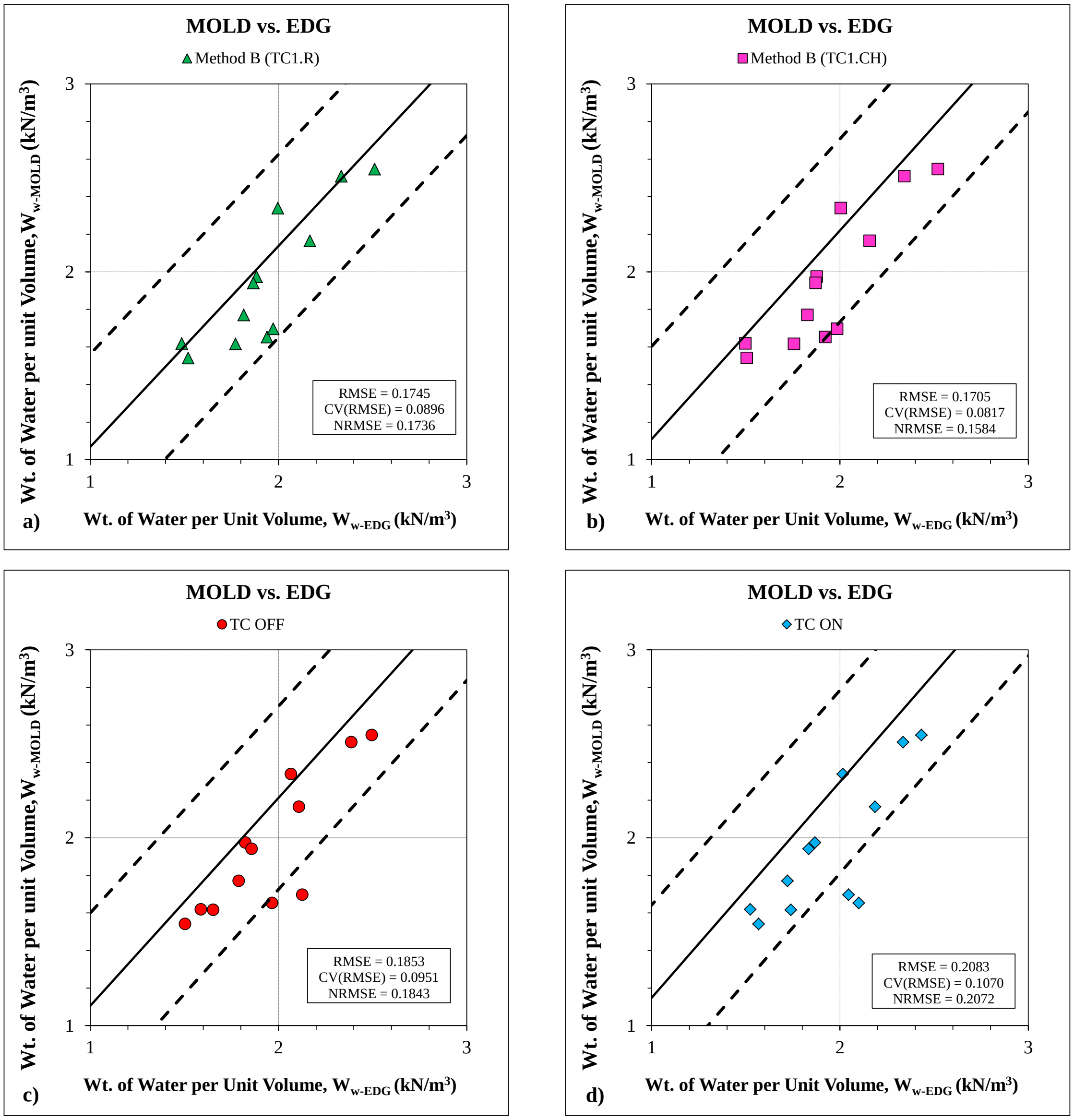


Figure 9.10 1:1 Plots Mold Soil Model (Method B)
a) 1:1 Plot – Wt. of Water per Unit Volume (TC 1.R)
b) 1:1 Plot – Wt. of Water per Unit Volume (TC 1.CH)
c) 1:1 Plot – Wt. of Water per Unit Volume (TC OFF)
d) 1:1 Plot – Wt. of Water per Unit Volume (TC ON)

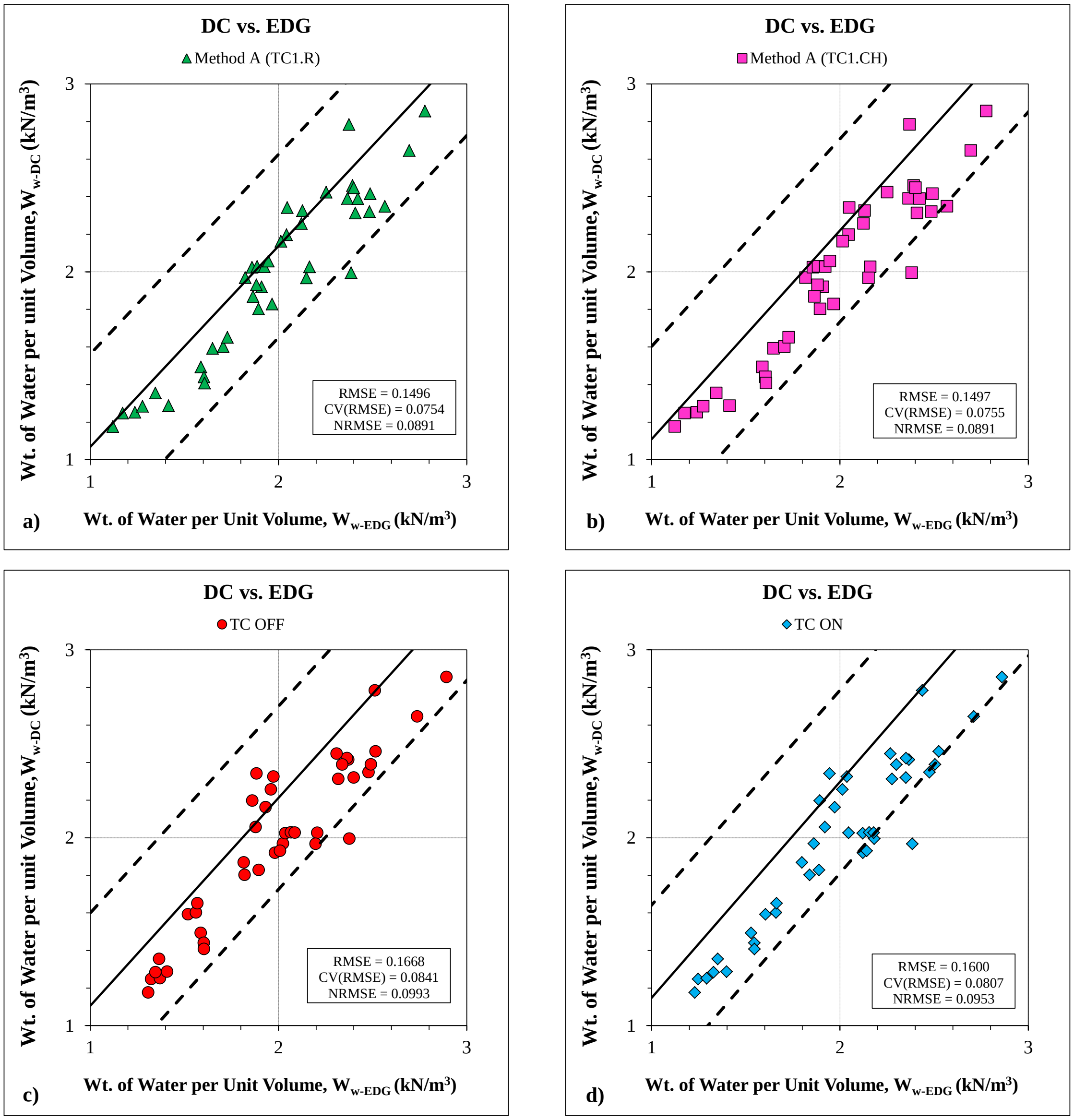


Figure 9.11 1:1 Plots Large Box Soil Model (Method A)
a) 1:1 Plot – Wt. of Water per Unit Volume (TC 1.R)
b) 1:1 Plot – Wt. of Water per Unit Volume (TC 1.CH)
c) 1:1 Plot – Wt. of Water per Unit Volume (TC OFF)
d) 1:1 Plot – Wt. of Water per Unit Volume (TC ON)

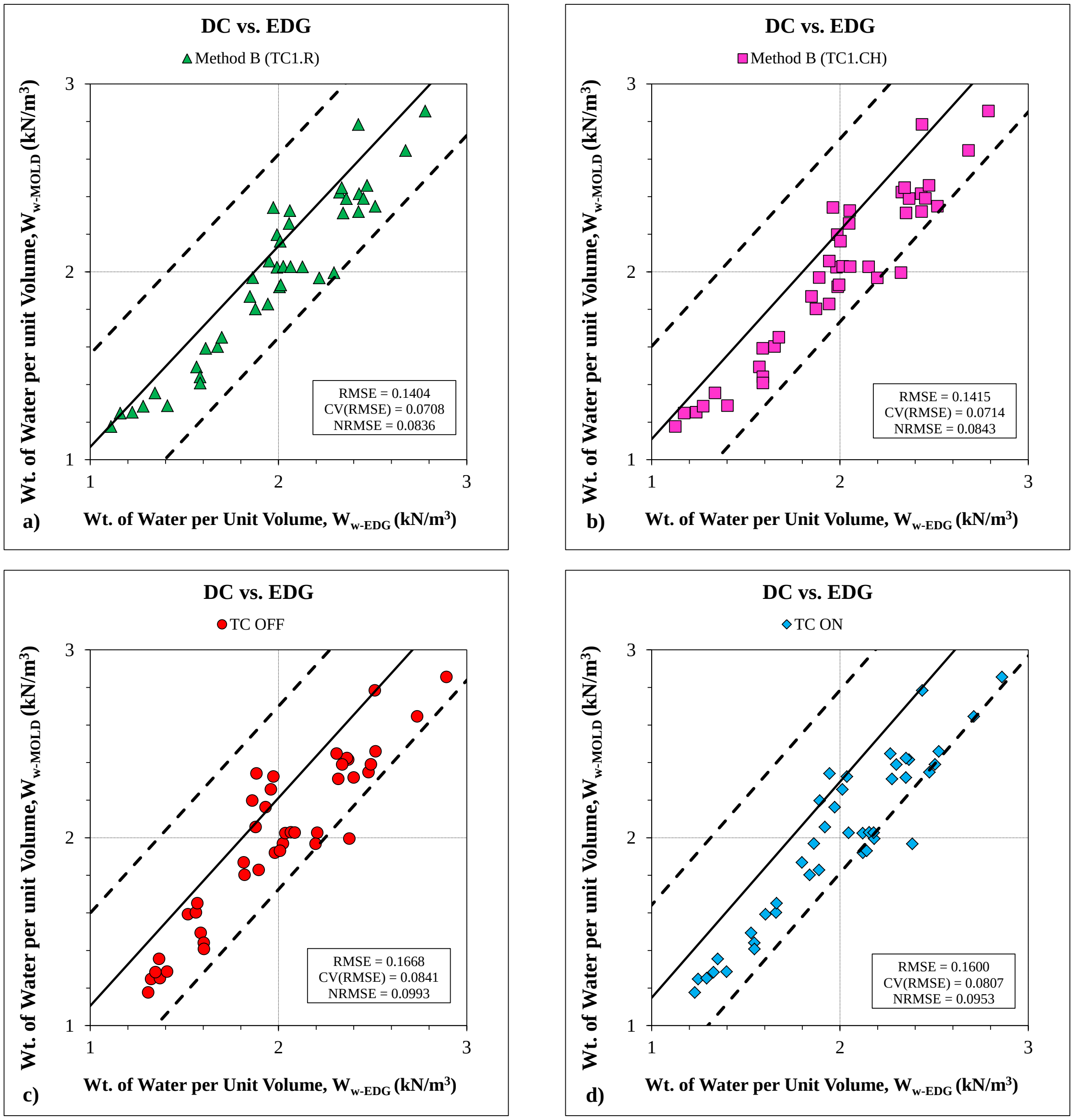


Figure 9.12 1:1 Plots Large Box Soil Model (Method B)
a) 1:1 Plot – Wt. of Water per Unit Volume (TC 1.R)
b) 1:1 Plot – Wt. of Water per Unit Volume (TC 1.CH)
c) 1:1 Plot – Wt. of Water per Unit Volume (TC OFF)
d) 1:1 Plot – Wt. of Water per Unit Volume (TC ON)

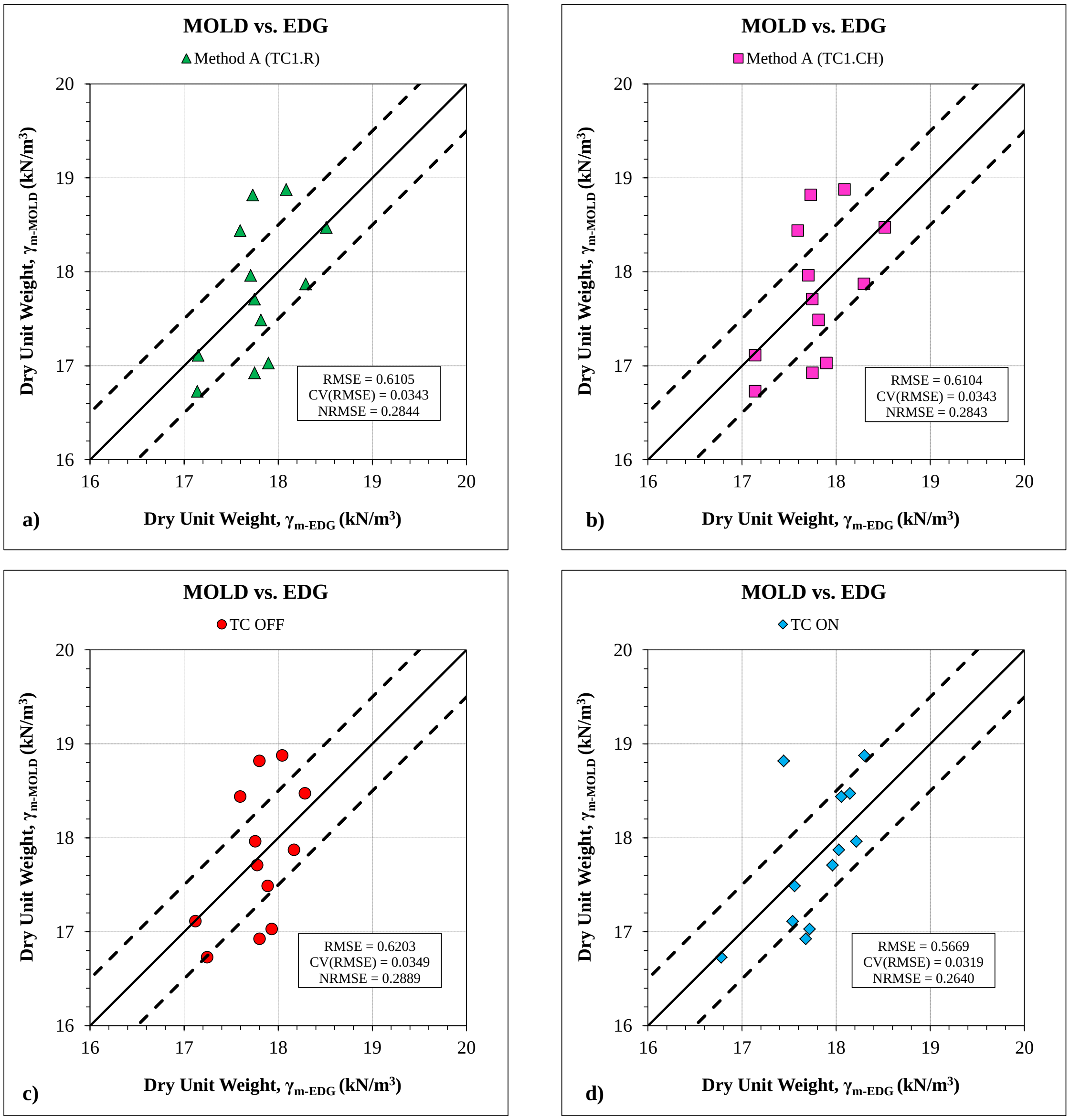


Figure 9.13 1:1 Plots – Mold Soil Model (Method A)
a) 1:1 Plot – Dry Unit Weight (TC 1.R)
b) 1:1 Plot – Dry Unit Weight (TC 1.CH)
c) 1:1 Plot – Dry Unit Weight (TC OFF)
d) 1:1 Plot – Dry Unit Weight (TC ON)

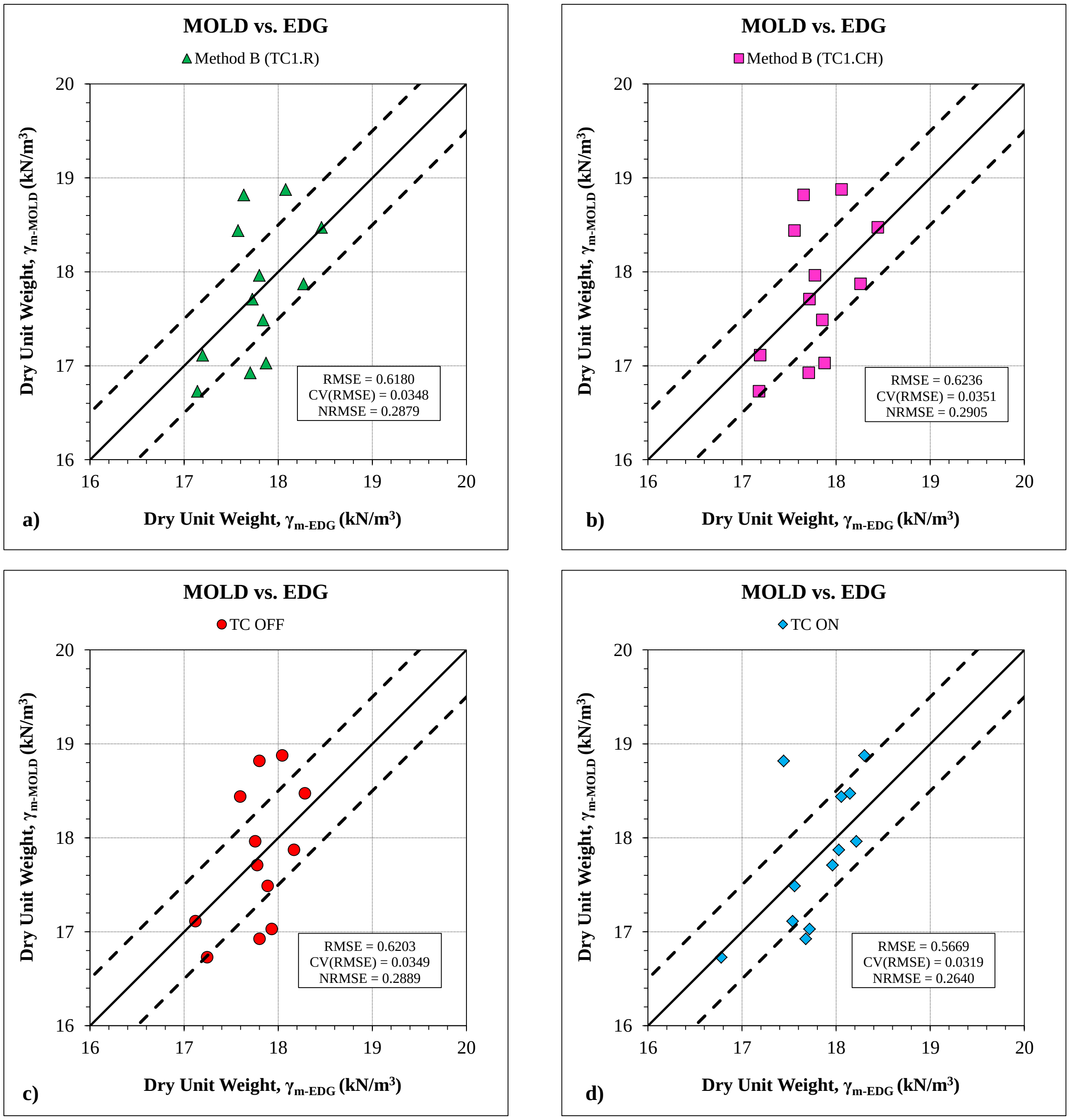


Figure 9.14 1:1 Plots – Mold Soil Model (Method B)
a) 1:1 Plot – Dry Unit Weight (TC 1.R)
b) 1:1 Plot – Dry Unit Weight (TC 1.CH)
c) 1:1 Plot – Dry Unit Weight (TC OFF)
d) 1:1 Plot – Dry Unit Weight (TC ON)

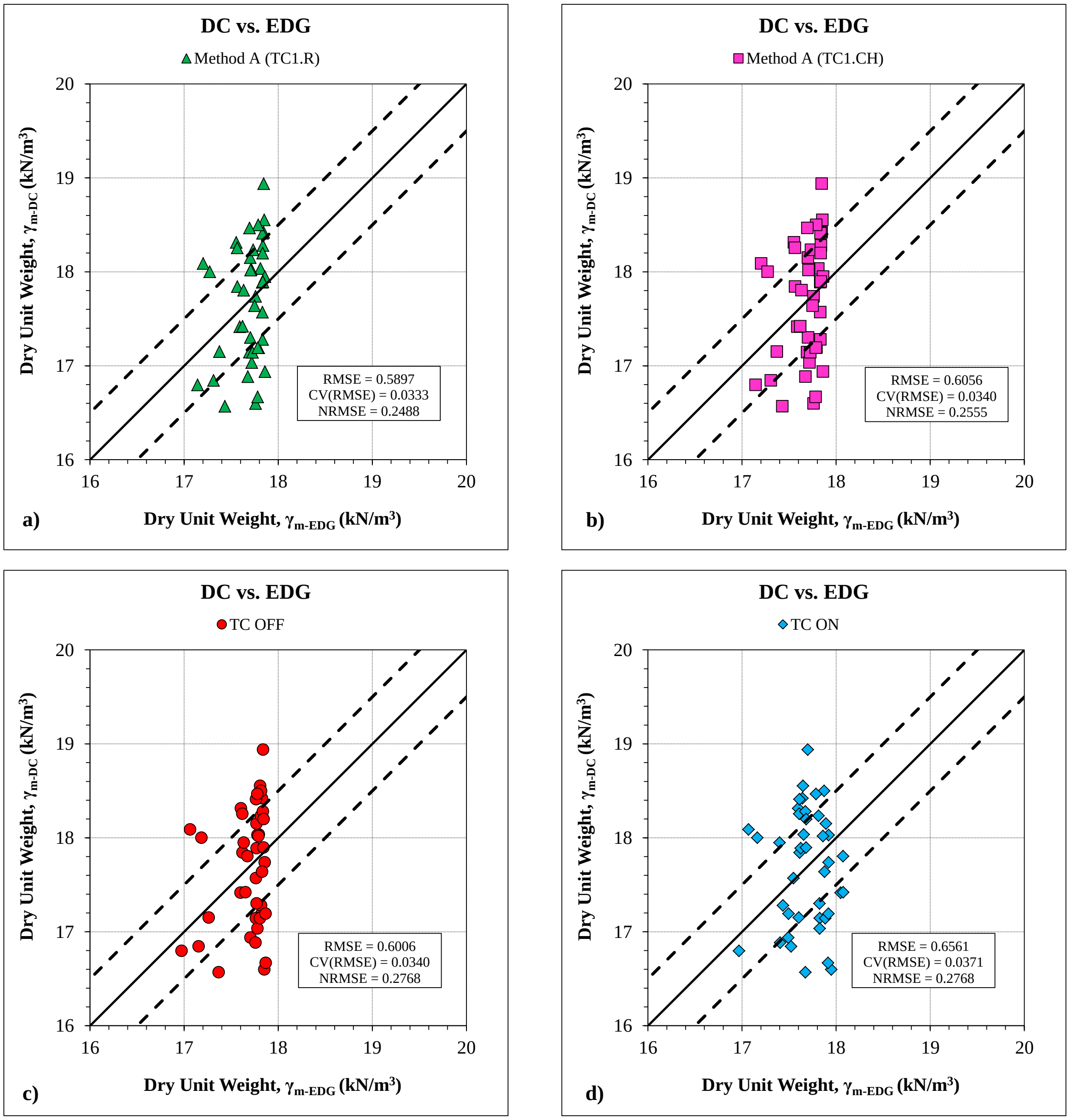


Figure 9.15 1:1 Plots – Large Box Soil Model (Method A)
a) 1:1 Plot – Dry Unit Weight (TC 1.R)
b) 1:1 Plot – Dry Unit Weight (TC 1.CH)
c) 1:1 Plot – Dry Unit Weight (TC OFF)
d) 1:1 Plot – Dry Unit Weight (TC ON)

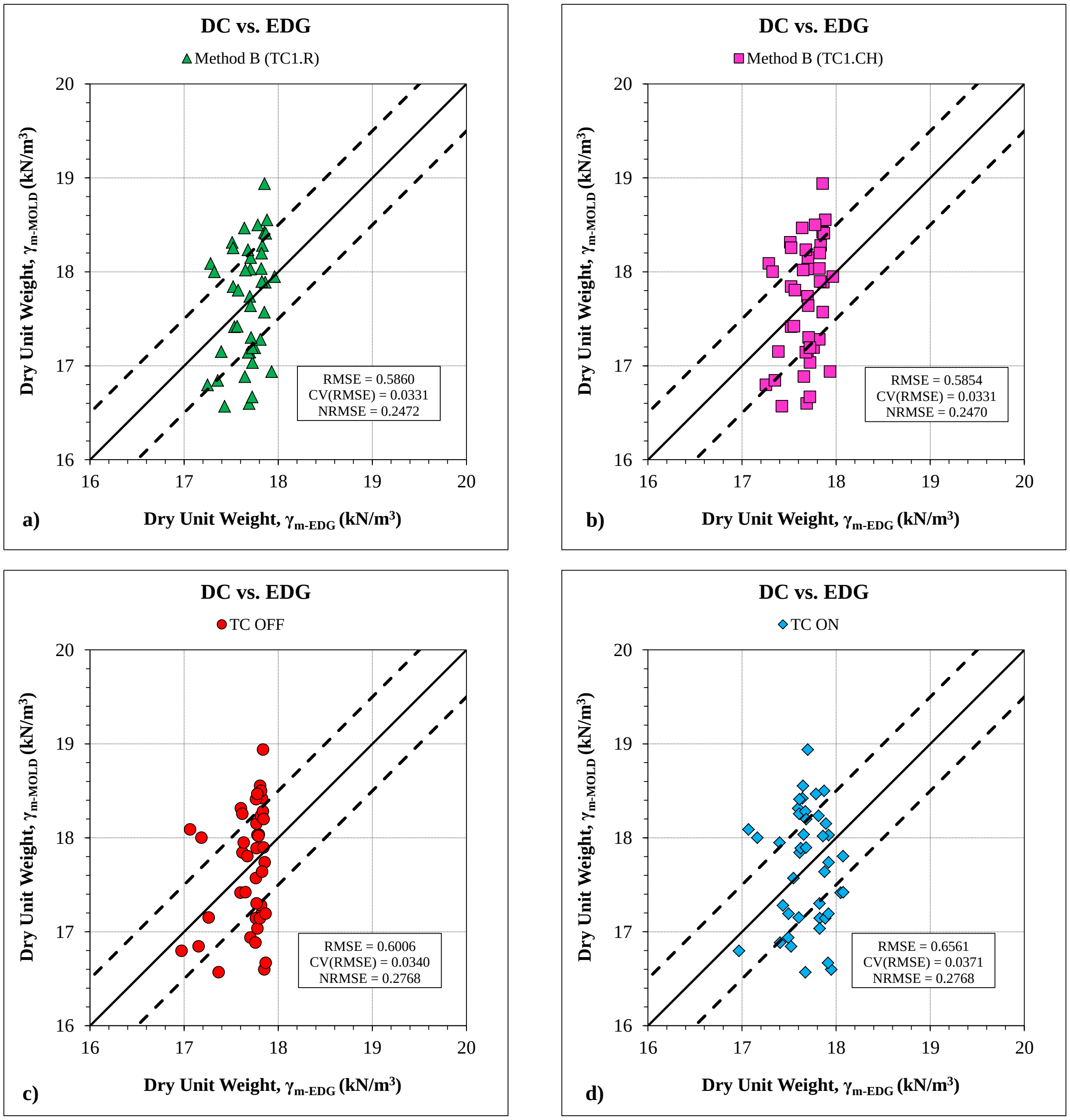


Figure 9.16 1:1 Plots – Large Box Soil Model (Method B)
a) 1:1 Plot – Dry Unit Weight (TC 1.R)
b) 1:1 Plot – Dry Unit Weight (TC 1.CH)
c) 1:1 Plot – Dry Unit Weight (TC OFF)
d) 1:1 Plot – Dry Unit Weight (TC ON)

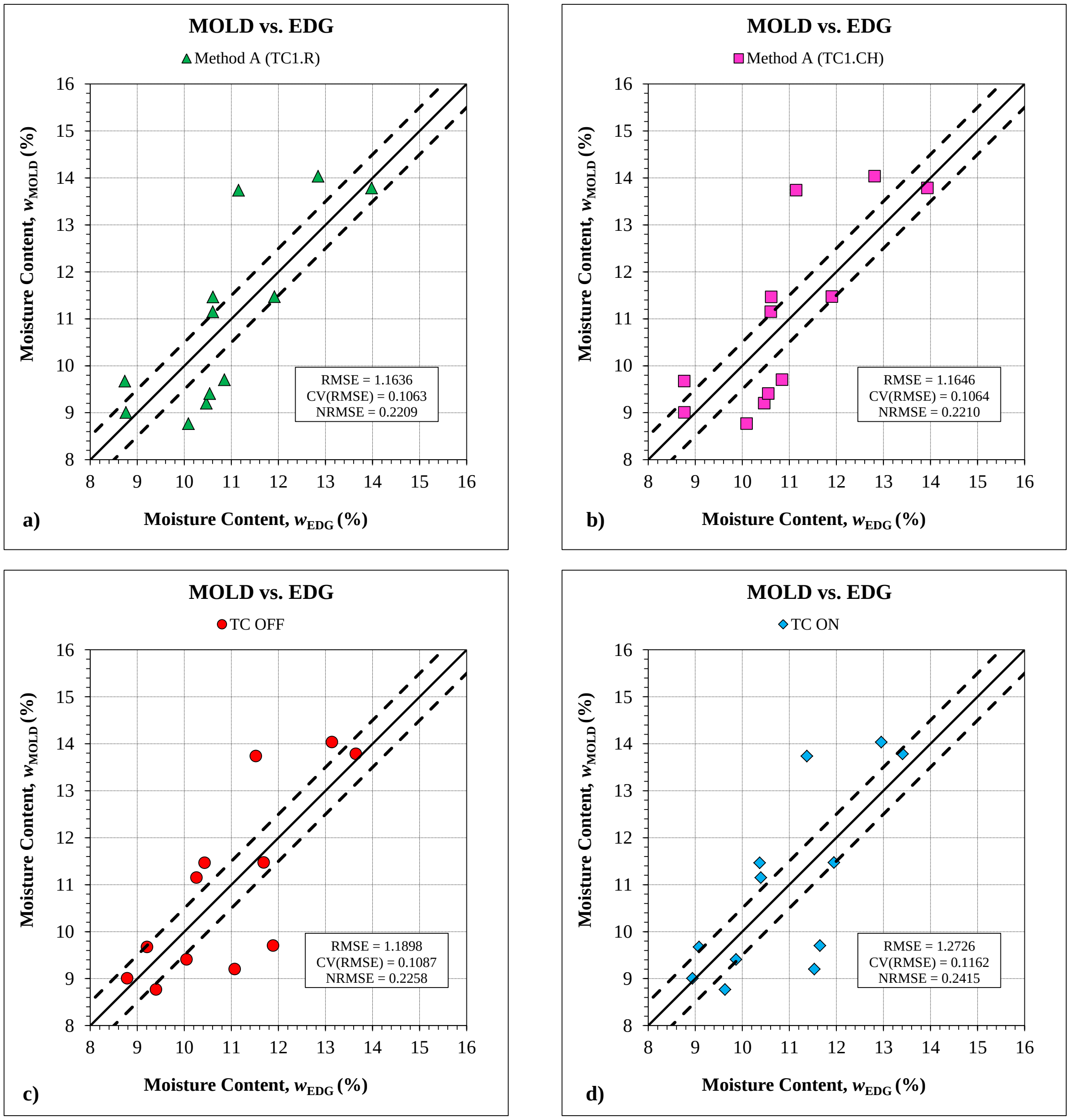


Figure 9.17 1:1 Plots – Mold Soil Model (Method A)
a) 1:1 Plot – Moisture Content (TC 1.R)
b) 1:1 Plot – Moisture Content (TC 1.CH)
c) 1:1 Plot – Moisture Content (TC OFF)
d) 1:1 Plot – Moisture Content (TC ON)

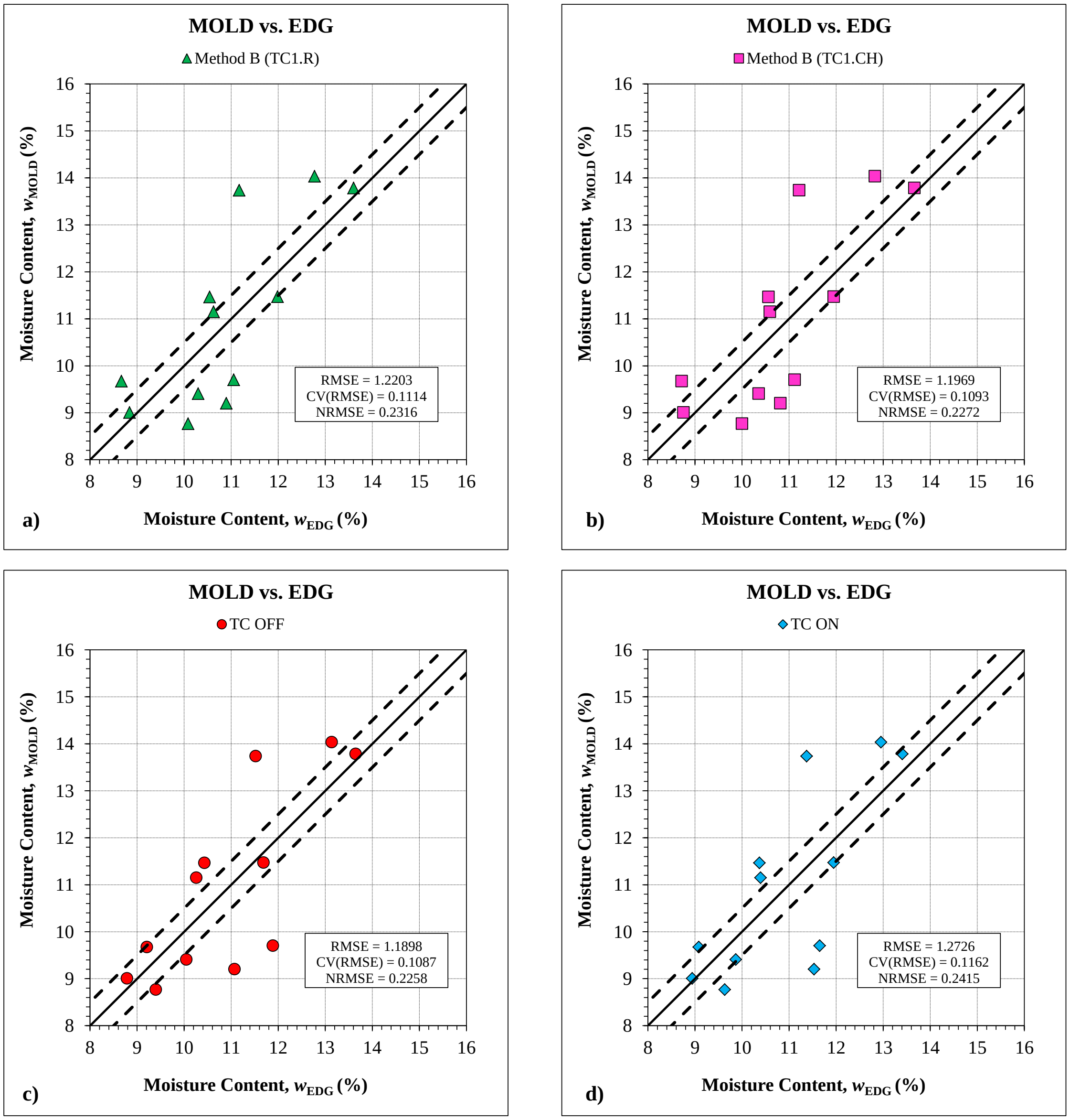


Figure 9.18 1:1 Plots – Mold Soil Model (Method B)
a) 1:1 Plot – Moisture Content (TC 1.R)
b) 1:1 Plot – Moisture Content (TC 1.CH)
c) 1:1 Plot – Moisture Content (TC OFF)
d) 1:1 Plot – Moisture Content (TC ON)

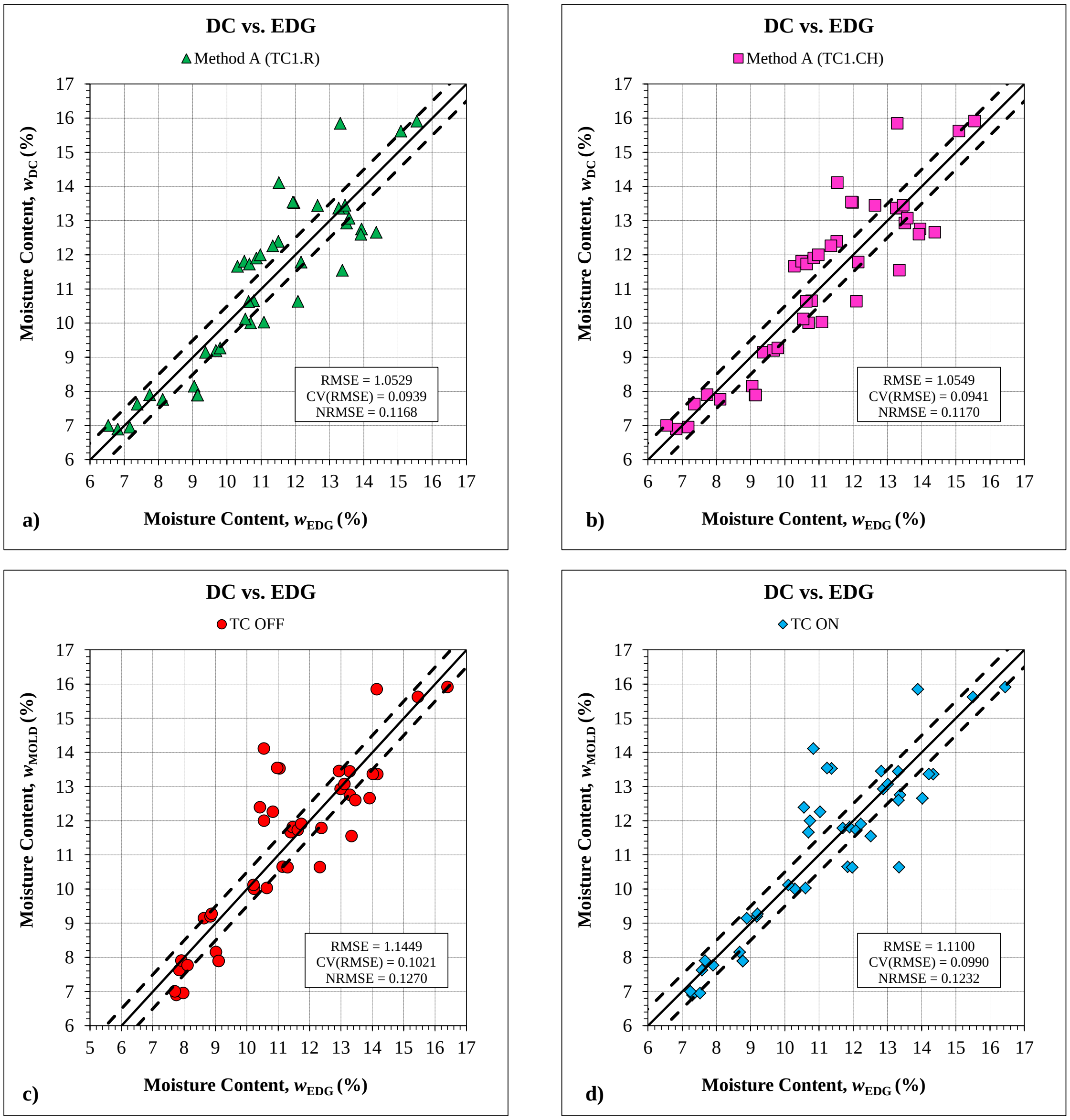


Figure 9.19 1:1 Plots – Large Box Soil Model (Method A)
a) 1:1 Plot – Moisture Content (TC 1.R)
b) 1:1 Plot – Moisture Content (TC 1.CH)
c) 1:1 Plot – Moisture Content (TC OFF)
d) 1:1 Plot – Moisture Content (TC ON)

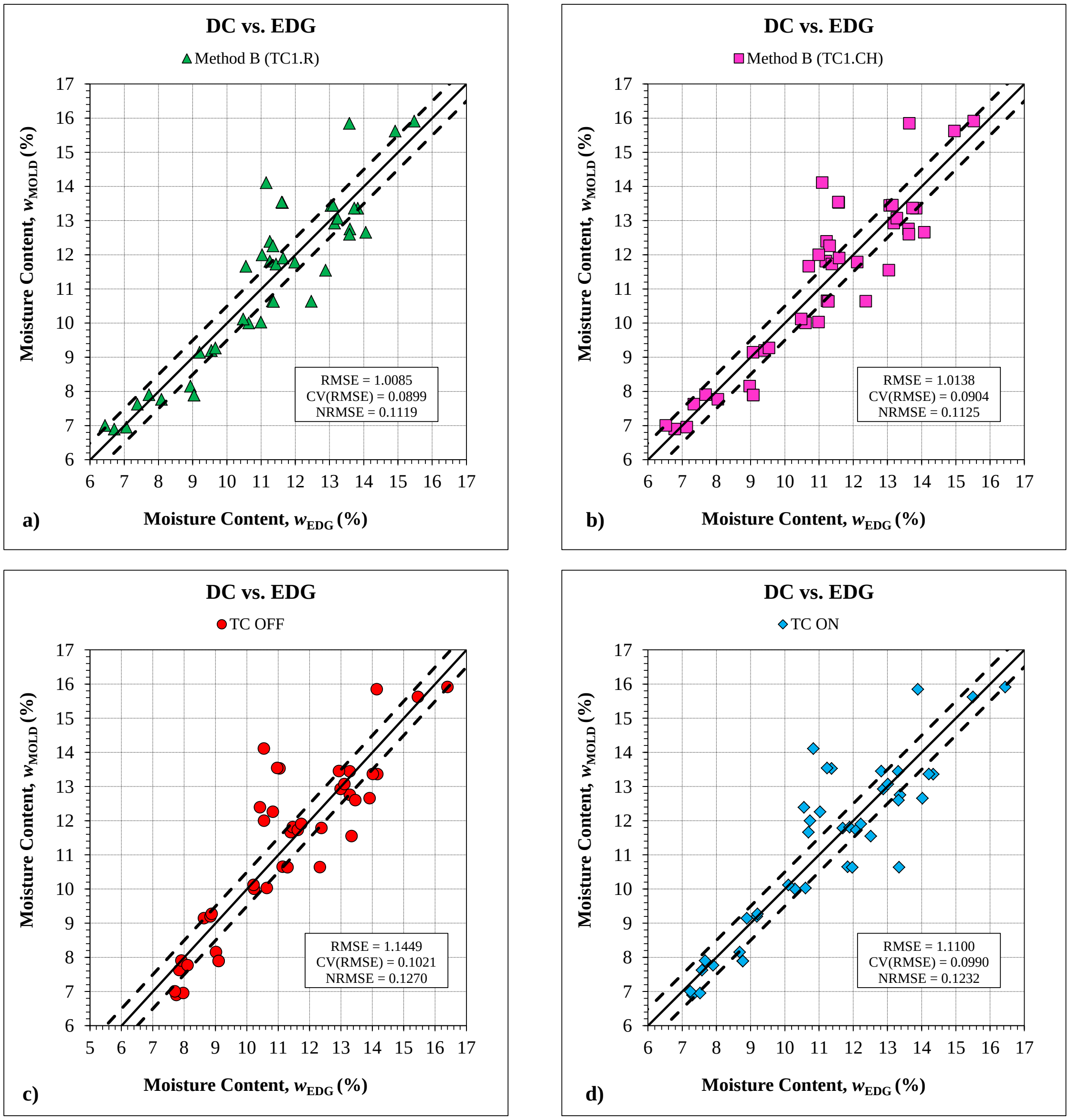


Figure 9.20 1:1 Plots – Large Box Soil Model (Method B)
a) 1:1 Plot – Moisture Content (TC 1.R)
b) 1:1 Plot – Moisture Content (TC 1.CH)
c) 1:1 Plot – Moisture Content (TC OFF)
d) 1:1 Plot – Moisture Content (TC ON)

