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Rapid Non-Nuclear In Situ Density and Moisture Content Measurement of Soil

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Rapid Non-Nuclear In Situ Density and Moisture Content Measurement of Soil

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ABSTRACT

Adequate soil compaction is important for the stability and safety of structures and transportation infrastructure. Thus, methods utilized to obtain properties that control the quality of compaction in the field are essential to ensure proper construction. These properties include; total density, dry density, total unit weight and dry unit weight of the compacted soil. The most common method to measure these properties in the field is the Nuclear Density Gauge. Moisture content and density results are obtained using the Nuclear Density Gauge in one to four minutes. However, this method requires specialized training and strict storage requirements in addition to licensing and certification, due to the radioactive nature of the device. Other methods like the Sand Cone Test and the Rubber Balloon Test are tedious, labor intensive and cumbersome. Additionally, the sand cone requires Ottawa Silica Sand, which increases the costs of the method and is heavy to transport to the site if multiple tests are required to be performed.

A photogrammetry-based method to determine total density and total unit weight soil properties by volume estimation combined with separate soil weight measurements is presented herein. This method includes a photogrammetric analysis, using the Photomodeler software, on photographs obtained from an uncalibrated regular mobile phone camera. To validate this method, the images were obtained of a circular excavation dug in compacted soil. The image acquisition process takes less than five minutes. The Photomodeler processing time takes approximately 15 minutes to develop a three-dimensional model and volume of the excavated hole. The results obtained with this analysis method were compared with in-situ results obtained from the Troxler nuclear density gauge, sand cone and from the Humboldt electrical density gauge. Based on the obtained, results the photogrammetric method is capable to provide similar results to the nuclear density gauge and the sand cone (within four pcf for total unit weight).

The soil moisture content is necessary to obtain the dry density and dry unit weight of soils. Laboratory tests to obtain soil moisture content by means of oven drying typically require at least of 24 hours to complete. Also, it is possible to measure soil moisture content by means of evaporation using microwave oven. This method was tested on different soils to determine the feasibility of using this method as an alternative to the density nuclear gauge or laboratory procedures. Modifications to the standard method resulted in positive results at lower power settings of the microwave oven. The ideal amount of time required to obtain results using the microwave oven method was 5 to 20 minutes depending on the soil. An alternative testing method to determine water content was the microwave sensor Hidromix HM-08. This sensor was capable to measure soil moisture content of different types of unsaturated soils including sand, clay and base coarse. This sensor allowed for the instant (within 5 seconds) measurement of soil moisture content of loose and compacted soil.

DEDICATION

This thesis is dedicated to everyone that supported me during my masters degree. To my parents Jose Luis Lopez and Velma Barrientos, to my grandparents Gonzalo Barrientos, Corina Barrientos and Rosario Bustillo, and to my brothers Esteban Lopez and Sergio Lopez. I would also like to acknowledge the guidance and support of my advisor Dr. Richard Coffman. Thanks are also expressed to my thesis committee Dr. Michelle Barry, and Dr. Jason Tullis. My friends and colleagues that helped me through these two years are also acknowledged: Julia Loshelder, Viktor Hoestbo, Ana Laura Errigo, Johnathan Blanchard, and Anh Tuan Tran.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1. Chapter Overview

Multiple studies were performed to obtain the total unit weight and soil moisture content that can be then combined to obtain dry unit weight or dry density of the soil. A photogrammetric analysis was performed to obtain the soil volume and used with the exhumed weight of soil to determine the total soil unit weight. Additionally, a method to obtain the in-situ soil moisture content was tested to compliment the results photogrammetrically obtained total density to obtain soil dry density. The characteristics and scope of these methods, in conjunction with an extensive description of the tests are described in this document. Additionally, comparisons between results obtained from the photogrammetric method, the nuclear density gauge and the sand cone were performed to determine the accuracy of the methods presented herein. The combination of results obtained from the aforementioned methods were also compared to results from an EDGe Humboldt electrical gauge to investigate the results with another non-nuclear method. An overview of the work performed is presented in Section 1.2. The motivations behind these investigations are described in Section 1.3. The outline of the thesis document is presented in Section 1.4.

1.2. Description of Work

The aforementioned photogrammetric tests were performed on two compacted clay test pads located at the University of Arkansas Engineering Research Center (ERC) in Fayetteville, Arkansas. One of the tests pads was located under normal outdoor conditions and the other was also located within the ERC building. The tests performed on the compacted clay pads were compared with the sand cone (ASTM D1556/D1556M, 2016) initially and were also compared to a Troxler nuclear density gauge (ASTM D6938, 2021). Tests were also conducted along the sides and within the center of a base coarse (gravel) driveway at the ERC building. The tests that were performed on the driveway were conducted along the sides and at the center. The tests performed on the base coarse were compared to tests performed using the sand cone method. A complete description of the tests performed is presented in Chapter 3.

The microwave oven method to determine soil moisture content (ASTM D4643, 2019), provides results within 30 minutes. However, the high temperatures within the microwave oven can cause the chemistry of clays to change. Multiple tests were performed by using a microwave oven at different low to high power settings and were compared to laboratory oven obtained moisture content values. Specifically, the tests were performed at different power level settings and the total duration required to achieve a dry soil was recorded. Other moisture content tests were performed using the HydroMix HM-08 microwave sensor, these tests were rapid (less than 3 minutes) and required no calibration.

The electrical density EDGe nuclear gauge was tested on the environmentally controlled clay test pad and the obtained results from this method were compared with the results obtained from the photogrammetric method, the sand cone method, and the nuclear density gauge method. The EDGe device required a calibration of the compacted soil; this calibration was performed prior to performing the tests on the compacted clay pad. The calibration was performed on soil compacted into six-inch diameter proctor molds (AASHTO T180, 2019). Additionally, the EDGe obtained moisture content was compared with laboratory oven moisture content measurements.

1.3. Motivations

The nuclear density gauge method (ASTM D6938, 2021) and (AASHTO T310, 2019) is the most common method used to obtain the in-situ soil total unit weight, soil dry unit weight, and soil moisture content (Berney et al., 2011). However, multiple state transportation departments are looking for alternative methods to replace the nuclear density gauge. The certification, licensing, training, transportation and storage requirements and regulations for a nuclear density gauge are extensive due to the radioactive nature of the device. Therefore, a reliable in-situ method to obtain the required aforementioned soil properties may reduce the costs and time required to operate the nuclear density gauge. For a new method to replace the nuclear density gauge, it is necessary that the method is able to measure the total unit weight of soil and the moisture content of the soil to obtain the dry unit weight in a timely manner. The majority of methods, including the sand cone test (ASTM D1556/D1556M, 2016) and (AASHTO T191, 2014) and the rubber balloon test (ASTM D2167, 2016) and (AASHTO T205, 1986), require the moisture content of the soil to be obtained using the 12 to 24-hour oven dry method; Therefore, the properties cannot be obtained at the time of testing.

A combination of the photogrammetric method to obtain total unit weight, and the microwave oven or microwave sensor method to obtain moisture content, can be used to obtain dry unit weight while in the field. These methods require minimal training and require no certification or licensing for use. Therefore, the utilization of these methods can provide the necessary soil properties at the moment of testing. Additionally, the cost of testing may be significantly reduced as the methods only require common items that are commercially available to the public.

1.4. Document Overview

Seven chapters and two appendices are contained in this document. The introduction, which contains a description of the investigation, and the motivation of the project are presented in Chapter 1. Background information and the corresponding literature review are presented in in Chapter 2. The photogrammetric method is presented in Chapter 3, this chapter describes the photogrammetric method that was implemented. The determination of soil moisture content with the microwave oven and the microwave sensor HM-08 are presented in Chapter 4. The testing of the Humboldt EDGe electrical gauge and the methodology and results related to this gauge are presented in Chapter 5. The conclusions obtained from the results of the investigations are presented in Chapter 6. A comprehensive list of references for the whole document is presented in Chapter 7. Additionally, detailed information on the tests performed for the photogrammetric method are presented in Appendix A. Other test information related to the microwave oven and microwave sensor methods are presented in Appendix B.

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CHAPTER 2: BACKGROUND

2.1. Chapter Overview

A literature review of previous work performed to obtain an alternative method of obtaining compacted soil properties including density and unit weight was performed. In-situ measurement methods for determining soil moisture content were reviewed including previous studies that used microwave moisture content sensors. Additionally, previous investigations related to photogrammetric applications for determination of soil volume at different scales was reviewed. Challenges related to the determination of soil total and dry density by different methods is presented in this chapter.

2.2. Soil Density Determination Using Electrical Density Gauges

Multiple studies have assessed the feasibility of alternative methods for soil density determination. For instance, results obtained from an electrical density gauge were compared with results obtained from the rubber balloon method (Rathje et al, 2006). The electrical density gauge had difficulty with determining the density and moisture content of high plasticity clays and stiff soils. Additionally, the results were inconsistent with the results obtained from rubber balloon tests. The electrical density gauge was also tested in granular soils and coarser material (Brown et al, 2007). For this case, the electrical density gauge compared well to a nuclear density gauge with a 0.90. However, the electrical density gauge required the gauge to be calibrated with a nuclear density gauge on site; thus, making a nuclear density gauge necessary in the field. More current studies with electrical gauges reveal that the devices still require laboratory calibration or provide low accuracy in determining soil density (Berney et al., 2017).

2.3. Soil Density Determination Using Photogrammetry

The use of photogrammetry, as an alternative to electric density gauge, has been tested with increased success. For instance, the Photomodeler software was used to monitor volume changes in triaxial tests using cameras located around the cell (Zhang et al., 2015). The method was able to measure small changes in the volume of a soil cylinder during triaxial testing. This photogrammetry method was expanded by introducing cameras inside the triaxial cell, providing a higher accuracy of the obtained results (Salazar et al., 2015). This method allowed for small-scale determination of changes in the volume of soil. Therefore, using this method total density of something like a small hole on the field could be obtained.