Table 9.11 Summary of Statistical Measures: Mold Soil Model (Method A/TC1.R)

Mold Soil Model (Method A/TC 1.R)	γ_m	γ_d	W_w	w
RMSE	0.5351	0.6105	0.1591	1.1636
CV(RMSE)	0.0271	0.0343	0.0817	0.1063
NRMSE	0.1986	0.2844	0.1583	0.2209

Table 9.12 Summary of Statistical Measures: Mold Soil Model (Method A/TC 1.CH)

Mold Soil Model (Method A/TC 1.CH)	γ_m	γ_d	W_w	w
RMSE	0.5344	0.6104	0.1592	1.1646
CV(RMSE)	0.0271	0.0343	0.0817	0.1064
NRMSE	0.1984	0.2843	0.1584	0.2210

Table 9.13 Summary of Statistical Measures: Mold Soil Model (Method B/TC1.R)

Mold Soil Model (Method B/TC 1.R)	γ_m	γ_d	W_w	w
RMSE	0.5570	0.6180	0.1745	1.2203
CV(RMSE)	0.0282	0.0348	0.0896	0.1114
NRMSE	0.2068	0.2879	0.1736	0.2316

Table 9.14 Summary of Statistical Measures: Mold Soil Model (Method B/TC 1.CH)

Mold Soil Model (Method B/TC 1.CH)				
	γ_m	γ_d	W_w	w
RMSE	0.5655	0.6236	0.1705	1.1969
CV(RMSE)	0.0287	0.0351	0.0876	0.1093
NRMSE	0.2099	0.2905	0.1696	0.2272

Table 9.15 Summary of Statistical Measures: Large Box Soil Model (Method A/TC1.R)

Large Box Soil Model (Method A/TC 1.R)				
	γ_m	γ_d	W_w	w
RMSE	0.5556	0.5897	0.1496	1.0529
CV(RMSE)	0.0282	0.0333	0.0754	0.0939
NRMSE	0.1588	0.2488	0.0891	0.1168

Table 9.16 Summary of Statistical Measures: Large Box Soil Model (Method A/TC 1.CH)

Large Box Soil Model (Method A/TC 1.CH)				
	γ_m	γ_d	W_w	w
RMSE	0.5542	0.5893	0.1497	1.0549
CV(RMSE)	0.0282	0.0333	0.0755	0.0941
NRMSE	0.1584	0.2486	0.0891	0.1170

Table 9.17 Summary of Statistical Measures: Large Box Soil Model (Method B/TC1.R)

Large Box Soil Model (Method B/TC 1.R)				
	γ_m	γ_d	W_w	w
RMSE	0.5516	0.5860	0.1404	1.0085
CV(RMSE)	0.0280	0.0331	0.0708	0.0899
NRMSE	0.1576	0.2472	0.0836	0.1119

Table 9.18 Summary of Statistical Measures: Large Box Soil Model (Method B/TC 1.CH)

Large Box Soil Model (Method A/TC 1.CH)				
	γ_m	γ_d	W_w	w
RMSE	0.5507	0.5854	0.1415	1.0138
CV(RMSE)	0.0280	0.0331	0.0714	0.0904
NRMSE	0.1574	0.2470	0.0843	0.1125

Table 9.19 Summary of Statistical Measures: Net Difference between TC 1.R and TC OFF/TC ON - Mold Soil Model (Method A)

Mold Soil Model	(TC1.R - TC OFF)				(TC 1.R - TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-0.0770	-0.0098	-0.0261	-0.0262	-0.0453	0.0437	-0.0492	-0.1089
CV(RMSE)	-0.0039	-0.0005	-0.0134	-0.0024	-0.0023	0.0025	-0.0253	-0.0100
NRMSE	-0.0286	-0.0045	-0.0260	-0.0050	-0.0168	0.0203	-0.0489	-0.0207

Table 9.20 Summary of Statistical Measures: Net Difference between TC 1.CH and TC OFF/TC ON – Mold Soil Model (Method A)

Mold Soil Model	(TC 1.CH - TC OFF)				(TC 1.CH - TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-0.0778	-0.0099	-0.0261	-0.0252	-0.0460	0.0436	-0.0491	-0.1080
CV(RMSE)	-0.0039	-0.0006	-0.0134	-0.0023	-0.0023	0.0025	-0.0252	-0.0099
NRMSE	-0.0289	-0.0046	-0.026	-0.0048	-0.0171	0.0203	-0.0489	-0.0205

Table 9.21 Summary of Statistical Measures: Net Difference between TC 1.R and TC OFF/TC ON - Mold Soil Model (Method B)

Mold Soil Model								
	(TC1.R - TC OFF)				(TC 1.R - TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-0.0551	-0.0023	-0.0108	0.0305	-0.0234	0.0512	-0.0338	-0.0523
CV(RMSE)	-0.0028	-0.0001	-0.0055	0.0028	-0.0012	0.0029	-0.0174	-0.0048
NRMSE	-0.0205	-0.001	-0.0107	0.0058	-0.0087	0.0238	-0.0336	-0.0099

Table 9.22 Summary of Statistical Measures: Net Difference between TC 1.CH and TC OFF/TC ON – Mold Soil Model (Method B)

Mold Soil Model								
	(TC 1.CH - TC OFF)				(TC 1.CH - TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-0.0466	0.0033	-0.0148	0.0072	-0.0148	0.0568	-0.0378	-0.0756
CV(RMSE)	-0.0024	0.0002	-0.0076	0.0065	-0.0008	0.0032	-0.0194	-0.0069
NRMSE	-0.0173	0.0016	-0.0147	0.0014	-0.0055	0.0264	-0.0376	-0.0144

Table 9.23 Summary of Statistical Measures: Net Difference between TC 1.R and TC OFF/TC ON – Large Box Soil Model (Method A)

Large Box Soil Model

	(TC1.R - TC OFF)				**(TC 1.R - TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-0.0099	-0.0108	-0.0172	-0.0921	-0.0750	-0.0664	-0.0105	-0.0571
CV(RMSE)	-0.0005	-0.0006	-0.0087	-0.0082	-0.0038	-0.0038	-0.0053	-0.0051
NRMSE	-0.0028	-0.0046	-0.0103	-0.0102	-0.0214	-0.028	-0.0062	-0.0063

Table 9.24 Summary of Statistical Measures: Net Difference between TC 1.CH and TC OFF/TC ON – Large Box Soil Model (Method A)

Large Box Soil Model

	(TC 1.CH - TC OFF)				**(TC 1.CH - TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-0.0113	-0.0113	-0.0171	-0.0901	-0.0764	-0.0668	-0.0103	-0.0552
CV(RMSE)	-0.0006	-0.0006	-0.0086	-0.008	-0.0039	-0.0038	-0.0052	-0.0049
NRMSE	-0.0032	-0.0048	-0.0102	-0.01	-0.0218	-0.0282	-0.0062	-0.0061

Table 9.25 **Summary of Statistical Measures: Net Difference between TC 1.R and TC OFF/TC ON – Large Box Soil Model (Method B)**

Large Box Soil Model								
	(TC1.R - TC OFF)				(TC 1.R - TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-0.0140	-0.0146	-0.0264	-0.1364	-0.0790	-0.0701	-0.0196	-0.1015
CV(RMSE)	-0.0007	-0.0008	-0.0133	-0.0122	-0.004	-0.004	-0.0099	-0.0091
NRMSE	-0.0040	-0.0062	-0.0157	-0.0151	-0.0226	-0.0296	-0.0117	-0.0113

Table 9.26 **Summary of Statistical Measures: Net Difference between TC 1.CH and TC OFF/TC ON – Large Box Soil Model (Method B)**

Large Box Soil Model								
	(TC 1.CH - TC OFF)				(TC 1.CH - TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-0.0149	-0.0151	-0.0253	-0.1311	-0.0799	-0.0707	-0.0185	-0.0962
CV(RMSE)	-0.0008	-0.0009	-0.0127	-0.0117	-0.0041	-0.004	-0.0093	-0.0086
NRMSE	-0.0042	-0.0064	-0.0151	-0.0145	-0.0228	-0.0298	-0.011	-0.0107

Table 9.27 Summary of Statistical Measures: Net Percent Change between TC 1.R and TC OFF/TC ON - Mold Soil Model (Method A)

Mold Soil Model								
	(TC 1.R - TC OFF)				(TC 1.R - TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-12.59%	-1.57%	-14.10%	-2.20%	-7.80%	7.70%	-23.60%	-8.56%
CV(RMSE)	-12.59%	-1.57%	-14.10%	-2.20%	-7.80%	7.70%	-23.60%	-8.56%
NRMSE	-12.59%	-1.57%	-14.10%	-2.20%	-7.80%	7.70%	-23.60%	-8.56%

Table 9.28 Summary of Statistical Measures: Net Percent Change between TC 1.CH and TC OFF/TC ON - Mold Soil Model (Method A)

Mold Soil Model								
	(TC 1.CH - TC OFF)				(TC 1.CH - TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-12.70%	-1.59%	-14.09%	-2.12%	-7.93%	7.69%	-23.59%	-8.49%
CV(RMSE)	-12.70%	-1.59%	-14.09%	-2.12%	-7.93%	7.69%	-23.59%	-8.49%
NRMSE	-12.70%	-1.59%	-14.09%	-2.12%	-7.93%	7.69%	-23.59%	-8.49%

Table 9.29 **Summary of Statistical Measures: Net Percent Change between TC 1.R and TC OFF/TC ON - Mold Soil Model (Method B)**

Mold Soil Model

	(TC 1.R - TC OFF)				**(TC 1.R - TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-9.01%	-0.36%	-5.81%	2.56%	-4.03%	9.03%	-16.23%	-4.11%
CV(RMSE)	-9.01%	-0.36%	-5.81%	2.56%	-4.03%	9.03%	-16.23%	-4.11%
NRMSE	-9.01%	-0.36%	-5.81%	2.56%	-4.03%	9.03%	-16.23%	-4.11%

Table 9.30 **Summary of Statistical Measures: Net Percent Change between TC 1.CH and TC OFF/TC ON - Mold Soil Model (Method B)**

Mold Soil Model

	(TC 1.CH - TC OFF)				**(TC 1.CH - TC ON)**			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-7.61%	0.54%	-7.97%	0.60%	-2.56%	10.01%	-18.15%	-5.94%
CV(RMSE)	-7.61%	0.54%	-7.97%	0.60%	-2.56%	10.01%	-18.15%	-5.94%
NRMSE	-7.61%	0.54%	-7.97%	0.60%	-2.56%	10.01%	-18.15%	-5.94%

Table 9.31 Summary of Statistical Measures: Net Percent Change between TC 1.R and TC OFF/TC ON – Large Box Soil Model (Method A)

Large Box Soil Model								
	(TC 1.R - TC OFF)				(TC 1.R - TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-1.75%	-1.80%	-10.34%	-8.04%	-11.89%	-10.11%	-6.53%	-5.15%
CV(RMSE)	-1.75%	-1.80%	-10.34%	-8.04%	-11.89%	-10.11%	-6.53%	-5.15%
NRMSE	-1.75%	-1.80%	-10.34%	-8.04%	-11.89%	-10.11%	-6.53%	-5.15%

Table 9.32 Summary of Statistical Measures: Net Percent Change between TC 1.CH and TC OFF/TC ON – Large Box Soil Model (Method A)

Large Box Soil Model								
	(TC 1.CH - TC OFF)				(TC 1.CH - TC ON)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
RMSE	-2.00%	-1.88%	-10.27%	-7.87%	-12.11%	-10.18%	-6.46%	-4.97%
CV(RMSE)	-2.00%	-1.88%	-10.27%	-7.87%	-12.11%	-10.18%	-6.46%	-4.97%
NRMSE	-2.00%	-1.88%	-10.27%	-7.87%	-12.11%	-10.18%	-6.46%	-4.97%

Table 9.33 Summary of Statistical Measures: Net Percent Change between TC 1.R and TC OFF/TC ON – Large Box Soil Model (Method B)

Large Box Soil Model								
	(TC 1.R - TC OFF)				(TC 1.R - TC ON)			
	γ_m	γ_d	W_w	*w*	γ_m	γ_d	W_w	*w*
RMSE	-2.47%	-2.43%	-15.83%	-11.92%	-12.54%	-10.69%	-12.25%	-9.15%
CV(RMSE)	-2.47%	-2.43%	-15.83%	-11.92%	-12.54%	-10.69%	-12.25%	-9.15%
NRMSE	-2.47%	-2.43%	-15.83%	-11.92%	-12.54%	-10.69%	-12.25%	-9.15%

Table 9.34 Summary of Statistical Measures: Net Percent Change between TC 1.CH and TC OFF/TC ON – Large Box Soil Model (Method B)

Large Box Soil Model								
	(TC 1.CH - TC OFF)				(TC 1.CH - TC ON)			
	γ_m	γ_d	W_w	*w*	γ_m	γ_d	W_w	*w*
RMSE	-2.63%	-2.52%	-15.16%	-11.45%	-12.68%	-10.77%	-11.55%	-8.67%
CV(RMSE)	-2.63%	-2.52%	-15.16%	-11.45%	-12.68%	-10.77%	-11.55%	-8.67%
NRMSE	-2.63%	-2.52%	-15.16%	-11.45%	-12.68%	-10.77%	-11.55%	-8.67%

9.5 Relative Error

The following section shows histograms of the relative error calculated for moist unit weight, weight of water per unit volume, dry unit weight, and moisture content for the Mold Soil Model and Large Box Soil Model using the new temperature correction (TC 1) combined with the new calibration relationships (Method A and Method B) . A cumulative distribution function (CDF) is displayed on each histogram as well. Relative error values are calculated using Equation 5.1 in Chapter 5.

9.5.1 Relative Error Results: Mold Soil Model and Large Box Soil Model (Method A and Method B)

Table 9.35 to Table 9.38 provide a summary of the minimum, maximum, range, and mean of the relative error histograms of the Mold Soil Model and Large Box Soil Model using the new temperature correction (TC 1) combined with the new calibration relationships (Method A and Method B).

Table 9.39 to Table 9.46 provide a summary of the net percent difference of the minimum, maximum, range, and mean of the relative error histograms when the new temperature correction (TC 1) combined with the new calibration relationships (Method A and Method B) are compared to the standard EDG relative error measurements (TC OFF & TC ON).

Figure 9.21 to Figure 9.24 are histogram plots of relative error between $\gamma_{m\text{-}MOLD} \backslash \gamma_{m\text{-}DC}$ and $\gamma_{m\text{-}EDG}$.

For the Mold Soil Model (Method A and Method B), relative error values for γ_m range from -4.07% to 5.53%. For the Mold Soil Model (Method A and Method B), the net percent change in the mean relative error between TC 1 and TC ON range from -83.04% to -57.23% and between TC 1 and TC OFF ranges from -84.93% to

-62.00%. This corresponds to an extremely significant decrease from TC ON, and an extremely significant decrease from TC OFF.

For the Large Box Soil Model (Method A and Method B), relative error values for γ_m range from -5.57% to 5.02%. For the Large Box Soil Model (Method A and Method B), the net percent change in the mean relative error between TC 1 and TC ON ranges from -11.42% to -9.05% and between TC 1 and TC OFF is -12.99 to -10.66%. This corresponds to a moderately significant decrease from TC ON, and a moderately significant decrease from TC OFF.

Figure 9.25 to Figure 9.28 are histogram plots of relative error between $W_{W\text{-}MOLD}\backslash W_{w\text{-}DC}$ and $W_{W\text{-}EDG.}$

For the Mold Soil Model (Method A and Method B), relative error values for W_W range from -17.37% to 14.67%. For the Mold Soil Model (Method A and Method B), the net percent change in the mean relative error between TC 1 and TC ON range from -69.23% to -62.18% and between TC 1 and TC OFF range from -30.17% to -13.50%. This corresponds to a highly significant decrease from TC ON, and a moderately significant decrease from TC OFF.

For the Large Box Soil Model (Method A and Method B), relative error values for W_W range from -14.72% to 7.08%. For the Large Box Soil Model (Method A and Method B), the net percent change in the mean relative error between TC 1 and TC ON ranges from -23.79% to 12.27% and between TC 1 and TC OFF is -59.25% to -39.96%. This corresponds to a moderately significant decrease to a minimal increase from TC ON, and an extremely significant decrease from TC OFF.

Figure 9.29 to Figure 9.32 are histogram plots of relative error between $\gamma_{d\text{-}MOLD}$ or $\gamma_{d\text{-}DC}$ and $\gamma_{d\text{-}EDG.}$

For the Mold Soil Model (Method A and Method B), relative error values for γ_d range from -5.10% to 6.29%. For the Mold Soil Model (Method A and Method B), the net percent change in the mean relative error between TC 1 and TC ON range from -43.15% to 12.26% and between TC 1 and TC OFF range from -52.54% to -6.28%. This corresponds to a moderately significant decrease to a minimal increase from TC ON, and a moderately significant decrease from TC OFF.

For the Large Box Soil Model (Method A and Method B), relative error values for γ_d range from -5.22% to 5.77%. For the Large Box Soil Model (Method A and Method B), the net percent change in the mean relative error between TC 1 and TC ON ranges from -9.43% to -2.85% and between TC 1 and TC OFF is -21.35 to -15.63%. This corresponds to a relatively minimal decrease from TC ON, and a moderately significant decrease from TC OFF.

Figure 9.33 to Figure 9.36 are histogram plots of relative error between w_{MOLD} or w_{DC} and $w_{EDG.}$

For the Mold Soil Model (Method A and Method B), relative error values for w range from -18.44% to 18.68%. For the Mold Soil Model (Method A and Method B), the net percent change in the mean relative error between TC 1 and TC ON range from -55.78% to -47.10% and between TC 1 and TC OFF range from -46.28% to -33.21%. This corresponds to an extremely significant decrease from TC ON, and a moderately significant decrease from TC OFF.

For the Large Box Soil Model (Method A and Method B), relative error values for w range from -16.02% to 8.05%. For the Large Box Soil Model (Method A and Method B), the net percent change in the mean relative error between TC 1 and TC ON range from -18.65% to 7.53% and between TC 1 and TC OFF is -49.85% to

-33.72%. This corresponds to a moderately significant decrease from TC ON, and a moderately significant decrease from TC OFF.

Overall, the new calibration relationships combined with the new temperature correction generally improve the relative error results presented in this section.

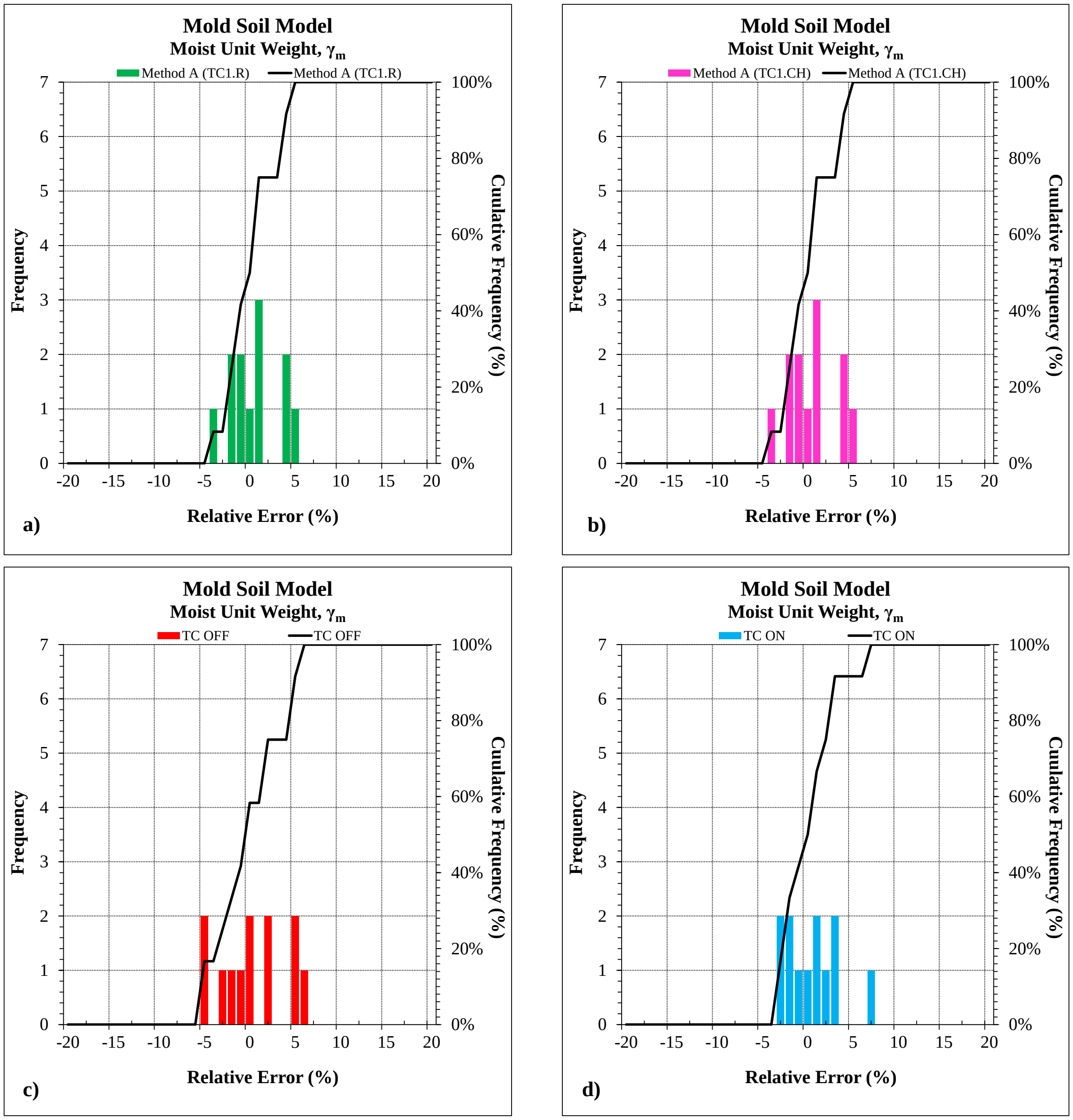


Figure 9.21 Relative Error Histograms and CDF Plots – Mold Soil Model (Method A)
a) Histogram & CDF – Moist Unit Weight (TC 1.R)
b) Histogram & CDF – Moist Unit Weight (TC 1.CH)
c) Histogram & CDF – Moist Unit Weight (TC OFF)
d) Histogram & CDF – Moist Unit Weight (TC ON)

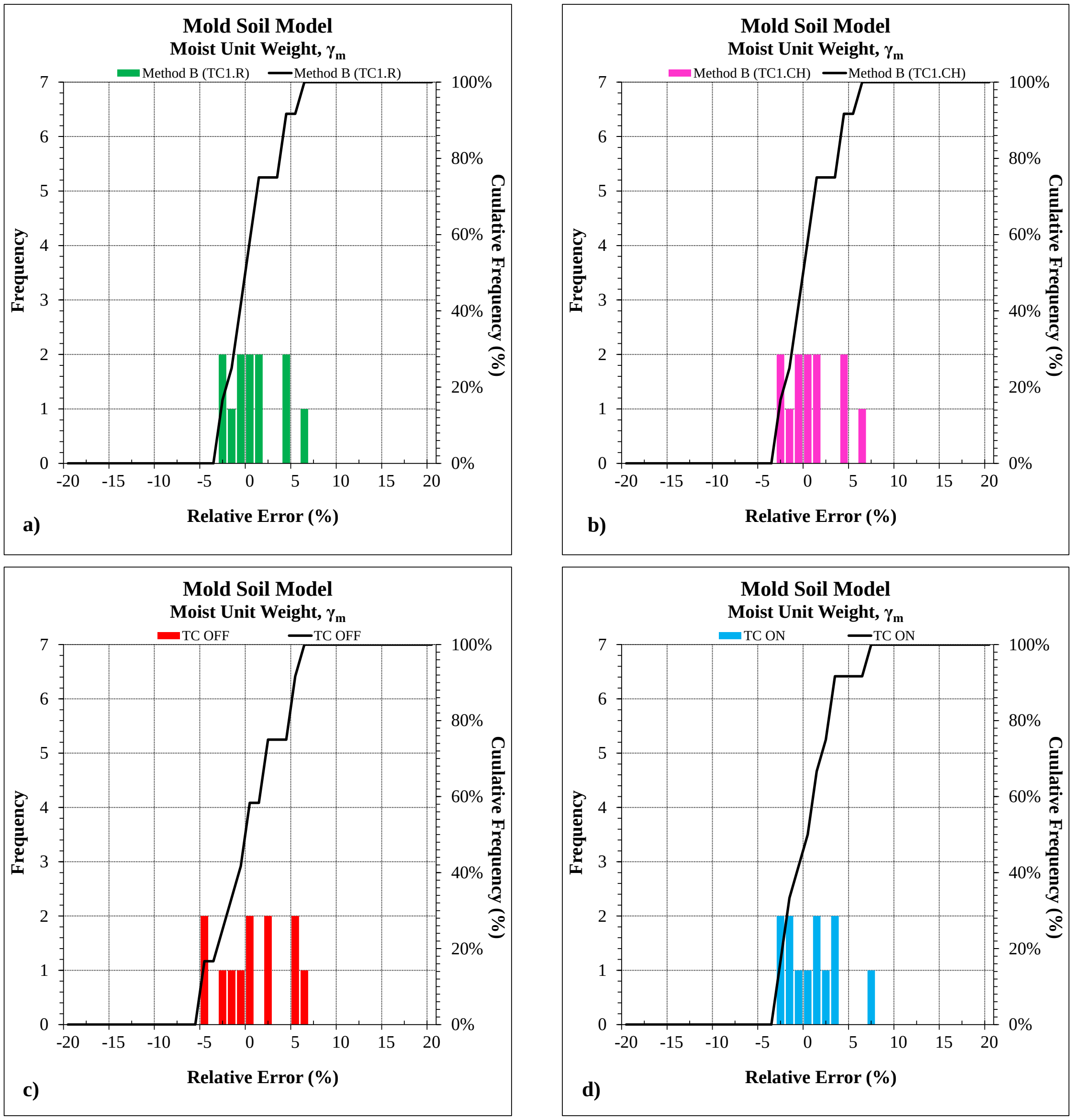


Figure 9.22 Relative Error Histograms & CDF Plots – Mold Soil Model (Method B)
a) Histogram & CDF – Moist Unit Weight (TC 1.R)
b) Histogram & CDF – Moist Unit Weight (TC 1.CH)
c) Histogram & CDF – Moist Unit Weight (TC OFF)
d) Histogram & CDF – Moist Unit Weight (TC ON)

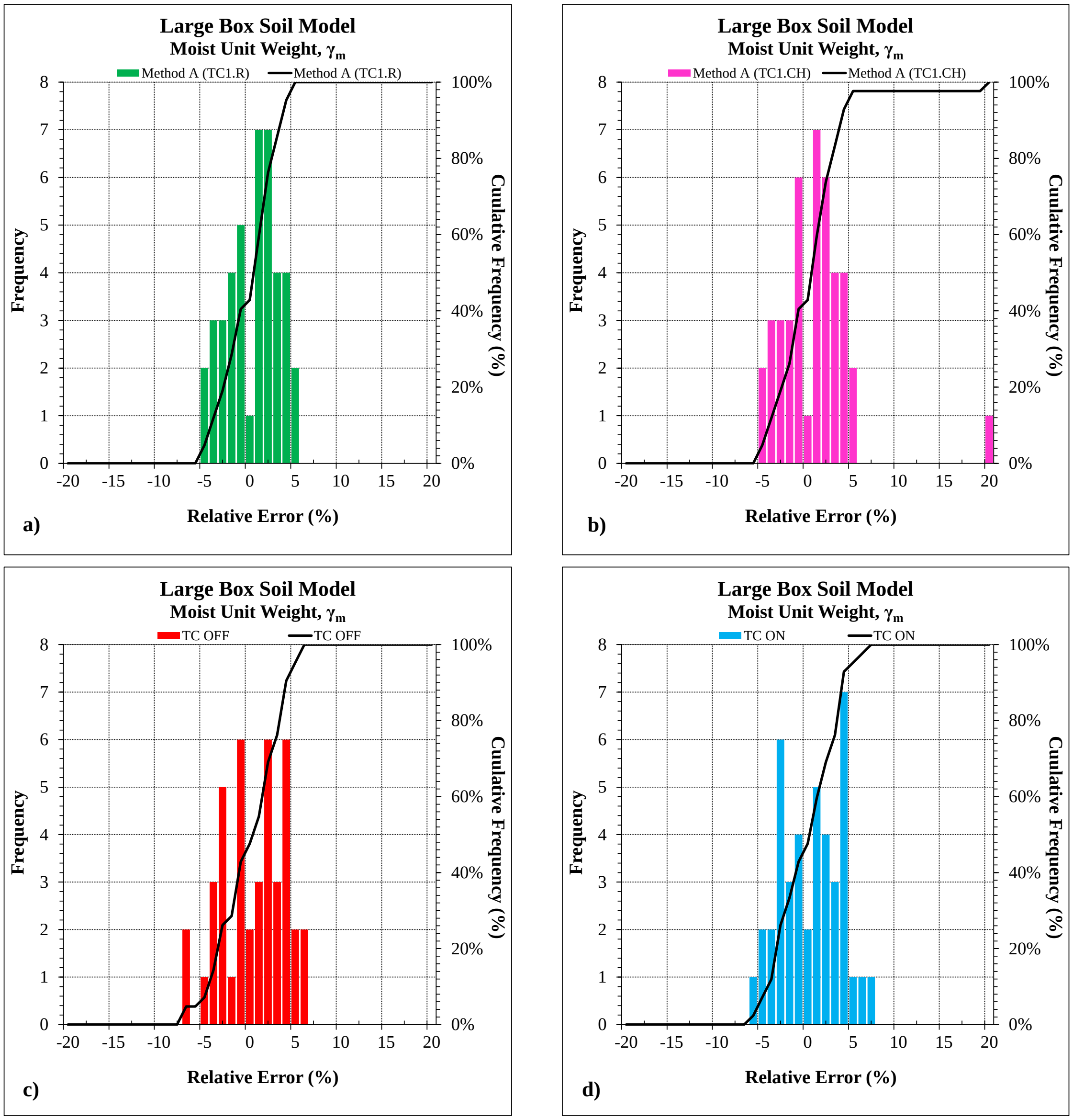


Figure 9.23 Relative Error Histograms & CDF Plots – Large Box Soil Model (Method A)
a) Histogram & CDF – Moist Unit Weight (TC 1.R)
b) Histogram & CDF – Moist Unit Weight (TC 1.CH)
c) Histogram & CDF – Moist Unit Weight (TC OFF)
d) Histogram & CDF – Moist Unit Weight (TC ON)

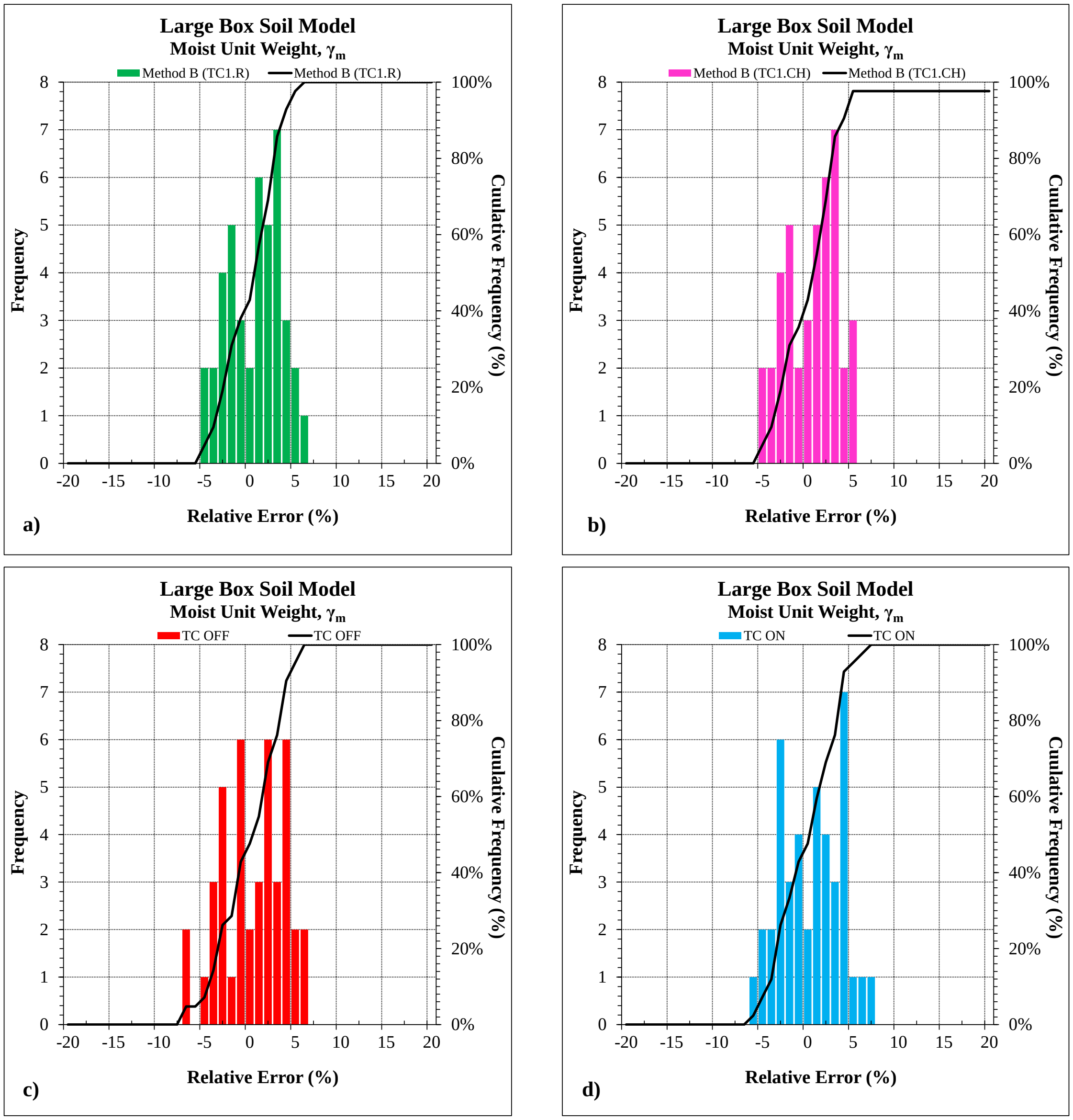


Figure 9.24 Relative Error Histograms & CDF Plots – Large Box Soil Model (Method B)
a) Histogram & CDF – Moist Unit Weight (TC 1.R)
b) Histogram & CDF – Moist Unit Weight (TC 1.CH)
c) Histogram & CDF – Moist Unit Weight (TC OFF)
d) Histogram & CDF – Moist Unit Weight (TC ON)

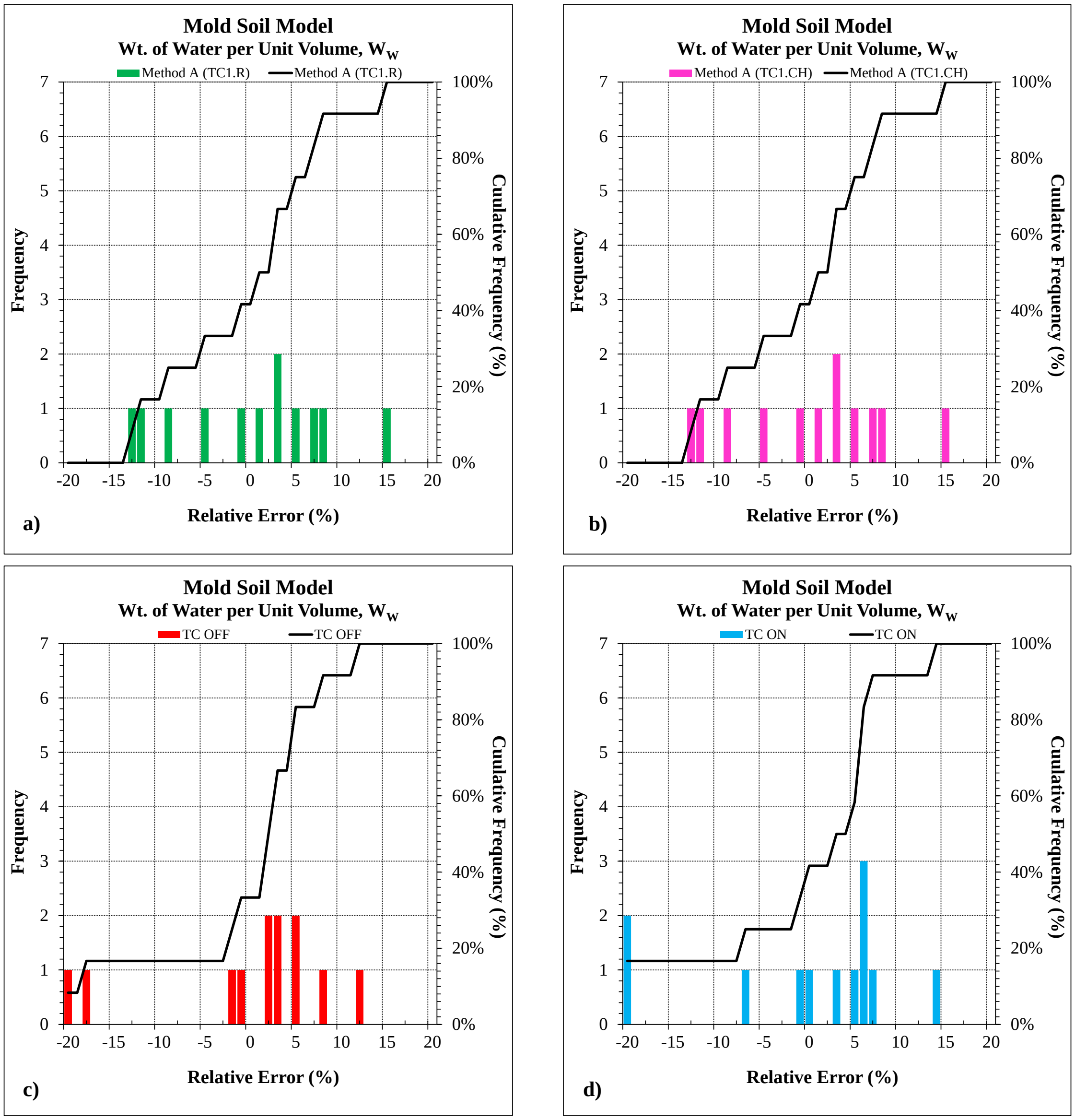


Figure 9.25 Relative Error Histograms and CDF Plots – Mold Soil Model (Method A)
a) Histogram & CDF – Wt. of Water per Unit Volume (TC 1.R)
b) Histogram & CDF – Wt. of Water per Unit Volume (TC 1.CH)
c) Histogram & CDF – Wt. of Water per Unit Volume (TC OFF)
d) Histogram & CDF – Wt. of Water per Unit Volume (TC ON)

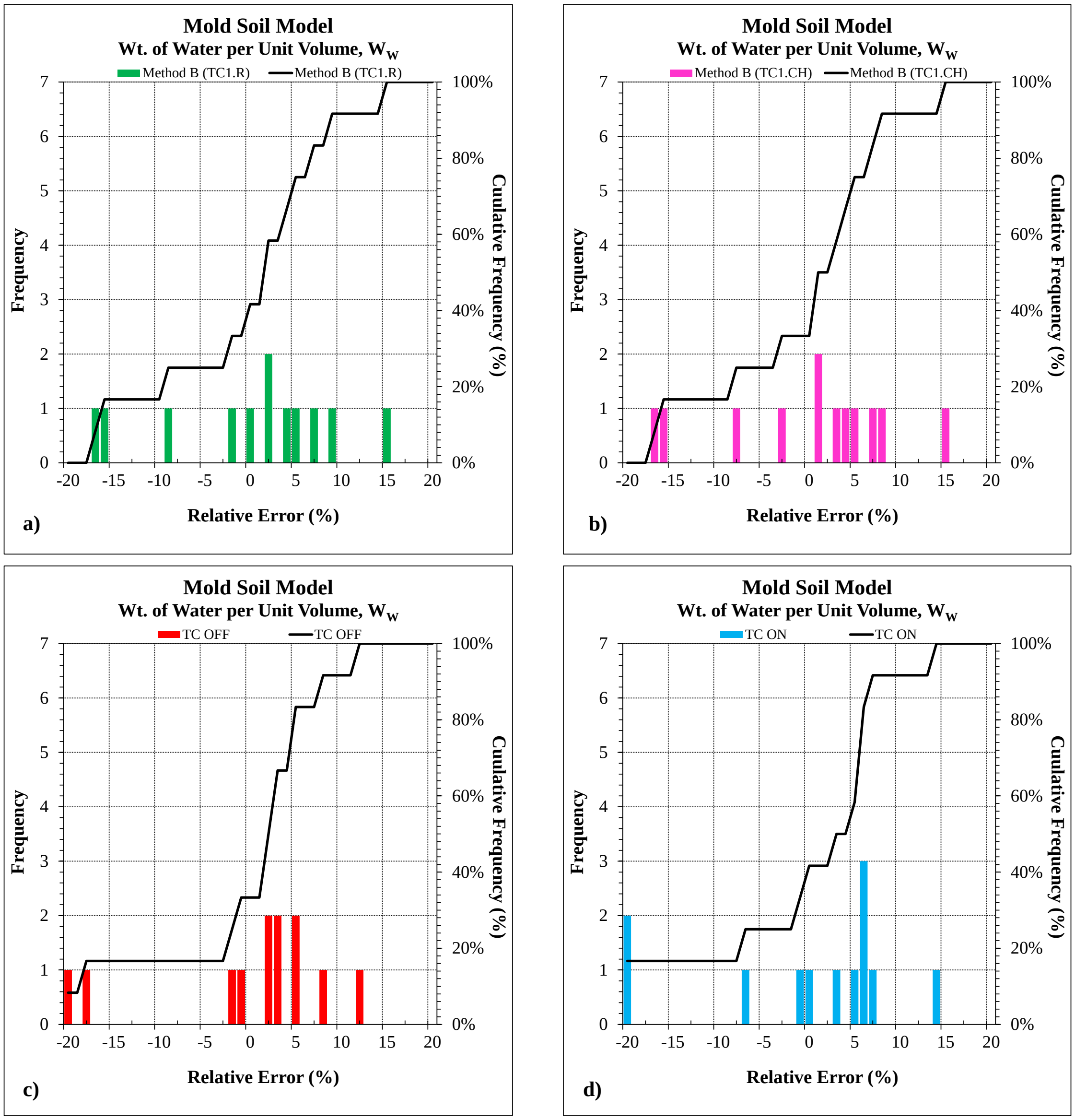


Figure 9.26 Relative Error Histograms and CDF Plots – Mold Soil Model (Method B)
a) Histogram & CDF – Wt. of Water per Unit Volume (TC 1.R)
b) Histogram & CDF – Wt. of Water per Unit Volume (TC 1.CH)
c) Histogram & CDF – Wt. of Water per Unit Volume (TC OFF)
d) Histogram & CDF – Wt. of Water per Unit Volume (TC ON)