Further photogrammetry studies allowed for three-dimensional surfaces to be created from photographs acquired from soil to determine aspects of roughness (Tran et al., 2017). Another photogrammetric investigation used multiple cameras, controlled by the DigiCamControl2 software, to determine the changes in volume of a sand surface (Suchan and Azam., 2021). This method was conducted under very strict environmental controlled conditions. The possibility of performing a photogrammetric analysis on photographs obtained from an uncalibrated camera from a mobile device was also explored successfully (Whithing et al., 2020). Multiple images of a soil ped were obtained with two different mobile devices; an iPhone 5 and a Samsung Galaxy Note 8. These images were obtained around the soil ped and were analyzed and processed, obtaining a three-dimensional model surface of the ped. The use of this method may allow for the determination of soil volume of many peds. Depending on the soil tested on the field, peds are not always an option especially with cohesionless soils or soils with a high moisture content. However, the study provided a basis for obtaining photographs of an excavation within soil at similar rotations and angles as described herein.

A method was developed to obtain the bulk density of soil pits excavated of approximately one cubic foot (Mohren et al., 2020). While this process was labor intensive, the results provided an accuracy of 95 % compared to laboratory methods of soil density determination. The method consisted of two sets of photographs collected, before and after the hole was excavated. These photographs were analyzed and combined using Regard3D (Version 1.0.0) and CloudCompare (Version 2.11) to scale and create a point cloud mesh that can be processed into a three-dimensional surface for volume determination. Mohren et al. (2020) used a commercially available camera (Olympus OM-D E-M10, 16 MP (megapixel); Lumix G 50 mm in 35 mm film equivalent f1.7 aspherical fixed-focal-length lens). The limitations of this study included highly reflective areas or shady areas in the excavation, which the software could not process correctly.

The most relevant method for performing a photogrammetric analysis of an excavation was performed using MATLAB on photographs obtained from an excavation with similar characteristics to the excavation for the sand cone method (Barney et al., 2018). The method entailed two sets of photographs, one collected before and one collected after the hole was completed. The images were obtained using a commercially available camera. A guide was placed next to the excavation to provide a reference for scaling during the analysis. During the image analysis, four points were selected around the hole to fit a surface and obtain the volume of the excavation. The MATLAB analysis was cumbersome and required knowledge of the programing for use. Barney et al. (2018) compared results from the photogrammetric technique with results from the nuclear density gauge, with an obtained accuracy of 92%. Barney et al. (2018) also compared the results from the photogrammetric technique with results from the sand cone and obtained an accuracy of 89%. This method established a guideline for obtaining total soil density. However, the investigation did not account for soil moisture content to obtain dry unit weight.

The Photomodeler software was used to obtain soil bulk density from holes created by core sampling (Bauer et al., 2014). A calibrated DSLR camera was used to obtain the necessary images of the excavation. A circular guide was placed around the excavation for scaling. Volume measurements were obtained; however, no relevant comparisons were provided to any in-situ density determination method. Additionally, problems were encountered during the analysis when sharp differences in light and shade were present.

2.4. Soil Moisture Content Determination

Multiple non-nuclear methods to measure in-situ soil moisture content were compared, including a comparison with the nuclear density gauge (Berney et al., 2011). Specifically, soil density gauge, electric density gauge, nuclear density gauge, gas stove, microwave oven, moisture analyzer, and speed moisture tester were compared by Barney et al., (2011). The microwave oven method provided relatively accurate results, however, it produced overheating in several cases. The soil and electric density gauges were unreliable without proper calibration. The moisture analyzer was unable to provide enough energy for evaporation. The speedy moisture tester tended to overestimate moisture content. The gas stove method provided accurate results without energy variations. The microwave oven method was also used in a different study on roadway base and subgrade with positive results (Sebasta et al., 2012). Specifically, the results were consistent for compacted or uncompacted material. In addition, no bias was detected during the investigation. However, it was concluded that the results had a high standard deviation.

As reported in Manchikanti. (2007), an investigation was performed for soil moisture content determination using a Hydronix HydroMix IV sensor was performed. The device was originally developed to measure real time water to cement ratios of Portland cement mixing during batching. This sensor has a penetration depth of 100 [mm] and required 3 seconds to stabilize the output. Manchikanti. (2007), investigated soil moisture content for compacted soils. Positive results were obtained from the tests performed; however, variations were found depending on the types of soil tested and soil texture.

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CHAPTER 3: IN SITU DENSIITY MEASUREMENT OF SOIL USING PHOTOGRAMMETRIC METHOD

3.1 Chapter Overview

The photogrammetric method used to obtain soil volume, and the corresponding total unit weight and dry unit weight are described herein. The limitations of the study are presented in Section 3.2. The introduction of the method and the motivations are presented in Section 3.3. The necessary literature review and background related to the method are included in Section 3.4. Additionally, the methodology of the image acquisition and processing are presented in detail in Section 3.5. The results and accuracy derived from the results are presented in Section 3.6. The conclusions derived from the investigation is presented in Section 3.7. Detailed information and testing results are presented in Appendix A. The comparisons between the method and the results from the EDGe electrical gauge are presented in Chapter 4.

3.2. Limitations of the Described Study

The clay tested in the compacted clay pads may not reflect the same results as other clays. However, it can be defined as a characteristic locally obtained clay. The base coarse tested on the driveway has been used by vehicles consistently and cannot be considered to be in a newly state; multiple large particles crushed, especially at the center of the driveway. Additionally, weather conditions may have modified some properties of the outer compacted test pad. Faulty tests results from the sand cone were not considered as part of this investigation.

3.3. Abstract

Soil total density, dry density, total unit weight and dry unit weight are important engineering properties that are used to verify proper soil compaction. A photogrammetric volume analysis technique that uses images obtained from a regular mobile phone camera is

presented herein. The Photomodeler program was used to perform each analysis. The density of the soil was obtained by measuring the excavated soil weight along with the volume of an excavation by means of photogrammetric measurement for an excavation that was completed using a method similar to the sand cone analysis technique. The aforementioned acquired images were processed using the software, which combined the images into a three-dimensional model of a selected area that included the excavation. The results obtained from this photogrammetric method were compared to the results obtained from sand cone tests and with results obtained from the nuclear density gauge. The Photomodeler method obtained unit weight results were within 4 pcf of the corresponding sand cone and nuclear density gauge results.

3.4. Introduction

The nuclear density gauge is the most common method for obtaining soil density measurements (Berney et al., 2011). However, use of the nuclear density gauge is cumbersome because it requires specialized training, licensing, and certification to operate the equipment. In addition, due to the radioactive nature of the device, this method has specific storage and inspection requirements. These requirements inhibit usage and increase the costs associated with using the method. Currently, in-situ methods for verifying nuclear density test results are limited to tedious methods such as the sand cone and the rubber balloon methods.

A series of tests were performed to determine the volume of small excavations in a compacted clay liner test pad and base coarse roadway system, located at the University of Arkansas Engineering Research Center (ERC) in Fayetteville, Arkansas. Additional tests were performed on an environmentally controlled compacted clay test pad located inside the ERC building. The research described herein was performed to determine if a rapid non-nuclear method can be used to readily obtain soil total density values and soil dry density values. The sand cone test was also used to verify the results obtained from the photogrammetric analyses. Although the sand cone is a non-nuclear method that is commonly used to find the volume of an excavated hole, the sand cone method is tedious and requires calibration and the use of expensive Ottawa sand.

A second set of tests were performed to compare the photogrammetric obtained results with both the sand cone and a Troxler nuclear density gauge. The Photomodeler method, that is described herein, used photographs and a photogrammetric analysis technique to determine the volume of an excavated hole for each test. A description of the reviewed literature, the setup, image acquisition, image processing and the obtained results are provided for completeness.

3.5. Background

Private and public organizations including multiple transportation agencies are searching for a method to replace the Nuclear Density Gauge due to time, cost, and training requirements. Replacement options such as electric gauges, microwave sensors and photogrammetry methods have been investigated. However, current methods require extensive soil calibration or long times to obtain results. In addition, methods such as electric gauges were found to have low accuracies when compared to currently used methods (Berney et al., 2017).

Previous research has been conducted to investigate the determination of volume and unit weight measurements through photogrammetric techniques. However, the research was limited to the volume measurement and change in volume measurements of solid objects such as soil cylinders, soil peds, and separated large gravel rocks (Tran et al., 2017). Some researchers were able to use photogrammetric techniques on excavated soil holes, but the excavated holes were large and cumbersome to dig (Mohren et al., 2020). Other tests, which were performed using small excavations, were limited to 1) software that was difficult to operate without training or 2) required camera calibrations (Barney et al., 2018).

Tests performed to measure the volume changes of a soil cylinder during a triaxial test, by means of photogrammetric methods, were conducted successful during a time span of 10 minutes by placing cameras outside of the triaxial cell (Zhang et al., 2015). Subsequently, more accurate results were obtained by performing a similar test while placing cameras inside of the triaxial cell along with the use of the Photomodeler software (Salazar et al., 2015). However, in these methods, the soil was removed from the site by sampling methods prior to volume determination. Thus, the method from Salazar et al. (2015), provides useful knowledge related to the Photomodeler program but require a different photogrammetric analysis to measure in-situ density based on excavated soil volume.

Three-dimensional models of soil surfaces have been created and used for roughness calculations by means of photogrammetry along with associated MATLAB codes (Tran et al. 2017). While the surface measurement was appropriate, no attempts were made to measure volumes in these studies. In addition, the described Tran et al. (2017) study had multiple limitation, as testing was not performed at multiple locations or of multiple materials.

As described previously in Suchan and Azam. (2021), photogrammetric characterizations were performed in an effort to measure changes of volume between wet and dry sand. Photographs were obtained at different viewing angles using the DigiCamControl2, which is a multiple camera controlling software, and referenced into a three-dimensional model to determine volume changes in a surface resulting from evaporative losses (Suchan and Azam, 2021). However, tests performed by Suchan and Azam. (2021), required a controlled environment and more than 30 minutes of images capture and processing time, which is not practical for an in-situ density testing application.

A study performed by Whithing et al. (2020) included the measurement of bulk density of soil using photographs obtained from a mobile device. Whithing et al. (2020) documented the manual acquisition of photographs with the use of an iPhone 5 and a Samsung Galaxy Note 8 at a quarter rotation around a ped of soil. A three-dimensional model of the ped of soil was obtained using Autodesk Recap. This method proved successful and almost identical to the control data set, that was collected using laser scanning. This method required the extraction and maintaining of an intact soil ped, which may prove difficult, depending on the soil type and variable moisture contents.