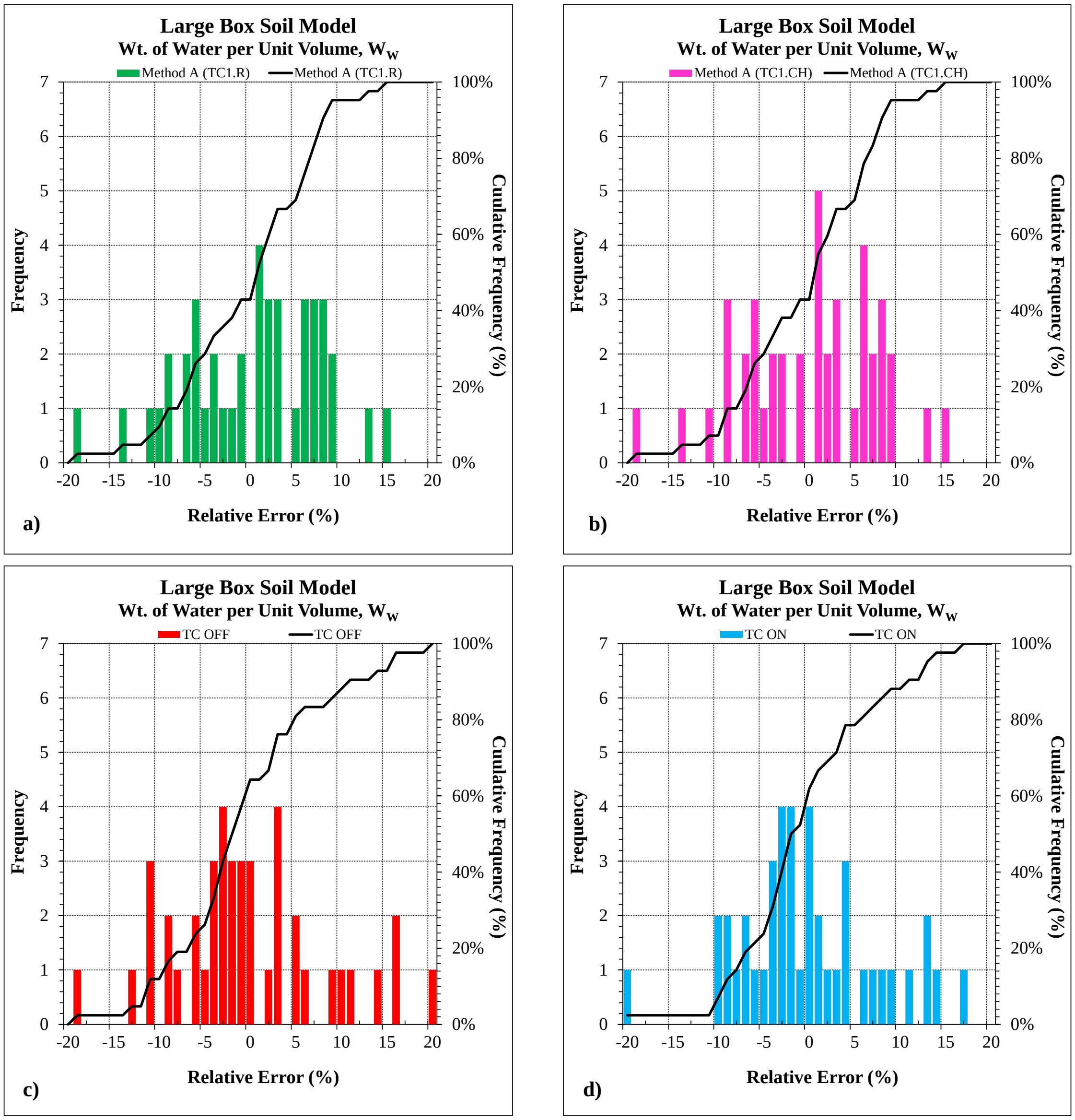


Figure 9.27 Relative Error Histograms and CDF Plots – Large Box Soil Model (Method A)
a) Histogram & CDF – Wt. of Water per Unit Volume (TC 1.R)
b) Histogram & CDF – Wt. of Water per Unit Volume (TC 1.CH)
c) Histogram & CDF – Wt. of Water per Unit Volume (TC OFF)
d) Histogram & CDF – Wt. of Water per Unit Volume (TC ON)

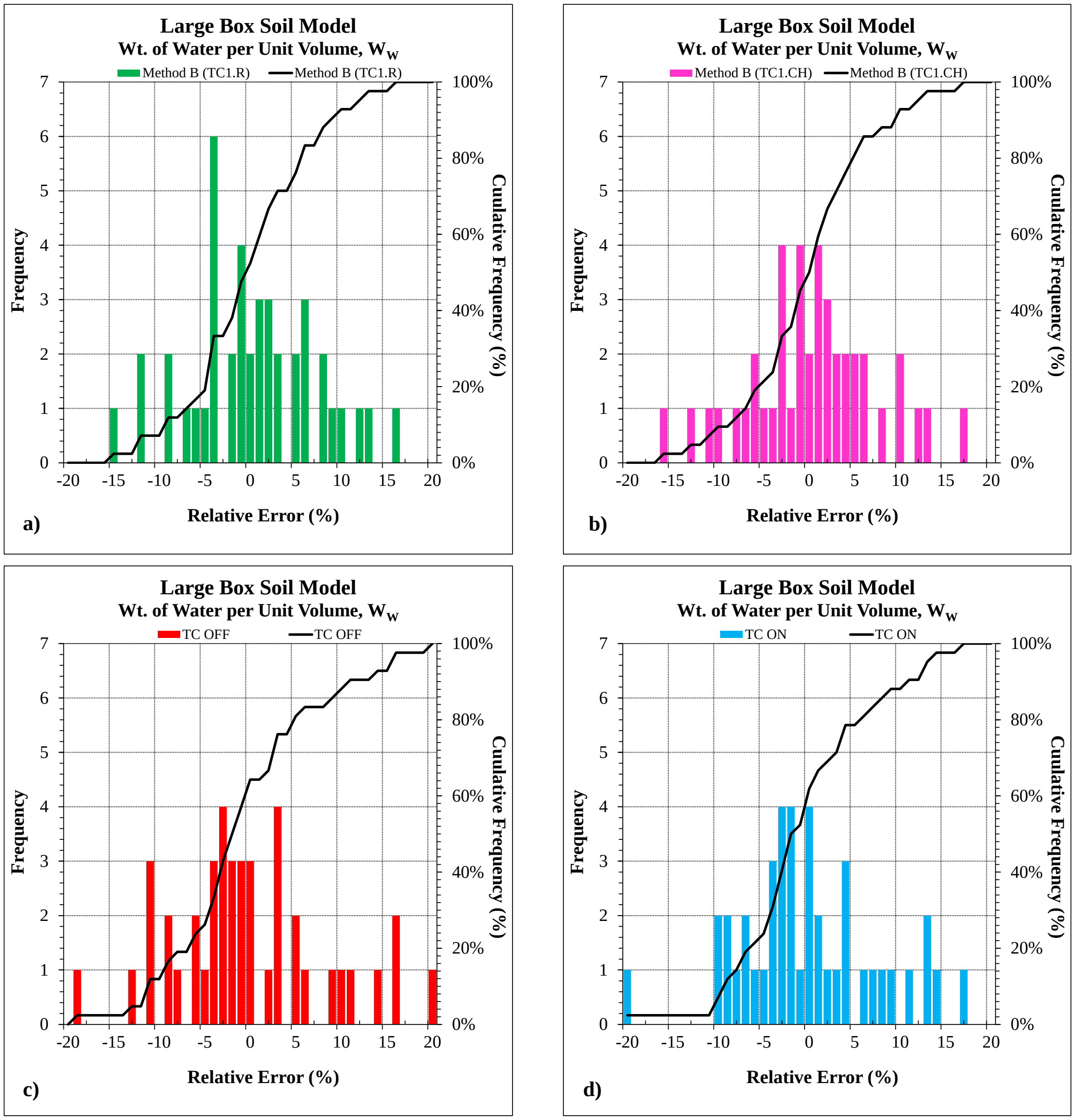


Figure 9.28 Relative Error Histograms and CDF Plots – Large Box Soil Model (Method B)
a) Histogram & CDF – Wt. of Water per Unit Volume (TC 1.R)
b) Histogram & CDF – Wt. of Water per Unit Volume (TC 1.CH)
c) Histogram & CDF – Wt. of Water per Unit Volume (TC OFF)
d) Histogram & CDF – Wt. of Water per Unit Volume (TC ON)

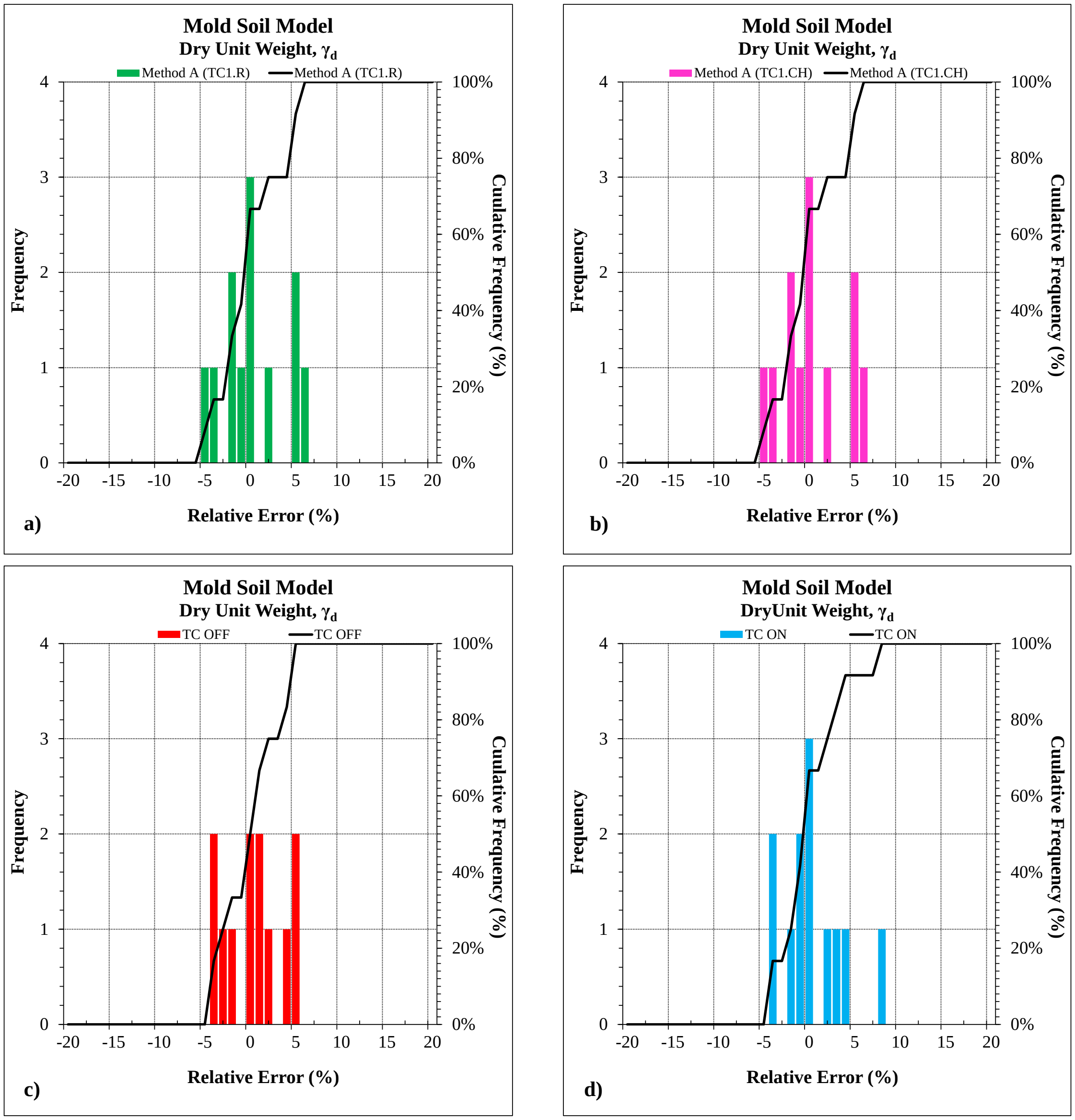


Figure 9.29 Relative Error Histograms and CDF Plots – Mold Soil Model (Method A)
a) Histogram & CDF – Dry Unit Weight (TC 1.R)
b) Histogram & CDF – Dry Unit Weight (TC 1.CH)
c) Histogram & CDF – Dry Unit Weight (TC OFF)
c) Histogram & CDF – Dry Unit Weight (TC ON)

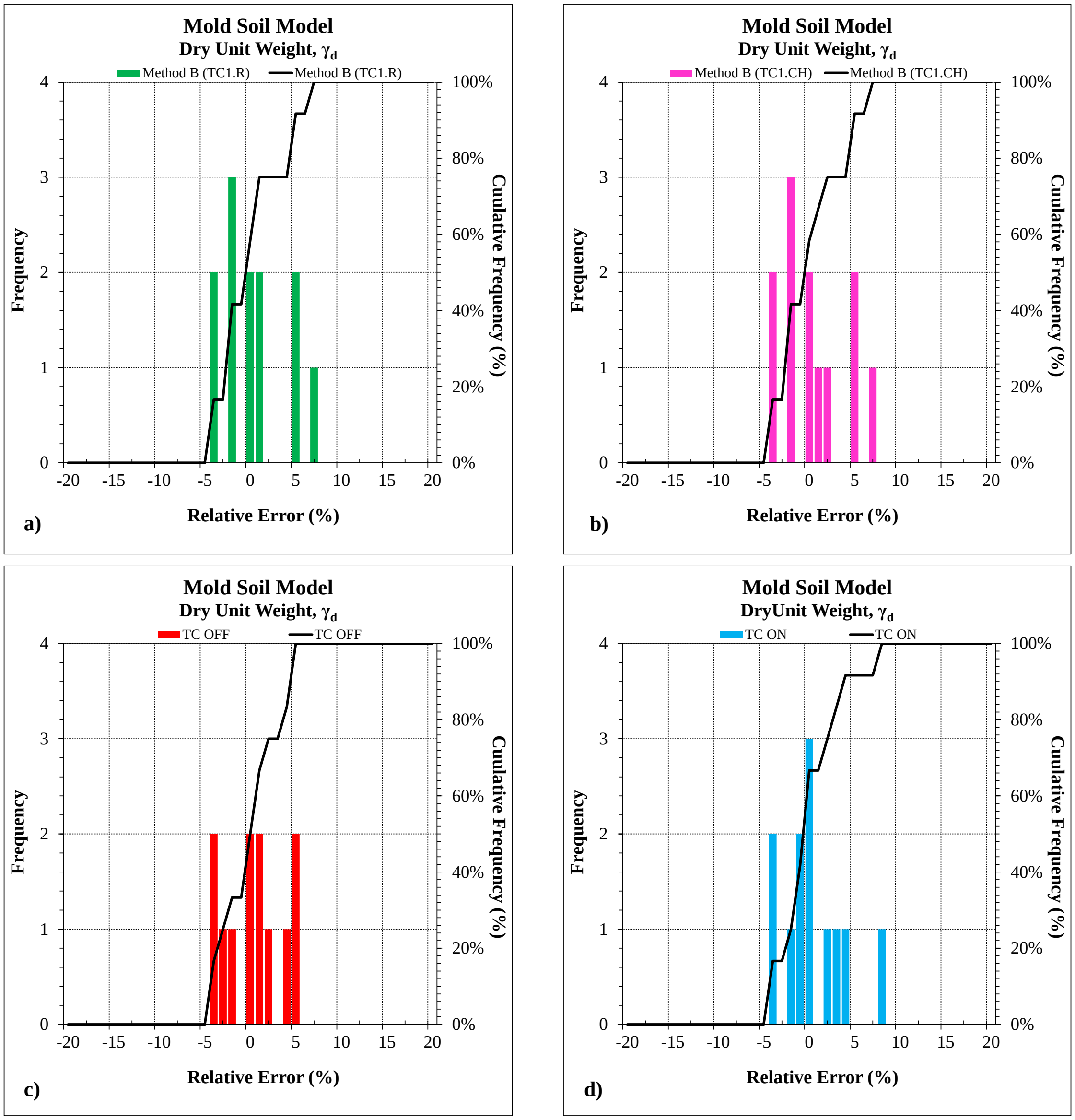


Figure 9.30 Relative Error Histograms and CDF Plots – Mold Soil Model (Method B)
a) Histogram & CDF – Dry Unit Weight (TC 1.R)
b) Histogram & CDF – Dry Unit Weight (TC 1.CH)
c) Histogram & CDF – Dry Unit Weight (TC OFF)
c) Histogram & CDF – Dry Unit Weight (TC ON)

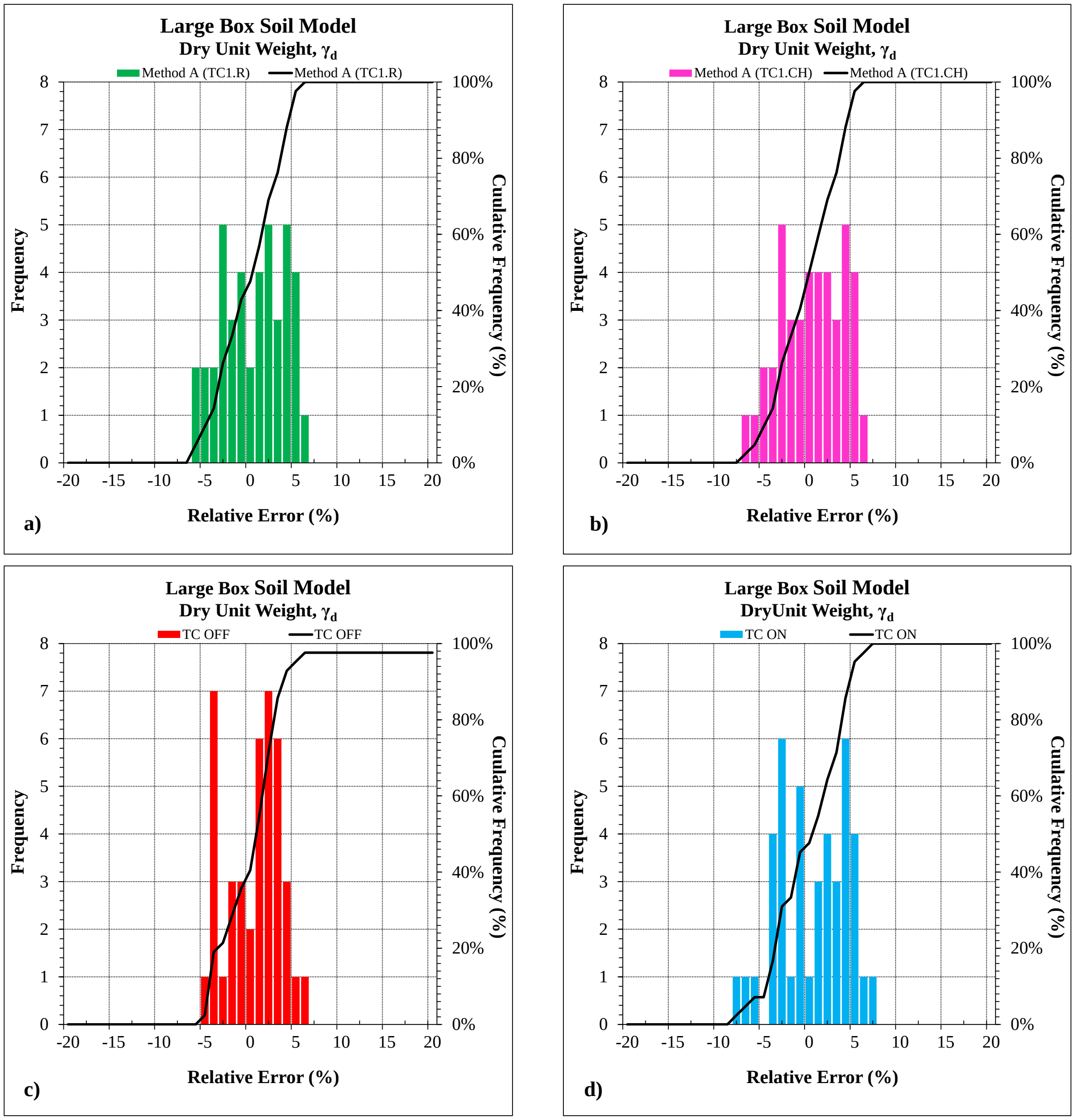


Figure 9.31 Relative Error Histograms and CDF Plots – Large Box Soil Model (Method A)
a) Histogram & CDF – Dry Unit Weight (TC 1.R)
b) Histogram & CDF – Dry Unit Weight (TC 1.CH)
c) Histogram & CDF – Dry Unit Weight (TC OFF)
c) Histogram & CDF – Dry Unit Weight (TC ON)

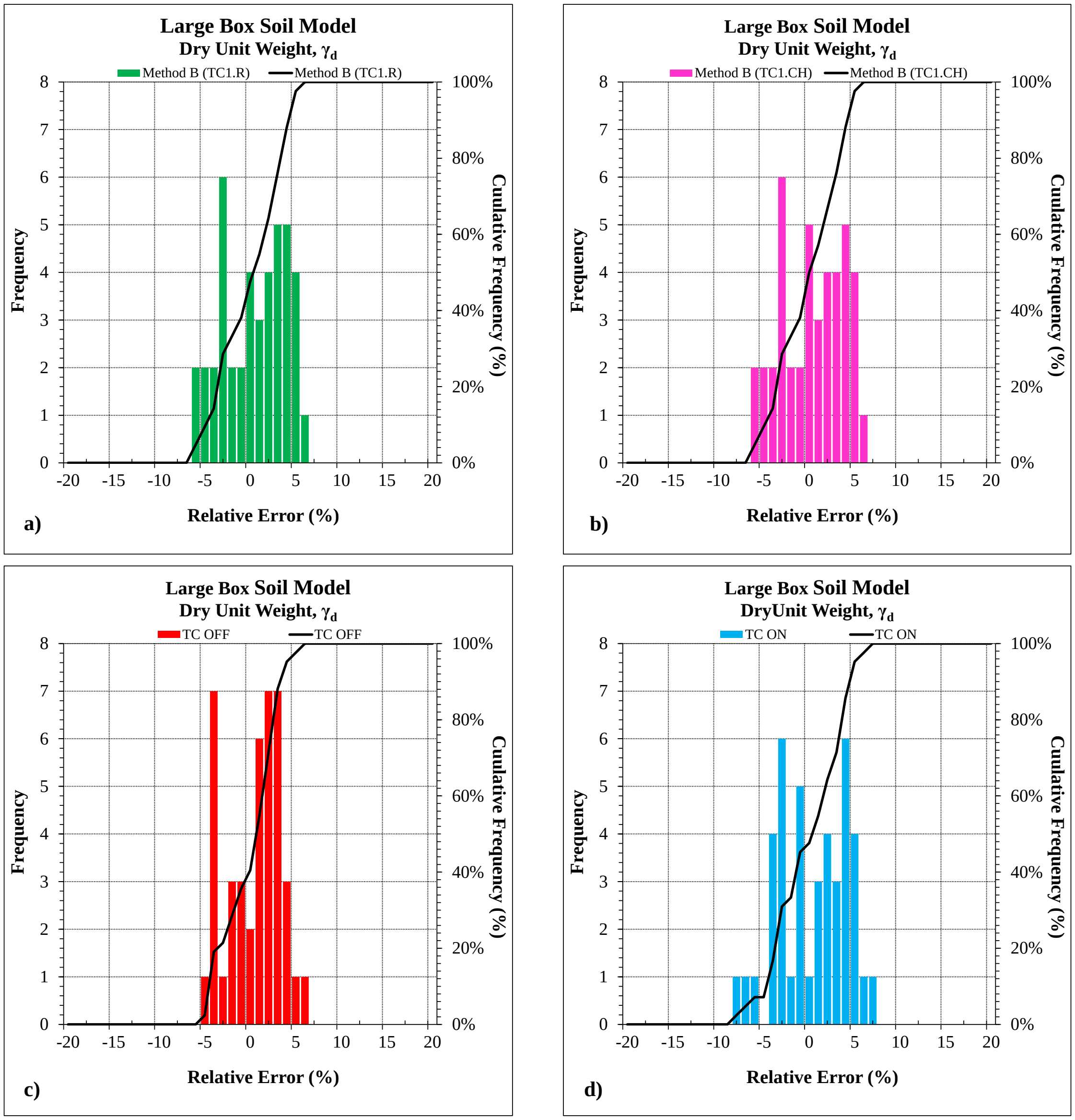


Figure 9.32 Relative Error Histograms and CDF Plots – Large Box Soil Model (Method B)
a) Histogram & CDF – Dry Unit Weight (TC 1.R)
b) Histogram & CDF – Dry Unit Weight (TC 1.CH)
c) Histogram & CDF – Dry Unit Weight (TC OFF)
c) Histogram & CDF – Dry Unit Weight (TC ON)

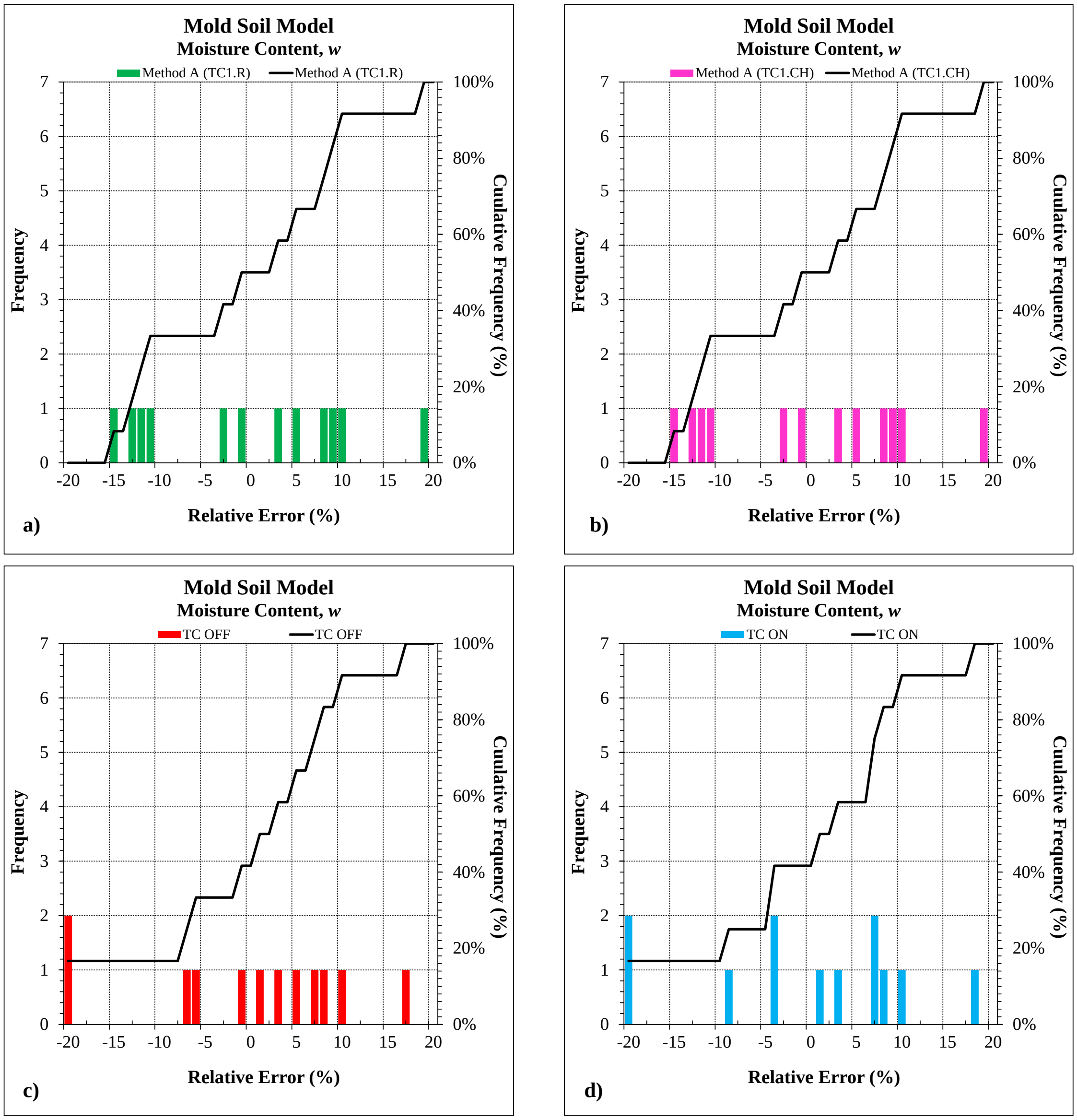


Figure 9.33 Relative Error Histograms and CDF Plots – Mold Soil Model (Method A)
a) Histogram & CDF – Moisture Content (TC 1.R)
b) Histogram & CDF – Moisture Content (TC 1.CH)
c) Histogram & CDF – Moisture Content (TC OFF)
c) Histogram & CDF – Moisture Content (TC ON)

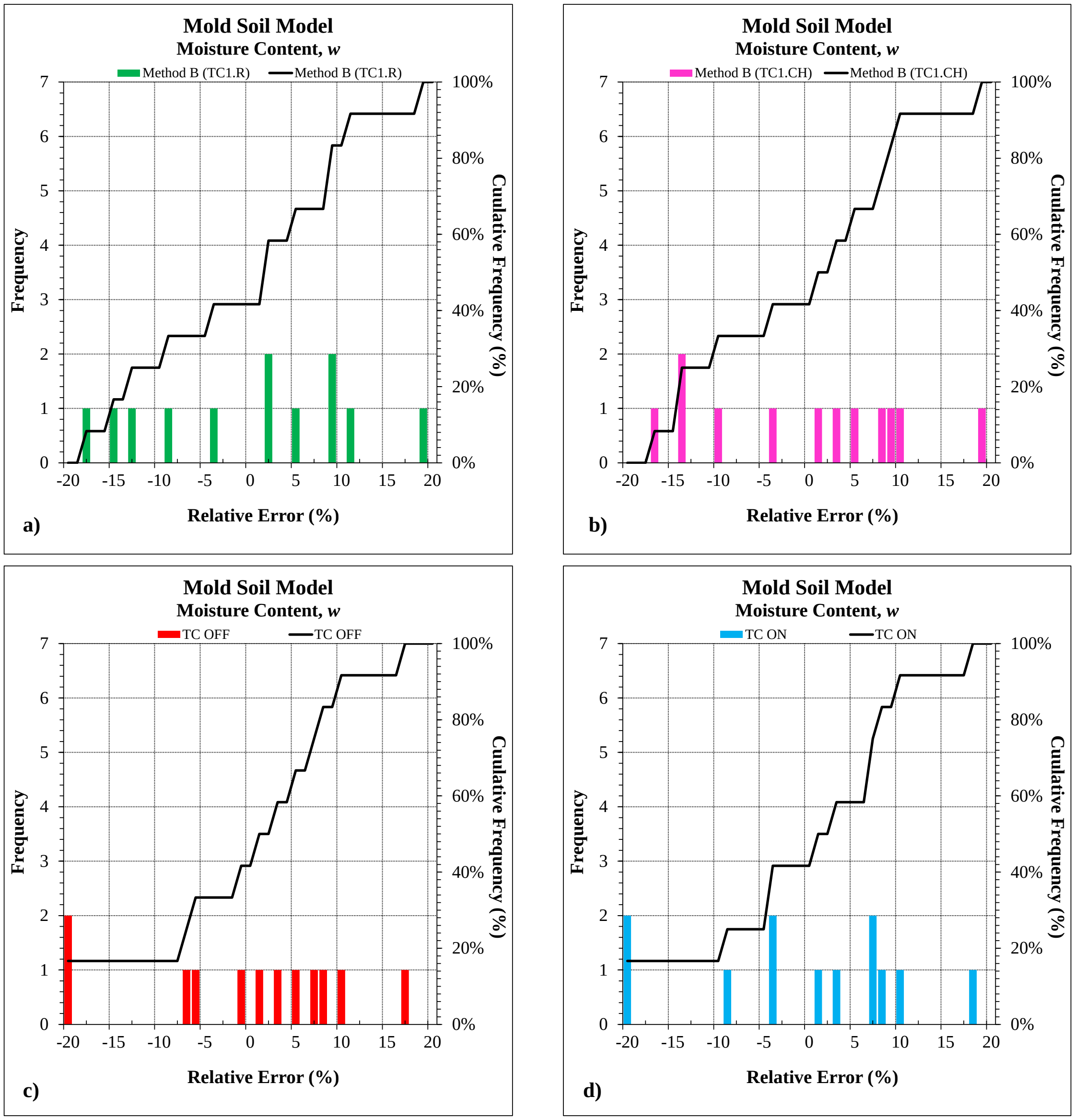


Figure 9.34 Relative Error Histograms and CDF Plots – Mold Soil Model (Method B)
a) Histogram & CDF – Moisture Content (TC 1.R)
b) Histogram & CDF – Moisture Content (TC 1.CH)
c) Histogram & CDF – Moisture Content (TC OFF)
c) Histogram & CDF – Moisture Content (TC ON)

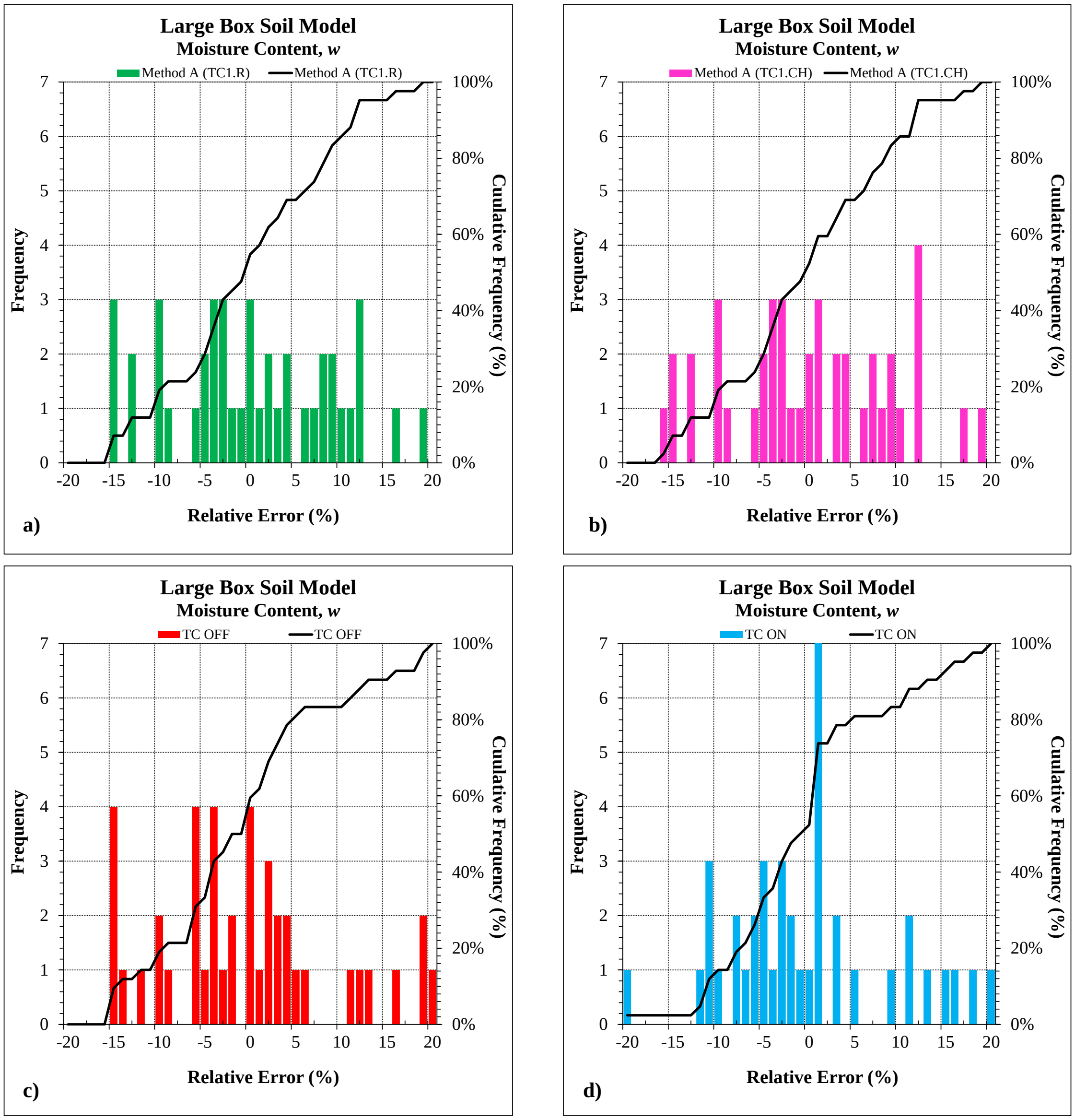


Figure 9.35 Relative Error Histograms and CDF Plots – Large Box Soil Model (Method A)
a) Histogram & CDF – Moisture Content (TC 1.R)
b) Histogram & CDF – Moisture Content (TC 1.CH)
c) Histogram & CDF – Moisture Content (TC OFF)
c) Histogram & CDF – Moisture Content (TC ON)

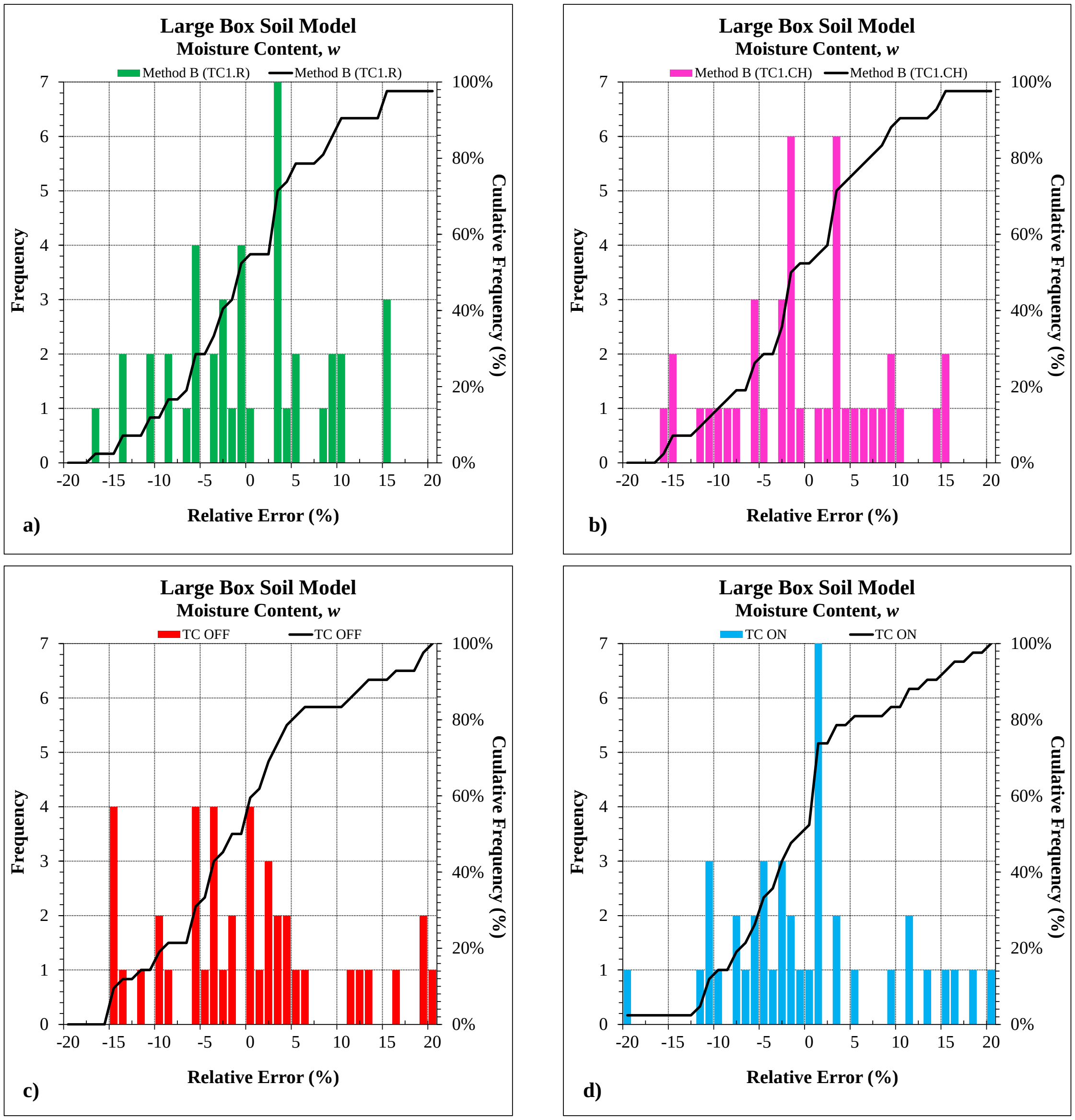


Figure 9.36 Relative Error Histograms and CDF Plots – Large Box Soil Model (Method B)
a) Histogram & CDF – Moisture Content (TC 1.R)
b) Histogram & CDF – Moisture Content (TC 1.CH)
c) Histogram & CDF – Moisture Content (TC OFF)
c) Histogram & CDF – Moisture Content (TC ON)

Table 9.35 Summary of Relative Error (%) – Mold Soil Model (Method A)

Mold Soil Model (Method A)								
	(TC 1.R)				(TC 1.CH)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-4.06	-5.10	-13.96	-15.07	-4.07	-5.10	-13.89	-15.13
MAX	4.81	5.78	14.67	18.81	4.78	5.77	14.70	18.84
RANGE	8.87	10.88	28.63	33.87	8.86	10.87	28.59	33.97
MEAN	-0.04	-0.12	-0.34	-0.50	-0.04	-0.12	-0.34	-0.50

Table 9.36 Summary of Relative Error (%) – Mold Soil Model (Method B)

Mold Soil Model (Method B)								
	(TC 1.R)				(TC 1.CH)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-3.73	-4.95	-17.37	-18.44	-3.80	-4.99	-17.02	-17.55
MAX	5.53	6.29	14.66	18.68	5.37	6.18	14.27	18.35
RANGE	9.26	11.24	32.03	37.12	9.16	11.17	31.29	35.90
MEAN	0.02	-0.06	-0.42	-0.62	0.01	-0.06	-0.40	-0.60

Table 9.37 Summary of Relative Error (%) – Large Box Soil Model (Method A)

Large Box Soil Model (Method A)	(TC 1.R)				(TC 1.CH)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-5.57	-5.22	-14.19	-15.99	-5.54	-5.20	-14.22	-16.02
MAX	4.96	5.77	6.06	6.71	4.95	5.76	5.84	6.45
RANGE	10.54	10.99	20.25	22.70	10.49	10.96	20.05	22.47
MEAN	1.12	1.64	-4.00	-5.87	1.12	1.65	-4.04	-5.92

Table 9.38 Summary of Relative Error (%) – Large Box Soil Model (Method B)

Large Box Soil Model (Method B)	(TC 1.R)				(TC 1.CH)			
	γ_m	γ_d	W_w	w	γ_m	γ_d	W_w	w
MIN	-5.52	-5.21	-12.55	-14.62	-5.44	-5.17	-13.06	-15.12
MAX	5.02	5.72	7.08	8.05	4.98	5.71	5.98	6.84
RANGE	10.54	10.93	19.63	22.67	10.43	10.88	19.04	21.96
MEAN	1.14	1.54	-2.74	-4.48	1.11	1.53	-3.08	-4.83

Table 9.39 Summary of Relative Error (%): Net Percent Change between TC 1.R and TC OFF/TC ON - Mold Soil Model (Method A)

Mold Soil Model (Method A)

(TC 1.R - TC OFF)

	γ_m	γ_d	W_w	*w*
MIN	-6.41%	-3.95%	-44.96%	-33.18%
MAX	-0.77%	7.13%	25.82%	16.74%
RANGE	-3.44%	1.64%	-22.68%	-12.38%
MEAN	-62.00%	-7.35%	-61.31%	-46.28%

(TC1.R - TC ON)

	γ_m	γ_d	W_w	*w*
MIN	13.64%	14.61%	-48.45%	-40.50%
MAX	-30.48%	-20.82%	5.91%	9.34%
RANGE	-15.44%	-7.41%	-30.06%	-20.34%
MEAN	-57.23%	10.97%	-69.23%	-55.78%

Table 9.40 Summary of Relative Error (%): Net Percent Change between TC 1.CH and TC OFF/TC ON - Mold Soil Model (Method A)

Mold Soil Model (Method A)

(TC 1.CH - TC OFF)

	γ_m	γ_d	W_w	*w*
MIN	-6.16%	-3.88%	-45.25%	-32.90%
MAX	-1.29%	6.88%	26.09%	16.94%
RANGE	-3.59%	1.54%	-22.79%	-12.13%
MEAN	-62.24%	-6.28%	-60.78%	-45.84%

(TC1.CH - TC ON)

	γ_m	γ_d	W_w	*w*
MIN	13.94%	14.68%	-48.73%	-40.25%
MAX	-30.84%	-21.00%	6.14%	9.53%
RANGE	-15.57%	-7.49%	-30.17%	-20.11%
MEAN	-57.50%	12.26%	-68.81%	-55.41%

Table 9.41 Summary of Relative Error (%): Net Percent Change between TC 1.R and TC OFF/TC ON - Mold Soil Model (Method B)

Mold Soil Model (Method B)

(TC 1.R - TC OFF)

	γ_m	γ_d	W_w	w
MIN	-14.05%	-6.73%	-31.52%	-18.21%
MAX	14.02%	16.46%	25.71%	15.95%
RANGE	0.75%	4.96%	-13.50%	-3.97%
MEAN	-81.35%	-52.54%	-52.45%	-33.21%

(TC1.R - TC ON)

	γ_m	γ_d	W_w	w
MIN	4.35%	11.28%	-35.87%	-27.16%
MAX	-20.11%	-13.92%	5.82%	8.60%
RANGE	-11.77%	-4.38%	-21.77%	-12.69%
MEAN	-79.01%	-43.15%	-62.18%	-45.02%

Table 9.42 Summary of Relative Error (%): Net Percent Change between TC 1.CH and TC OFF/TC ON - Mold Soil Model (Method B)

Mold Soil Model (Method B)

(TC 1.CH - TC OFF)

	γ_m	γ_d	W_w	w
MIN	-12.55%	-5.93%	-32.91%	-22.16%
MAX	10.76%	14.43%	22.45%	13.91%
RANGE	-0.26%	4.33%	-15.48%	-7.13%
MEAN	-84.93%	-51.46%	-54.63%	-35.74%

(TC1.CH - TC ON)

	γ_m	γ_d	W_w	w
MIN	6.19%	12.23%	-37.17%	-30.68%
MAX	-22.40%	-15.42%	3.07%	6.69%
RANGE	-12.65%	-4.95%	-23.56%	-15.56%
MEAN	-83.04%	-41.86%	-63.92%	-47.10%

Table 9.43 Summary of Relative Error (%): Net Percent Change between TC 1.R and TC OFF/TC ON – Large Box Soil Model (Method A)

Large Box Soil Model (Method A)

(TC 1.R - TC OFF)

	γ_m	γ_d	W_w	w
MIN	7.89%	8.13%	1.49%	3.74%
MAX	-7.21%	-0.46%	227.55%	3562.30%
RANGE	0.21%	3.44%	27.92%	49.07%
MEAN	-12.17%	-15.88%	-40.57%	-34.28%

(TC1.R - TC ON)

	γ_m	γ_d	W_w	w
MIN	-18.12%	-21.68%	44.45%	41.97%
MAX	-17.72%	-11.83%	197.82%	130.13%
RANGE	-17.93%	-16.80%	70.77%	60.10%
MEAN	-10.58%	-3.14%	11.13%	6.62%

Table 9.44 Summary of Relative Error (%): Net Percent Change between TC 1.CH and TC OFF/TC ON – Large Box Soil Model (Method A)

Large Box Soil Model (Method A)

(TC 1.CH - TC OFF)

	γ_m	γ_d	W_w	w
MIN	7.24%	7.69%	1.70%	3.97%
MAX	-7.52%	-0.64%	215.39%	3420.06%
RANGE	-0.27%	3.15%	26.68%	47.59%
MEAN	-12.11%	-15.63%	-39.96%	-33.72%

(TC1.CH - TC ON)

	γ_m	γ_d	W_w	w
MIN	-18.62%	-22.00%	44.75%	42.28%
MAX	-18.00%	-11.99%	186.76%	121.19%
RANGE	-18.33%	-17.04%	69.12%	58.51%
MEAN	-10.53%	-2.85%	12.27%	7.53%

Table 9.45 Summary of Relative Error (%): Net Percent Change between TC 1.R and TC OFF/TC ON – Large Box Soil Model (Method B)

Large Box Soil Model (Method B)				
(TC 1.R - TC OFF)				
	γ_m	γ_d	W_w	w
MIN	6.92%	7.84%	-10.22%	-5.15%
MAX	-6.24%	-1.26%	282.78%	4294.65%
RANGE	0.23%	2.88%	24.03%	48.88%
MEAN	-10.66%	-21.09%	-59.25%	-49.85%
(TC1.R - TC ON)				
	γ_m	γ_d	W_w	w
MIN	-18.86%	-21.89%	27.78%	29.80%
MAX	-16.86%	-12.53%	248.04%	176.15%
RANGE	-17.92%	-17.26%	65.59%	59.91%
MEAN	-9.05%	-9.14%	-23.79%	-18.65%

Table 9.46 Summary of Relative Error (%): Net Percent Change between TC 1.CH and TC OFF/TC ON – Large Box Soil Model (Method B)

Large Box Soil Model (Method B)				
(TC 1.CH - TC OFF)				
	γ_m	γ_d	W_w	w
MIN	5.42%	7.03%	-6.58%	-1.87%
MAX	-6.86%	-1.55%	223.19%	3633.83%
RANGE	-0.83%	2.35%	20.28%	44.25%
MEAN	-12.99%	-21.35%	-54.20%	-45.94%
(TC1.CH - TC ON)				
	γ_m	γ_d	W_w	w
MIN	-20.00%	-22.48%	32.96%	34.29%
MAX	-17.41%	-12.79%	193.86%	134.63%
RANGE	-18.78%	-17.68%	60.58%	54.93%
MEAN	-11.42%	-9.43%	-14.35%	-12.29%

9.6 Discussion of Results

The coefficient of determination (R^2) values for the calibration equations created using Method A and Method B with the new temperature correction applied (TC 1) are all higher than the R^2 values for the standard default calibration equations with both the EDG temperature correction applied (TC ON) and without the EDG temperature correction applied (TC OFF).