Mohren et al. (2020) developed a method to determine soil bulk density with a photogrammetric technique that used the program Regard3D (Version 1.0.0) to build point clouds and developed meshes combined with CloudCompare (Version 2.11). The meshes were used to 1) develop a three-dimensional model of the excavated pit and 2) to align and merge it with the pre-dug surface. The method required two sets of photographs before and after an excavation of approximately 1 ft by 1 ft by 1 ft soil cube. Accurate results (within 95% of the results obtained from laboratory methods) were obtained with photographs acquiered from a commercially available camera and a mobile device. The limitations of this method were densification of the mesh on shaded or rocky areas of the excavation. In addition, the method required greater than 60 minutes to upload and process the images (Mohren et al., 2020). The Mohren et al., (2020) research did not compare the obtained results with any field measurement methods.

Barney et al. (2018) performed research to obtain soil density from a photogrammetric method, based on a photogrammetric procedure that was similar to the sand cone method but used photographs analyzed by a MATLAB program to determine volume instead of sand to determine the volume. The method included the use of a calibrated, commercially available, camera to obtain two sets of photographs before and after the excavation of a hole. A scale guide was also used for reference. The collection of photographs was used to develop a three-dimensional mesh using the MATLAB code. A volume value was obtained and was then combined with the weight of the material excavated and a moisture content to obtain the total and dry unit weight of the soil. This method provided accurate results (within 92% of the nuclear density gauge obtained value and 89% of the sand cone obtained value). However, the MATLAB program process was complicated and only accounted for the top of the hole by placing a plane surface through four surface points.

The Photomodeler software program was used for a study to obtain soil bulk density (Bauer et al., 2014). For the Bauer et al. (2014) research, the volume of excavations obtained by core sampling of differently sized holes were photographed using a calibrated DSLR camera. A square scale guide was placed around the excavation to provide reference points within the program. A single point cloud was used to process the images. The limitations of this method include shaded areas and light differences causing problems for the point cloud development.

3.6. Methods and Procedures

3.6.1. Setup

A 12MP iPhone 12 camera, a sand cone plate, a hand trowel, an 11 [inch] long guide with black and white one inch and one-centimeter marks, a Husky 10,000 lumens LED portable work light, and a black matte colored rubber sealant spray were used to complete the different tests that are described herein. The objects used (except for the iPhone 12 camera, the sand cone plate, and the can of rubber spray) are shown in Figures 3.1 and 3.2. The clay testing area is shown in Figure 3.1. while base coarse testing area is shown in Figure 3.2. The aforementioned work light was required to remove shadows that were created by the angle of the sun at different times during the day.

The equipment required for the inside clay pad was the same as the equipment used for the outside clay pad. In addition to the previous equipment, a water dispenser was used to develop different moisture contents within the soil. Multiple tests were performed to investigate the influence of water content on the obtained results.

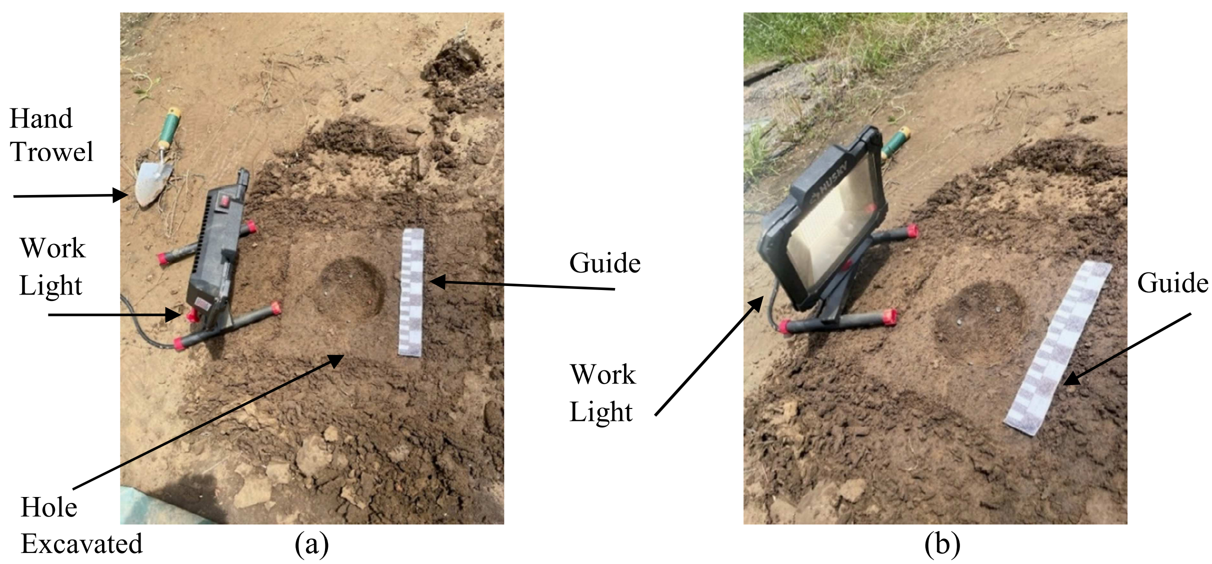
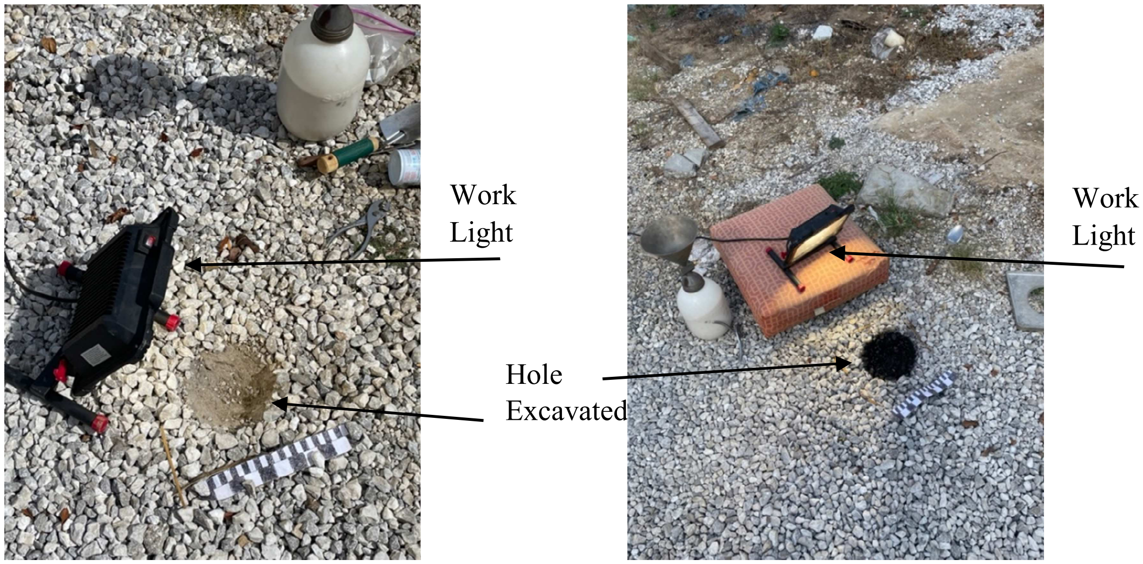


Figure 3.1. Photographs of a sand cone excavation in a compacted clay test pad after removal of the base plate, (a) without the light on and (b) and with the light on.



(c) (d)

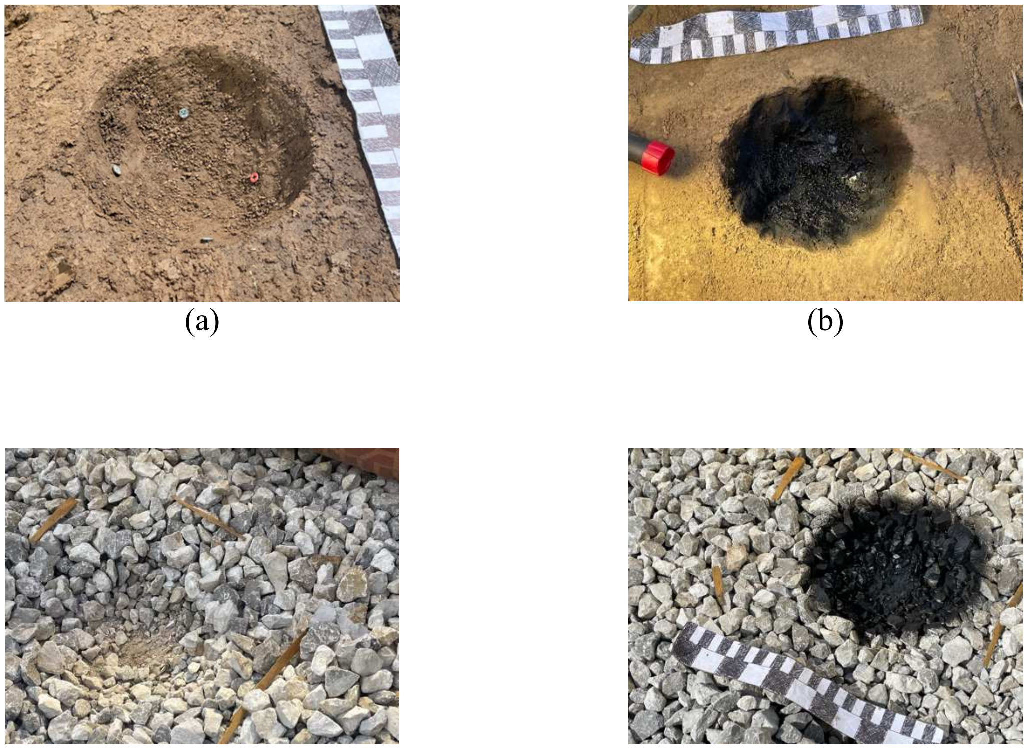
Figure 3.2. Photographs of a sand cone excavation in base coarse material after removal of base plate, (a) without the light on and (b) with light on. Image (b) includes the applied rubber sealant spray within the excavation.

Prior to excavating, the sand cone plate was used to scrape the surface to create a flat surface. Like with the sand cone test, the excavation proceeded through the center of the sand cone plate, as is typical for a sand cone test. The soil removed from the excavation was stored in a sealed Ziploc bag, and a portion of the obtained soil was used to obtain the water content of the excavated soil. The plate was then removed, and a measurement guide was placed next to the excavation to serve as a reference during the Photomodeler volume determination process. As previously mentioned, depending on the time of day, the portable work light was placed opposite of the shadow and as close as possible to the excavation, without interfering in the photographs, to increase the effectiveness of the work light. To overcome the variations caused by the poor condition of the outside soil pad, an inside clay pad was created from the same soil that was contained in the outside pad. The sand cone, nuclear density gauge, and Photomodeler methods were performed in the same manner on the inside test pad as were performed in previous tests.

Three different sets of tests were performed. The first test was performed on a dry clay pad, the second test was performed on a wet pad one day after wetting, and the third test performed 10 days after the wetting of the soil.

3.6.2. Image Acquisition

The iPhone 12, a 12 MP camera, with a fixed optical zoom of two-times magnification was used for this Photomodeler method. Twenty (20) to 25 images per test, like those shown in Figure 3.3, were acquired of the outdoor clay test pad. The same number of images were obtained of the base coarse area. The base coarse pictures included the gravel without and with a rubber spray coating. The coating was used to prevent sand from flowing into the base coarse during the sand cone test. The Photomodeler software required 15 to 17 images to obtain a volume of the hole. One of the images was obtained from directly above the hole (NADIR). The remaining images were obtained around the excavation at regular approximately 10-degree circumferential intervals and at elevation angles of 20 to 40 degrees. The Photomodeler software may reject one or more images, so it is advisable to obtain around four to five additional images. Because the soil surface lacks distinguishing features, the measurement guide must be present in all of the images for accurate image processing. Image acquisition was completed in five to ten minutes. However, if the rubber spray sealant was applied, the sealant required an approximatly 20 minutes to properly dry. It was important to wait for the rubber coating to dry into a matte color because the Photomodeler software had difficulties with processing the shinny wet surface of the rubber coating (Figure 3.3).

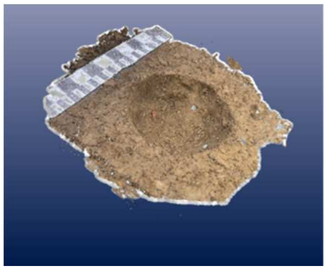


(a) (b) (c) (d)

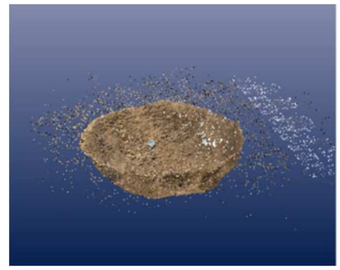
Figure 3.3. Photograms obtained for use in the Photomodeler volume determination. (a) clay, (b) clay with rubber coat, (c) base coarse, and (d) base coarse with rubber coat

3.6.3. Image Processing

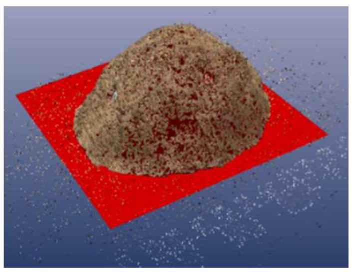
The uncalibrated images were uploaded into Photomodeler in a HEIC format. Photomodeler was able to automatically create a dense point cloud and mesh and subsequently create a surface using triangulation. The model created was scaled using the reference guide within the photographs to replicate the actual scale. The point mesh was then reduced to the edges of the excavation, and the dense point cloud was left unchanged. Eight to ten points, from the point cloud, from directly around the excavation were selected to create a best fit plane was created through the points on top of the excavation. A volume was calculated between the surface of the unexcavated plane and the measured excavated surface. The Photomodeler analysis took eight to 15 minutes to process. The process is presented in Figure 3.4.



(a)



(b)



(c)

Figure 3.4. (a) dense point cloud creation and surface creation, (b) point mesh reduction, (c) best fit plane and volume calculation.

Equations 1 and 2 were used to determine the total unit weight and the dry unit weight. The total unit weight and dry unit weight values were then calculated using the volumes obtained from the Photomodeler software and the sand cone method and the values were compared.

$$\gamma_T = \frac{W_T}{V_T} \qquad \text{Equation 3.1}$$

$$\gamma_D = \frac{W_T(1-w)}{V_T} \qquad \text{Equation 3.2}$$

γ_T: Total Unit Weight [pcf]
γ_D: Dry Unit Weight [pcf]
W_T: Total Soil Weight
V_T: Total Soil Volume
w: Gravimetric Soil Moisture Content

A second set of tests were performed to obtain the volume of an excavation in the outside clay test pad. The tests were performed to determine the consistency of the Photomodeler

Method after the a set of tests were unsuccessful due to a bad sand cone measurement. The tests consisted of obtaining two sets of photographs, processing a three-dimensional model using the Photomodeler software and then comparing the volume total, total unit weight, and dry unit weight results, to the results obtained from the same hole using a calibrated sand cone test. The photogrammetry method was also used in a base coarse driveway at the ERC. This base coarse was predominantly light gray limestone.

3.7. Results

For the first set of results, obtained from the clay test pad that was located outside the ERC, the total volume (V_T) of the excavation based on the Photomodeler method was 802.3 [cc], the volume of the excavation was determined using the sand cone method; the volume from the sand cone method was 813.7 [cc]. The resultant values were reported as displayed in the program, no sensitivity analysis was performed for accuracy. These volumes were used along with 1) the weight of the material excavated and 2) the oven based gravimetric water content of the material to obtain the total unit weight and dry unit weight values. The total and dry unit weight values that were obtained using the Photomodeler volume for the outside clay pad were: 117.6 [pcf] and 100.1 [pcf] respectively. The total and dry unit weight values obtained using the sand cone test were 115.9 [pcf] and 98.7 [pcf], respectively. Small differences in the total and dry unit weight values from the two methods were obtained (1.46% difference and 1.41% difference, respectively).

The volumes obtained from the Photomodeler software from the first and second sets were 908 [cc] and 905 [cc], respectively. The sand cone test that was performed on the same excavation resulted in a total volume of 881.5 [cc]. The total unit weights for the first set and second set of photographs were 103.9 [pcf] and 104.2 [pcf], respectively. Based on these results, the Photomodeler method is extremely consistent when shadows in the excavation are properly eliminated with the use of a work light during daylight. The measured sand cone total unit weight was 107.1 [pcf]. The dry unit weights obtained from the Set 1 and Set 2 photographs were 90.5 [pcf] and 90.8 [pcf]. The dry unit weight obtained from the sand cone test was 93.17 [pcf]. In this third test on the outdoor clay test pad, the values obtained were consistent with the previous results that were obtained for the same soil pad.

The first trial of photogrammetry testing in the base coarse produced errors due to the brightness of the base coarse. Additionally, the sand cone had inaccuracies due to the sand infiltrating between the large base coarse particles. A rubber spray coating was used to alleviate these issues.

A second set of tests were performed on the base coarse. To limit some sources of error, the work light was placed closer to the hole and 18 photographs were collected instead of 15 photographs to increase the accuracy of the Photomodeler program. The total volumes obtained using the Photomodeler software were 1161.52 [cc], 1036.45 [cc], and 1076.51 [cc]. The total volume obtained from the sand cone test resulted on 1157.87 [cc]. The total density results obtained from the Photomodeler method were 95.37 [pcf], 106.97 [pcf] and 102.90 [pcf]. The total density of the sand cone result was 95.72 [pcf].

A third set of tests were performed using a rubber spray coating to resolve the accuracy problems of the method when testing base coarse. Two sets of photographs were collected: one withtout the rubber coating and one with the coating. The total volumes acquired with the Photomodeler method resulted in volumes of 648.98 [cc] without the rubber coating and 617.25 [cc] with the coating. The sand cone, which was performed in an excavation that had the coating, resulted in a volume of 672.14 [cc]. The total unit weight obtained was 108.92 [pcf] and 116.33

[pcf] for the respective Photomodeler method tests and 106.79 for the sand cone test. Dry unit weight values of 103.28 [pcf] and 110.31 [pcf] were obtained using the Photomodeler method for the uncoated and coated excavation and 101.26 [pcf] for the sand cone. Based on these results it appears that the coating did not help with the improving the accuracy of the method.

Additional tests were performed at different times on the outside clay pad with the use of a Troxler nuclear density gauge. The tests were performed adjacent to the excavation where the sand cone test was performed and where Photomodeler measurements were collected. The results from these three different sets of tests can be observed in Table 3.1.

Table 3.1. Outside clay pad sand cone and nuclear density gauge comparison

	Set 1			Set 2			Set 3		
	Photomodeler	Sand Cone	Nuclear Density Gauge	Photomodeler	Sand Cone	Nuclear Density Gauge	Photomodeler	Sand Cone	Nuclear Density Gauge
Volume [cc]	665.5	703.01	N/A	717.53	663.56	N/A	756.27	767.5	N/A
Total Unit Weight [pcf]	126.42	119.76	126.7	117.26	126.88	118.6	107.72	107.72	123.7
Dry Unit Weight [pcf]	106.42	100.42	107.5	99.64	107.81	100.9	93.49	93.49	107.5

The results from the Photomodeler and the nuclear gauge were similar for the Set 2 tests and the sand cone and Photomodeler results were similar for the Set 3 tests. However, the wide variations between results in the methods was determined to be due to the poor condition of the outside clay pad and the proximity to a hard asphalt surface near the testing location causing variations in the nuclear gauge results during collection of the Set 3 data. Thus, more tests were required to obtain viable results. The results from the tests performed on the inside test pad are presented in Table 3.2.

Table 3.2. Outside pad sand cone and nuclear density gauge comparison

	Dry Pad			Wet Pad (after 1 day)			Wet Pad (After 10 days)		
	Photomodeler	Sand Cone	Nuclear Density Gauge	Photomodeler	Sand Cone	Nuclear Density Gauge	Photomodeler	Sand Cone	Nuclear Density Gauge
Volume [cc]	732.00	659.36	N/A	835	823.65	N/A	769.6	751.69	N/A
Total Unit Weight [pcf]	90.91	100.87	98.7	105.71	107.16	111.3	105.55	108.19	108
Dry Unit Weight [pcf]	89.76	99.59	97	94.03	95.33	102	96.03	98.43	100.3

The dry soil had large variations due to these methods not being designed for a completely dry soil. The second test resulted in similar results between the Photomodeler and the sand cone method; however, due to most of the water within the the top one inch of the soil, the nuclear density gauge was not as accurate. On the last test, the water was homogeneous within the soil layer because the water that was placed on the surface had percolated through the profile. Thus, all the results were within 4 [pcf] for total density and dry density for this set of tests.