The associated RMSE, CV(RMSE), and NRMSE values for the EDG predicted soil properties (γ_m, γ_d, W_w, w) using Method A and Method B with the new temperature correction applied (TC 1) are all generally lower than the RMSE, CV(RMSE), and NRMSE values for the EDG-predicted soil properties using the standard default calibration relationships with both the EDG temperature correction applied (TC ON) and without the EDG temperature correction applied (TC OFF).

In addition, the minimum, maximum, range, and mean of the relative error for the EDG predicted soil properties (γ_m, γ_d, W_w, w) using Method A and Method B with the new temperature correction applied (TC 1) are all lower than the values using the standard default calibration relationships with both the EDG temperature correction applied (TC ON) and without the EDG temperature correction applied (TC OFF).

9.7 Conclusions

From the raw data and associated analysis presented in this chapter, it is evident that the new calibration relationships (Method A and Method B) coupled with the new temperature correction (TC 1) generally improve the results in most cases compared to the standard default EDG calibration relationships and temperature correction.

In previous chapters and from the data presented in this chapter, it can be observed that dry unit weight predictions have a much lower standard deviation from the average value than their counterparts (i.e, NDG test values, DC test values, Mold values). This observation is typically illustrated by a nearly vertical line of data in 1:1 plots comparing dry unit weight values, which indicates there is typically much less variability in the EDG predicted values when compared to any of the other tests conducted. This signifies that there may not be a strong direct relationship between the dry unit weight of a soil and any of the electrical parameters measured by the EDG. This correlation analysis helps to reiterate that the relationship between the dry unit weight of a compacted soil and the electrical parameters measured by the EDG is not very strong.

Chapter 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

The effectiveness and accuracy of the Electrical Density Gauge (EDG) was evaluated in this research project. A preliminary field study was performed on two active construction projects in Dover, DE and Middletown, DE. Evaluation of the in-situ testing process and data gathered during this preliminary study led to the following conclusions:

- It is difficult to construct a soil model using a field calibration process that spans the potential range of moisture contents and soil densities that could be encountered during the field compaction process. This is in part because of the fact that, on a typical roadway project, contractors try to maintain the same moisture content and reach the same density for the fill material they are compacting. This creates a difficulty when trying to build a soil model that spans the range of densities and moisture contents that may be encountered in a fair and representative way. Getting the field variability in moisture content that is necessary to build a good moisture calibration relationship for the EDG can be particularly challenging under certain field conditions.
- There are inherent uncertainties and sources of error in the tests that are used for field calibration of the EDG. In particular, the field calibration

process requires the use of a NDG or other standard in-situ density test like the sand cone or rubber balloon test. These tests have their own uncertainty and sources of error in measurement, and consequently this error has the potential to become compounded when building a soil model. This means that the accuracy of the EDG can never be more than the accuracy of the test which it is calibrated against, which has the potential to limit the EDG's capabilities (e.g., it may be possible to achieve more accurate results with the EDG than those from the SC or NDG test, but this cannot be achieved if other tests are being used for EDG calibration). Further, the necessity of having to use the NDG as part of the EDG calibration process necessitates that DelDOT remain compliant with Nuclear Regulatory Commission (NRC) guidelines, which partially defeats some of the potential advantages of the EDG.

- Soil variability on a given construction project can cause difficulties when trying to build a soil model with the EDG. In particular, the EDG appears to be more sensitive than the NDG to variations in the soil borrow source. This effect is evident if the results from the Dover project are compared against those from the Middletown project. Changes in the quantity or nature of the fines in a borrow soil are believed to have a significant effect on measured EDG results. This is because the electrical characteristics of a soil matrix are significantly affected by the characteristics of the finer particles in the matrix.
- In some cases, it appears that the EDG temperature correction algorithm can lower the R^2 values for the calibration curves, thus not

improving the results. The EDG temperature correction algorithm does not seem to properly capture the effect of temperature on the soils that were tested in the current field study.

After considerable time was spent trying to acquire the necessary data on these two active construction projects to fairly assess the EDG, it was determined that this approach was not the most desirable. The inability to control moisture content and temperature of the soil precisely in the field, as well as practical contractual requirements which necessitated that EDG calibration should not significantly slow the process of field construction led to development of a second experimental study for calibration and assessment of the EDG. "Large box" testing of soil in conjunction with large mold testing was performed to acquire the necessary data to evaluate the accuracy of the EDG. The evaluation of the mold calibration procedure and large box testing indicated the following:

- EDG electrical measurements of soil are believed to be very sensitive to the fines content of the soil. The electrical characteristics of a soil matrix are significantly affected by the nature of the finer particles in the matrix, and may have a significant effect on the EDG electrical measurements.
- From the density based tests that were conducted (EDG, NDG, sand cone (SC), and drive cylinder (DC)), the nuclear density gauge and drive cylinder tests generally have the best agreement out of all of the tests for moist unit weight, weight of water per unit volume, and dry unit weight.

- The moisture content determined from the sand cone test and the drive cylinder test had the best agreement.
- All QA/QC compaction test results exhibit scatter, when compared to one another. When compared with the drive cylinder (DC) test, the electrical density gauge (EDG) provides results with slightly higher RMSE, CV(RMSE), NRMSE, and relative error (%) values than its comparable in situ density-based testing counterparts, particularly the nuclear density gauge (NDG).
- The EDG temperature correction algorithm did not significantly improve the EDG test results for the soils tested in this study. The default EDG temperature correction algorithm does not seem to properly capture the effect of temperature on the soils that were tested in this study.
- Assessment approaches where one data set is used for calibration and a different data set is used for assessment are more rigorous than approaches that use the same data set for calibration and assessment. Approaches like this will consequently have more scatter, but are more likely a better representation of the behavior observed in a practical field testing environment for any of the conventional compaction QA/QC tests.

From the previous analysis, we recognized the default manufacturer temperature correction was not improving the results of the preliminary studies for the soils tested in this research study. In order to gain more understanding of the effect of changes in temperature on EDG electrical readings, a rigorous temperature testing procedure was performed using the molds. A new empirical temperature correction algorithm was developed and applied to some of the data sets obtained in this research study. From the analysis presented, it was clear that the new empirical temperature correction algorithm generally improved the results.

In addition to the new temperature correction algorithm developed, alternative calibration relationships were explored to see if better results for the EDG could be obtained. Two alternative methods were presented and applied to select data sets from this research study. Once again, from the analysis presented it was clear that the new calibration relationships combined with the new temperature correction algorithm generally improved the results and improve the accuracy of the EDG.

10.2 Future Research Recommendations

Based on the experience and data collected from this research study, the following areas of research should be explored to help improve the accuracy of the EDG and to aid in understanding the electrical properties of soil:

- Perform more field studies on a variety of commonly used soils and other construction materials to confirm the results that were observed in this initial evaluation study to further evaluate the accuracy and effectiveness of the EDG.
- Perform more tests in different soil types to further understand the effect of temperature on electrical measurements of the EDG.
- Explore more calibration relationships for the EDG using advanced statistical techniques.

- Perform extremely complex thermo-hydro-electro-chemo-mechanical modeling and develop constitutive relationships between thermal, hydrological, electrical, chemical, and mechanical forces that interact with one another during the compaction of soil.

REFERENCES

AASHTO (2004). "Standard Method of Test for Family of Curves-One-Point Method." AASHTO T 272, American Association of State Highway and Transportation Officials, Washington, D.C.

ASTM (2005). "Standard Test Method for Water Content and Density of Soil in Place by Time Domain Reflectometry (TDR)." ASTM D 6780, ASTM International, West Conshohocken, PA.

ASTM (2006). "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3))." ASTM D 1557, ASTM International, West Conshohocken, PA.

ASTM (2006). "Standard Test Methods for Particle Size (Sieve Analysis) of Plastic Materials." ASTM D 1921, ASTM International, West Conshohocken, PA.

ASTM (2006). "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft3(600 kN-m/m3))." ASTM D 698, ASTM International, West Conshohocken, PA.

ASTM (2007). "Standard Test Method for Density and Unit Weight of Soil in Place by the Sand-Cone Method." ASTM D 1556, ASTM International, West Conshohocken, PA.

ASTM (2007). "Standard Test Method for Particle Size Analysis of Soils." ASTM D 422-63, ASTM International, West Conshohocken, PA.

ASTM (2008). “Standard Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating .” ASTM D 4643, ASTM International, West Conshohocken, PA.

ASTM (2008). “Standard Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method .” ASTM D 2167, ASTM International, West Conshohocken, PA.

ASTM (2008). “Standard Practice for Description and Identification of Soils (Visual Manual Procedure). ” ASTM D 2488, ASTM International, West Conshohocken, PA.

ASTM (2010). “Standard Test Methods for Density of Soil in Place by the Drive-Cylinder Method.” ASTM D 2937, ASTM International, West Conshohocken, PA.

ASTM (2010). “Standard Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth).” ASTM D 6938, ASTM International, West Conshohocken, PA.

ASTM (2010). “Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.” ASTM D 4318, ASTM International, West Conshohocken, PA.

ASTM (2010). “Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass.” ASTM D 2216, ASTM International, West Conshohocken, PA.

ASTM (2011). “Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).” ASTM D 2487, ASTM International, West Conshohocken, PA.

ASTM (2011). “Standard Test Methof for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance Method.” ASTM D 7698, ASTM International,West Conshohocken, PA.

DelDOT (2001). *Division 200 Earthwork*, Delaware Department of Transportation.

Drnevich, V. P., Lin, C. P., Yi, Q., Yu, X., and Lovell J. (2001a). ‘‘Realtime determination of soil type, water content and density using electromagnetics.’’ *Rep. No.: FHWA/IN/JTRP-2000-20,* Joint Transportation Research Program, Indiana Department of Transportation-Purdue University. (http://rebar.ecn.purdue.edu/jtrp/final–report/spr–2201–final–form1700.pdf)

Drnevich, V. P., Yu, X., and Lovell, J. (2002). ‘‘A new method for water content and in situ density determination.’’ *Proc., Great Lakes Geotechnical and Geoenvironmental Conference*, Toledo, Ohio.

Fares, A., Hamdhani, H., and Jenkins, D.M. (2007). “Temperature-Dependent Scaled Frequency: Improved Accuracy of Multisensor Capacitance Probes.” *Soil Science Society of America Journal*, 71, 894-900.

Freedman, David, Pisani, Robert, and Purves, Roger (1998). *Statistics*. New York: W.W. Norton.

Gabr, M.A, Gray, C.A., Taylor, H.M. (1995). “Nuclear Gage Tests on Soils Containing Various Sized Aggregates,” *American Society of Civil Engineers, Geotechnical Special Publication,* (56) , 35-47.

Gamache, Ronald W., Kianirad, Ehsan, Pluta, Sarah E., Jersey, Sarah, and Alshawabkeh, Akram N. (2009). “Rapid Field Soil Characterization System for Construction Control.” *Transportation Research Board 88th Annual Meeting, Paper No. 09-2767.*

Ishai, Ilan & Livneh, Moshe (1983). “Comparative Accuracy of In-Situ Nuclear Density Testing.” *Geotechnical Engineering*, 14(1), 1-21.

Kaderabek, T.J., and Ferris, W.R. (1979). “Comparisons of Field Density Test Results.” *ASTM Geotechnical Testing Journal,* 2(4), 206–210.

Kelleners, T.J., Soppe, R.W.O, Robinson, D.A., Schaap, M.G., Ayars, J.E., and Skaggs, T.H. (2004). “Calibration of capacitance probe sensors using electric circuit theory.” *Soil Science Society of America Journal*, 68, 430-439.

Kraus, J.D., 1984. Electromagnetics. 3rd ed., McGraw-Hill, New York.

Lin, C., Siddiqui, S.I., Feng, W., Drnevich, V.P., and Deschamps, R.J. (1999). “Quality Control of Earth Fills Using Electromagnetic Waves.” *Constructing and Controlling Compaction of Earth Fills, ASTM STP1384*. American Society for Testing and Materials, West Conshohocken, PA.

Neiber, J.L., and Baker, J.M. (1989). "In Situ Measurement of Soil Water Content in the Presence of Freezing/Thawing Conditions." *State of the Art of Pavement Response Monitoring Systems for Roads and Airfields*, V. Janoo and R. Eaton, Eds., U.S. Army CRREL, Spec. Rep. 89-23.

Noorany, I., Gardner, W.S., Corley, D.J., and Brown, J.L. (2000). "Variability in Field Density Tests." *Constructing and Controlling Compaction of Earth Fills, ASTM STP 1384.* American Society for Testing and Materials, West Conshohocken, PA, 58–71.

Randrup, Thomas B., and Lichter, John M. (2001). "Measuring Soil Compaction on Construction Sites: A Review of Surface Nuclear Gauges and Penetrometers." *Journal of Arboriculture*, 27(3), 109-117.

Rosser, Thomas B., and Webster, Steve L. (1969). "Evaluation of Nuclear Methods of Determining Surface In Situ Soil Water Content and Density." U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Schwank, Mike and Green, Timothy R. (2007). "Simulated Effects of Soil Temperature and Salinity on Capacitance Sensor Measurements." *Sensors,* 7, 548-577.

Siddiqui, S.I. and Drnevich, V.P. (1995). "Use of Time Domain Reflectometry for the Determination of Water Content and Density of Soil." FHWA/IN/JHRP-95/9, Purdue University, West Lafayette.

Troxler Model 3430 Manual of Operation and Instruction, 1990-2006. Troxler Electronic Laboratories, Inc., Research Triangle Park, NC.

Topp, G.C., Davis, J.L., and Annan, A.P. (1980). "Electromagnetic Determination of Soil Water Content: Measurement in Coaxial Transmission Lines." *Water Resources Research*, 24, 945-952.

Yu, Xiong, and Drnevich, V. P. (2004). "Soil Water Content and Dry Density by Time Domain Reflectometry." *Journal of Geotechnical and Geoenvironmental Engineering*, 130(9), 922-934.

Yu, Xiong, Drnevich, Vincent P., and Nowack, Robert L. (2006). "Soil Property Variation by Time Domain Reflectometry." *Unsaturated Soil, Proceedings of the Fourth International Conference on Unsaturated Soils,* 1(417), 553-564.

Appendix A

INDIVIDUAL MOLDS:

COOLING, HEATING, & CONSTANT TEMPERATURE ROOM TESTING

This appendix contains figures that illustrate the electrical properties recorded by the Electrical Density Gauge (EDG) over a range of temperatures. There are 12 figures, one for each of the molds that were tested in the temperature controlled rooms. Within each figure, data is presented for the cooling cycle, heating cycle, and constant temperature room testing, as described in Chapter 7.

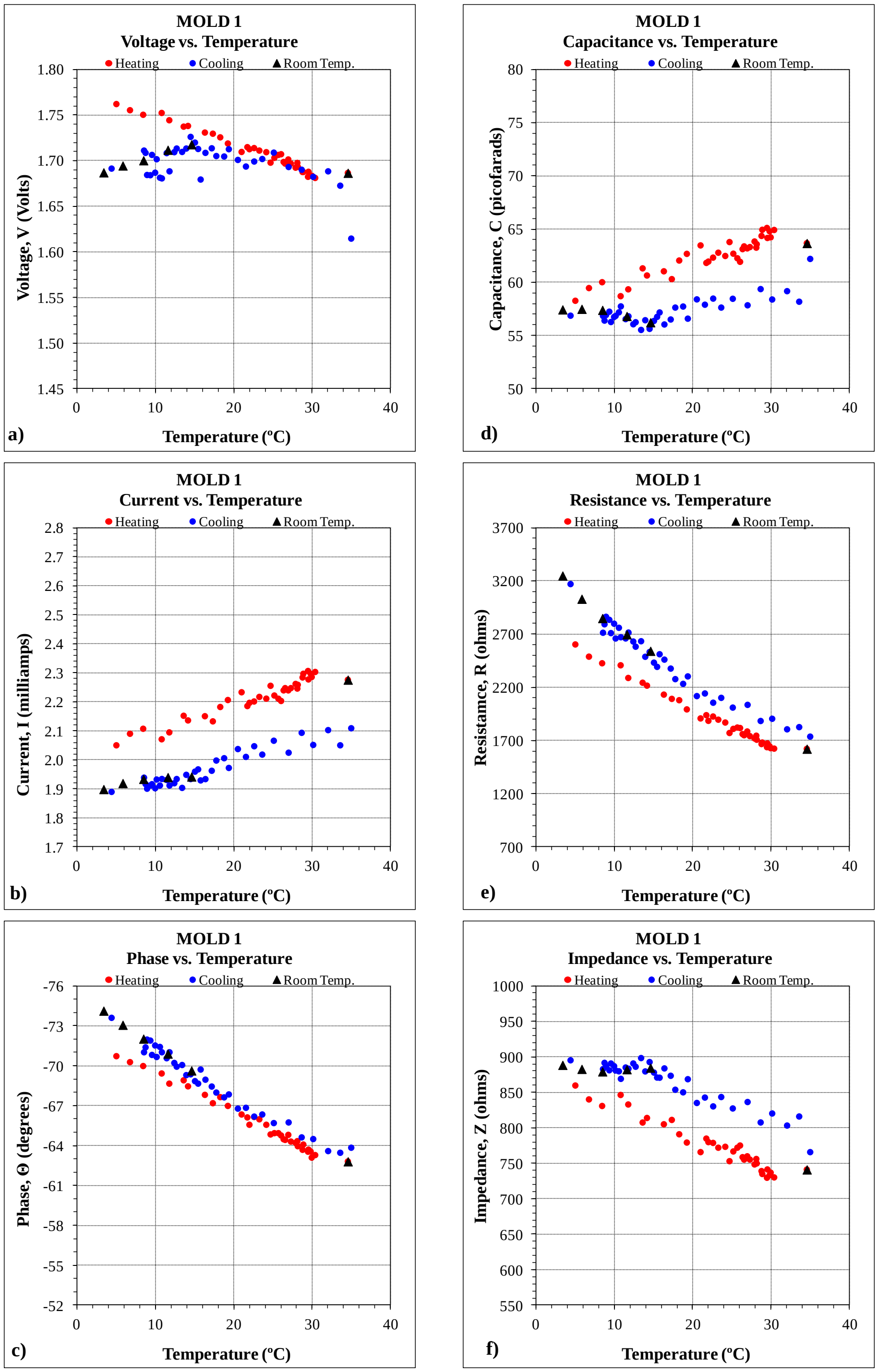


Figure A.1 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 1)

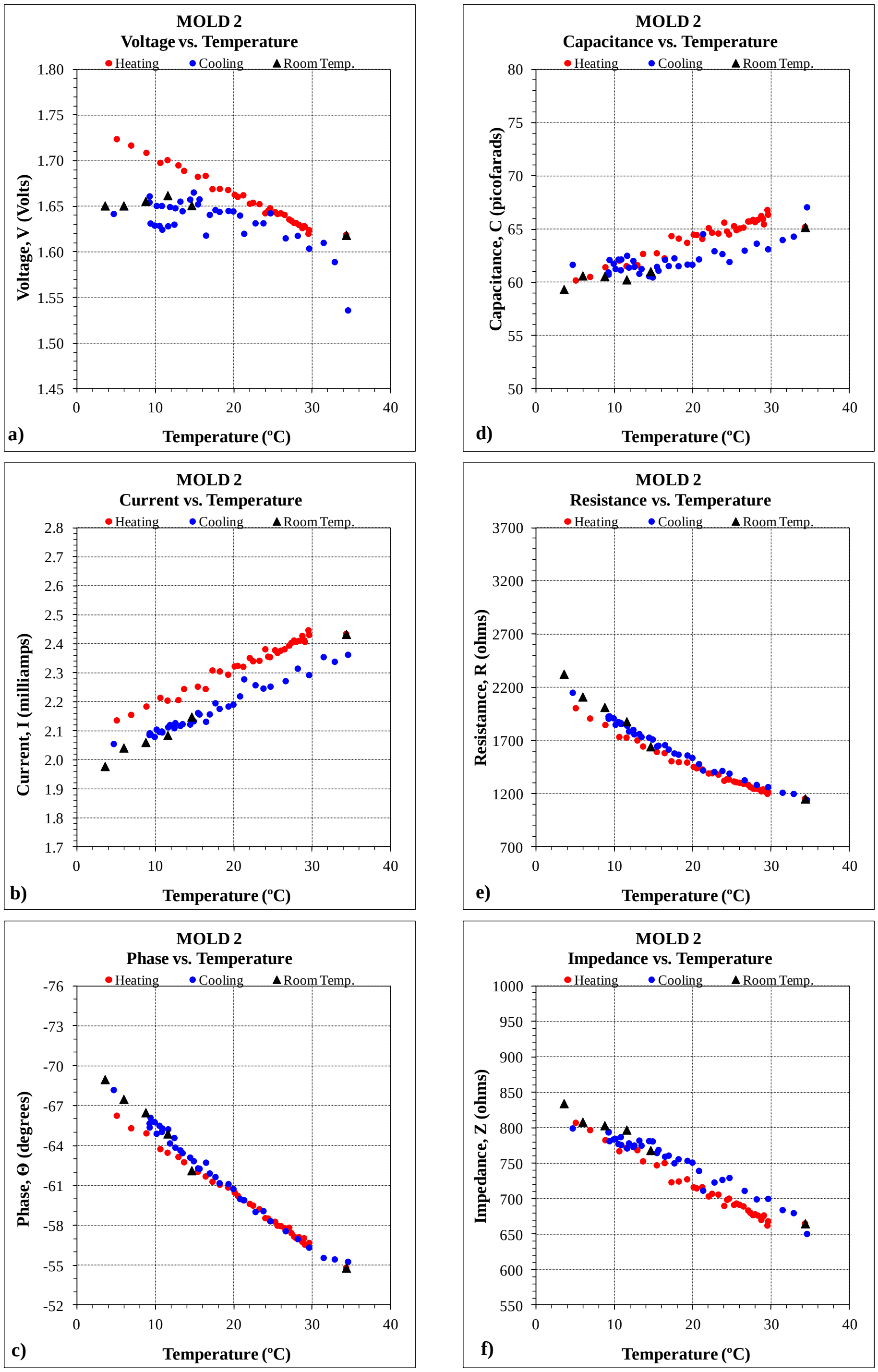


Figure A.2 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 2)

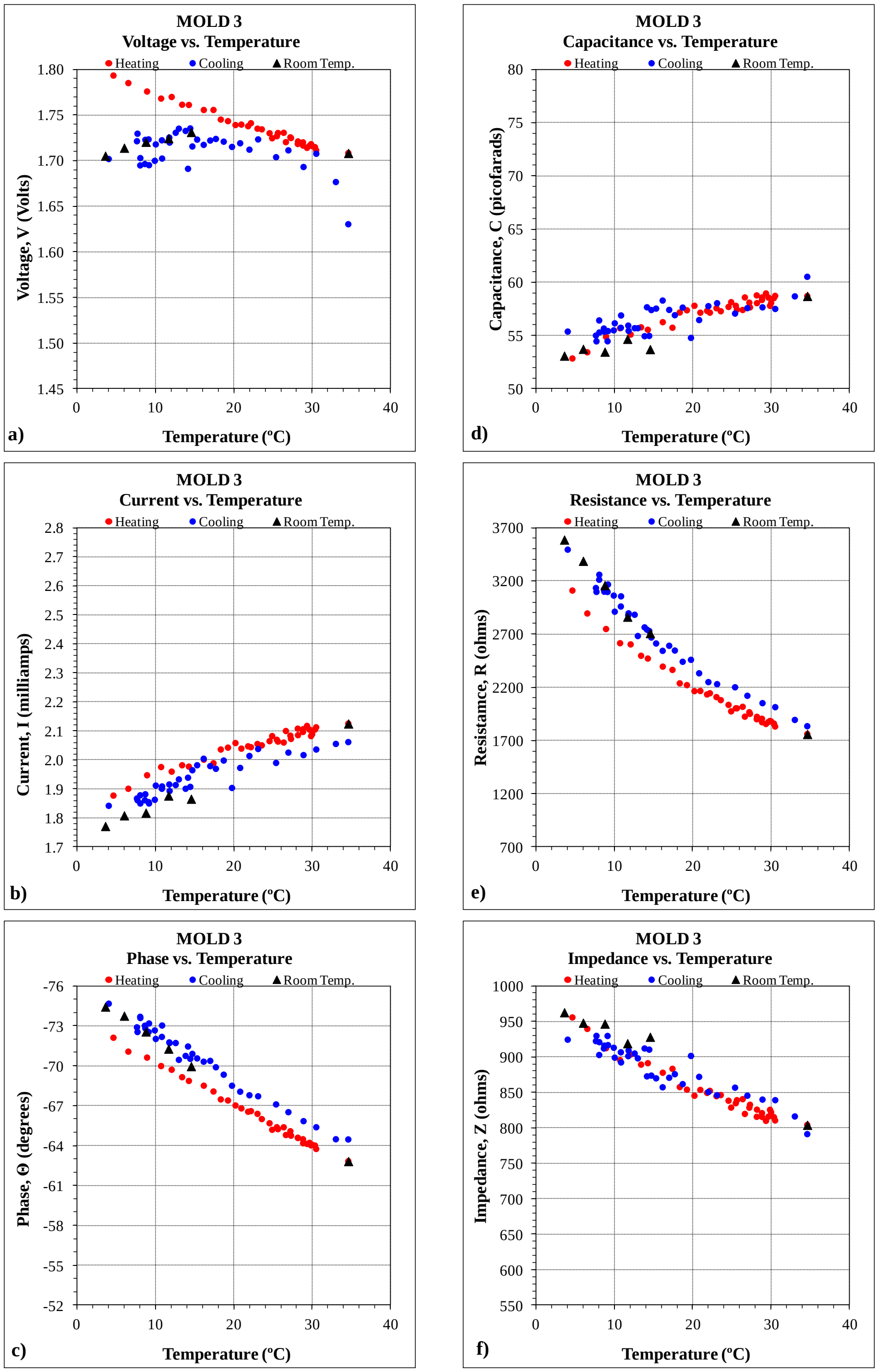


Figure A.3 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 3)

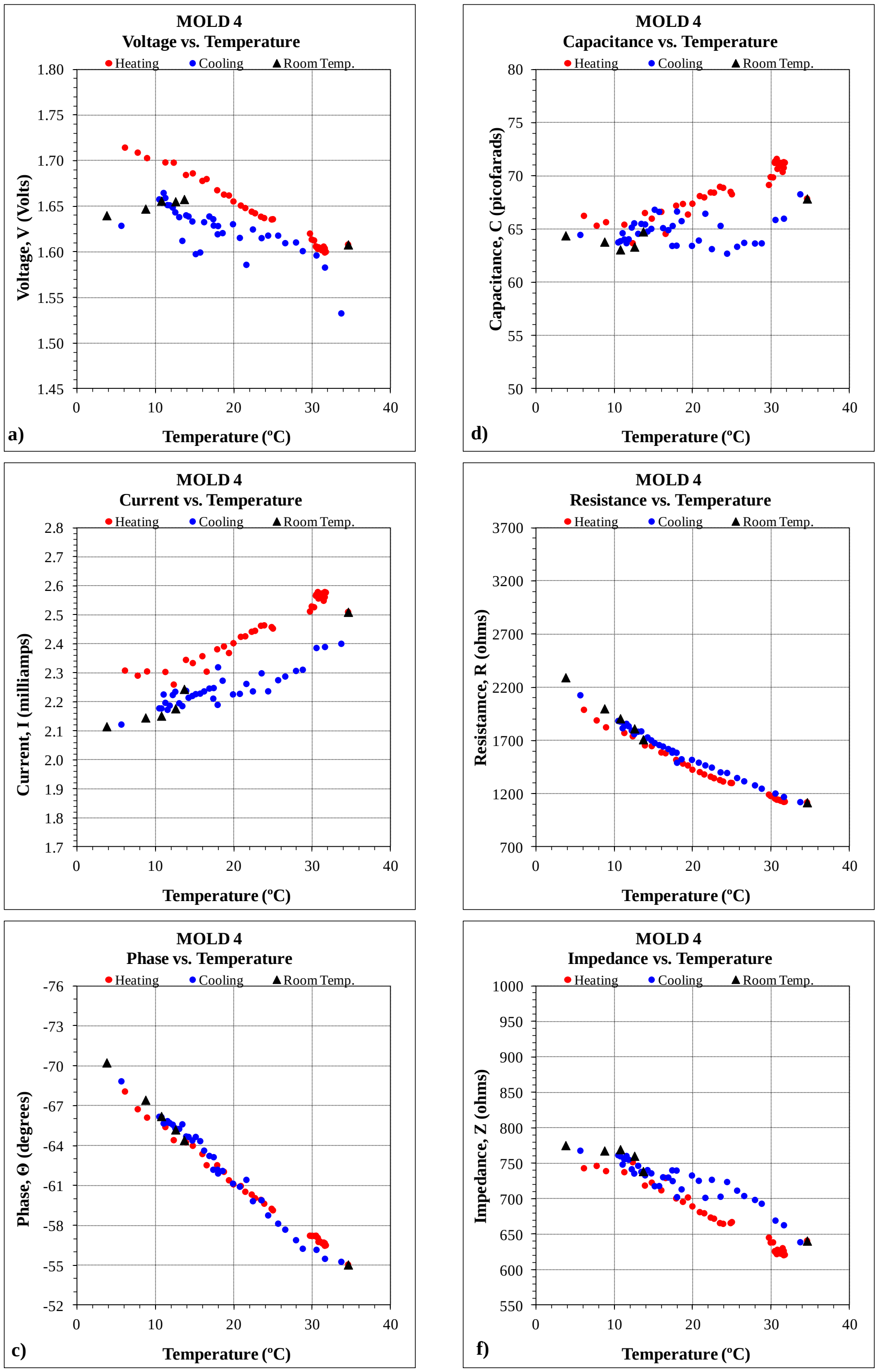


Figure A.4 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 4)

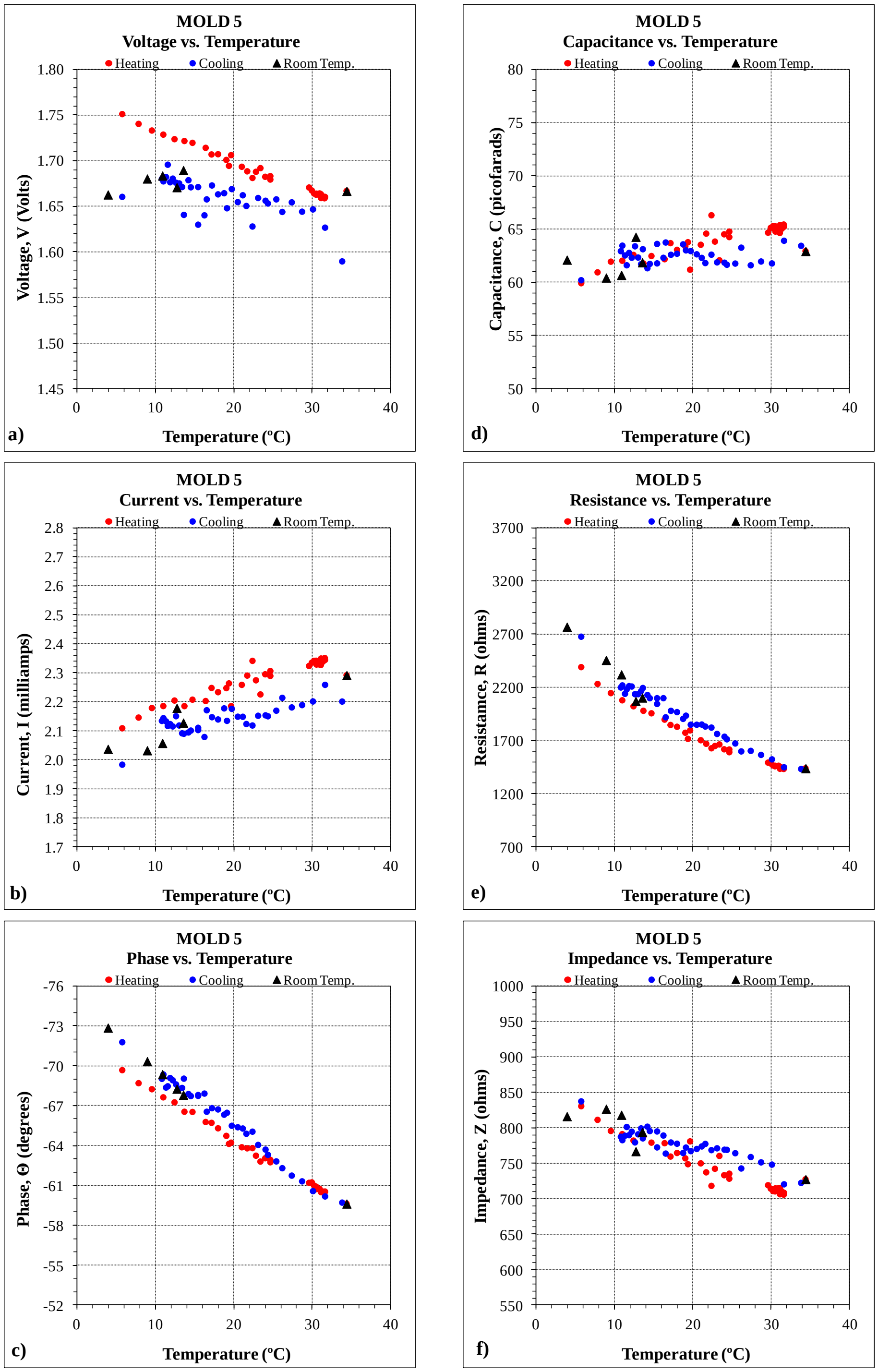


Figure A.5 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 5)

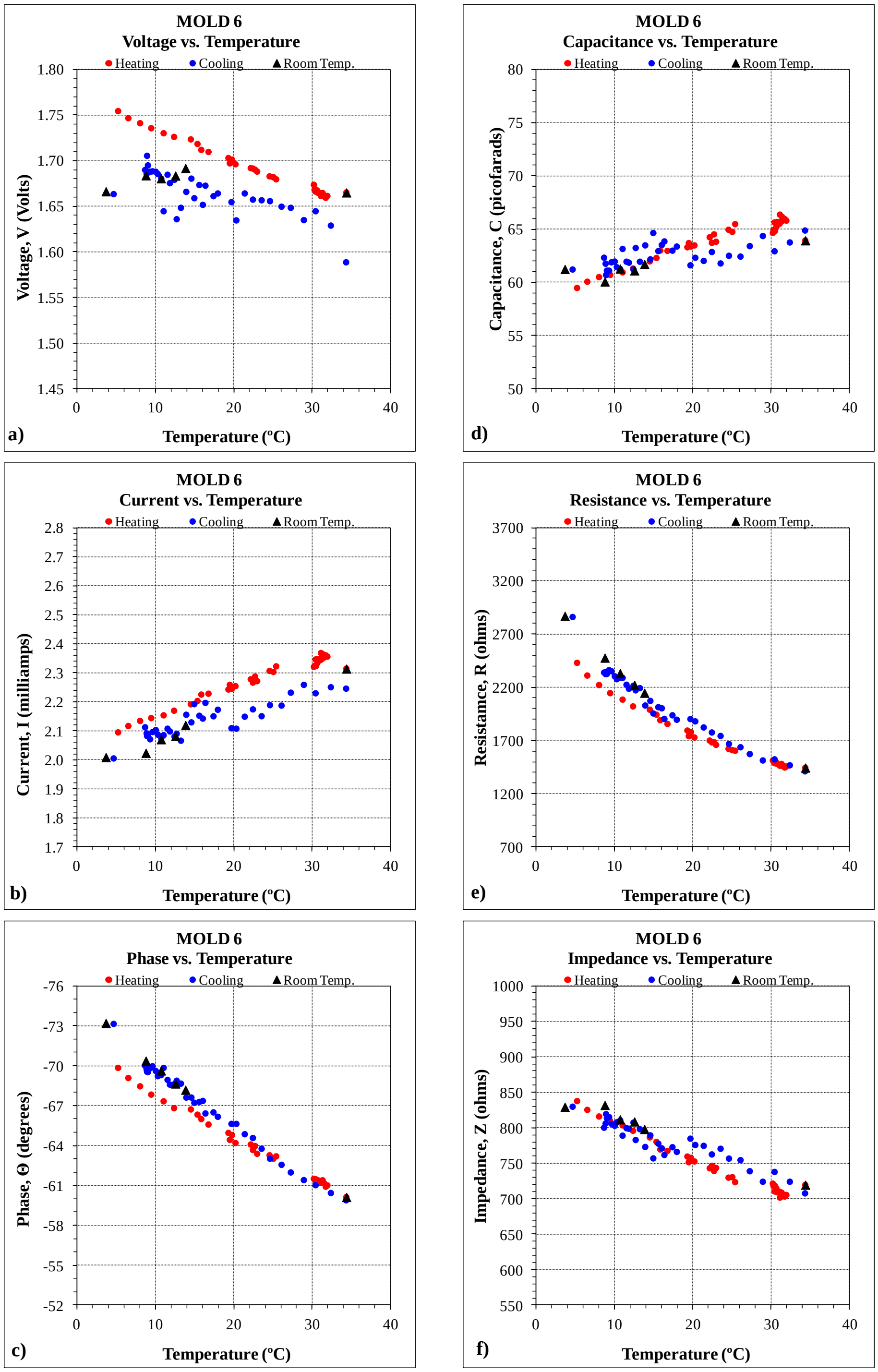


Figure A.6 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 6)

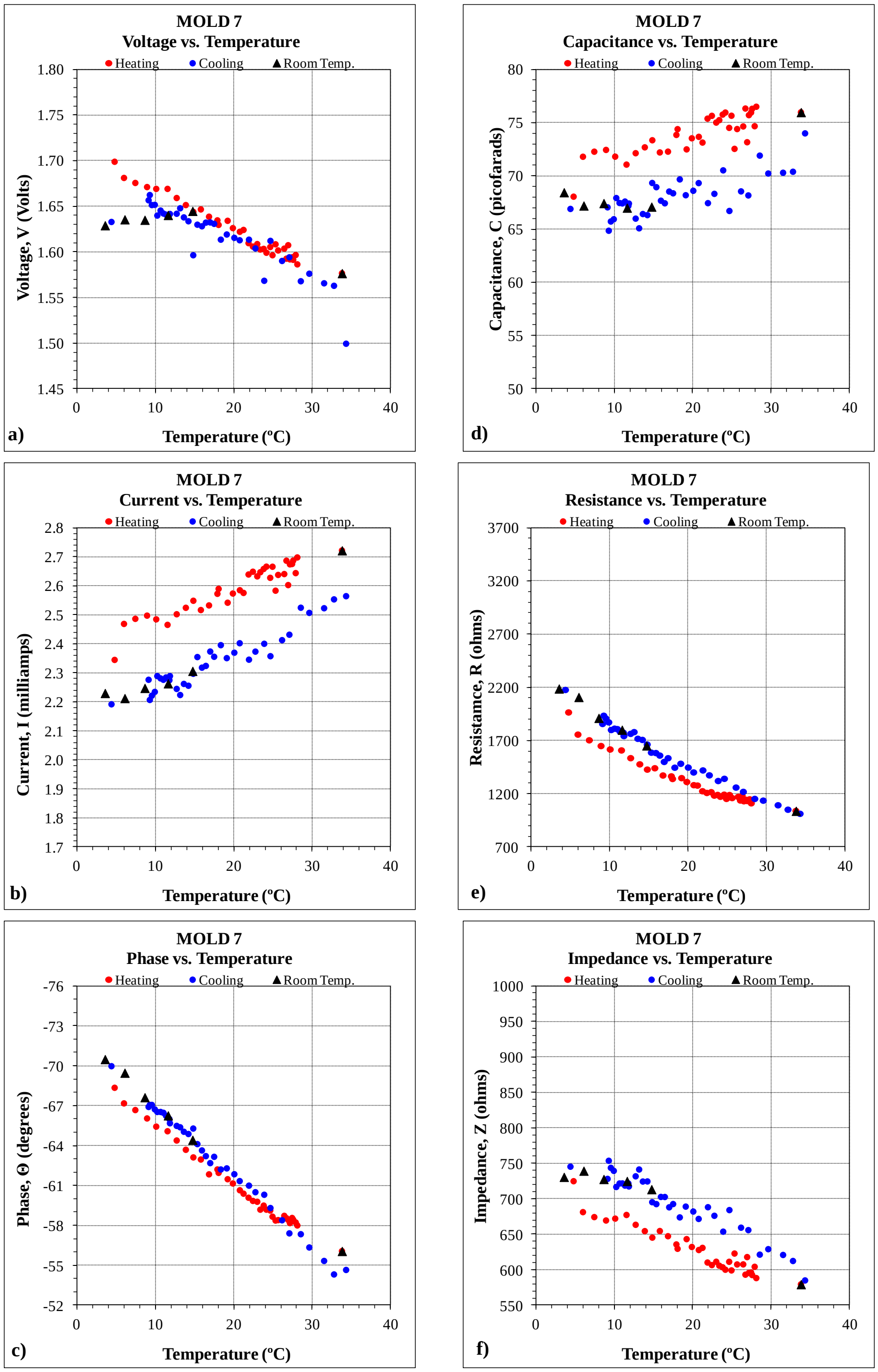


Figure A.7 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 7)