3.8. Conclusions

The results obtained from the Photomodeler Method were comparable with results obtained with the sand cone method and the nuclear density gauge method. The total measured volumes of the excavation were similar, and the measured total unit weight and dry unit weight values were within a difference of 4 [pcf] or a percent difference no greater than 4.5%. The time used to perform the Photomodeler method was significantly less than the sand cone but still more than the nuclear density gauge. The Photomodeler method required less equipment and eliminated the need for the continuous replacement of the expensive silica sand required for the sand cone. The Photomodeler method does require more time than the nuclear density gauge; however, it does not require significant training and special storage requirements.

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CHAPTER 4: DETERMINATION OF SOIL MOISTURE CONTENT USING MULTIPLE METHODS

4.1. Chapter Overview

Three methods for rapid testing of soil moisture content were tested and were compared to soil moisture content measured by oven drying. The limitations and challenges of this study are described in Section 5.2. An introduction of all of the methods is provided in Section 5.2. The testing methods including the use of a microwave oven, the HydroMix HM-08 microwave sensor, and a capacitance method. The aforementioned methods are described in Section 5.4.1, Section 5.4.2 and Section 5.4.3 respectively. The results are summarized in Section 5.5.1, 5.5.2, and 5.5.3, respectively. Conclusions and recommendations about use are presented in Section 5.6. The references used for the respective investigations are presented in Section 5.7.

4.2. Limitations of the Described Study

The microwave oven method is limited because the soil should be maintained at relatively cool temperatures (<105^{o} C). As the temperature of the soil rises, the soil will dust and blow around the inside the microwave oven. Thus, the soil sample loses mass and the moisture content measurement becomes unreliable. The formation of a crust on high plasticity soils results in the crust bursting after the water that is trapped below this crust begins to boil. This burst also results in a loss of mass as particles are sent outside the container.

The HydroMix HM-08 sensor must test samples that are larger than the diameter of the sensor and deeper than three to four inches. For compacted samples, a flat surface is required for the sensor to obtain accurate readings. Thus, successful readings were obtained from soil in contact with the base plate of the proctor mold, as the top and middle tended to be too coarse for reliable measurements. For the same reason, the method is limited to base coarse, clays, silts, and sands. Larger particles including open coarse gravels may produce irregular and unreliable measurements. The measurements from the capacitance sensor are limited to measurements of only the area surrounding the sensor.

4.3. Introduction

The most commonly used method for moisture content determination is oven drying the soils in a laboratory oven for over 24 hours. This method is unpractical for usage in the field due to the time required and the oven not being mobile. Currently, the microwave method is specified (ASTM D4643, 2019). The microwave oven method allows for the use of a microwave at maximum power. The use of maximum power results in a series of problems, which include: loss of material due to soil overheating, possible chemical changes occurring on some types of soil and a possible short life span of the microwave oven due to large quantities of dust within the microwave following use. Thus, tests were performed using the microwave oven at lower power (power 5 to 7) settings; the reduction in oven power settings results in an increase in the recommended time for drying. Various tests were performed on different types of soils to determine the moisture content in a rapid manner to be applied for field testing. The objective of these tests was to determine if a non-nuclear method for moisture content determination can be developed and used in the field. A description of the test, and the variations of the testing are described (Section 5.4.1).

The HydroMix HM-08 is a microwave sensor developed by Hydronix to measure soil moisture content of Portland cement mixtures. This sensor monitors the real time moisture content of certain elements through the use of the complimentary Hydro-Com software. Three different types of outputs, that vary from 0 to 100, for different types of measurements are provided in Hydro-Com. The outputs can be calibrated to provide a moisture content value or can be maintained as a raw value. The sensor is powered by an input 15-30 V power supply and can be connected to a regular computer to process and display the measurements. For this method, two different tests were performed, one on loose soils and the second to test on compacted soils.

A third method was investigated to obtain soil moisture. The third method consisted of a capacitance sensor connected to a Raspberry Pi board computer. These tests were used to determine if the capacitance method could be used in the field to rapidly measure moisture content measurement instead of using the nuclear gauge or long-duration laboratory testing methods. The capacitance sensor consisted of a two-prong plastic sensor inserted into the soil. The results obtained were later processed using Microsoft excel. The tests were performed on different types of soil, which included: a local red clay soil, Illite clay, Bentonite clay, coarse sand, and silica sand.

4.4. Methods and Procedures

4.4.1. Microwave oven soil moisture content methodology

For all of the microwave oven tests performed, a Hamilton Beach Model No. P90D23AL microwave oven, was used (Figure 4.1). This microwave oven is capable of operating at ten different power levels. A ceramic bowl without lid was used to contain and microwave the soil for all of the soil types that were investigated. The preparation of the tests included mixing the soils to a specific moisture content and the microwaving the soil immediately after mixing to avoid evaporation. Per the ASTM standard, samples larger than 100 [g] were tested to ensure a representative sample. All tests were compared to the traditional method of using a conventional oven in the laboratory for at least 24 hours.

Figure 4.1. Hamilton Beach model no P90D23AL microwave oven.

The first set of tests was performed by microwaving the soil sample for three minutes, allowing the soil to rest for one minute, and then microwaving the sample for one additional minute. For these tests, the following soils at the specified moisture contents were used. Red clay at 10 [%] and 20 [%], coarse sand at 10 [%] and 20 [%], the silica sand at 10 [%] and 20 [%], and bleached kaolinite at 10 [%], 20 [%], 50 [%] and 100 [%]. In addition, for the kaolinite sample at 100 [%] moisture content, one-minute intervals were added to completely dry the soil. Bentonite was also tested, however, due to dusting and water trapped in the clay, test results were inconclusive.

A second set of tests were performed to develop a method to avoid the sources of error that were encountered during the first set of tests. These tests were performed on Kaolinite and Bentonite soil types. For these tests a sample was prepared and separated for microwave and oven tests by separating the same sample for both tests. To solve the blowing and dusting at higher power levels, the tests were performed at lower power levels as follows; for Kaolinite, power levels 2, 3 or 4 were used, for Bentonite, power levels 2, 3, 4 or 5 were used depending on the amount of moisture present and the time elapsed.

A third set of tests were performed on the Kaolinite and Bentonite soil types due to wide variations between the tests obtained during the second set of tests, To avoid changes in moisture content, separate samples were made for the microwave and oven methods with the same water to dry soil ratios and were immediately tested. For these set of tests, Kaolinite was tested at an initial moisture content of 30% and a power level of 3, 4 or 5. In addition, Bentonite was tested at an initial moisture content of 50% at a microwave power level of 5.

Additional tests were performed on red clay samples to confirm that the moisture curve remained constant following several additional one-minute increments. The samples were removed from the microwave oven and weighed after each one-minute interval. The test was performed for a total time of 30 minutes.

A final set of tests were performed to measure the moisture content of compacted samples (ASTM D698, 2021) of red clay and kaolinite. Tests were also performed on a compacted base coarse sample (AASHTO T180, 2019). The specimens for the microwave oven and conventional oven methods were obtained from the center of the compacted samples, avoiding the edges which were generally drier. The red clay samples were tested using the microwave method using power levels of 3 or 4, the samples of Kaolinite were tested using the microwave method at power levels of 3 or 4. The sample compacted was prepared with a target of 26.5 percent moisture content. Four other points were used to develop a compaction curve which were selected for kaolinite based on previously obtained optimum moisture content for compaction. Portions of the same sample were used to compare the microwave and oven methods. Five points were developed for the red clay to develop a compaction curve for both power levels and for the conventional oven method.

For the base coarse, samples at seven different moisture contents were prepared to obtain a compaction curve. The moisture contents for each point on the compaction curve were tested using the microwave method at power levels of 3, 4 and were also tested using the conventional oven method for comparison. The previously described method of microwaving the sample for 3 minutes followed by one-minute increments until the difference between measurements was less than 0.1 percent.

4.4.2. HydroMix HM-08 microwave moisture sensor methodology

Two sets of tests were performed with the HydroMix HM-08 sensor. The first set of tests was performed on loose soils. These soils were: coarse sand, Ottawa silica sand, Ottawa F65 silica sand, a locally obyained red clay and base coarse. The soils were placed in ceramic containers to avoid any metal interference. All soils were tested at different soil moisture contents and compared with the oven moisture content obtained from the conventional oven method. After the sensor was connected to the computer software, a stabilization time of 10 seconds occurred before stable measurements were obtained and displayed. The Hydro-Com software produced three different outputs. However, the “F” output was selected as it was recommended by the manufacturer for use on denser materials and also because it provided the most consistent output when compared with the other outputs. The setup for these tests can be observed in Figure 5.2

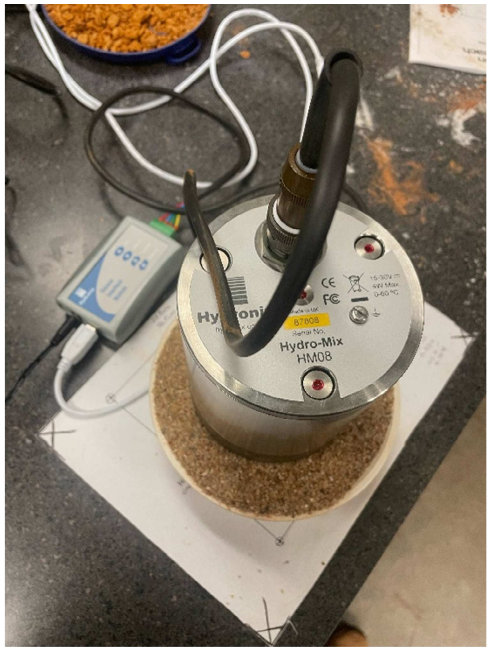

Figure 4.2. HydroMix HM-08 sensor setup on coarse sand placed in ceramic container.

The second set of tests was performed on compacted clay samples. This set was performed on compacted soil (ASTM 698, 2021) within a 6-inch proctor mold. The soil and mold were removed from the compaction base and the top and bottom of the sample were tested by flipping the sample and placing the sensor on the exposed surface. The sample was then extruded from the mold and the center of the sample was tested. Shavings obtained from the center of the sample that were placed in a ceramic bowl were also tested.

4.4.3. Capacitance sensor soil moisture content measurement method

Soil samples were prepared in a ceramic dish by mixing a specific amount of soil and water to obtain a desired moisture content. The mixed sample was then immediately divided into two samples, one for a comparative oven drying and the other for a capacitance test. For the capacitance test, the sample was placed in a glass petri dish. The capacitance sensor was covered with dialysis tubing to prevent direct contact between the sensor and the soil while allowing water to move through the tubing. To avoid any moisture interference between the sensor from the dialysis tubing, the tubing was placed in a descant container for 24 hours before the test. The sensor was then inserted into the sample allowing soil to surround the sensor on top and on the bottom and avoiding direct contact with the glass. The end of the sensor was also carefully placed outside the petri dish to avoid any electrical equipment from touching humid materials or wet surfaces.

The sensor was activated via a small portable computer and capacitance measurements were taken automatically every 30 seconds by the computer immediately after the sensor was placed in the sample. The test was allowed to continue until a stable capacitance number was reached or until a clear changing trend was identified. The following results (discussed in Section 4.5) were then processed by using Microsoft excel, and then comparing the moisture contents with the capacitance obtained.

4.5. Results

4.5.1. Microwave oven testing results

The first set of tests using the microwave oven to determine soil moisture content revealed multiple concerns regarding the testing process specified in the ASTM D4643, 2019 specification. These concerns included: dusting during testing of the clay soils at power levels higher than power level 5. Small peds “popcorned” when heated at high power levels, resulting in material jumping outside the container while drying. In addition, the 50 [%] and 100 [%] Kaolinite resulted in vapor trapped in the sample boiling and exploding, sending material outside the container, making weight measurements inaccurate.

The results from the second sets of tests proved to be more stable, causing less material loss due to dusting and blow out. A set of curves (Appendix B, Figures B1-14) were developed to provide the moisture content achieved at one-minute intervals for every power level. In addition, due to concerns of accuracy for the microwave method and the ability of bentonite to retain water, figures were developed comparing the results from oven drying and microwave drying the same sample. Wide discrepancies were observed between oven drying and microwave drying the sample.

The results obtained from the third set of tests accounted for the discrepancies caused by the moisture evaporation between tests. From the Kaolinite results, the highest microwave power resulted in more deviation from the oven tests (Figure 4.3). These deviations can be explained by some loss of material due to dusting. The curve settles at a constant moisture content over time and shows small to no changes for a 30-minute test.

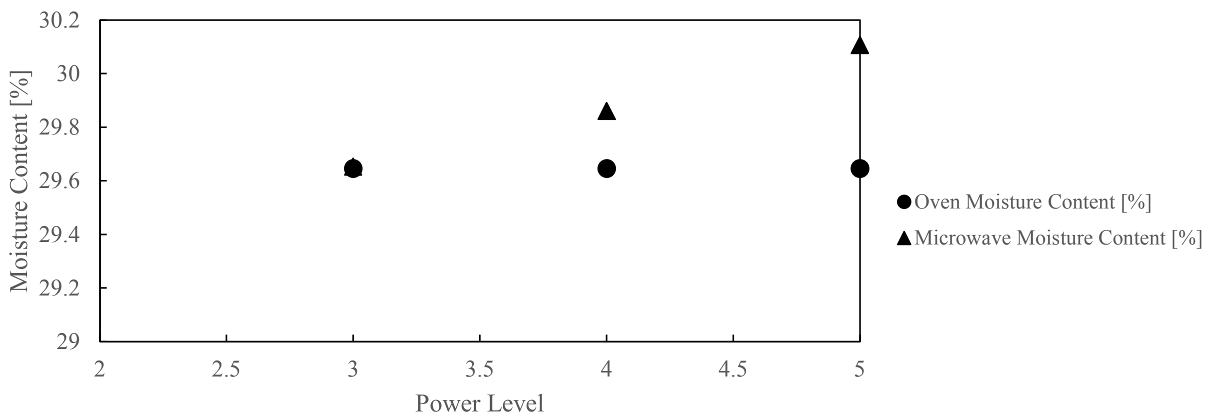

Figure 4.3. Kaolinite microwave results compared to the oven method with a sample aim of 30% moisture content

The microwave oven obtained curves for the compacted samples did not vary from the loose samples and demonstrated the same behavior (Appendix B, Figures B17-33). In addition, the compaction curves were constructed with moisture contents obtained from the oven method and both microwaves power levels. These curves for red clay and kaolinite have very similar numbers for optimum water content and maximum dry unit weight. The obtained optimum moisture content and optimum dry unit weigh are presented in Table 4.1. The results are similar between tests and are within one percentage point for moisture content for all methods and within 1[pcf] for maximum dry unit weights.

Table 4.1. Optimum water content and maximum dry unit weight parameter comparison between oven and microwave.

Soil	Red Clay		Kaolinite	
Method	Optimum Moisture Content [%]	Maximum Dry Unit Weight [pcf]	Optimum Moisture Content [%]	Maximum Dry Unit Weight [pcf]
Oven	13.16	115.35	24.82	92.94
Microwave Power 3	12.85	115.60	24.36	93.45
Microwave Power 4	13.04	115.92	25.00	92.88

In addition, the results for the typical base coarse Proctor curves were compared to typical results from base coarse and were plotted on compaction curves. The typical compaction curves used for comparison were compared with Preston Boundary Blend Proctors and Sharp Boundary Blend Proctors (from Welcher., 2004); Welcher (2004) also used the same AASHTO T180, 2019 to develop the comparison curves. The obtained base coarse results were significantly lower and less pronounced than the Welcher (2004) curves. The results were consistent between the oven and the microwave methods at microwave powers 3 and 4.

4.5.2. HydroMix HM-08 Microwave moisture sensor results

The results from the loose soil test show a similar trend between the output “F” parameter and the oven moisture content, with an observed linear regression coefficient of 0.92. All the soils were below saturation. It was observed that if saturation is reached, the sensor will display values between 90 to 100. The linear relationships for the different soil types were also analyzed separately. These linear relationships possess similar equations and slopes; this shows promise towards a method that can measure different types of soils without any calibration being required. The results of clay were not as linear as the sands; however, these results follow the same trend as the rest of the soils. The samples tested for base coarse were less than the other soils due to the material saturating at moisture contents greater than 12 [%]. The other outputs "V" and "E" were analyzed as well; however, the relationships are not as linear and precise as output "F" The results of all the soils tested are presented in Figure 5.3. The overall linear relationship is presented in Figure 5.4.

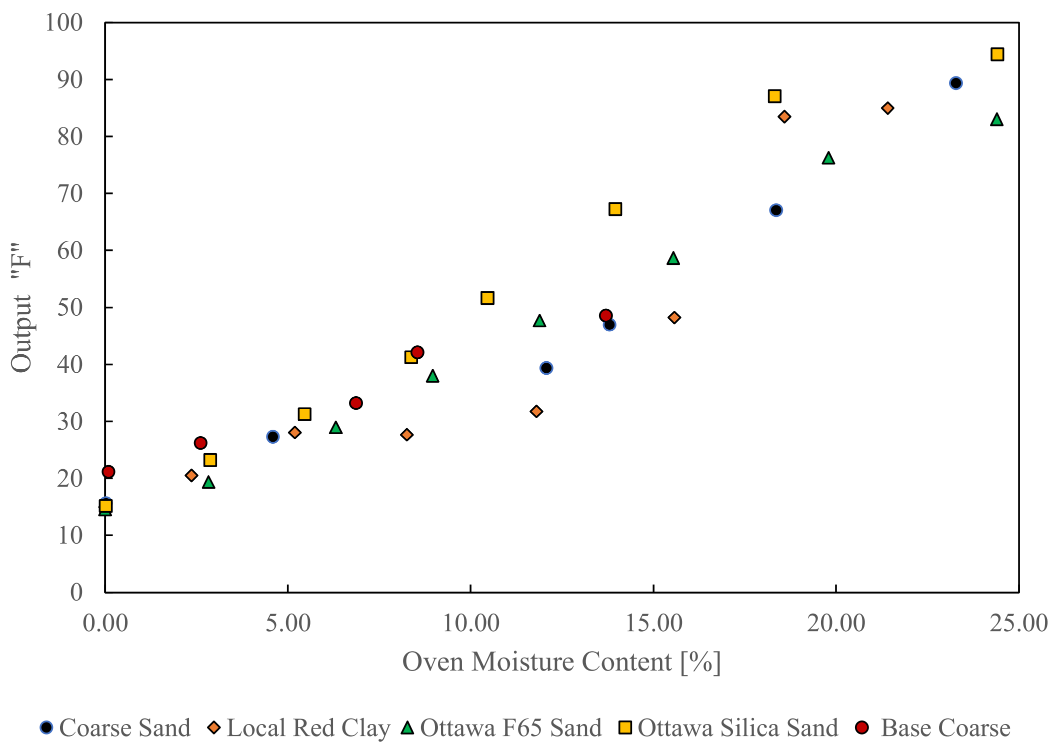

Figure 4.4. HydroMix HM-08 loose soils tested under "F" output with unsaturated conditions.