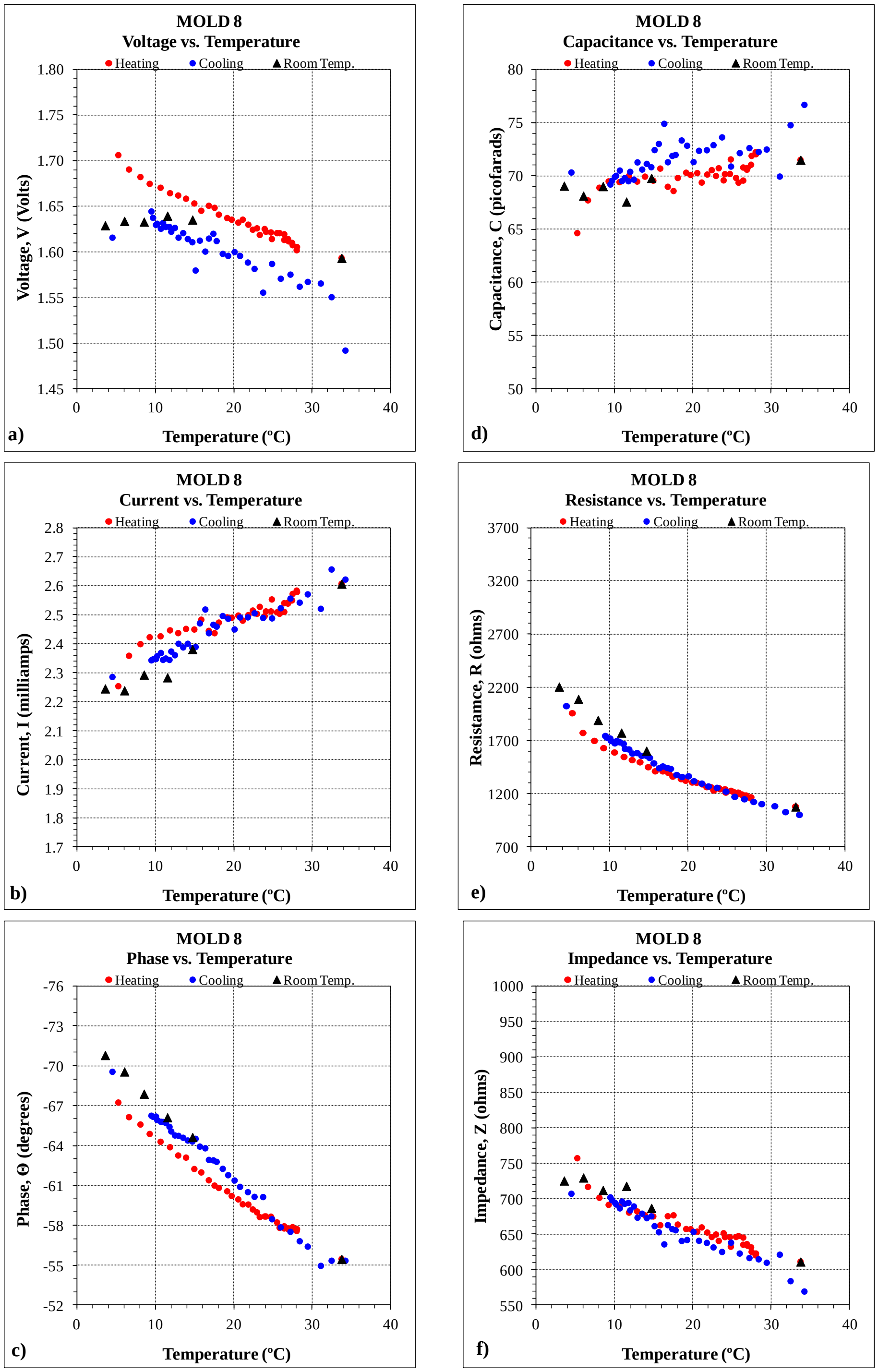


Figure A.8 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 8)

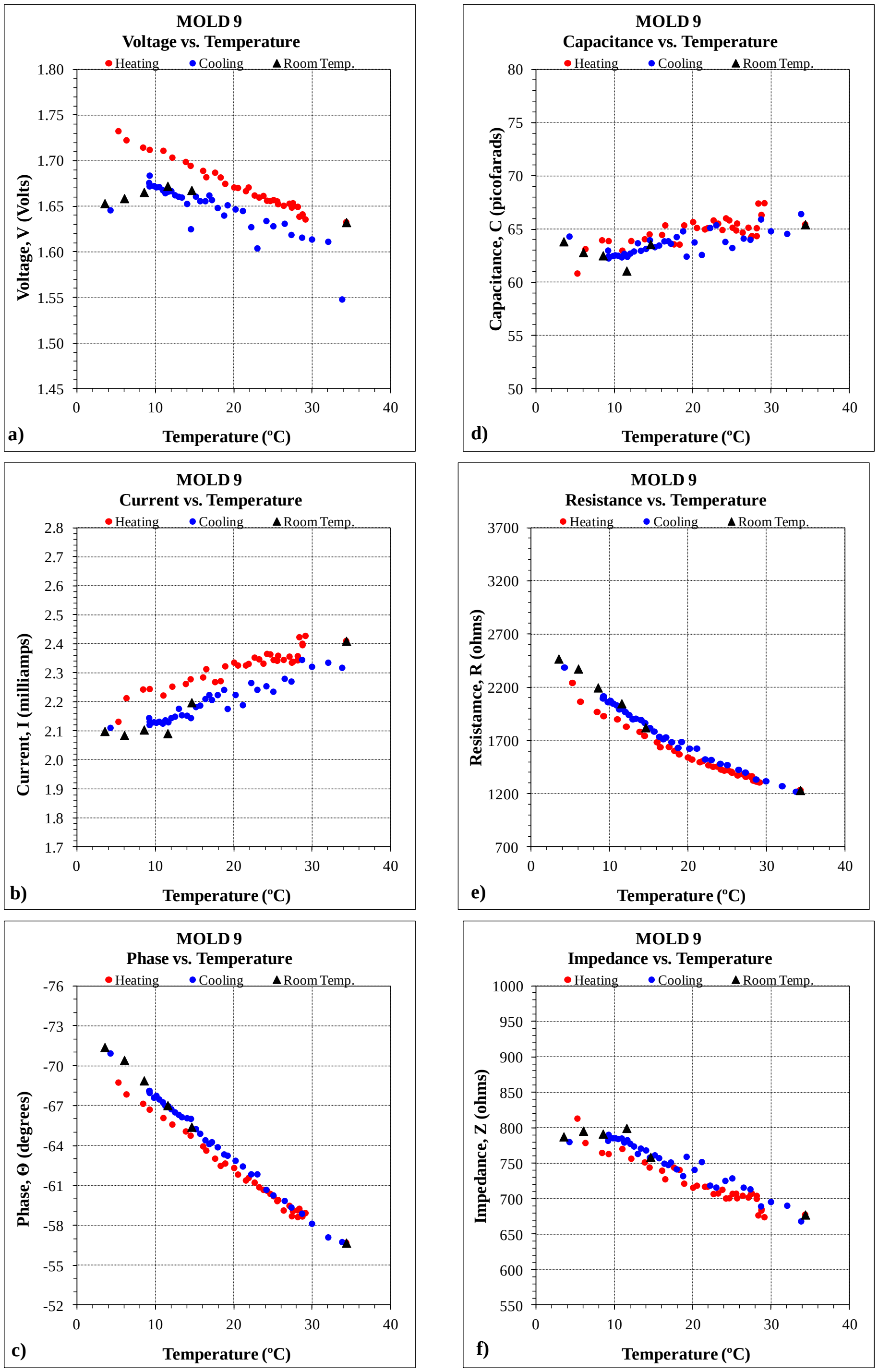


Figure A.9 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 9)

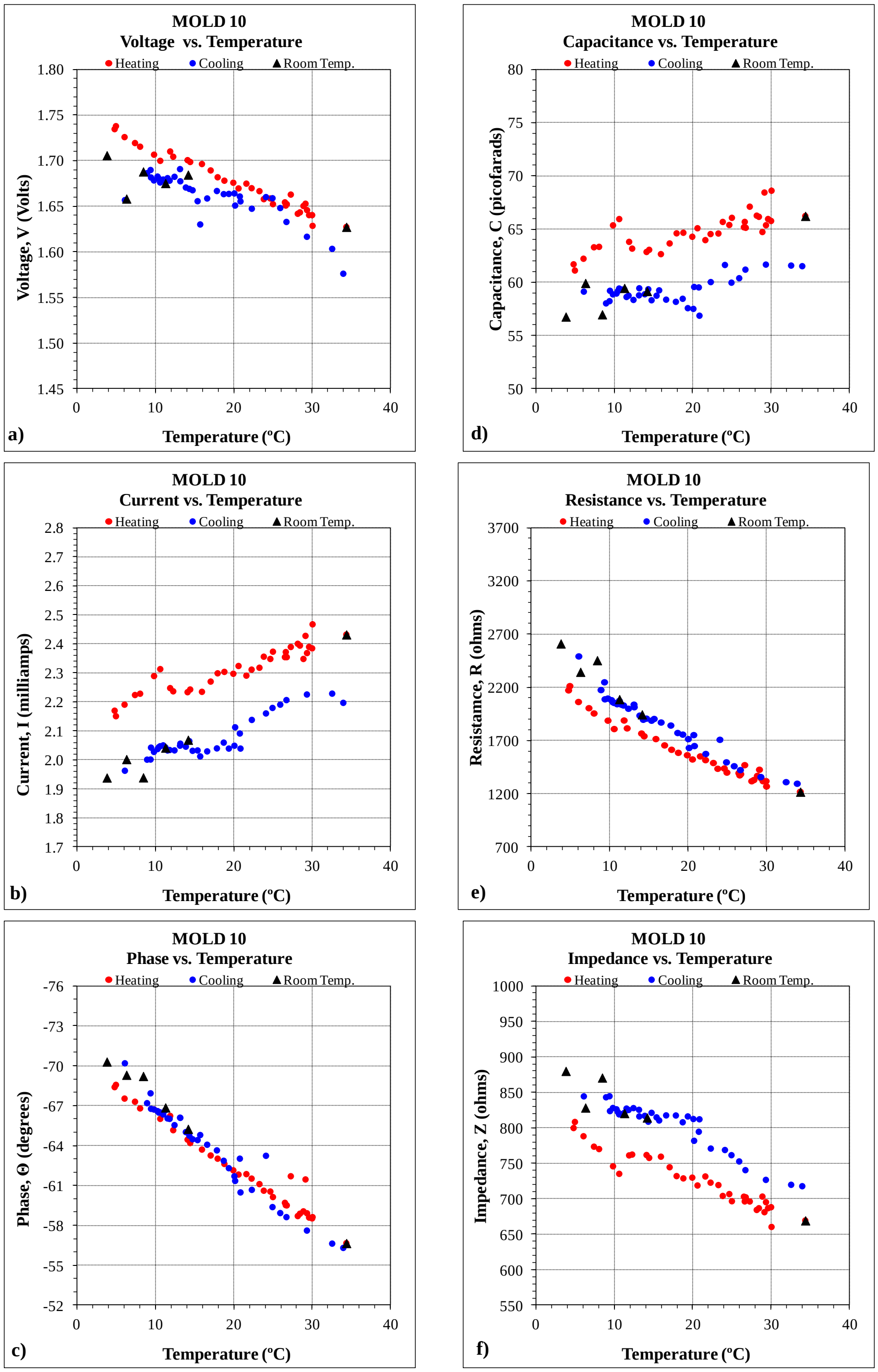


Figure A.10 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 10)

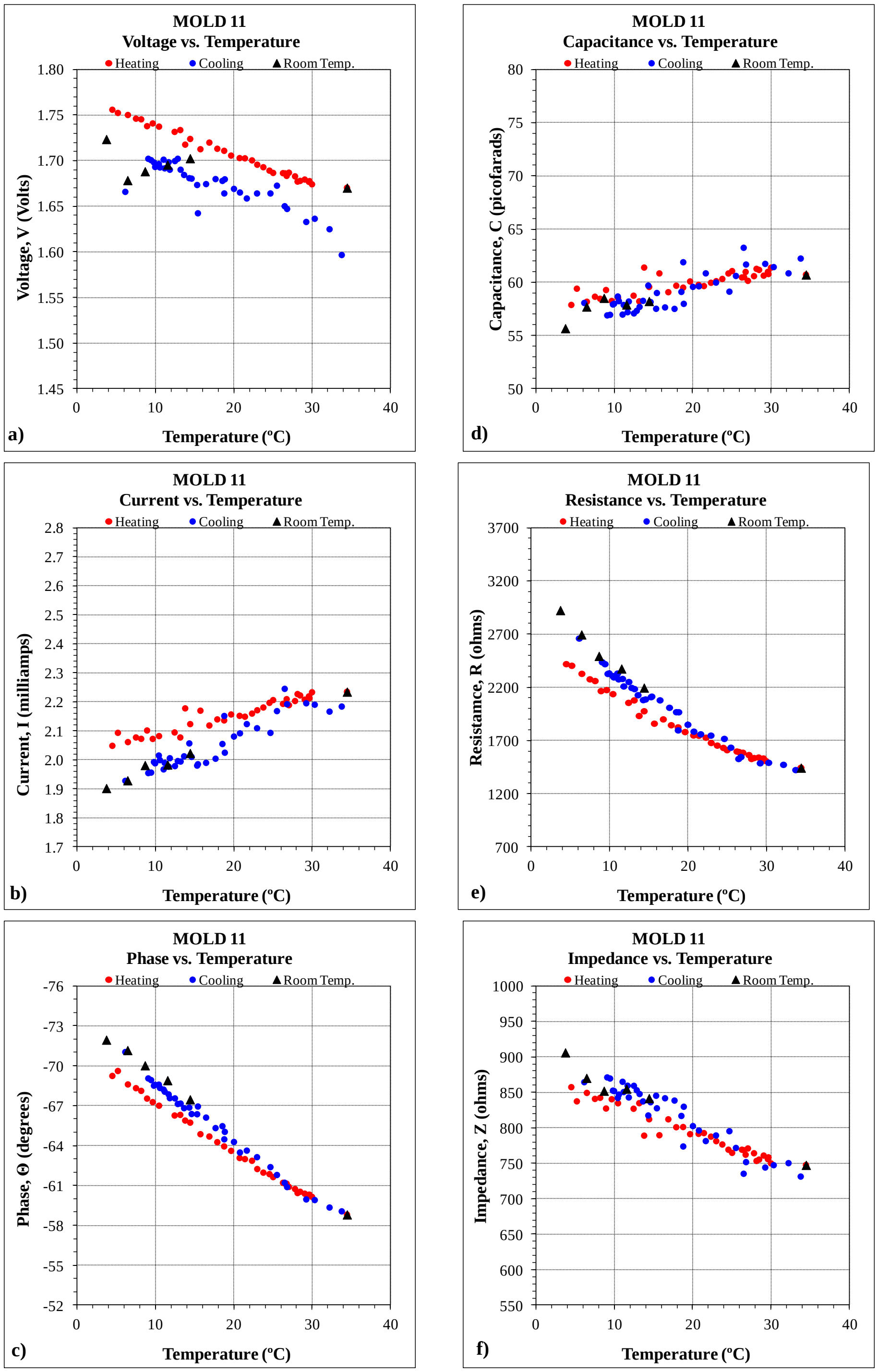


Figure A.11 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 11)

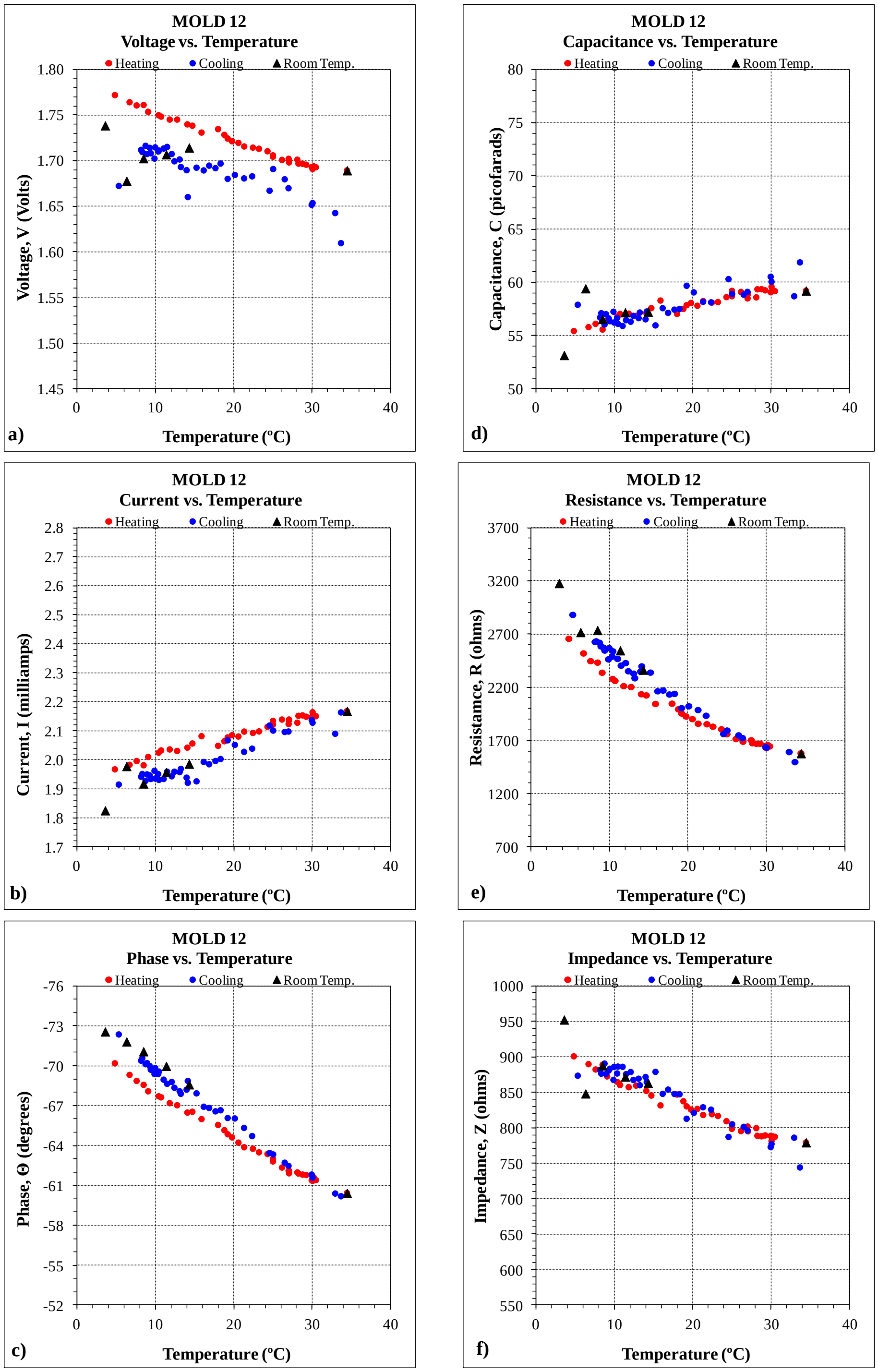


Figure A.12 Electrical Properties Recorded Using the EDG vs. Temperature (MOLD 12)

Appendix B

MOLDS GROUPED BY MOISTURE CONTENT:

COOLING, HEATING, & CONSTANT TEMPERATURE ROOM TESTING

This appendix contains figures that illustrate the electrical properties recorded by the Electrical Density Gauge (EDG) over a range of temperatures, grouped by moisture content and electrical property of interest during the cooling cycle, heating cycle, and constant temperature room testing, as described in Chapter 7.