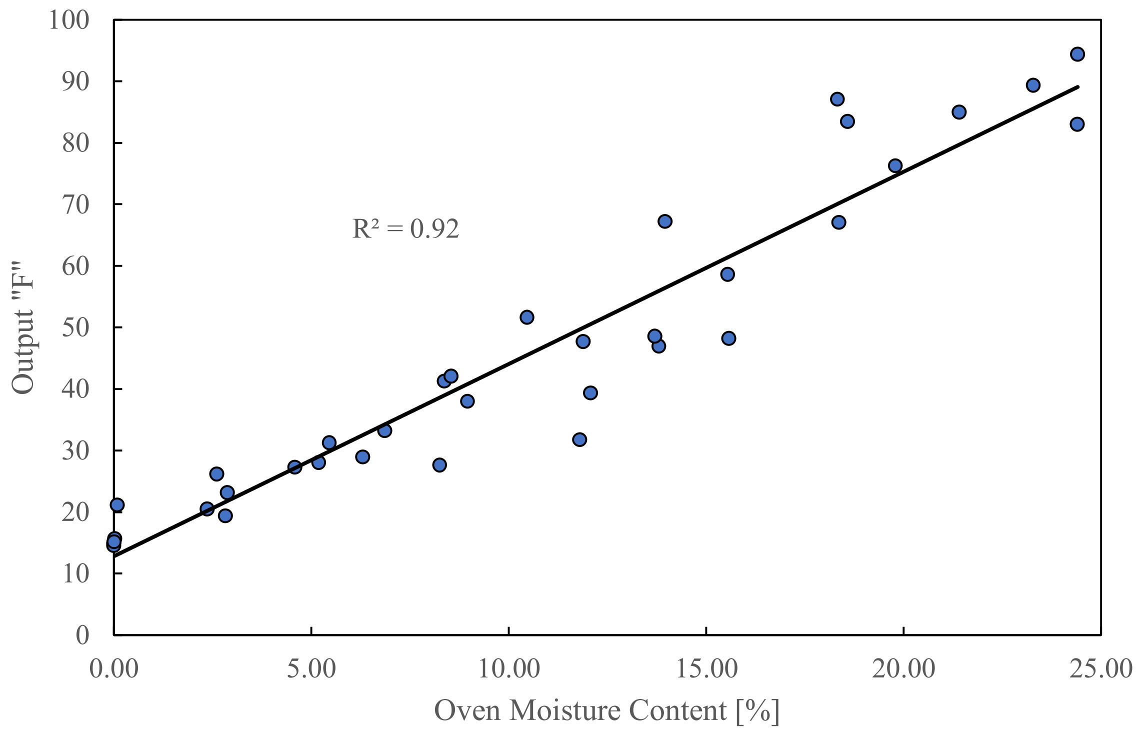

Figure 4.5. HydroMix HM-08 linear relationship of all soils combined.

A second set of tests were performed on compacted clay, compacted in 6-inch proctor molds with standard energy. The results from measuring the bottom of the mold displayed a strong linear relationship with a $R^2 = 0.98$, this relationship is presented in Figure 5.5. As shown in Appendix B, Figure B.40 the tests on samples from other locations revealed weak relationships, as the surfaces tested were not as smooth as the surface at the bottom of the mold.

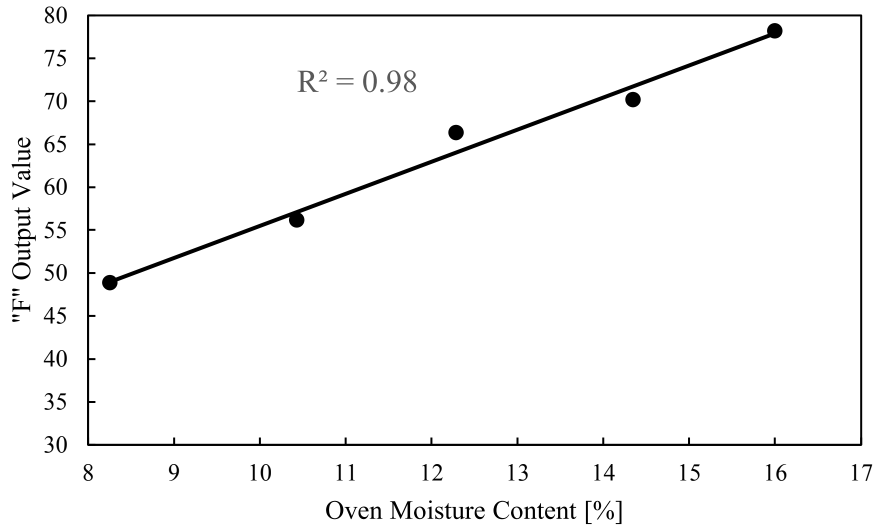

Figure 4.6. HydroMix bottom of the proctor mold “F” output linear relationship

4.5.3. Capacitance sensor soil moisture content test results

The initial testing with the capacitance sensor revealed that the capacitance numbers reduce as the water content increases. However, the results from each soil type varied and required specific calibration for each of the different types of soil. The different types of soils varied largely between each other in relation to the obtained capacitance values and actual moisture content values obtained from the oven method. Most of the observed curves had a decreasing trend but settled on a specific capacitance value.

Clays with higher moisture contents such as Bentonite developed different trends. It the types of soils show different trends and did not correlate to each other in a meaningful manner. It can also be observed that the readings obtained from the sensor can be unreliable over time. In addition, the different types of soils have different trends and rates of change over time.

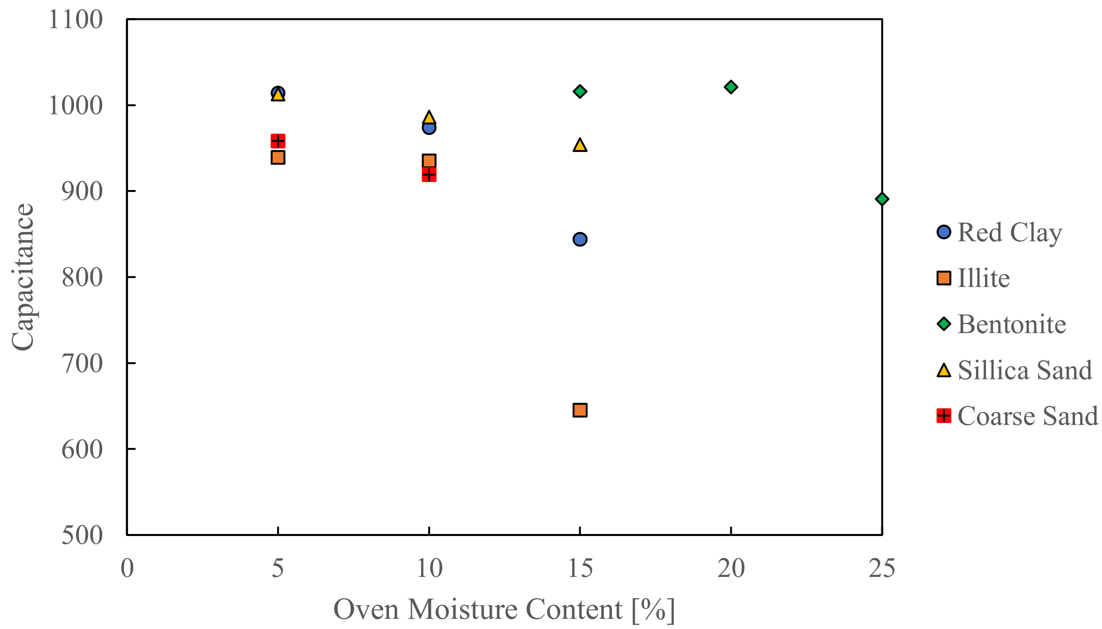

Figure 4.7. Capacitance sensor obtained values comparison for different types of soils.

4.6. Conclusion

The different sets of tests performed resulted in effective use of the microwave oven method with some modifications to the ASTM standard. To avoid dusting, material loss and material damage, power levels between 2 and 6 were effective. These low power levels allowed for an accurate measurement of moisture content. These lower power levels, however, required a longer amount of time in the microwave, which may vary between 5 to 20 minutes depending on the soil type and moisture content. This method proved to be most effective for moisture contents between 5 [%] to 30 [%]. High moisture contents of 50 [%] up to 100 [%] presented difficulties with the method depending on the soil tested.

When applied to compacted specimens, the microwave oven method proved to be consistent with the oven method at microwave power levels of 3 and 4. Overall, the microwave oven method can be successfully used by selecting low microwave power levels of 3 or 4, initially microwaving the soil for 3 minutes and then adding 1-minute intervals until the change in weigh of the sample is smaller than 0.1[%] difference.

The HydroMix HM-08 provided viable moisture content results for unsaturated soils. Further testing should be performed to validate the full use of the sensor; based on the collected information, the HydroMix HM-08 can be used with a single calibration for all types of soil. The device performance is accurate for clay specimens if the soil at the bottom of the compaction mold is tested. Additional testing on different soil types is recommended to determine if the obtained linear relationship is adequate for all types of soil. For field use it is recommended to flatten the surface before deploying the device to obtain accurate measurements. Additionally, this method is advantageous because it requires almost no training, and the total setup and use time is within 2 to 5 minutes.

4.7. References

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CHAPTER 5: IN SITU DENSITY DETERMINATION OF SOIL USING A HUMBOLDT EDGE ELECTRICAL DENSITY GAUGE

5.1. Chapter Overview

Testing of the Humboldt EDGe electric density gauge is described herein. The limitations and challenges of the study on this gauge are presented in Section 4.2. A detailed introduction about the device and the method developed to test the device are described in Section 4.3. The laboratory calibration of the device and the field testing performed on the compacted clay test pads are described in Section 4.4. The results derived from the tests performed and comparisons with other methods are presented in Section 4.5. Conclusion and recommendations associated with the EDGe are presented in Section 4.6. Additionally, the references related to the EDGe are described in Section 4.7.

5.2. Limitations of the Described Study

The testing performed for the Humboldt EDGe electrical gauge was limited to the surface of the compacted clay test pads. Specifically, only soil to a depth of four inches below the surface were tested for comparison purposes. The results were compared to the sand cone method and the photogrammetric method that was described in Chapter 3. A major limitation of this EDGe device was that the device required a laboratory calibration. This laboratory calibration procedure is necessary for acquiring accurate results and must be performed before the device can be used in the field. Additionally, the laboratory calibration procedure must be conducted for every soil type tested.

A computer with the installed EDGe software and wi-fi connection was required within close proximity to the device. The connection established between the device and the computer can disturb the test and multiple tests might be required to obtain the results. This test cannot be performed on very stiff soils, as the spikes required to be hammered into the soil may become broken. Additionally, the removal of the rods from stiff soils is cumbersome and requires extended times of up to 20 minutes to extract and remove the rods without producing damage. The EDGe test cannot be performed on gravel or different types of crushed rock, as the tips of the rods will become damaged and the laboratory calibration is complicated.

5.3. Introduction

Electric density gauges are able to perform measurements of total unit weight, dry unit weight and soil moisture content in a brief period of time, similar to the nuclear density gauge. However, these devices lack the ability to accurately measure these aforementioned properties without a previous laboratory calibration for each soil type (Berney et al., 2017). Even if properly used, these devices were previously found to not be accurate on stiff clays or very plastic clays (Rathje et al, 2006). In the aforementioned studies, electric density gauges were also found to provide inaccurate soil moisture content results. However, the newly developed EDGe devices are claimed to be able to overcome the previously mentioned challenges.