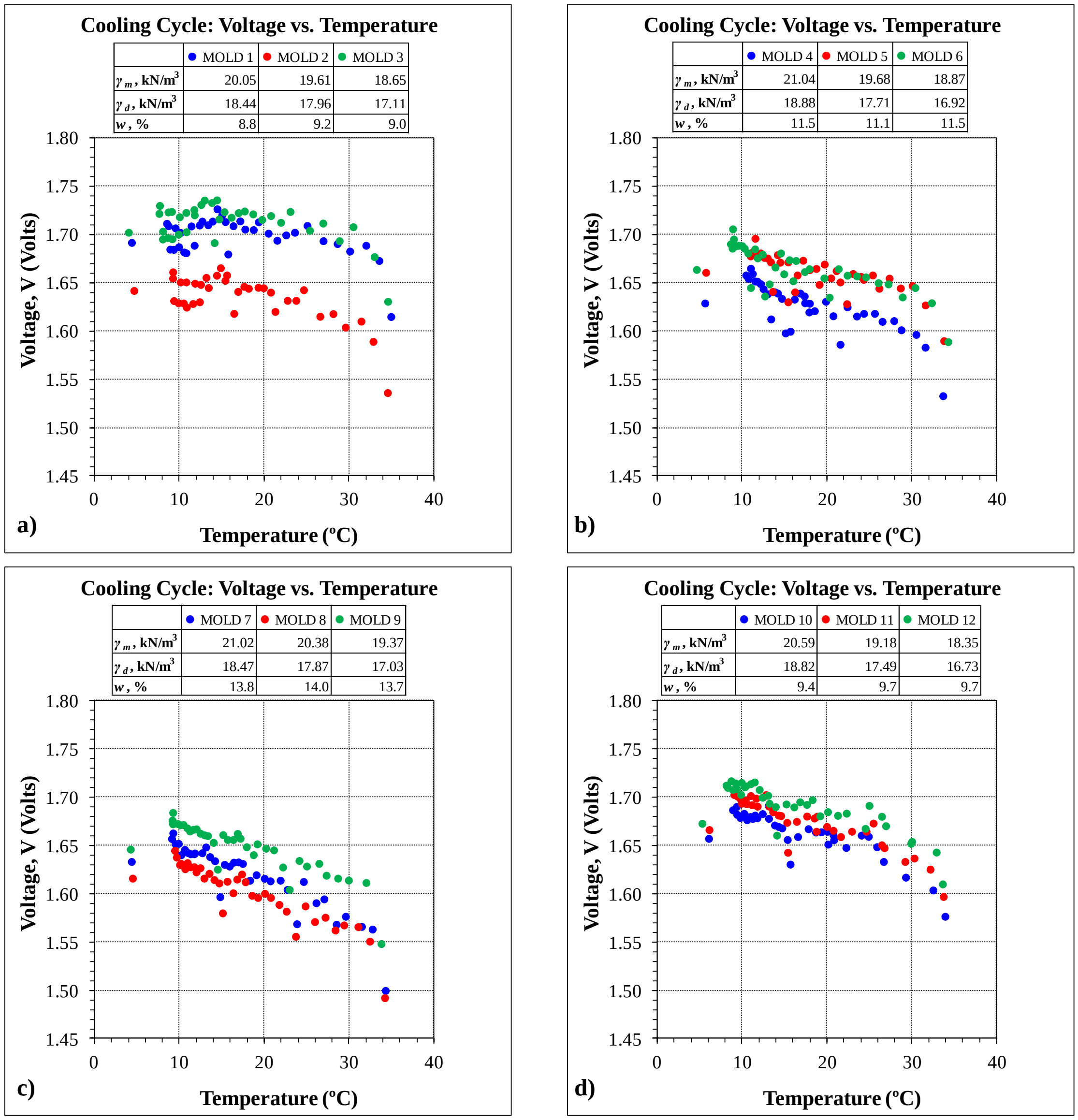


Figure B.1 Cooling Cycle: Voltage vs. Temperature

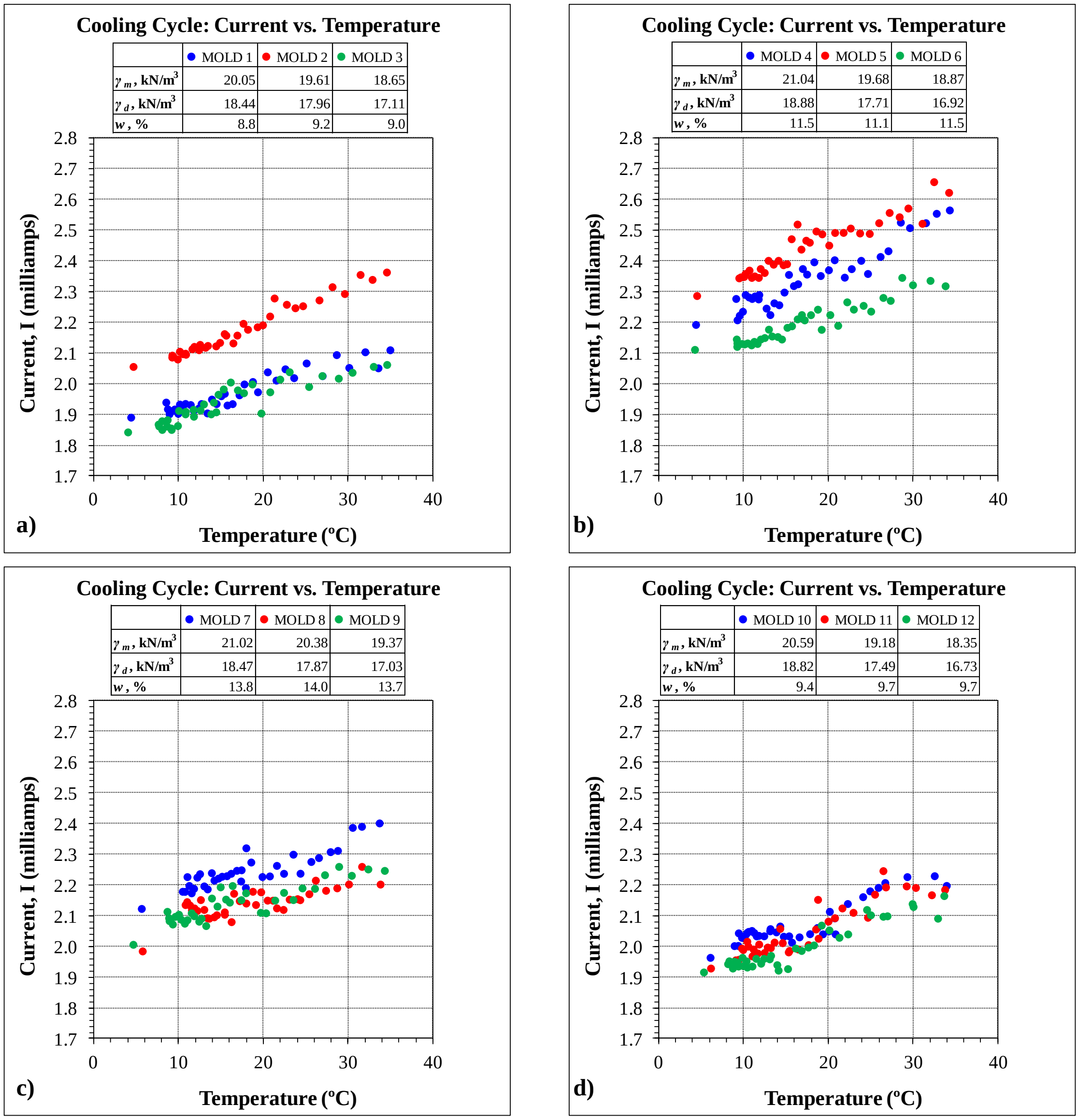


Figure B.2 Cooling Cycle: Current vs. Temperature

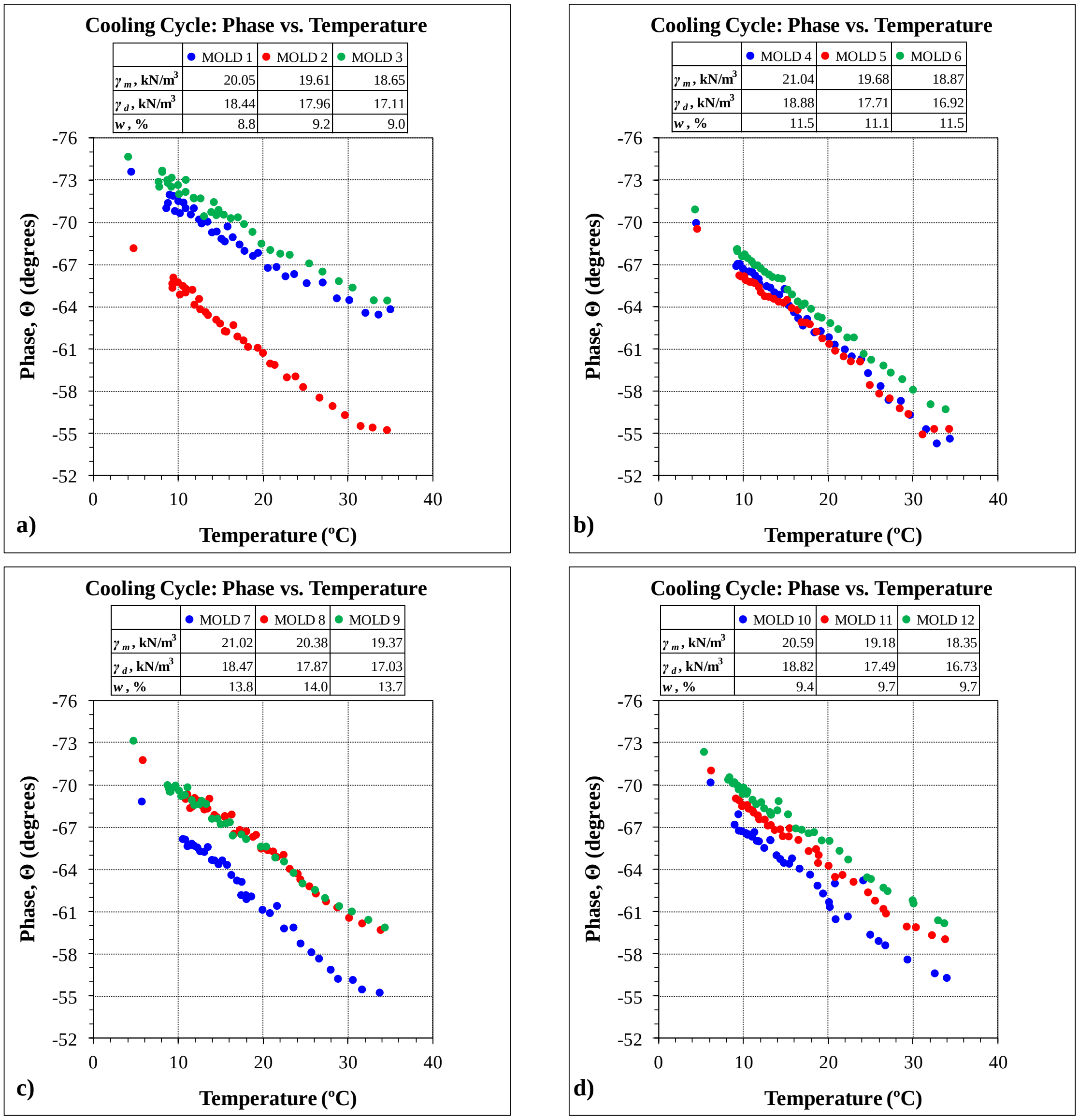


Figure B.3 Cooling Cycle: Phase vs. Temperature

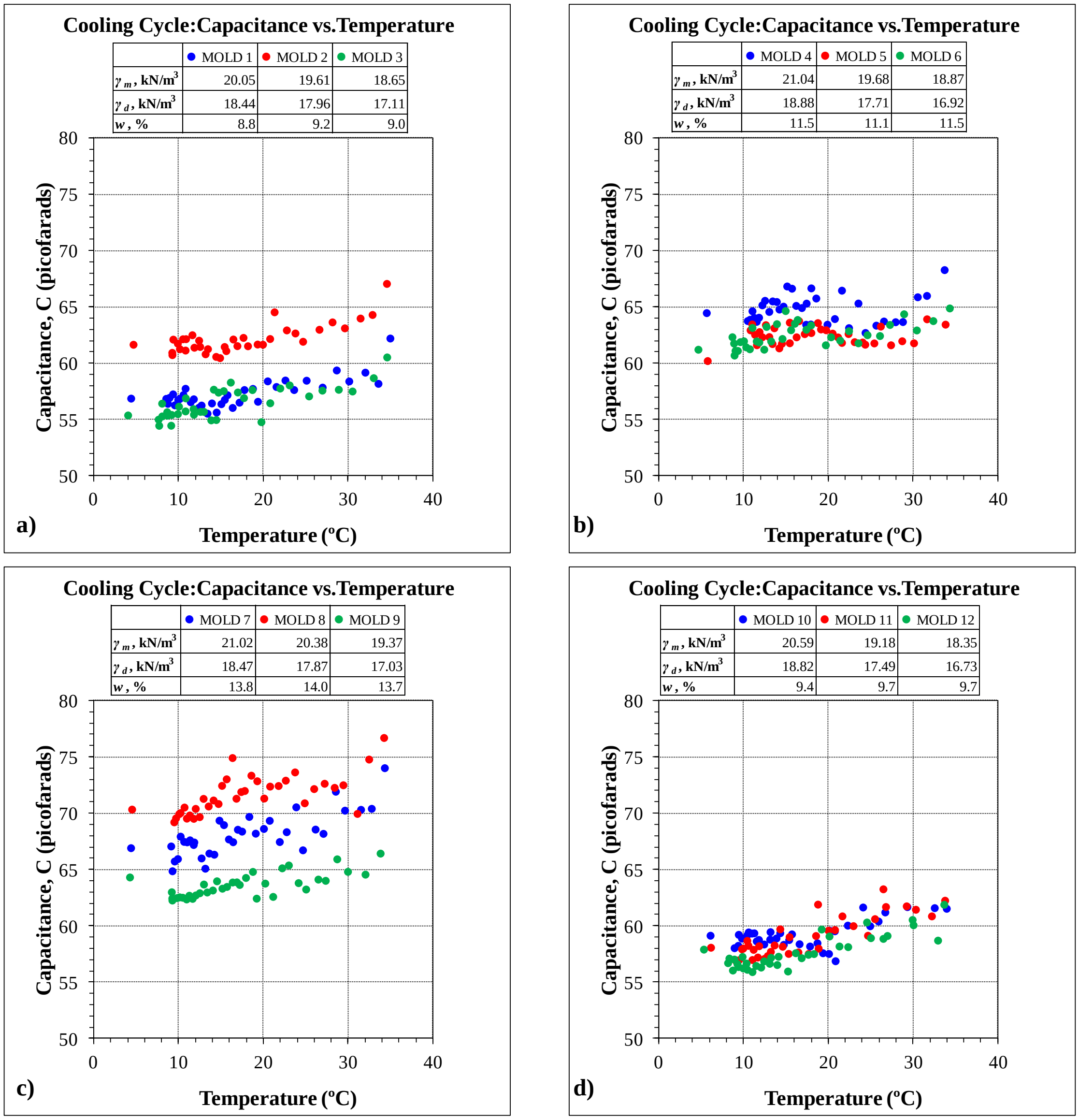


Figure B.4 Cooling Cycle: Capacitance vs. Temperature

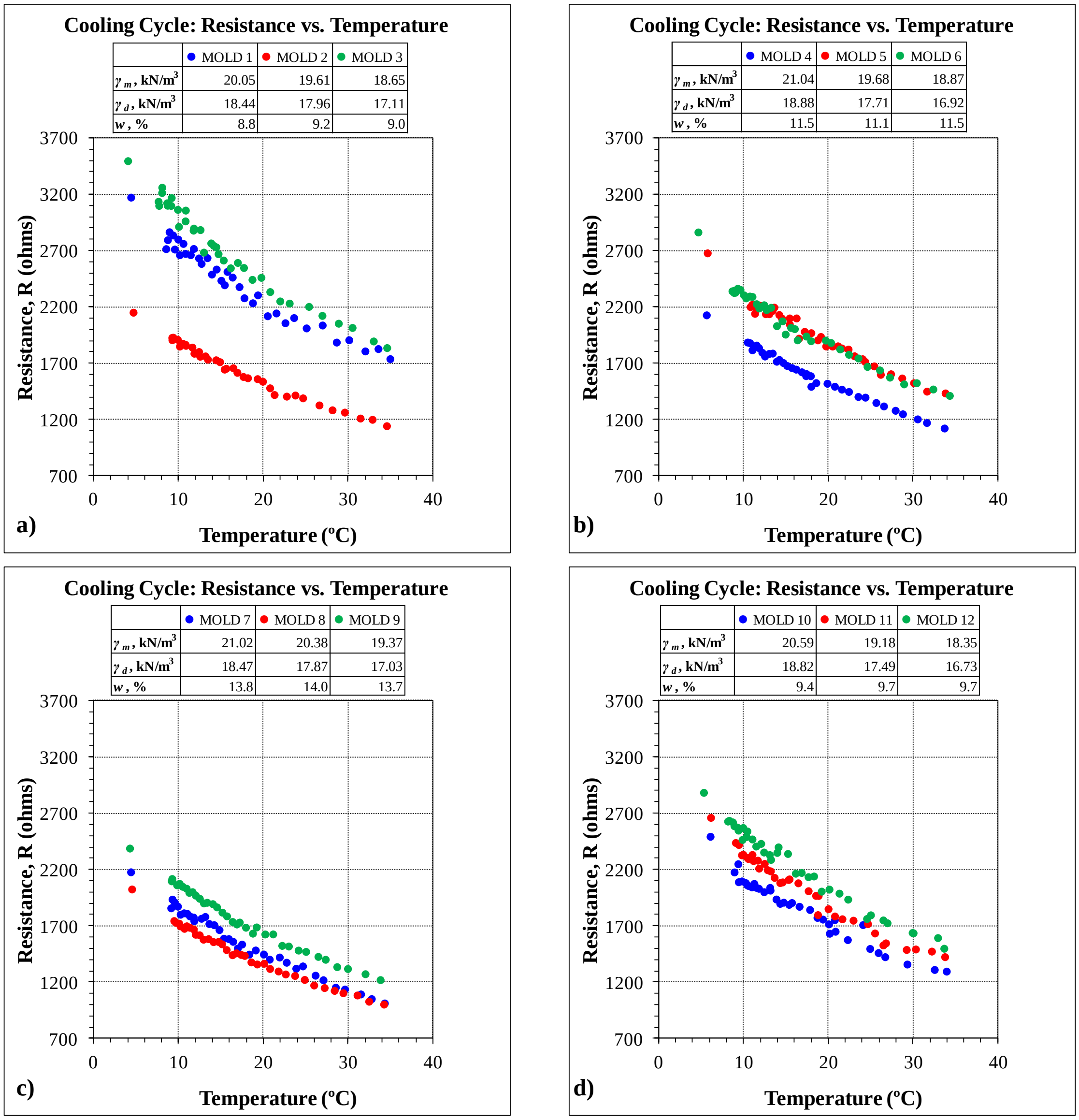


Figure B.5 Cooling Cycle: Resistance vs. Temperature

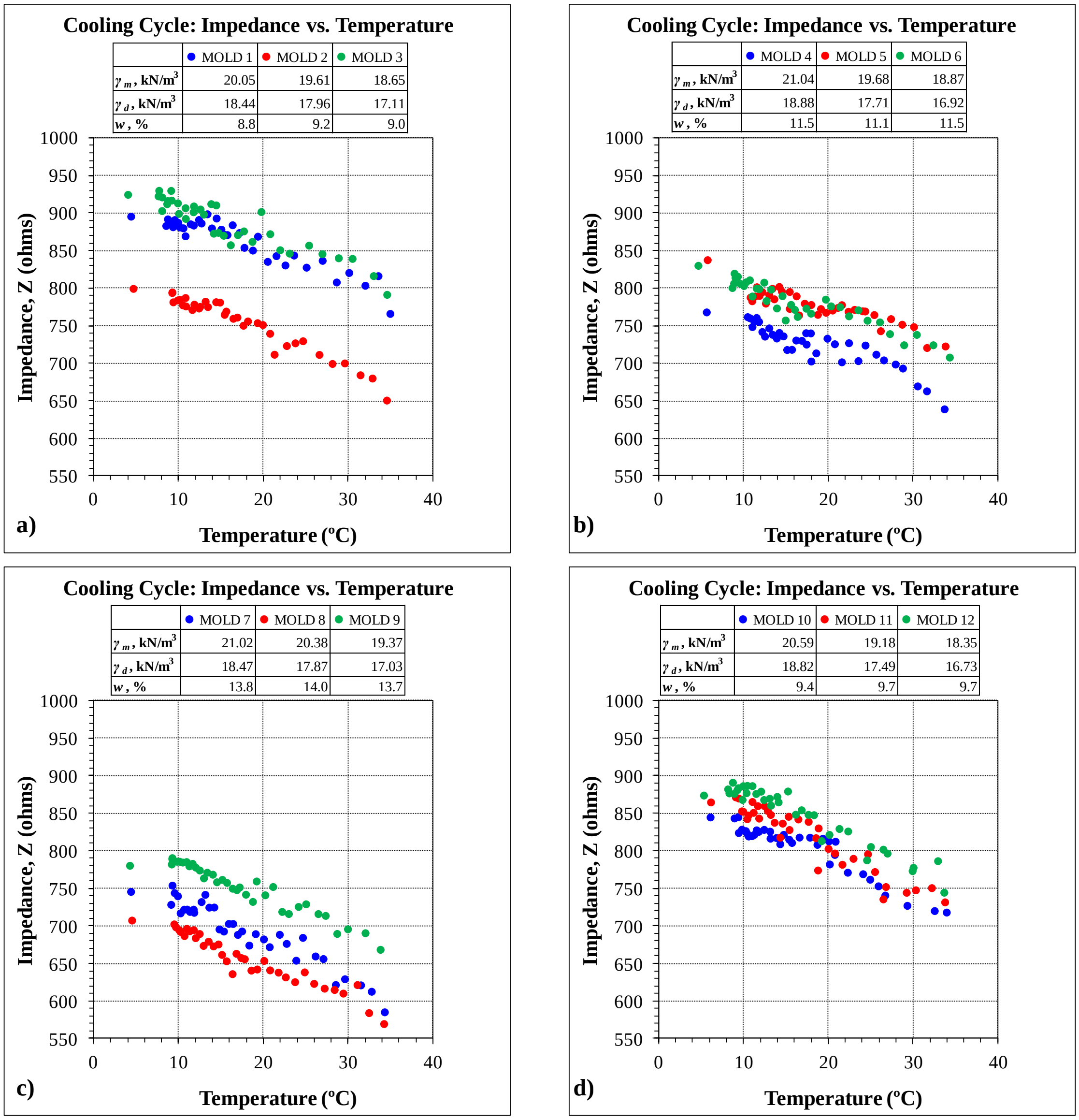


Figure B.6 Cooling Cycle: Impedance vs. Temperature

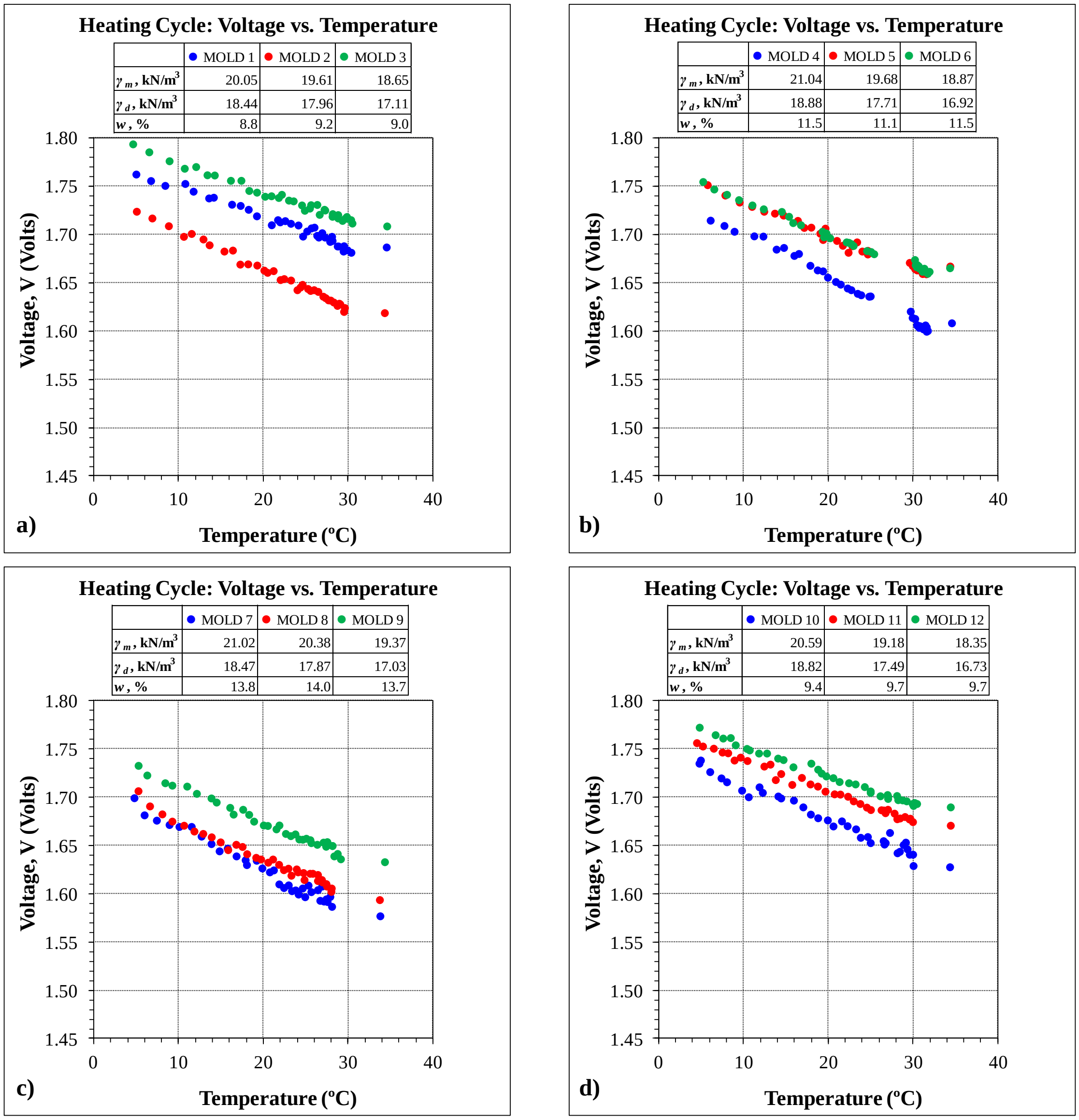


Figure B.7 Heating Cycle: Voltage vs. Temperature

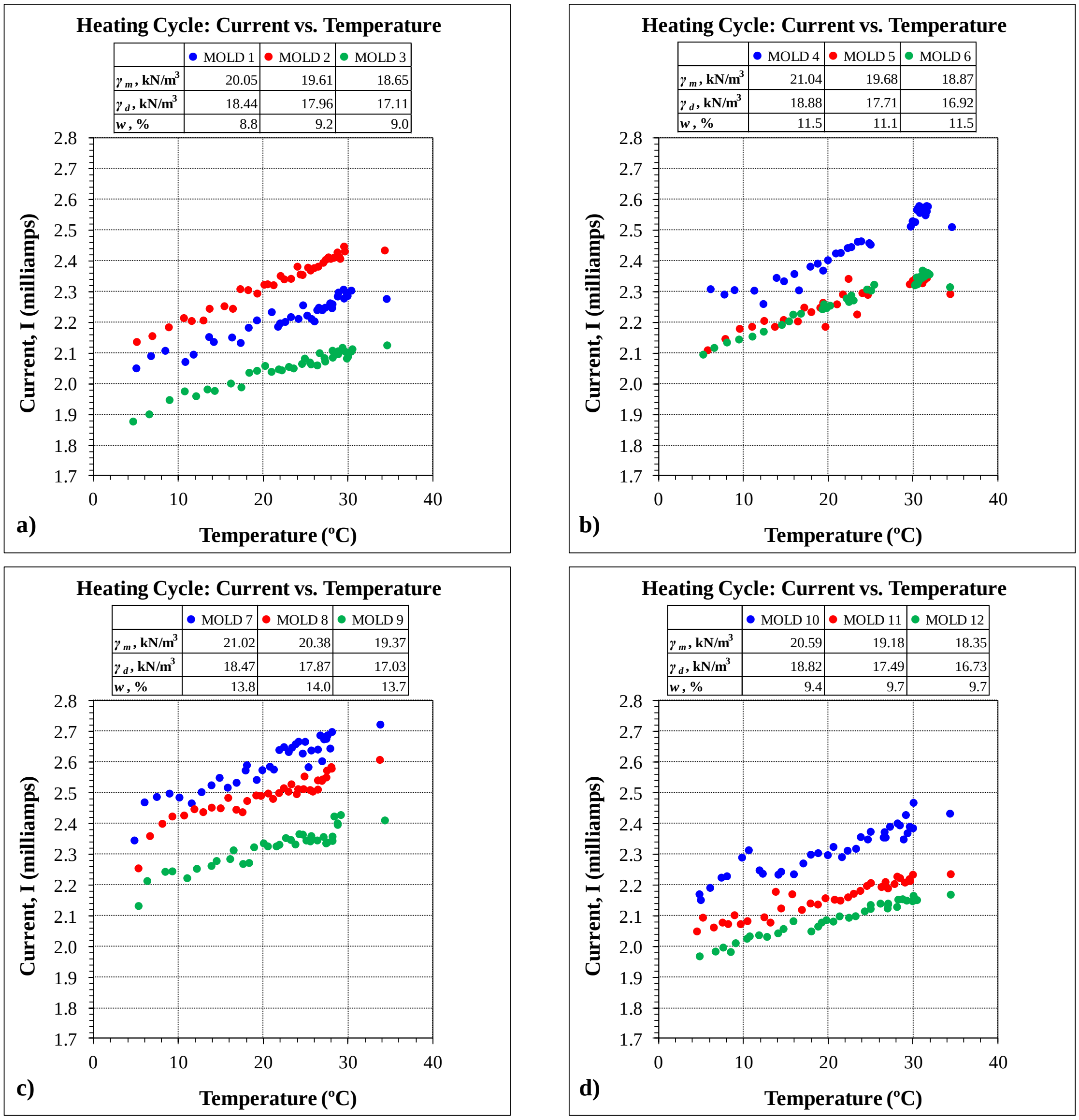


Figure B.8 Heating Cycle: Current vs. Temperature

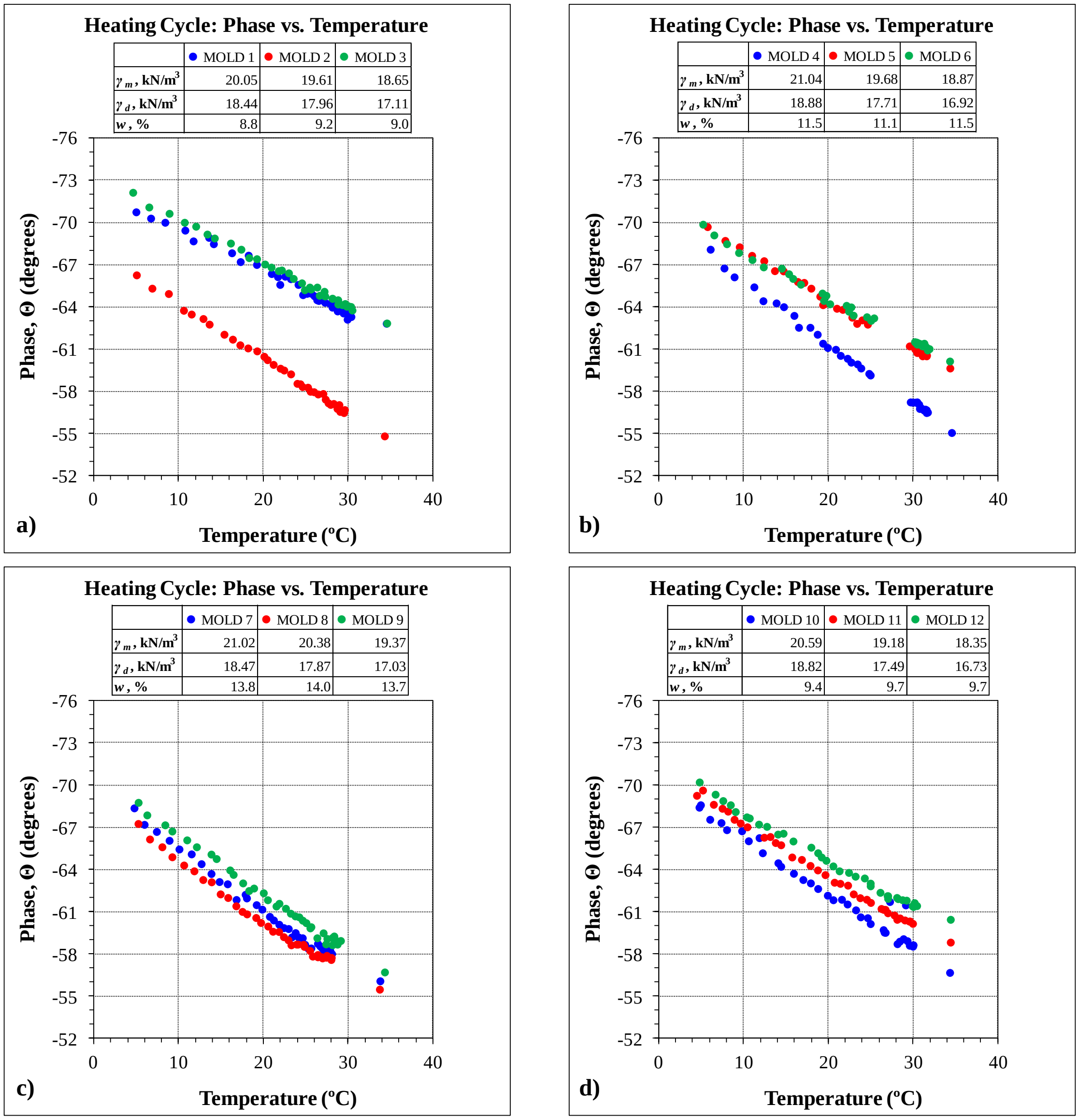


Figure B.9 Heating Cycle: Phase vs. Temperature

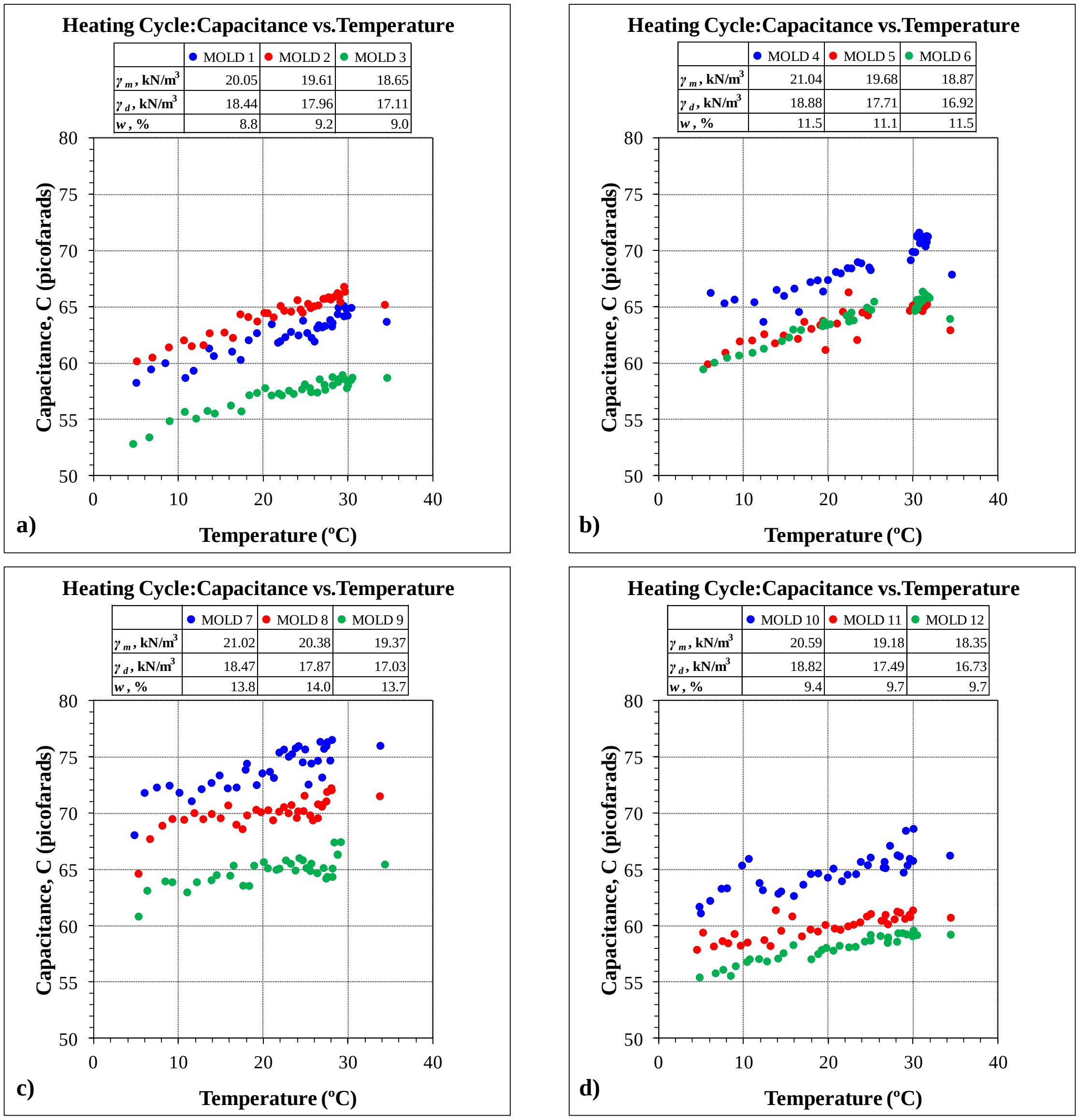


Figure B.10 Heating Cycle: Capacitance vs. Temperature

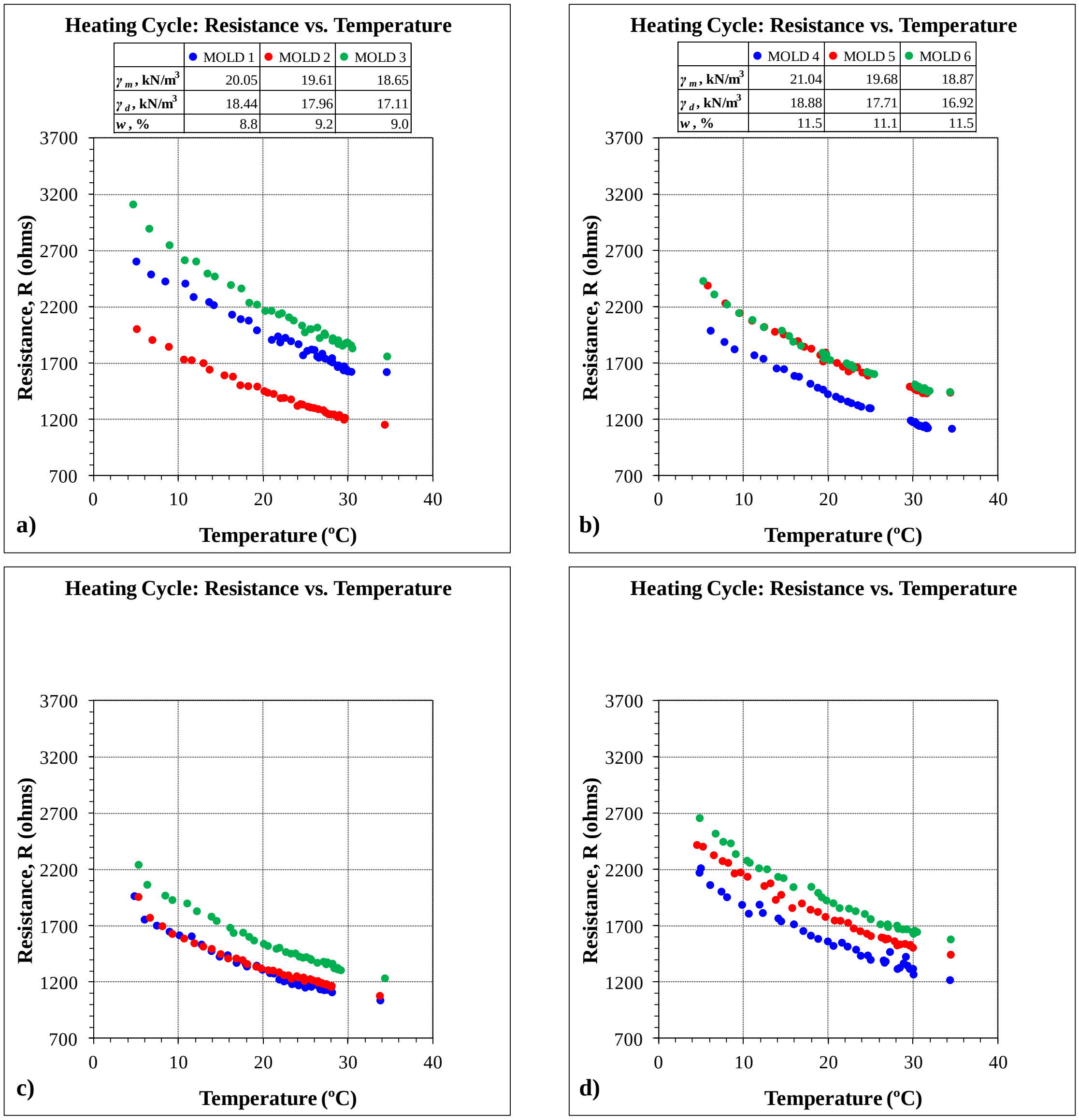


Figure B.11 **Heating Cycle: Resistance vs. Temperature**

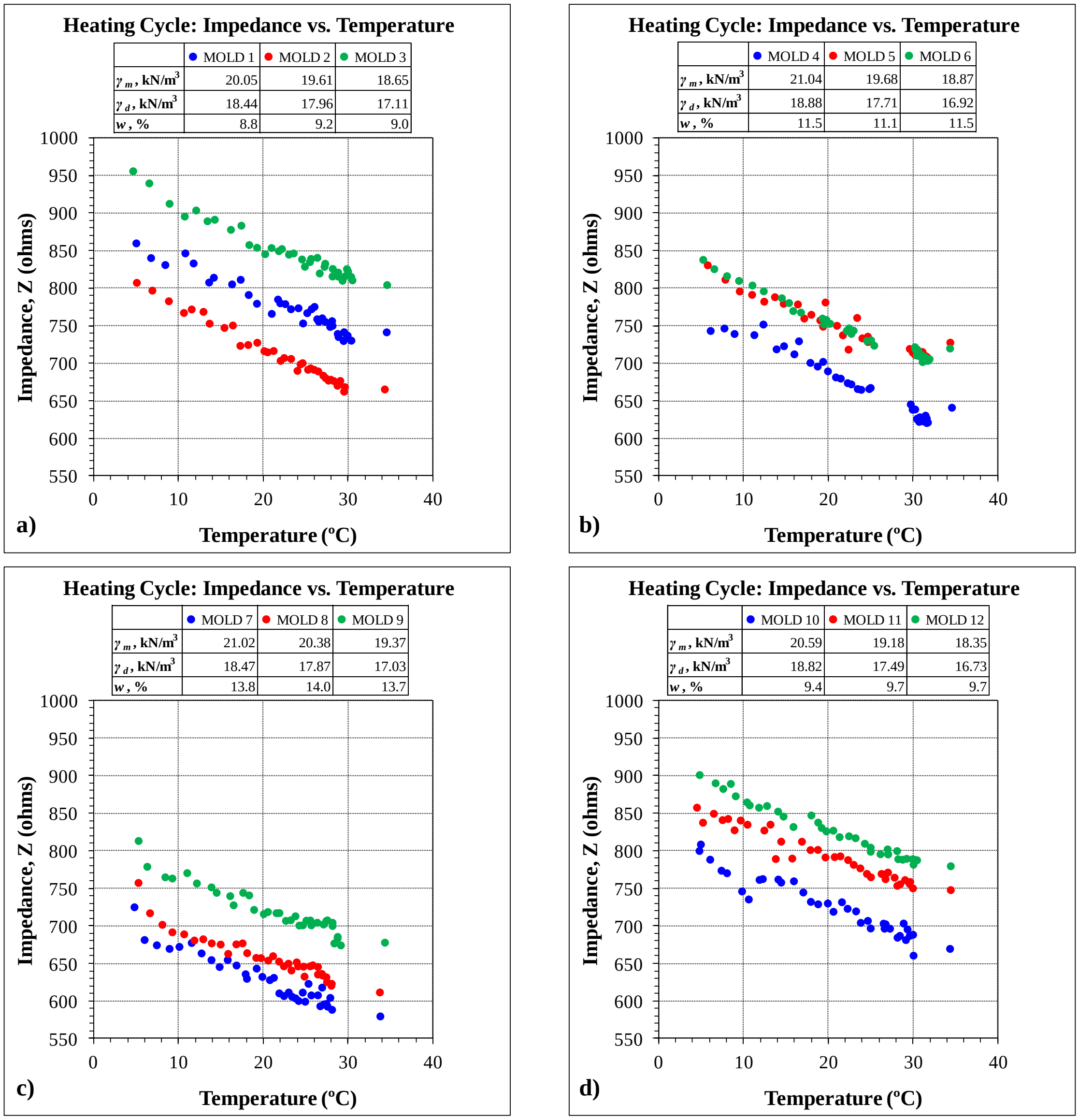


Figure B.12 Heating Cycle: Impedance vs. Temperature

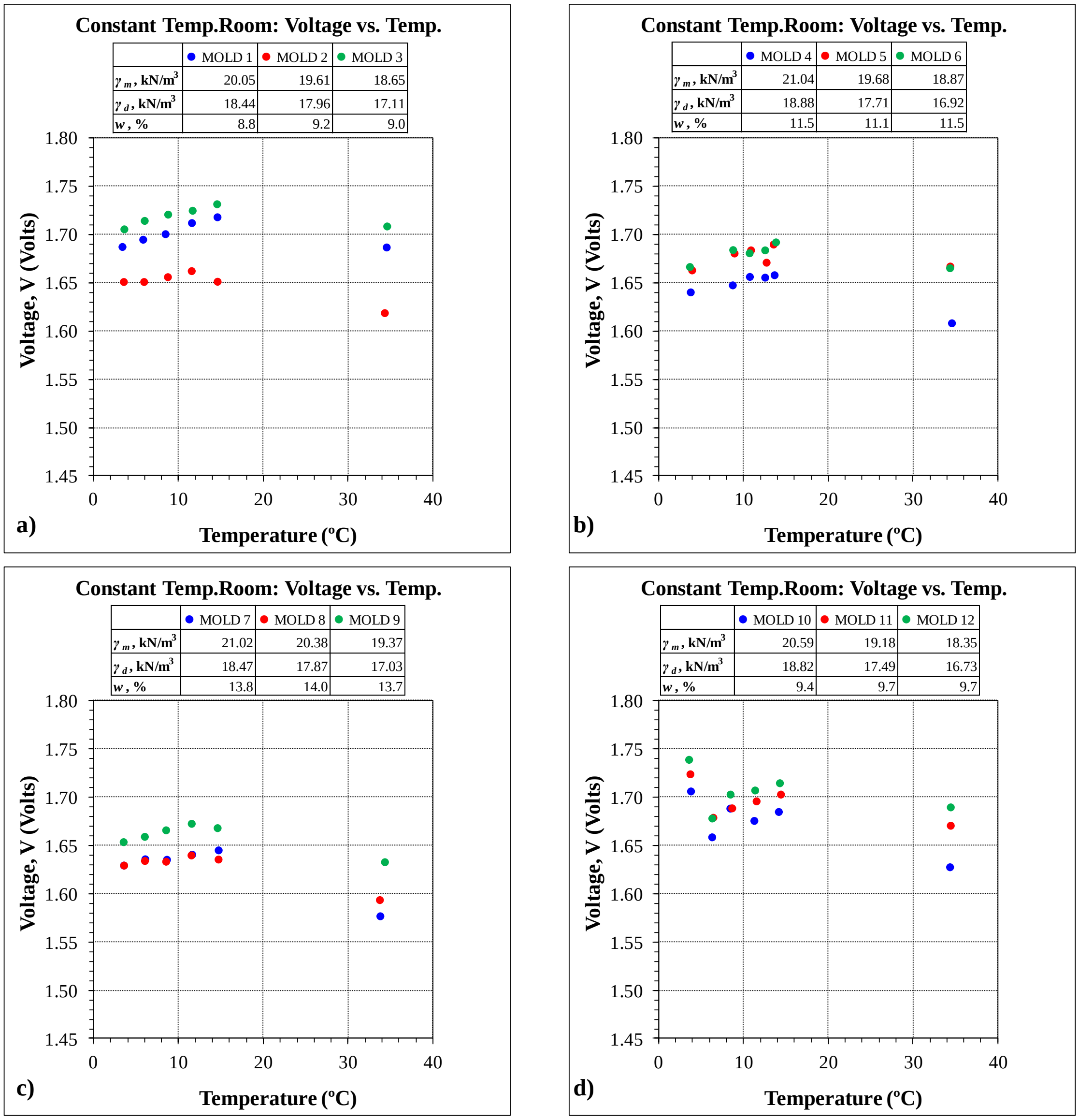


Figure B.13 Constant Temperature Room Testing: Voltage vs. Temperature

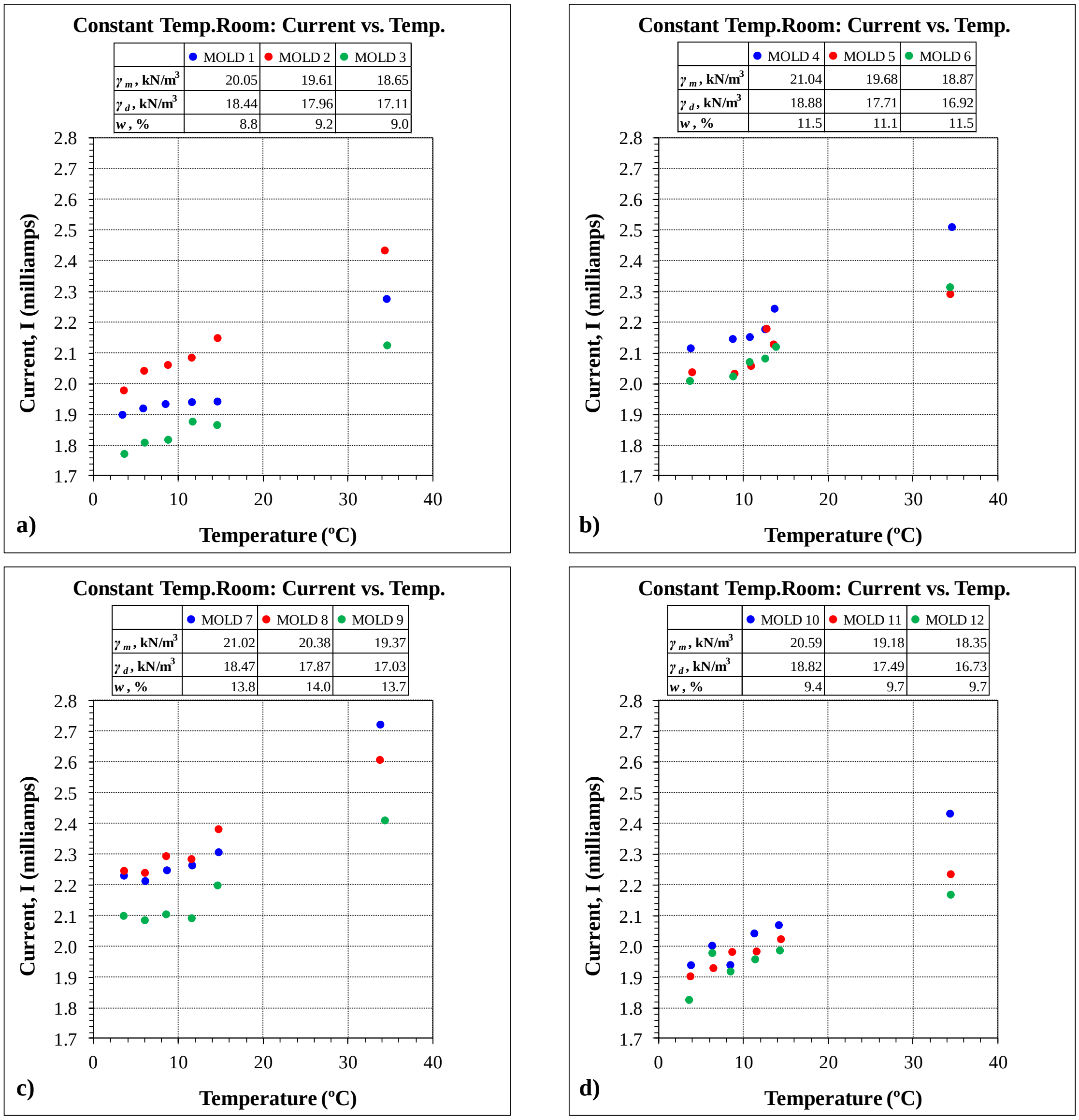


Figure B.14 Constant Temperature Room Testing: Current vs. Temperature

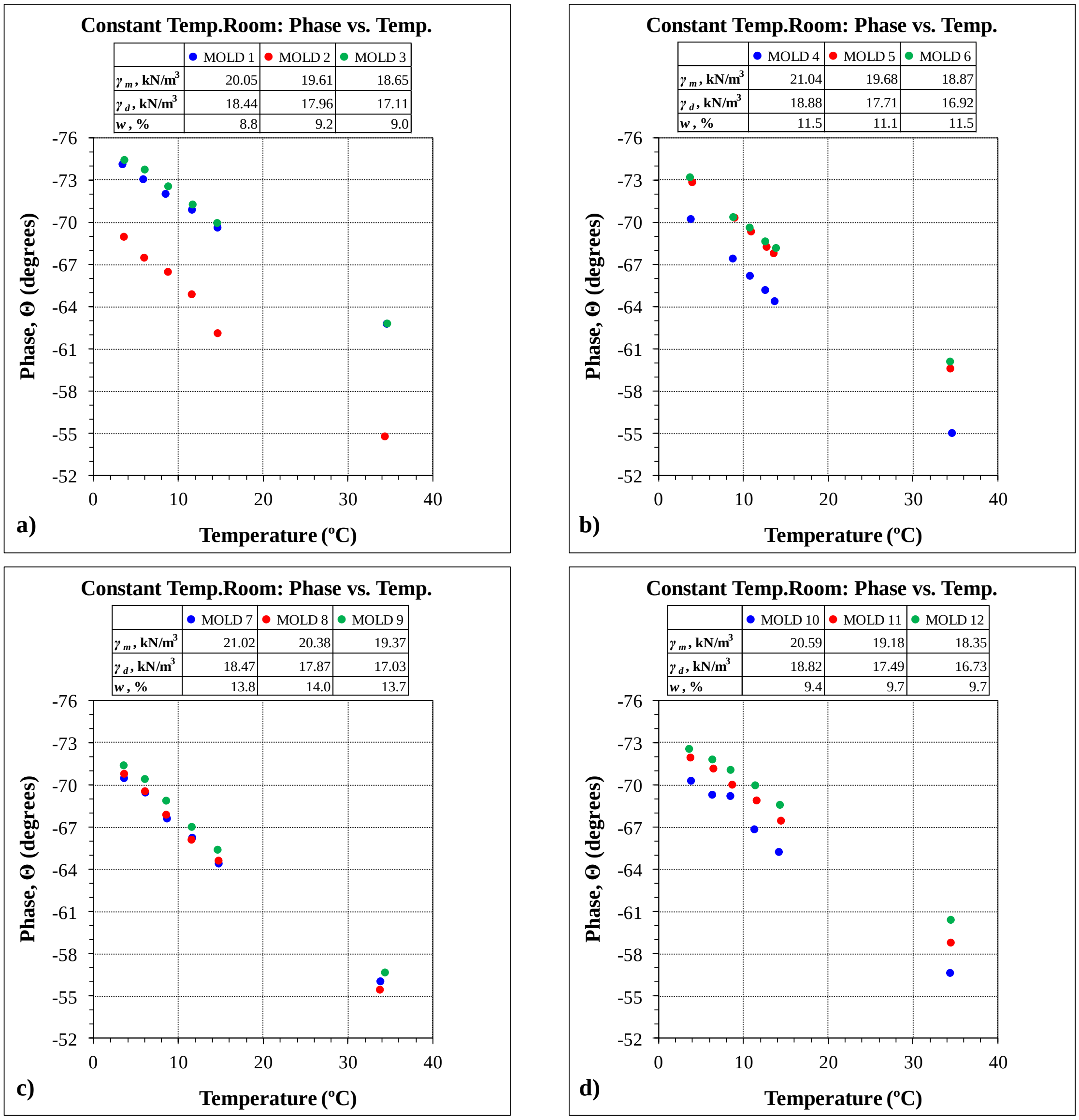


Figure B.15 Constant Temperature Room Testing: Phase vs. Temperature

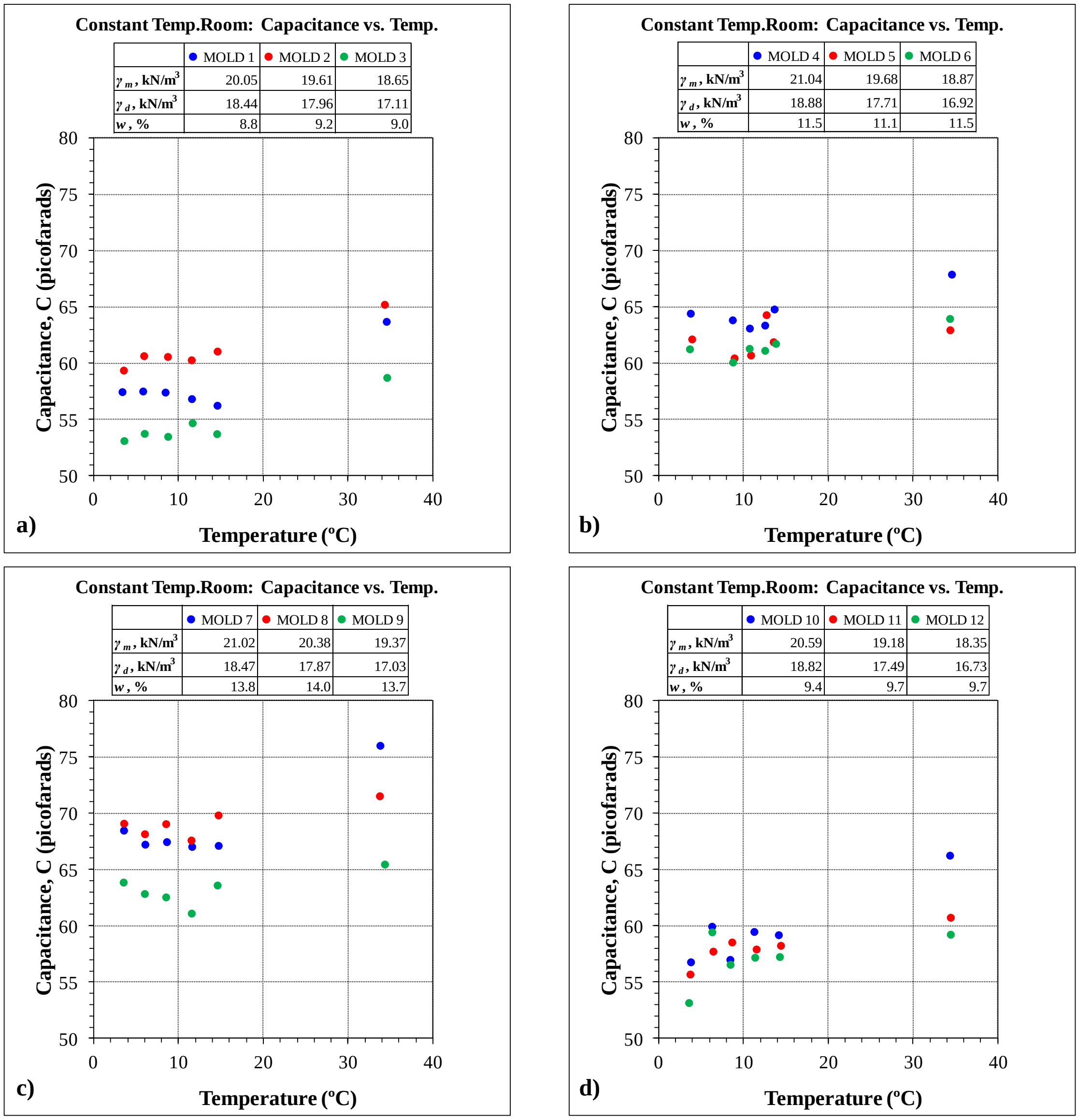


Figure B.16 Constant Temperature Room Testing: Capacitance vs. Temperature

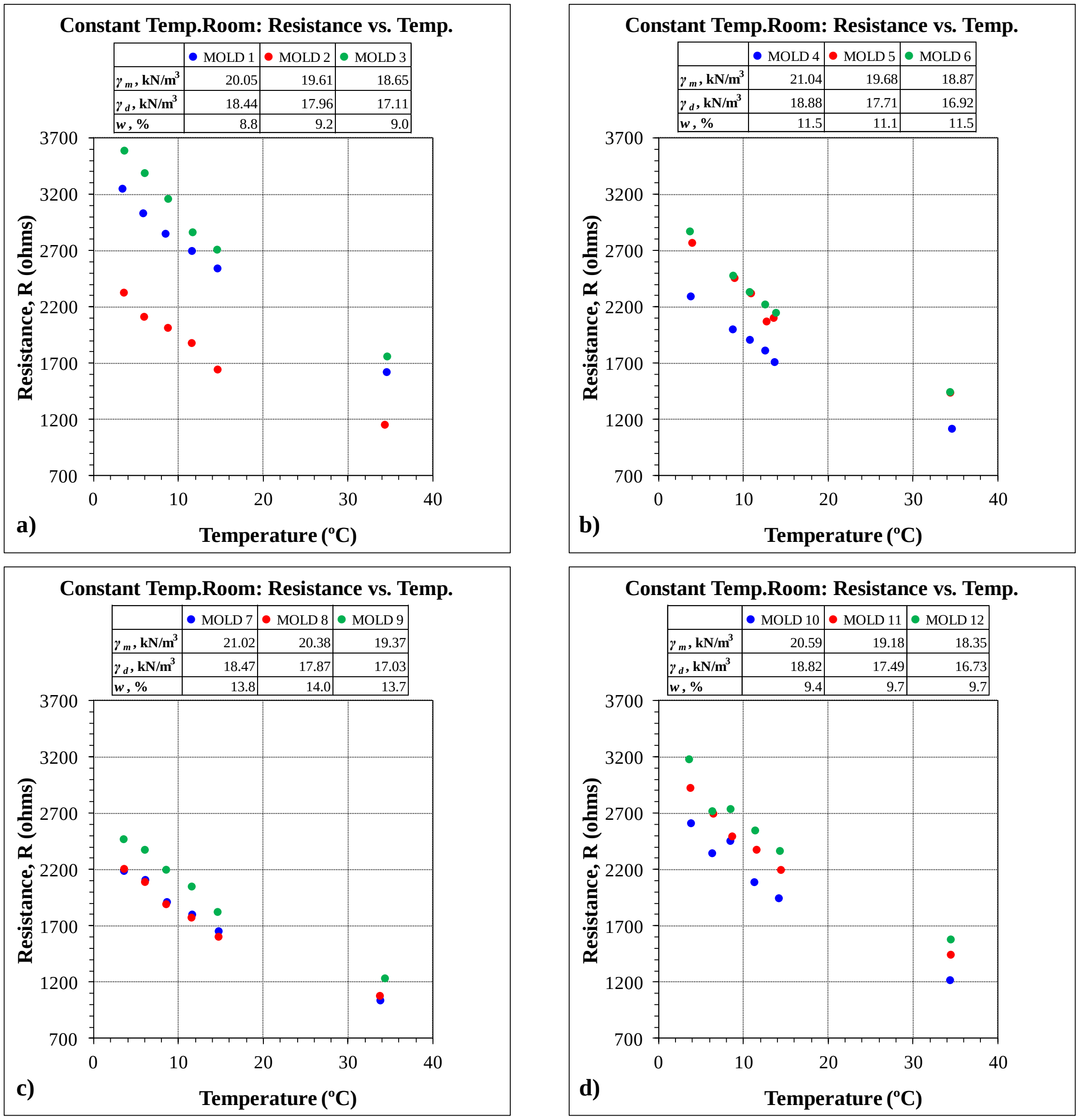


Figure B.17 Constant Temperature Room Testing: Resistance vs. Temperature

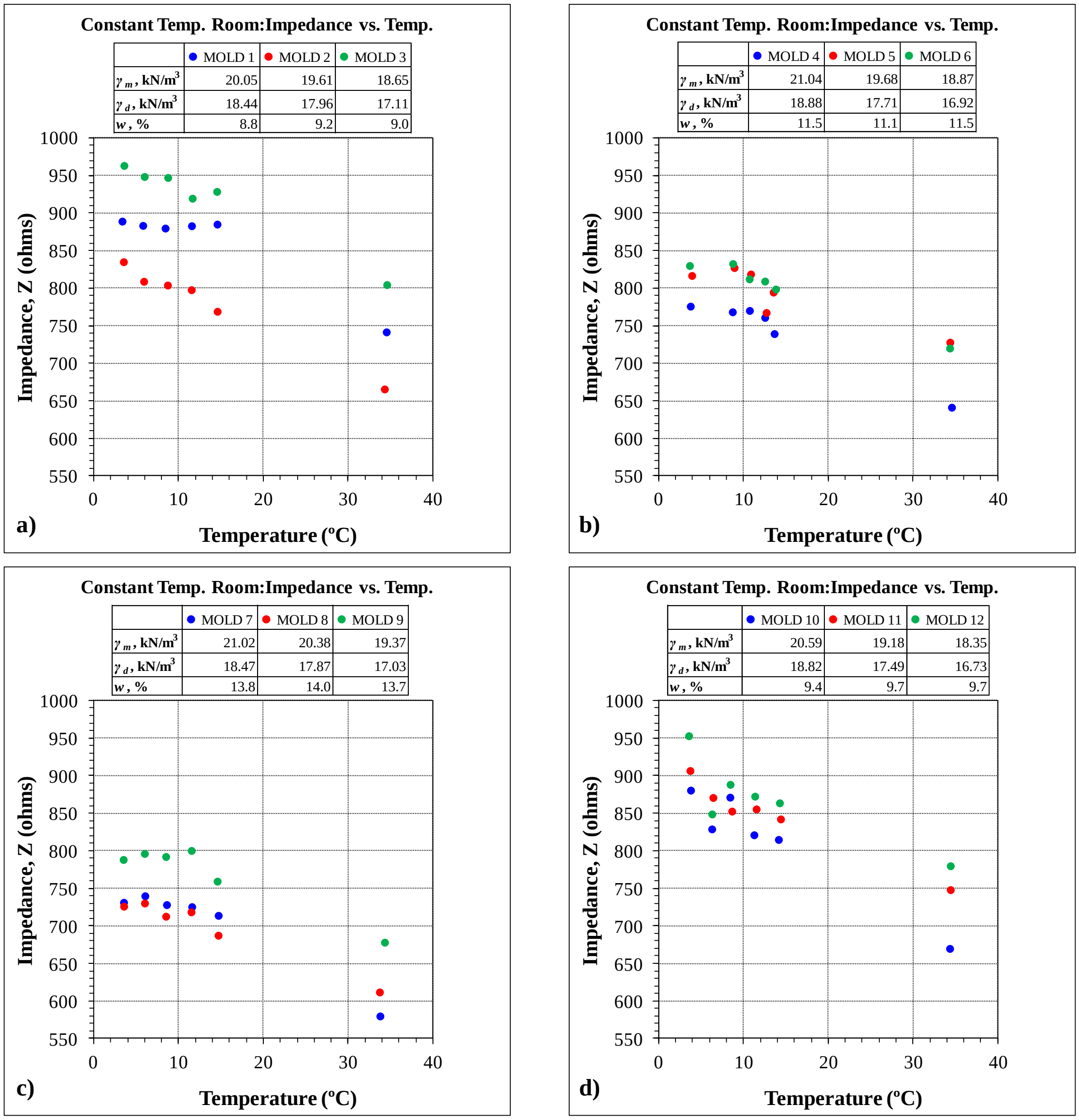


Figure B.18 Constant Temperature Room Testing: Impedance vs. Temperature

Appendix C

MOLDS GROUPED BY DRY UNIT WEIGHT:

COOLING, HEATING, & CONSTANT TEMPERATURE ROOM TESTING

This appendix contains figures that illustrate the electrical properties recorded by the Electrical Density Gauge (EDG) over a range of temperatures, grouped by dry unit weight and electrical property of interest during the cooling cycle, heating cycle, and constant temperature room testing, as described in Chapter 7.

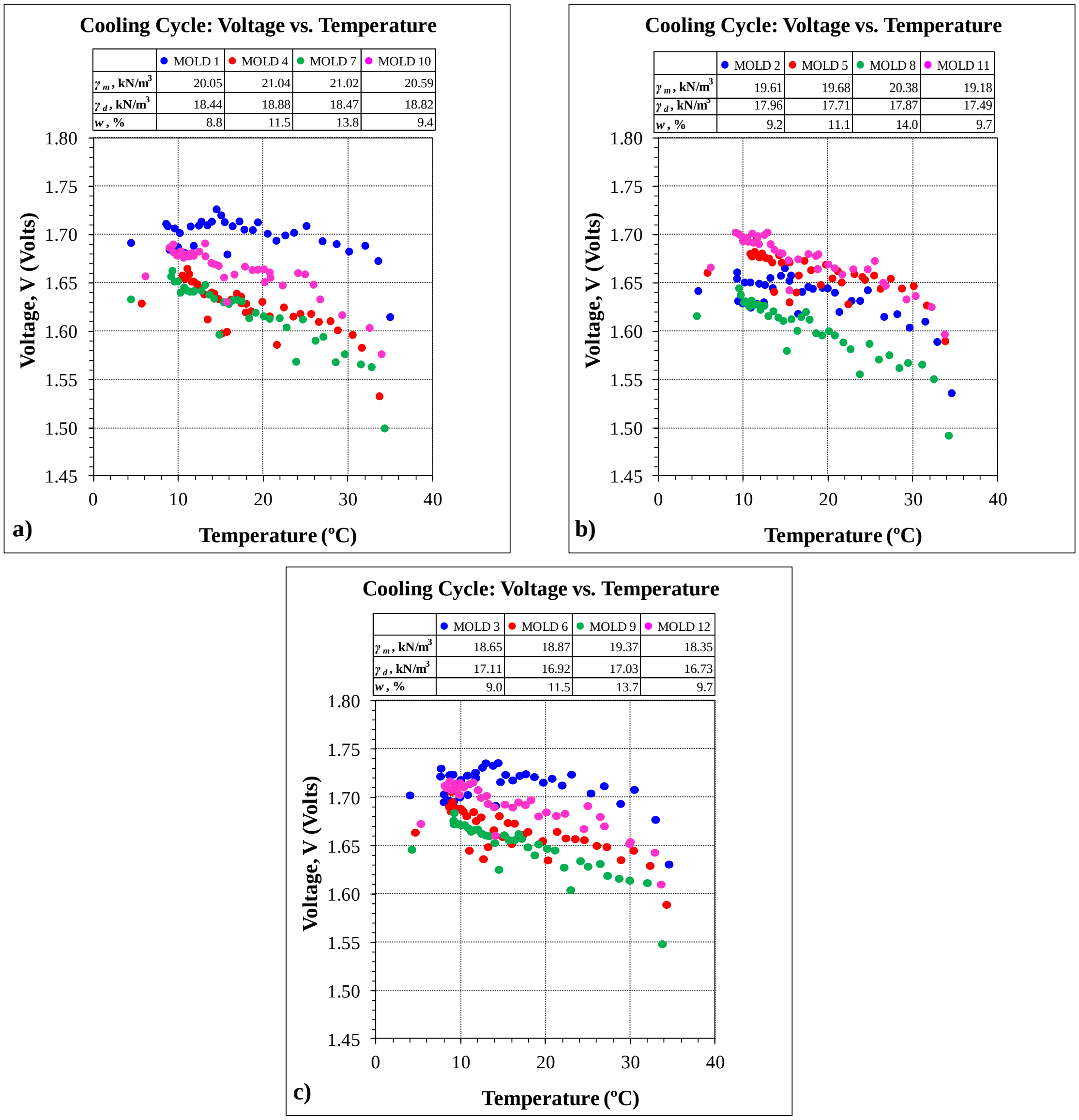


Figure C.1 Cooling Cycle: Voltage vs. Temperature

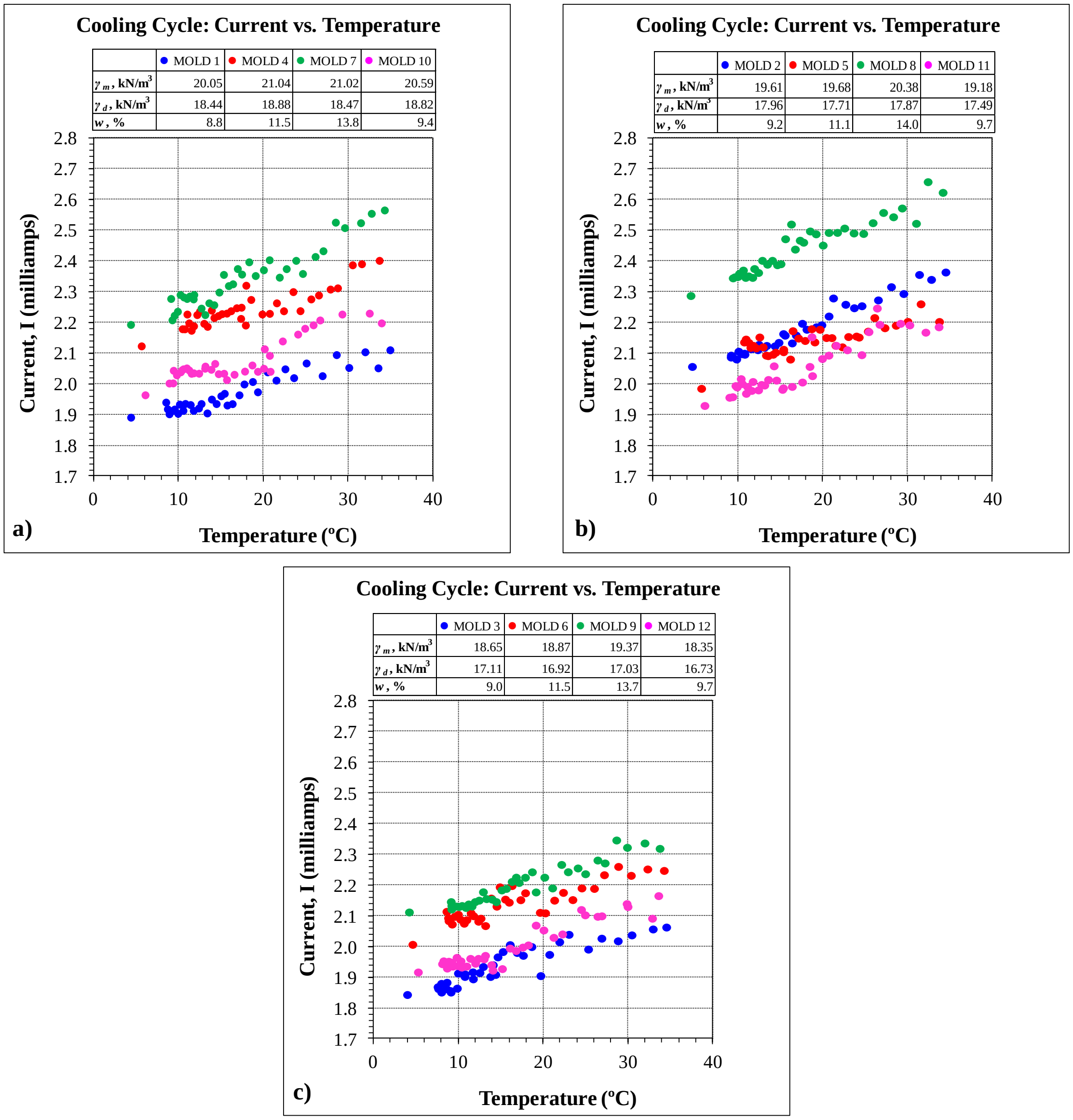


Figure C.2 Cooling Cycle: Current vs. Temperature

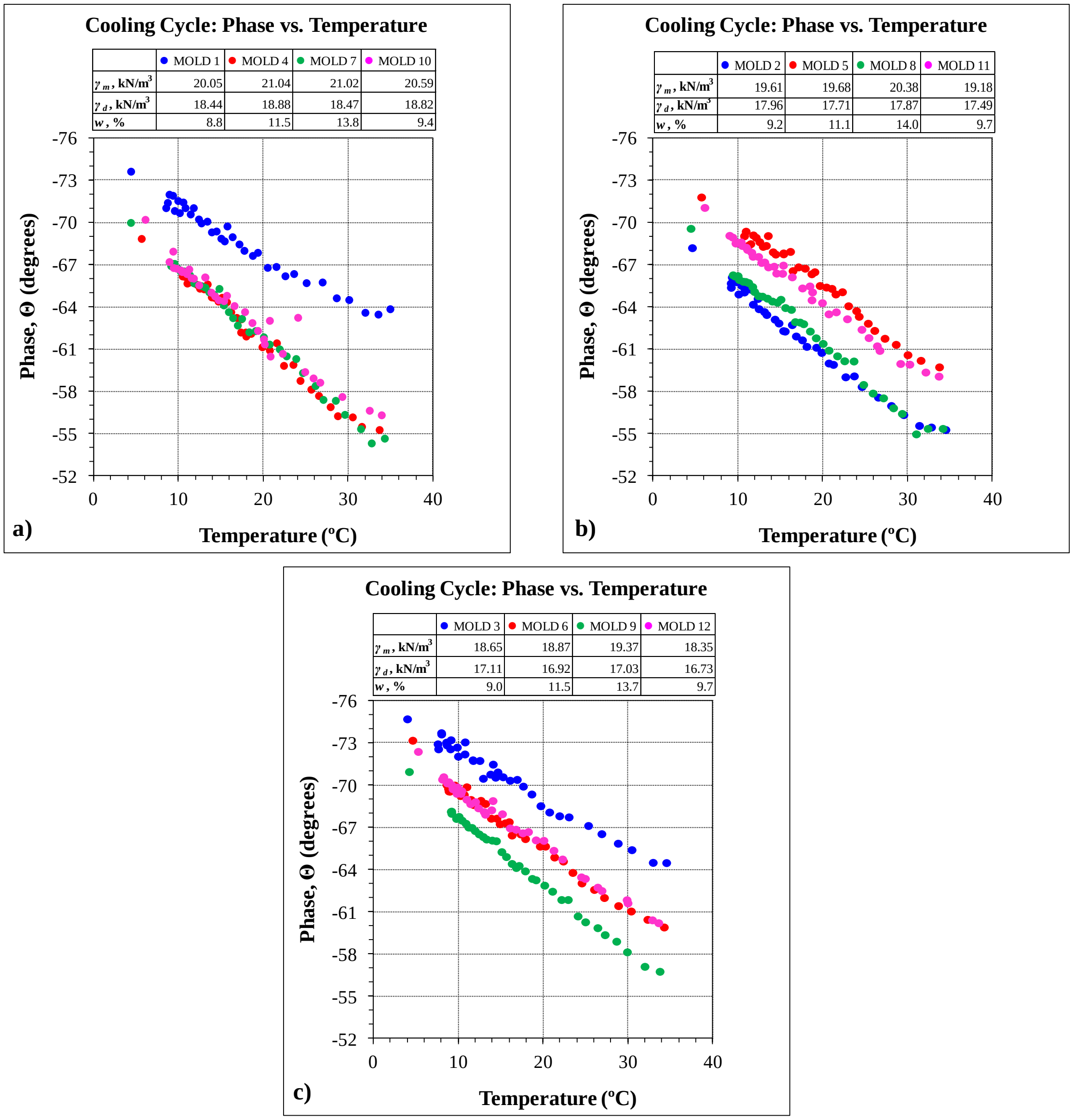


Figure C.3 Cooling Cycle: Phase vs. Temperature

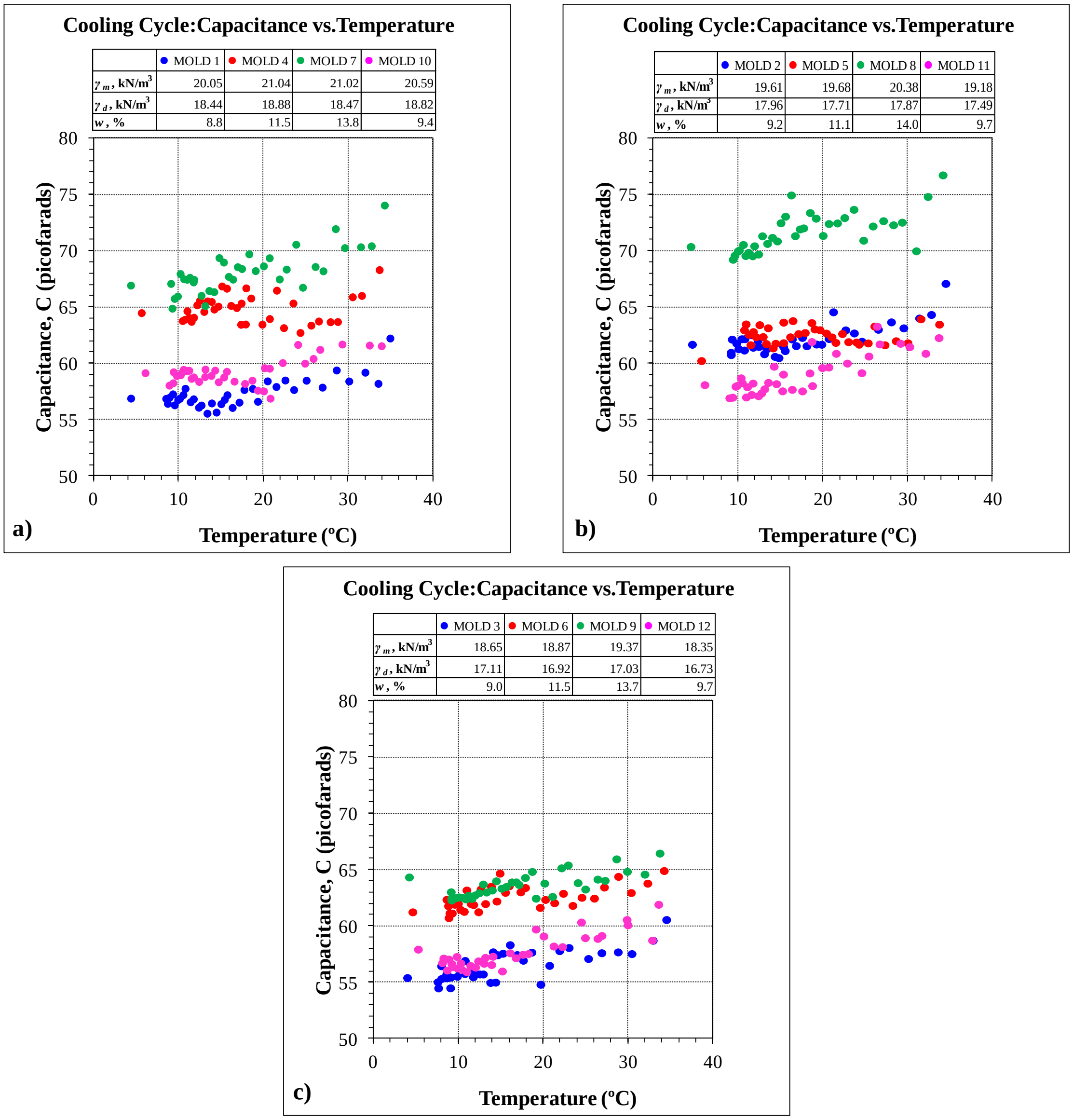


Figure C.4 Cooling Cycle: Capacitance vs. Temperature

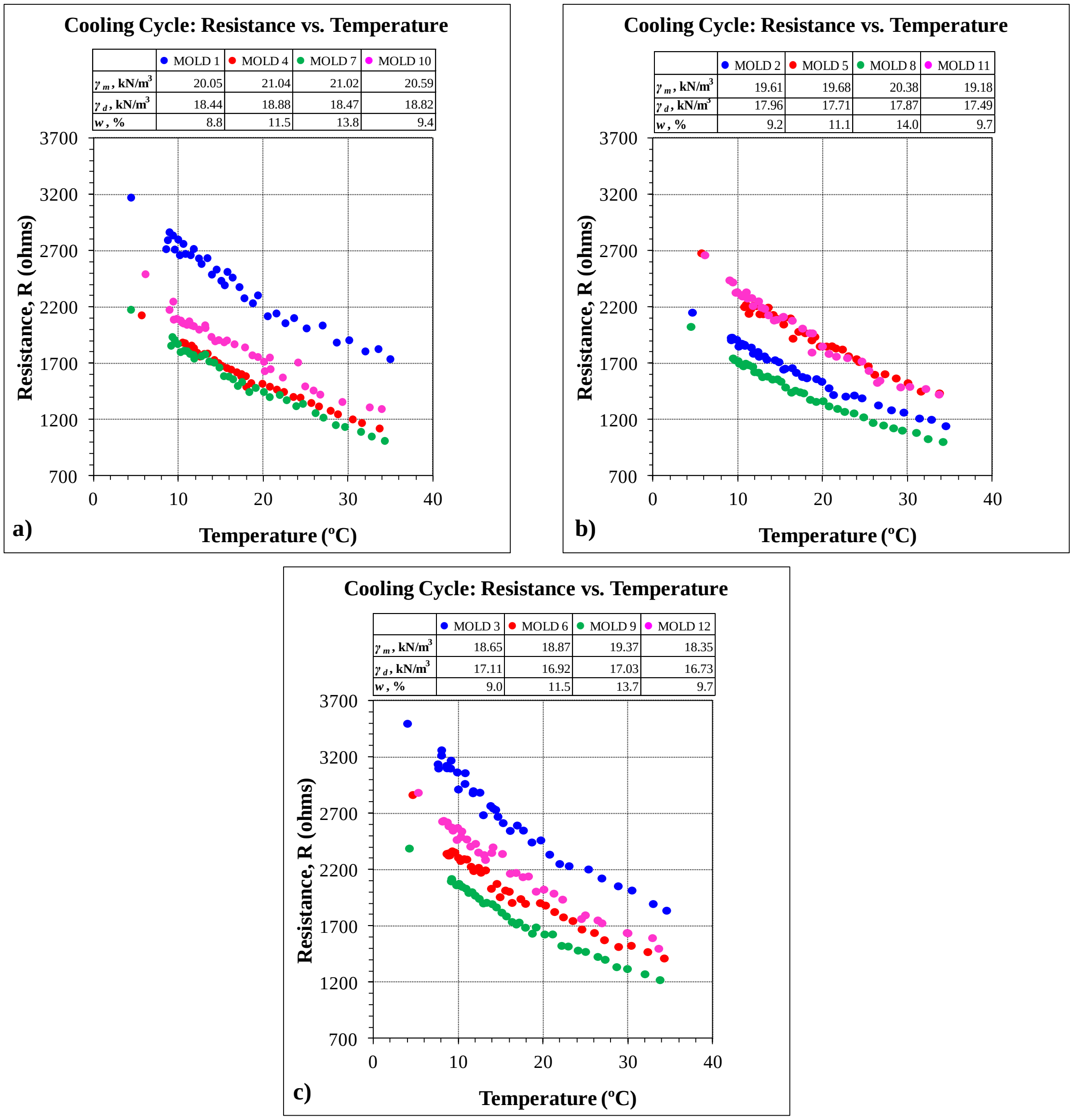


Figure C.5 Cooling Cycle: Resistance vs. Temperature

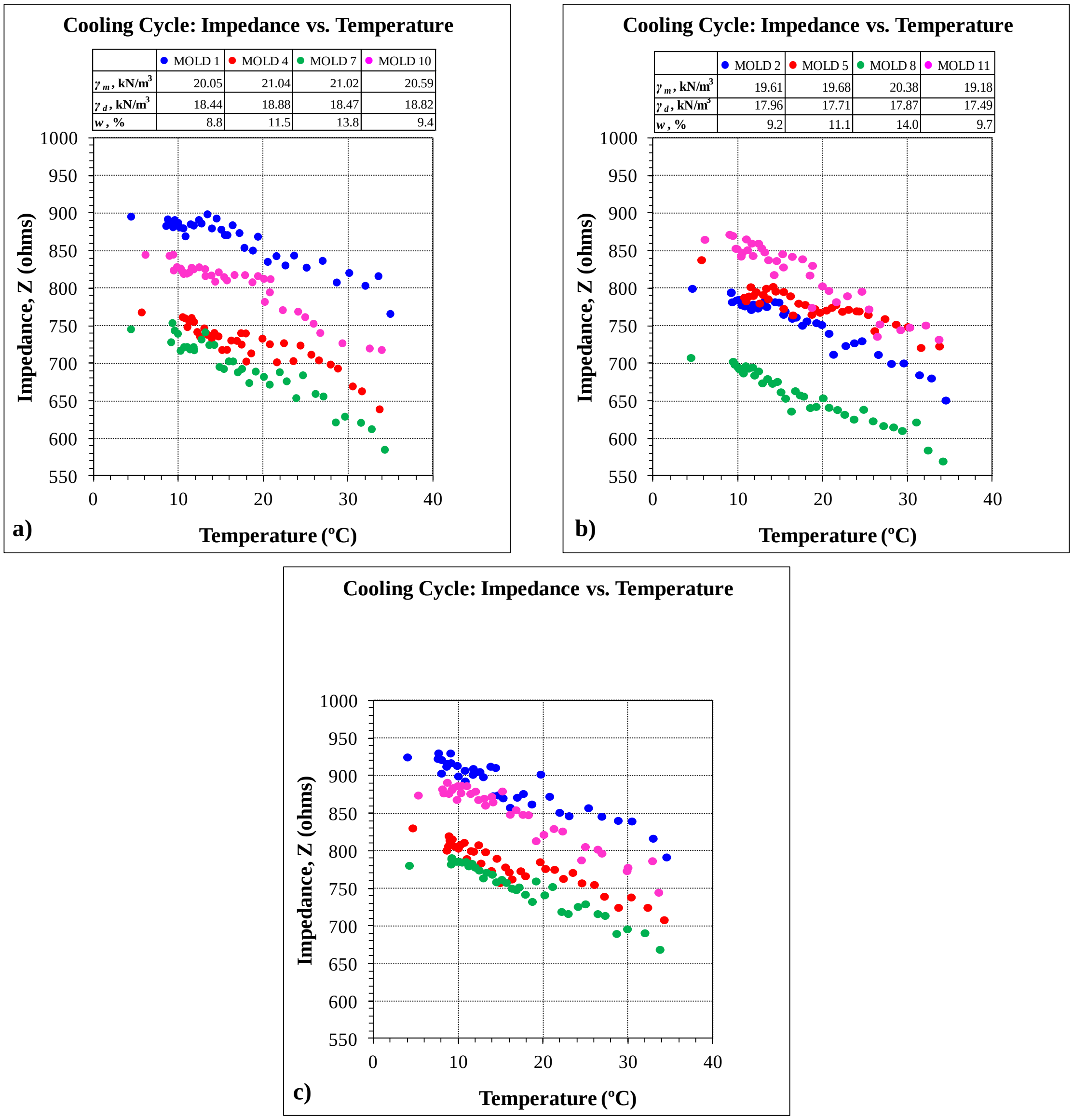


Figure C.6 Cooling Cycle: Impedance vs. Temperature

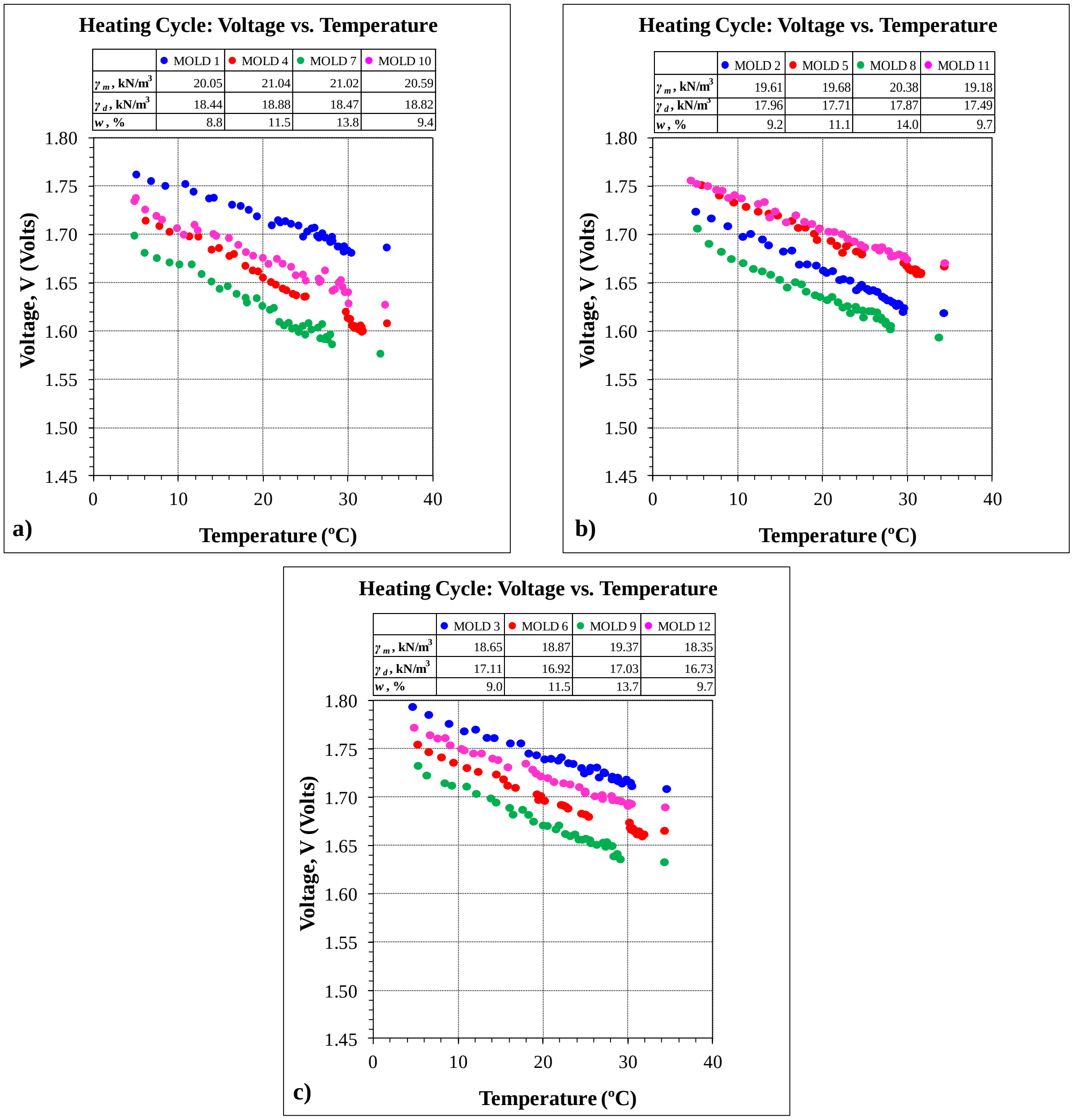


Figure C.7 Heating Cycle: Voltage vs. Temperature

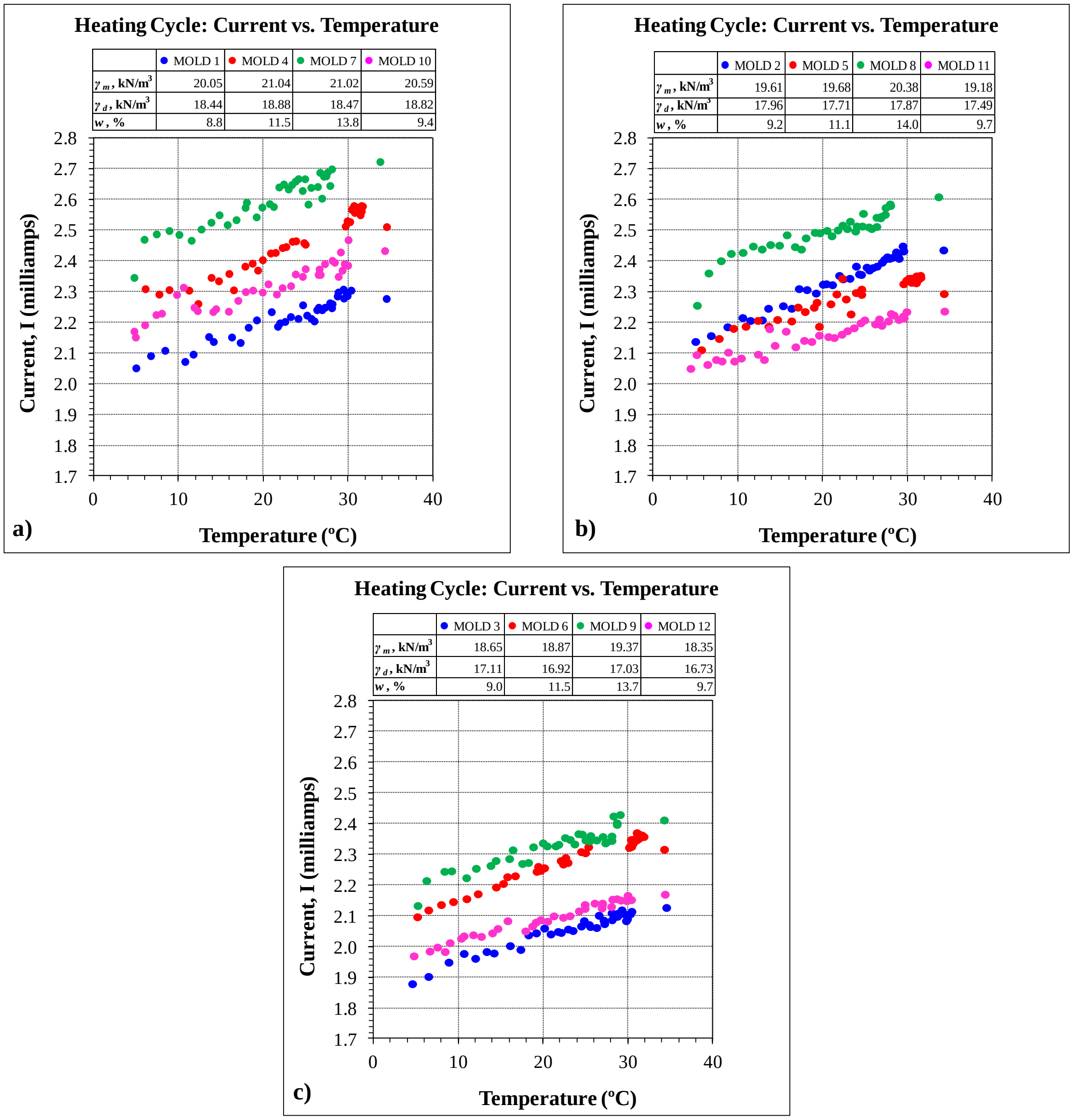


Figure C.8 Heating Cycle: Current vs. Temperature

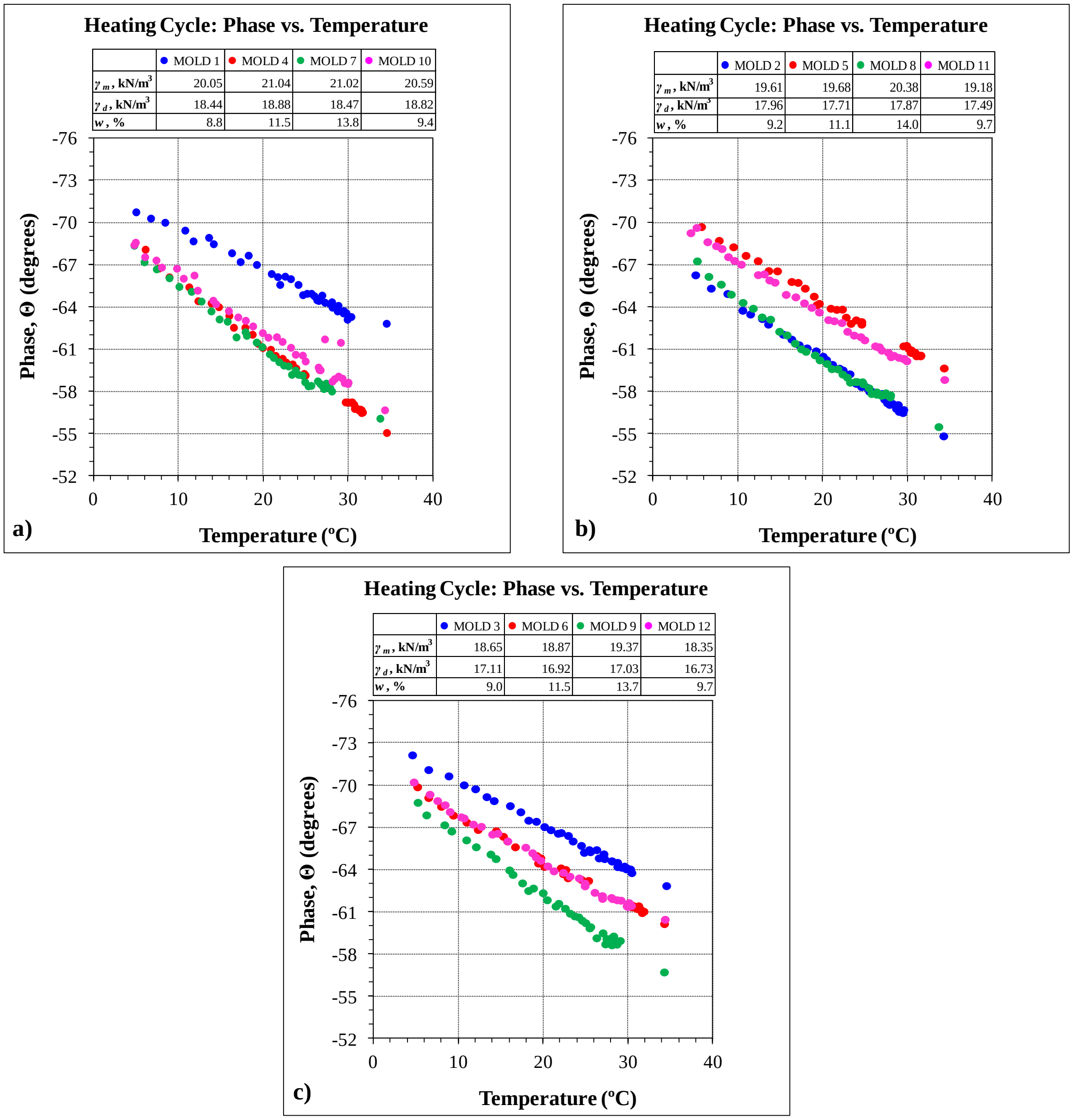


Figure C.9 Heating Cycle: Phase vs. Temperature

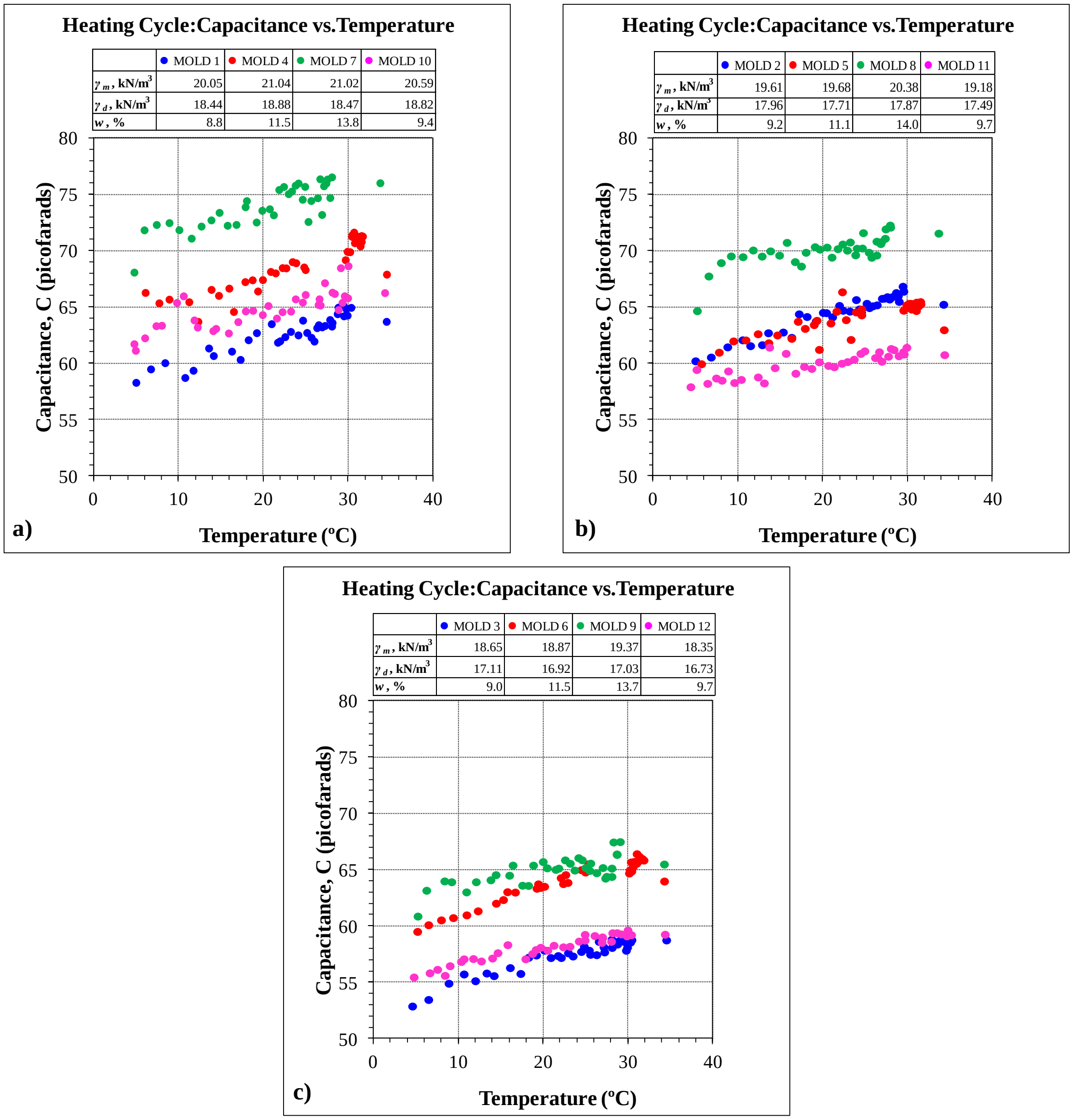


Figure C.10 Heating Cycle: Capacitance vs. Temperature

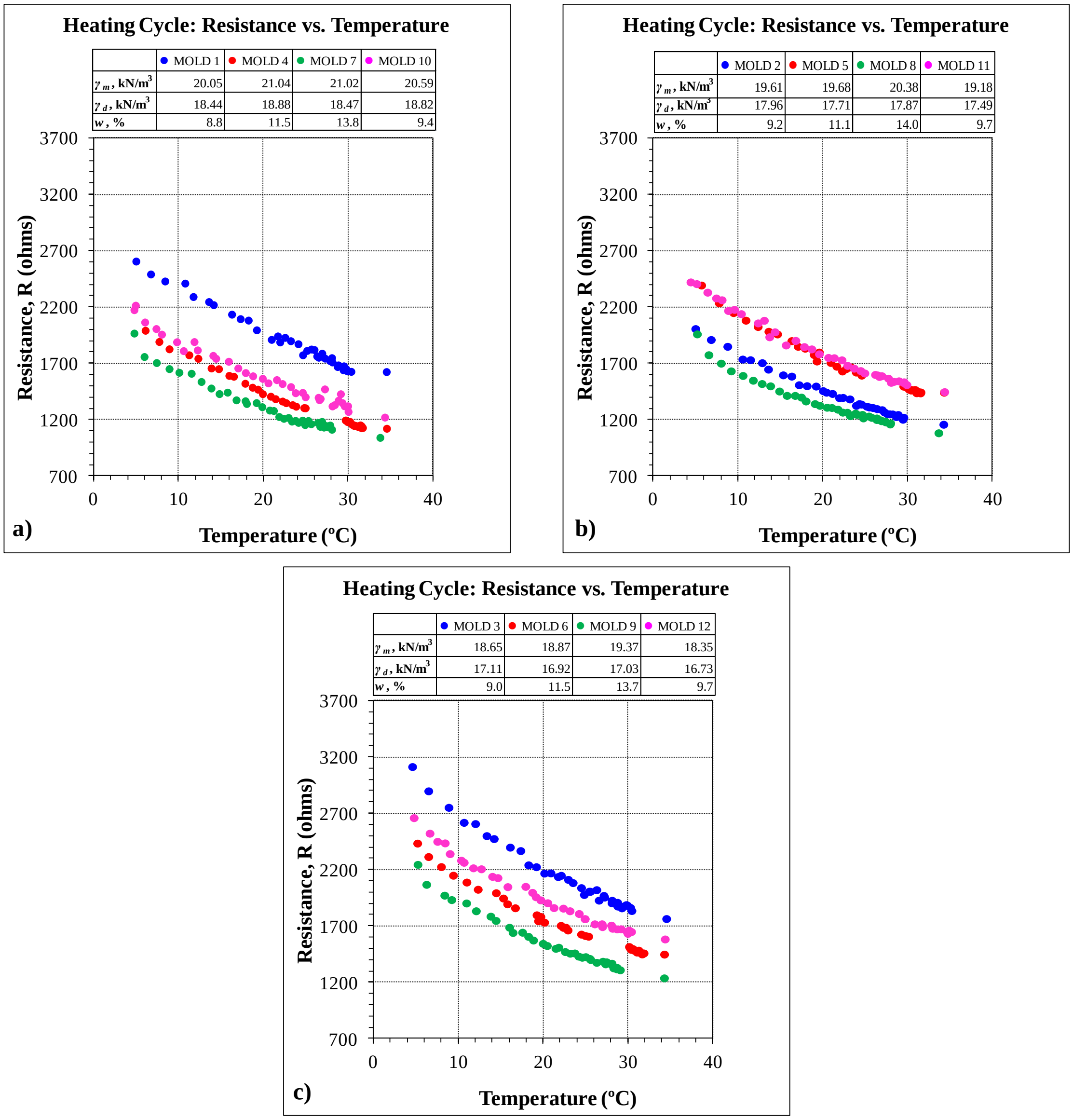


Figure C.11 Heating Cycle: Resistance vs. Temperature

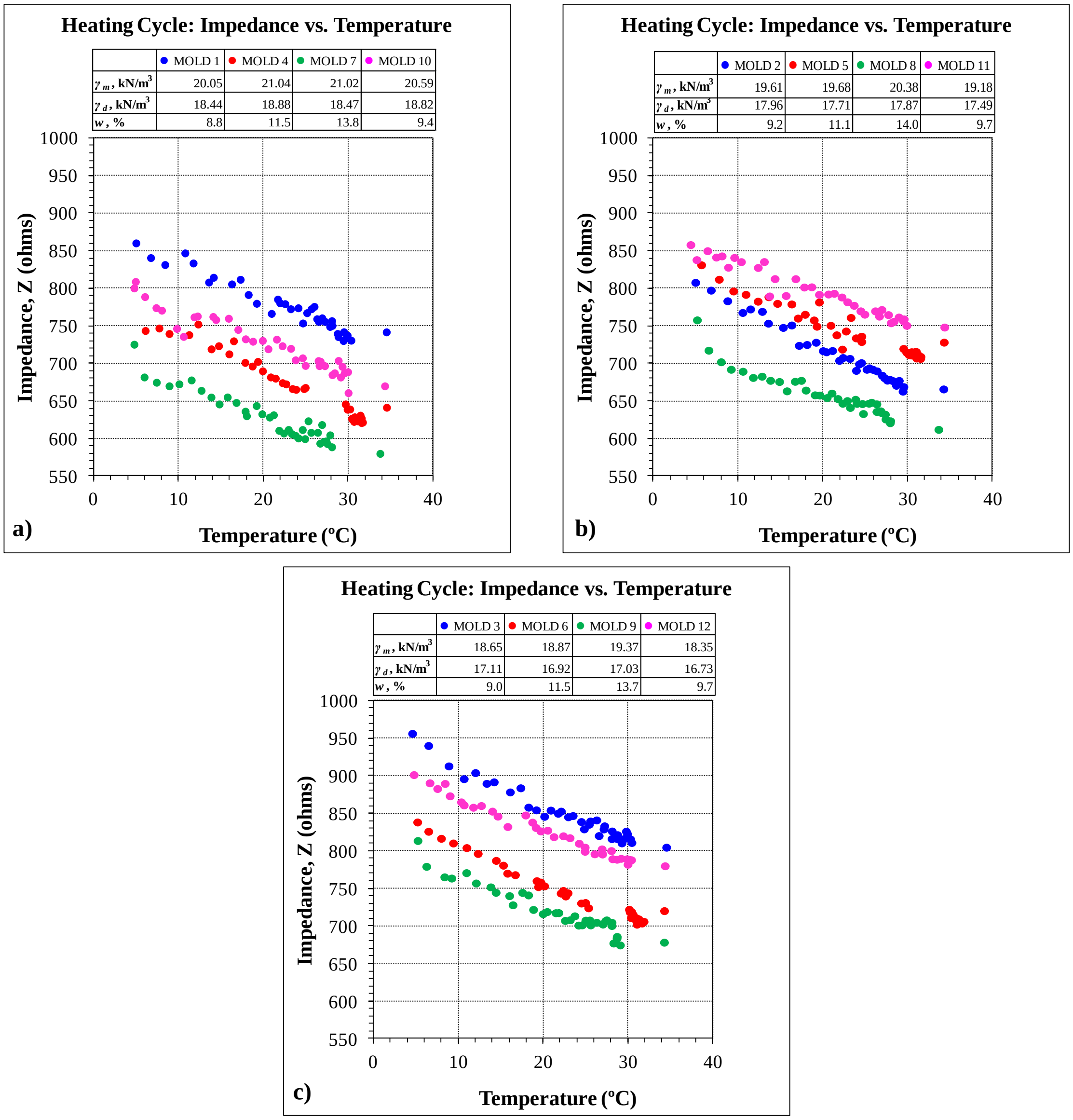


Figure C.12 Heating Cycle: Impedance vs. Temperature

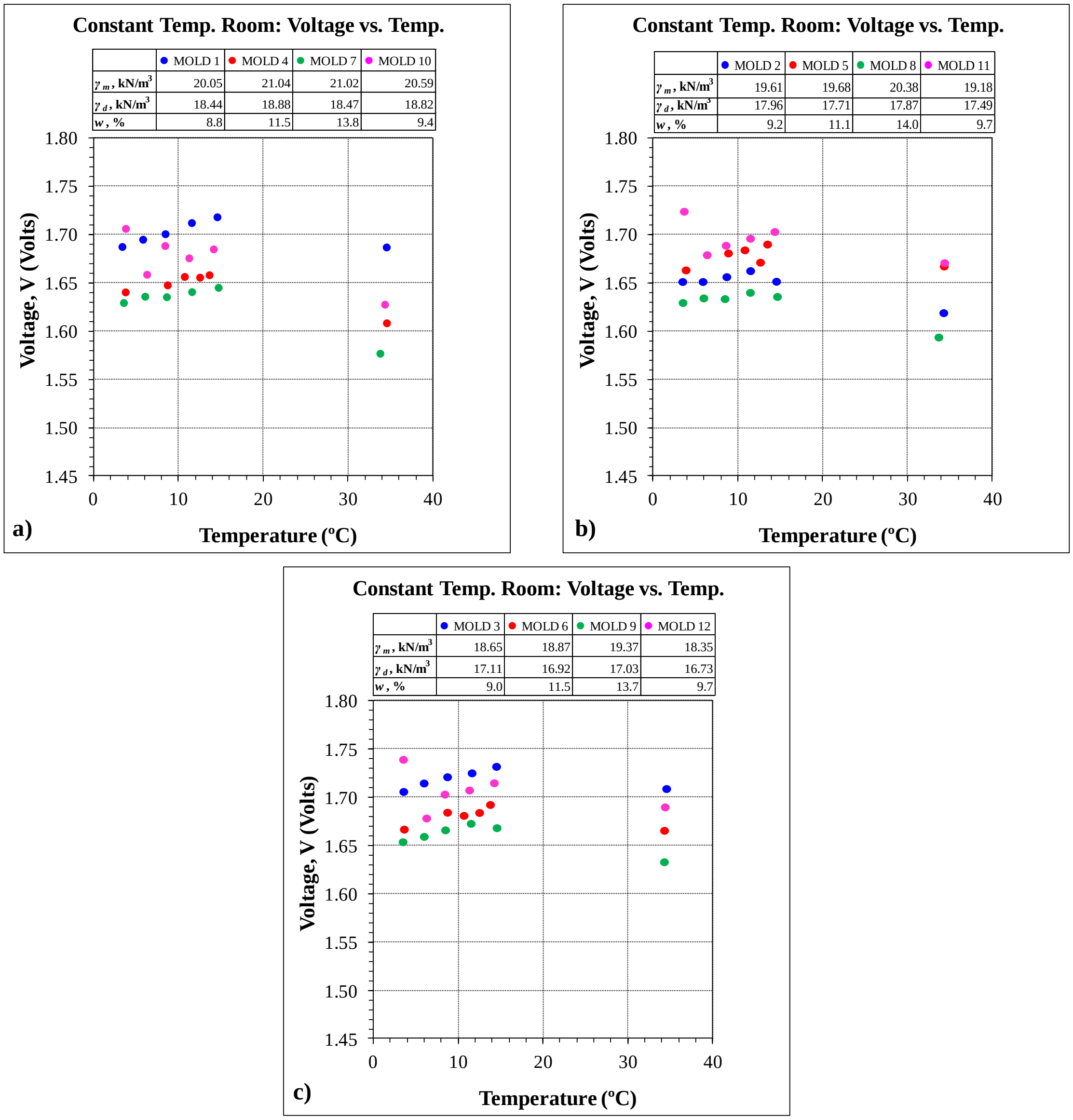


Figure C.13 Constant Temperature Room Testing: Voltage vs. Temperature

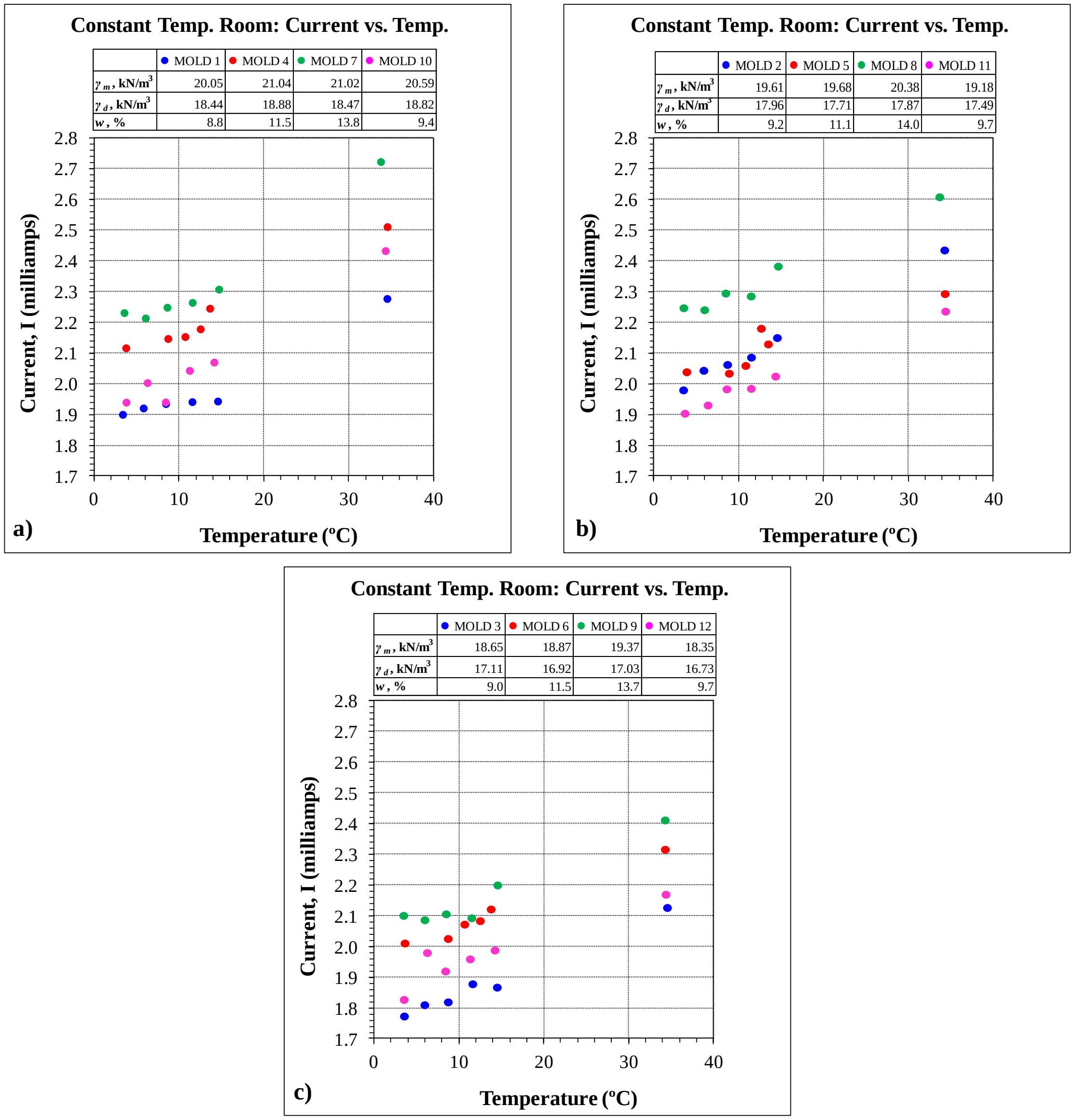


Figure C.14 Constant Temperature Room Testing: Current vs. Temperature

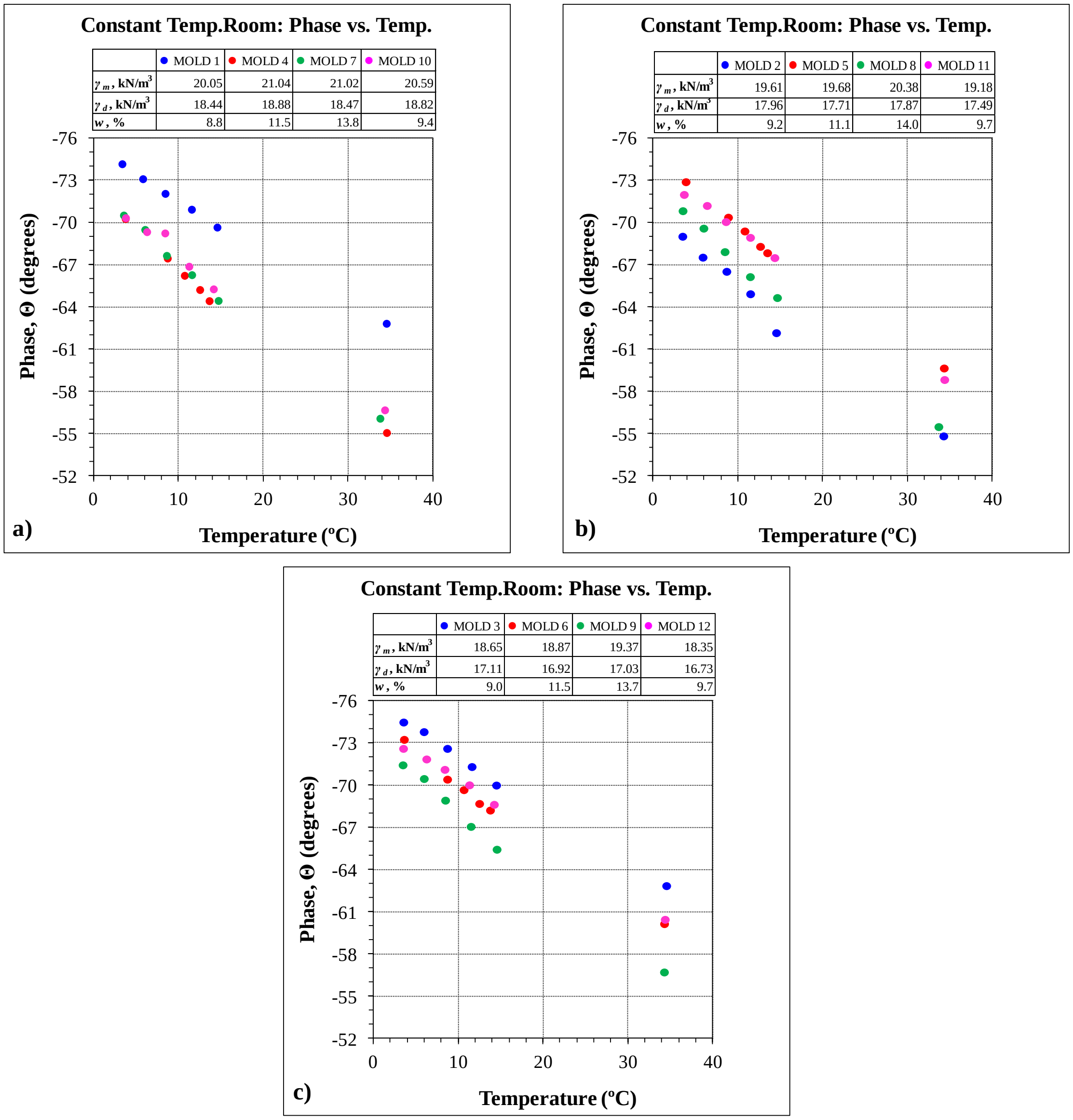


Figure C.15 Constant Temperature Room Testing: Phase vs. Temperature

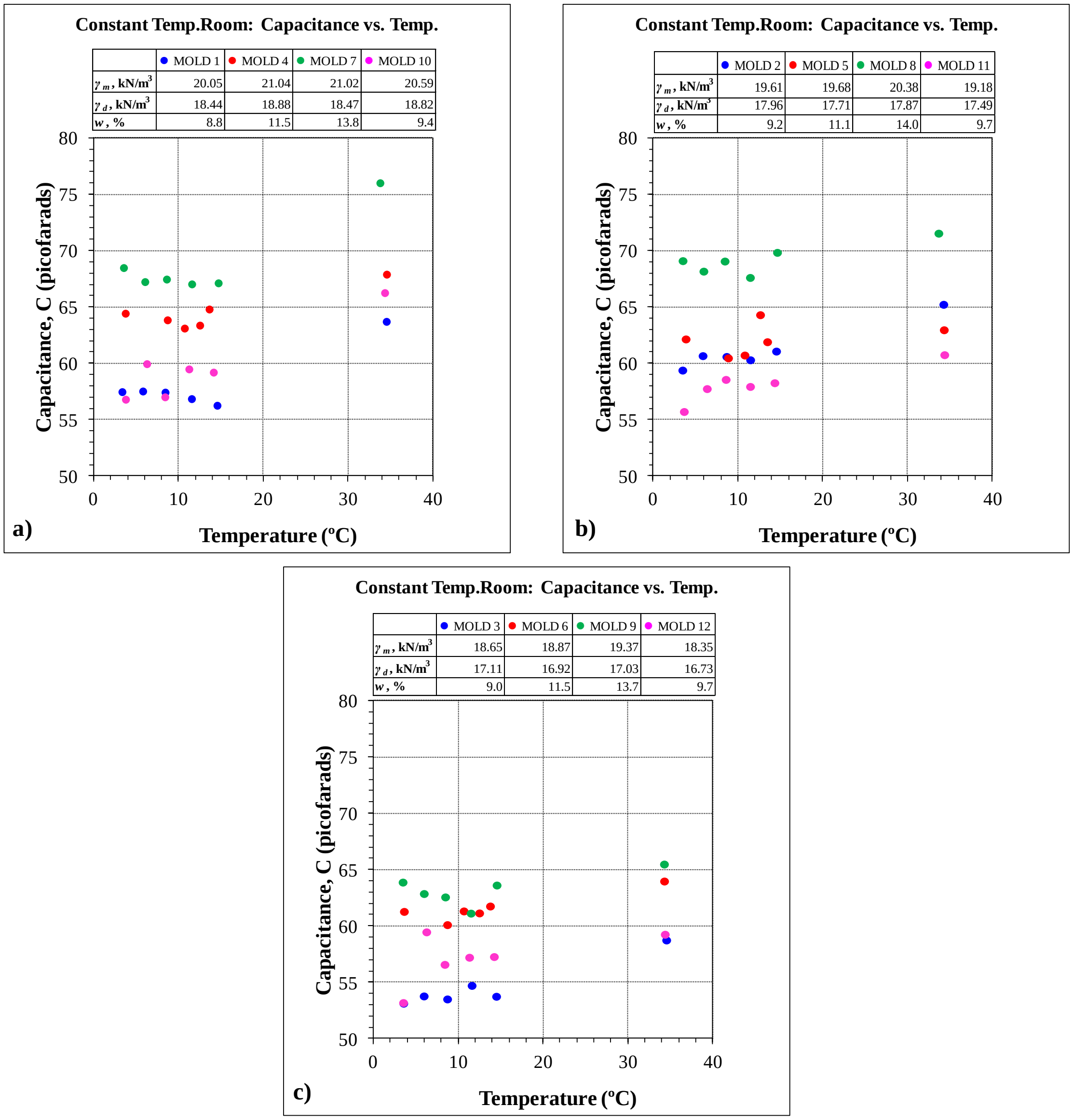


Figure C.16 Constant Temperature Room Testing: Capacitance vs. Temperature

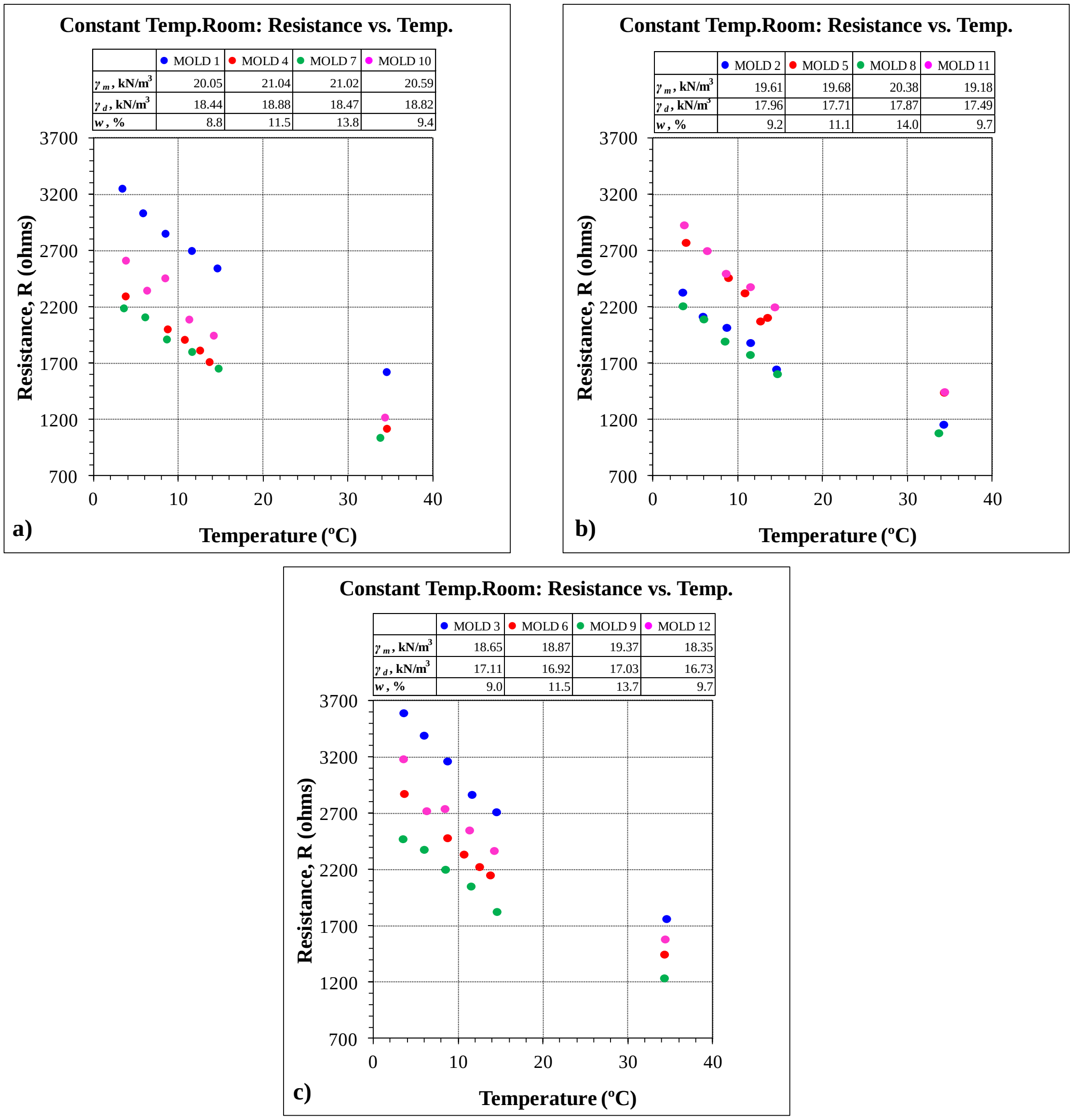


Figure C.17 Constant Temperature Room Testing: Resistance vs. Temperature

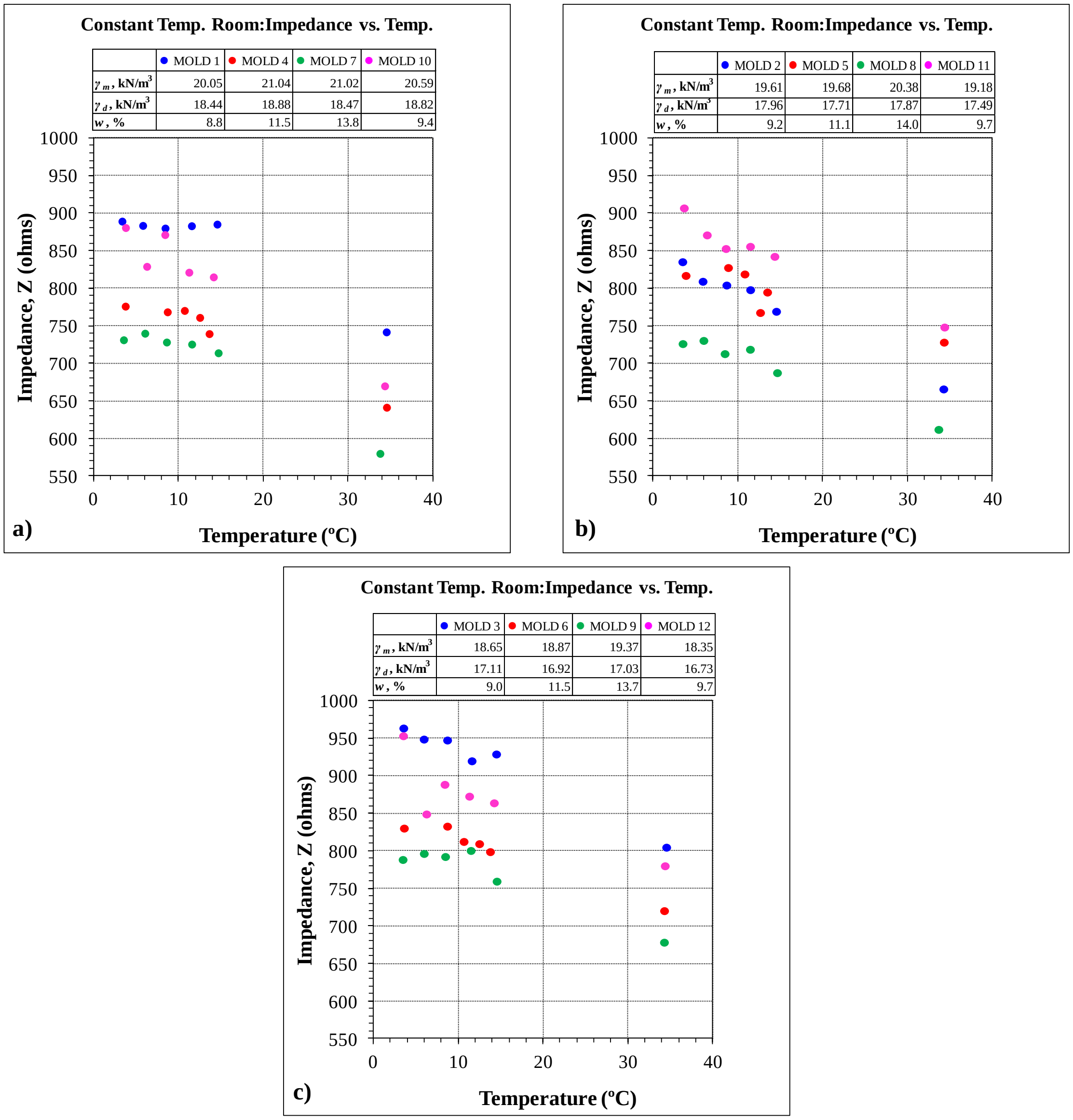


Figure C.18 Constant Temperature Room Testing: Impedance vs. Temperature

Appendix D

ALL MOLDS:

COOLING, HEATING, & CONSTANT TEMPERATURE ROOM TESTING

This appendix contains figures that illustrate the electrical properties recorded by the Electrical Density Gauge (EDG) over a range of temperatures, for all molds during the cooling cycle, heating cycle, and constant temperature room testing, as described in Chapter 7.

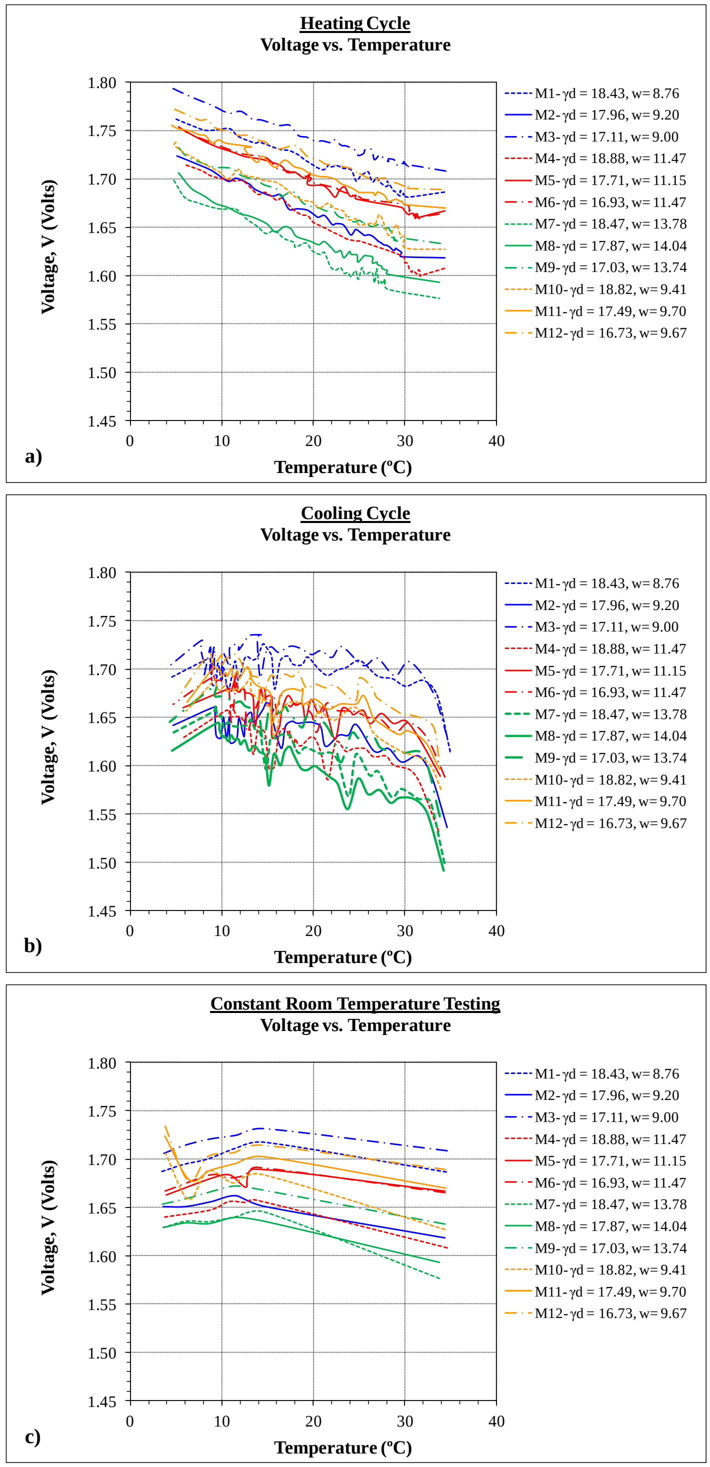


Figure D.1 Voltage vs. Temperature

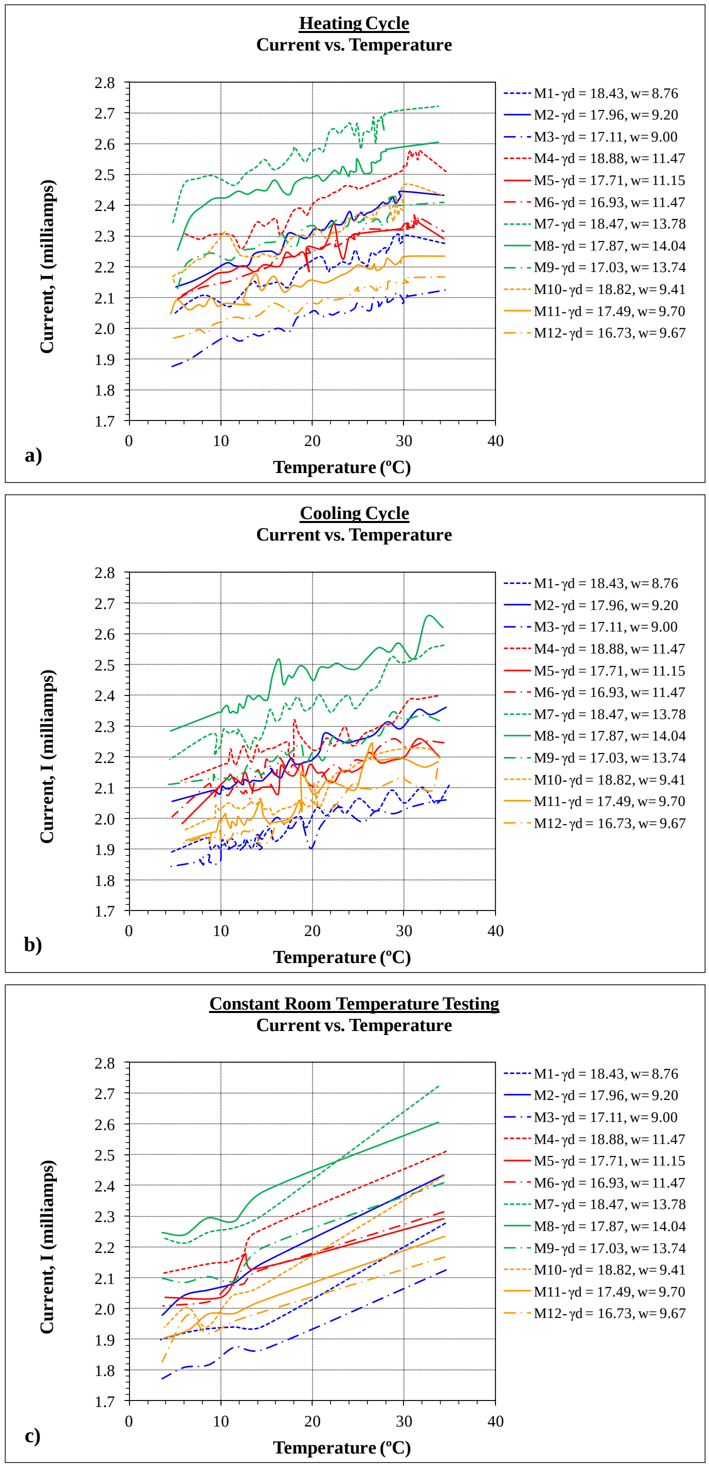


Figure D.2 Current vs. Temperature

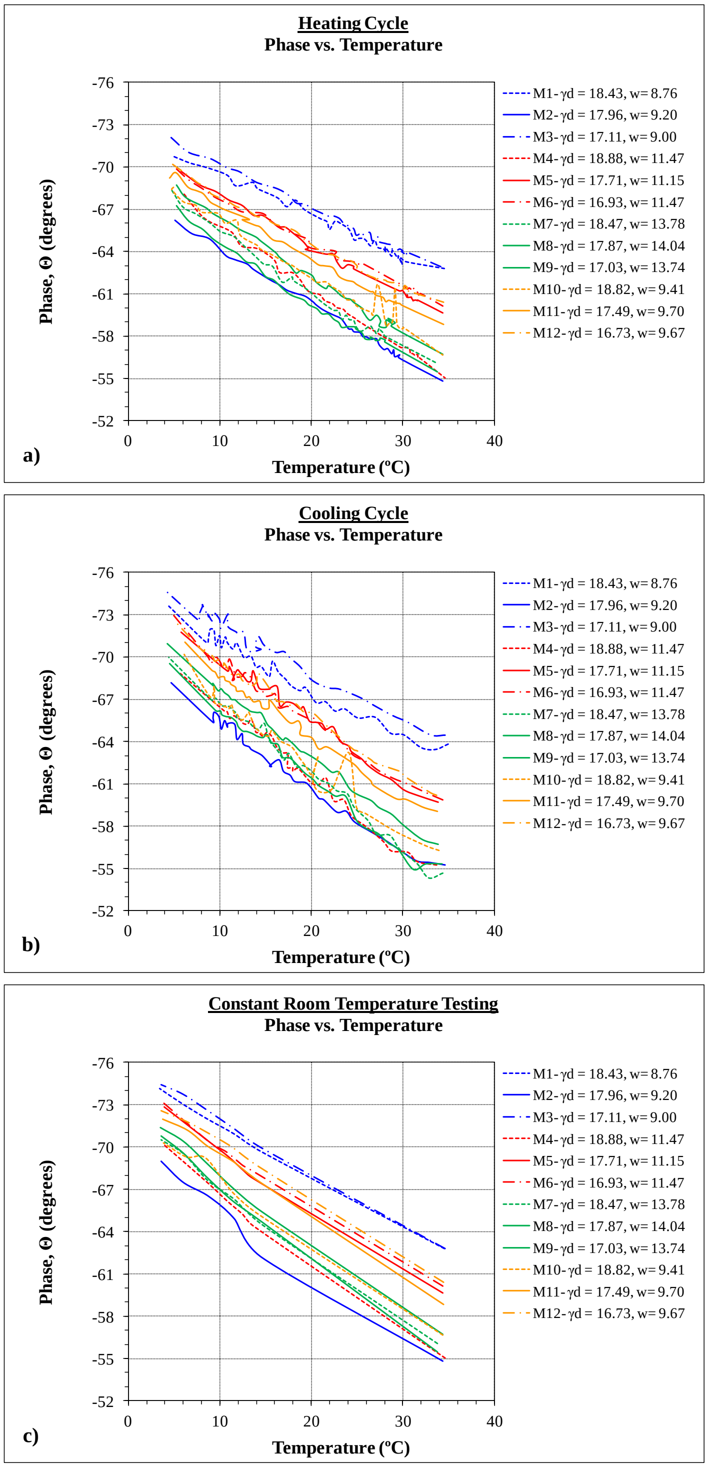


Figure D.3 Phase vs. Temperature

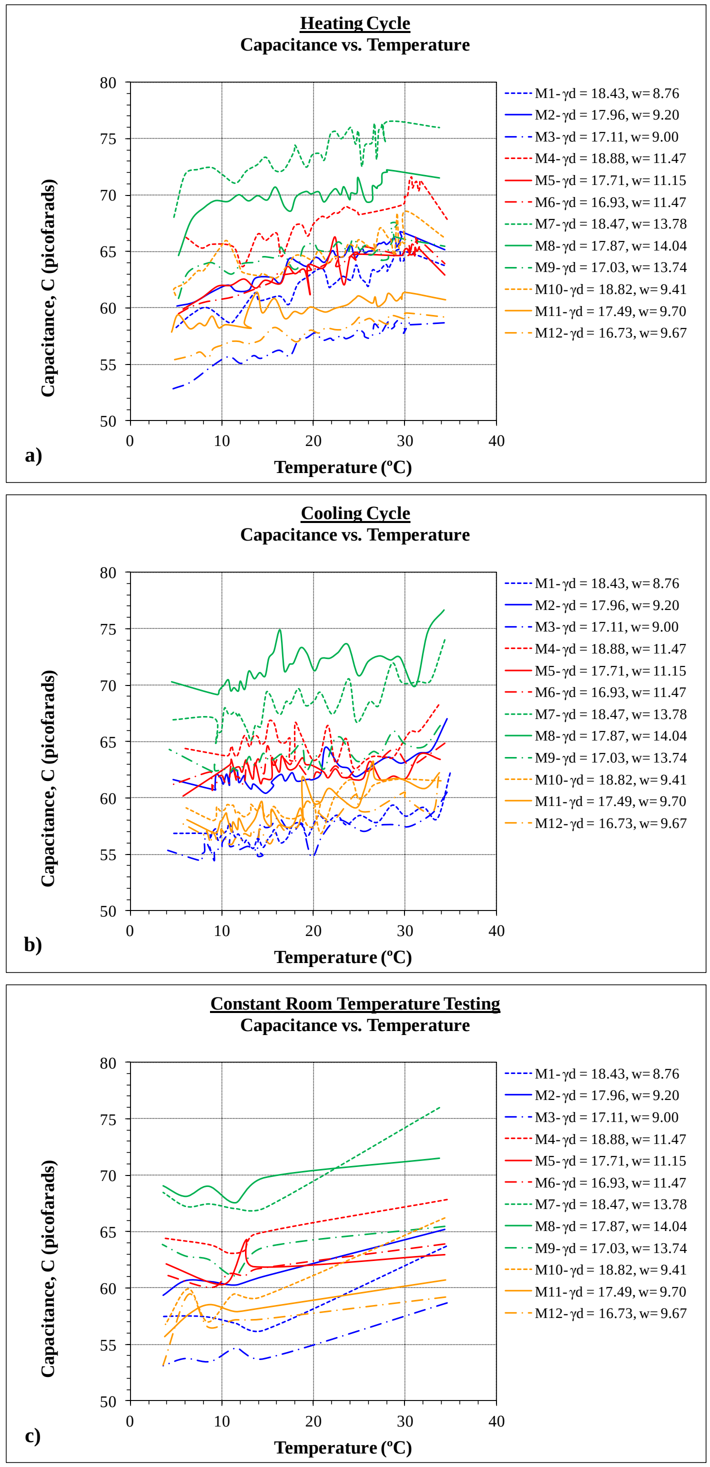


Figure D.4 Capacitance vs. Temperature

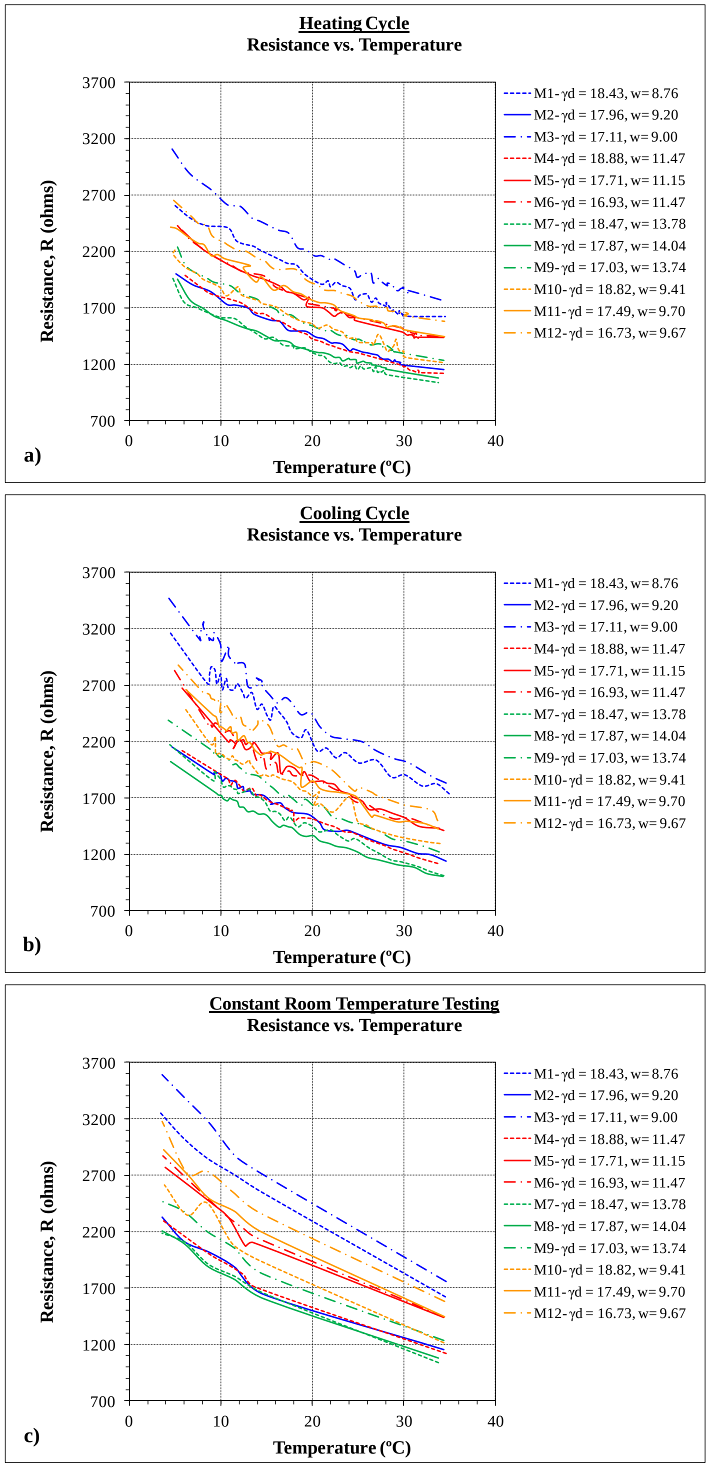


Figure D.5 Resistance vs. Temperature

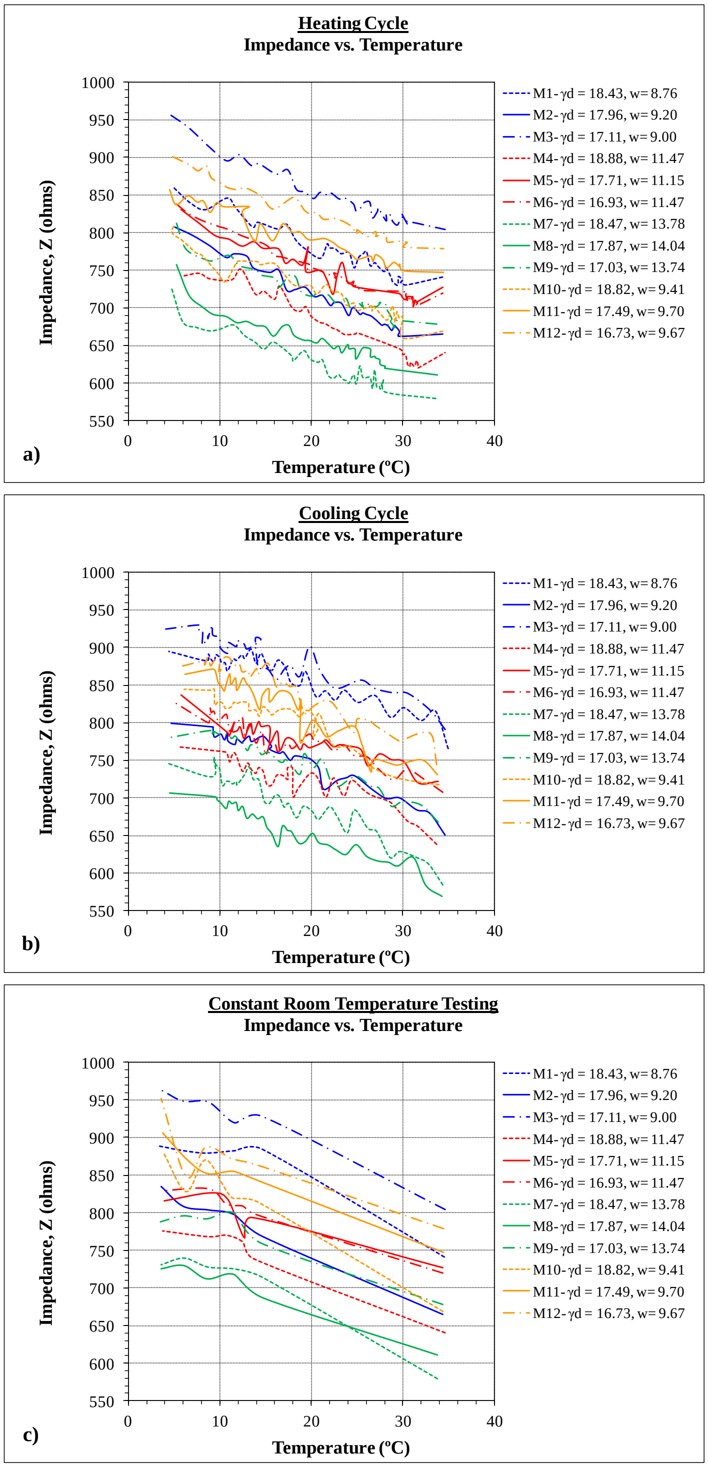


Figure D.6 Impedance vs. Temperature