Humboldt developed a new device in 2021, the Humboldt EDGe HF-6500.3F. This device is an electric density gauge that has two main components. It includes a laboratory device that is required to calibrate the device with the same soil that will be tested in the field. The laboratory calibration procedures involve performing standard proctor compaction tests (ASTM D698, 2021). Following calibration of the device is used to perform tests in the field using field components for the device. Both the laboratory components and the field components use and transmit information to the EDGe application and downloaded the information to a portable computer into a computer program. This computer program creates Proctor curves and it links the calibration tests to the in-situ compaction of the soil. The device is offered as a quality control and quality assurance method that is a non-nuclear method.

The EDGe electric density gauge was tested and compared to the photogrammetric method described in Chapter 3. Additionally, it was compared to the results obtained from the sand cone test (ASTM D1556/D1556M, 2016). And with the results of a Troxler nuclear density gauge (ASTM D6938, 2021). The tests were performed within two compacted clay pads, one test conducted under outdoor weather conditions, and the second test conducted under controlled indoor weather conditions. These tests were performed at the ERC. The soil moisture content provided by the device was compared to the soil moisture content provided by the nuclear density gauge and to the soil moisture content obtained from the oven method in the laboratory. The calibration of the soil was performed by obtaining a compaction curve based on five points utilizing six-inch Proctor molds subjected to standard compaction (ASTM D698, 2021).

5.4. Methods and Procedures

5.4.1. EDGe Laboratory Compaction Calibration

The laboratory calibration for the EDGe device required enough points to obtain a Proctor compaction curve. The laboratory procedure was performed using six-inch proctor molds and applying standard compaction energy equal to 12,400 [ft-lbf/ft^3] (ASTM D698, 2021) for the laboratory compaction collection tests, a representative amount of soil was retrieved from the ERC and transported to the laboratory. Six different compaction moisture content points were selected for testing based on an assumed optimum water content. The Proctor tests were performed, and the calibration procedure was applied to each Proctor point. Some Proctor points required the procedure to be completed multiple times, as the sensor connection can be disturbed if the clamps are not connected safely. The sensor provided the necessary readings, and the temperature was acquiered with the probe provided with the device. The compaction curve that was obtained from the EDGe software was compared to a regular compaction curve obtained by weighing and oven drying. The oven moisture content input is required to be provided to produce the EDGe curve, along with the device reading, The weight and volume of each sample are also required by the software. The points and curve were stored in the software to be used in the field. If necessary, multiple curves can be stored to be used in the field. The curve produced by the software is presented in Figure 4.1. The curve comparison is presented in Figure 4.2. The software curve slightly overestimates the laboratory curve. However, this overestimation is not significant as it is less than 1 [pcf] and the same optimum soil moisture content is predicted.

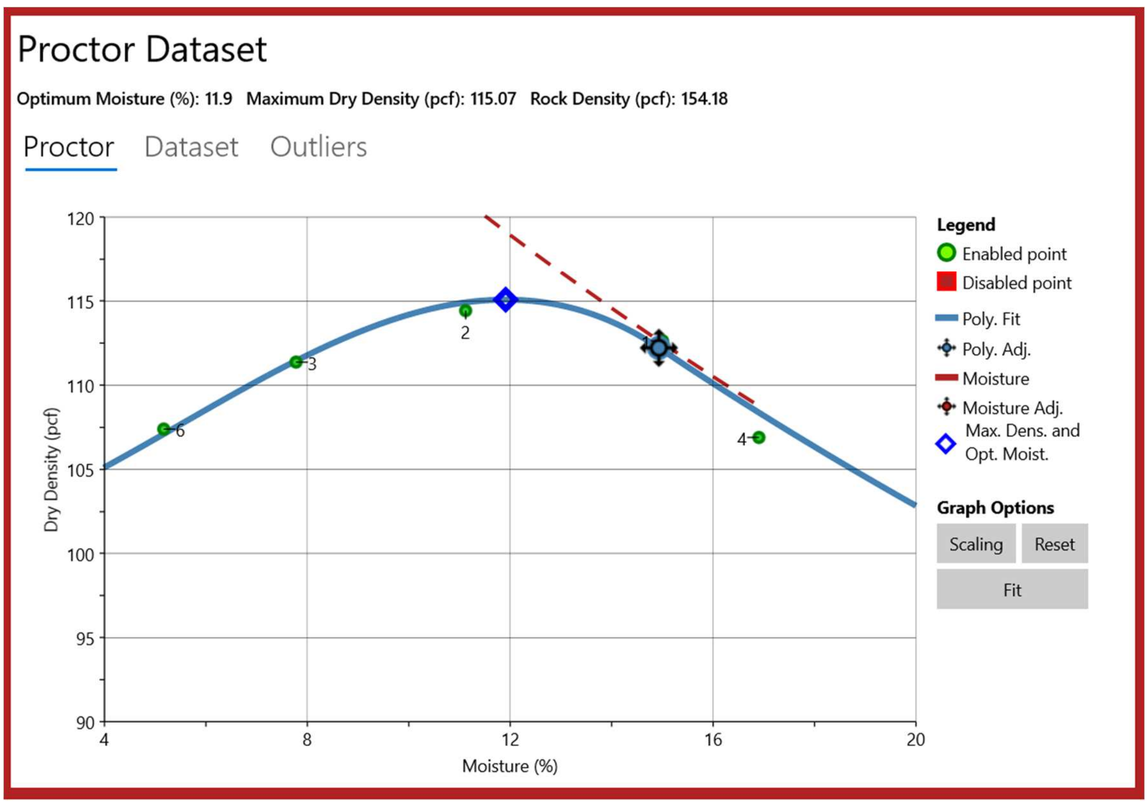

Figure 5.1. EDGe software calibration curve output (from EDGe gauge).

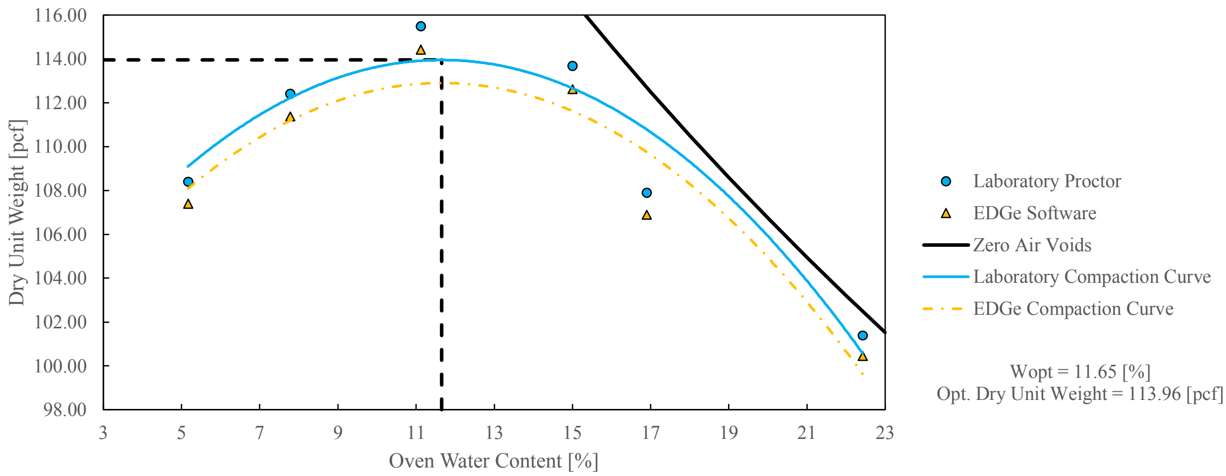

Figure 5.2. EDGe software calibration curve compared to laboratory proctor curve.

5.4.2. EDGe Testing on Compacted Clay Pads

After the calibration was performed, the field tests were performed. The device was installed into the test pad approximately 10 minutes, as the four darts were carefully hammered into the soil using the provided plastic guide. The device was connected directly into the center dart and the three clamps were adjusted to the external darts. The device was then synced to the computer containing the calibration compaction curve and the test was triggered via the computer. It was necessary to clear the surrounding area of objects such as tools that may disrupt the measurement of the soil properties. The procedure was performed multiple times in the event that the device failed to obtain the measurement on the first try. This procedure requires three to five minutes for the device to produce results; however, during testing, the testing required multiple tries, which might take additional time to perform. The software stored the results and allowed labeling. Additionally, when the tests were performed at the site without cover (roof, tree canopy), the device includes a GPS location of the test.

The photogrammetric test and the sand cone test were performed at the same location and within the reach of the locations of the dart holes for accuracy of the location. The nuclear density gauge was also performed close but away from the dart holes as these could produce inaccurate results in the gauge. The results obtained from each of the test methods are presented in Figure 4.5.

5.5. Results

The first test was conducted in the compacted clay pad under exposed to outdoor weather conditions. The EDGe device overestimated the total unit weight and the dry unit weight while underestimating the moisture content compared to all of the other field test methods. These results are presented in Table 4.1. In these tests, the sand cone and Photomodeler software were comparable, and the nuclear density gauge overestimated the unit weight measurements. The moisture content was consistent between the oven and nuclear gauge methods and was overestimated by more than 3 [pcf] by the EDGe device.

Table 5.1. Total unit weight, dry unit weight and moisture content comparison on outer compacted clay pad.

	Photomodeler	Nuclear Density Gauge	Sand Cone	EDGe Gauge
Total Unit Weight [pcf]	109.00	123.70	107.72	126.03
Dry Unit Weight [pcf]	94.91	107.50	93.49	112.83
Moisture Content [%]	15.23	15.10	15.23	11.7

The variations between the tests could have been caused the proximity of an asphalt surface that was within close proximity and other external factors. Thus, three more tests were performed on the environmentally controlled indoor compacted clay test pad. The first test was performed at a very dry condition, the second was performed one day after the pad was wetted and the third test was performed on the wetted pad after 10 days of wetting. The results of these tests are presented in Table 4.2, Table 4.3 and Table 4.4 respectively. The EDGe consistently overestimated the values for total unit weight and dry unit weight, and it consistently underestimated moisture contents under all conditions. With an erroneous negative moisture content number for the dry condition. The overestimations of the device were significant and cannot be neglected as they differ from current methods such as the nuclear density gauge and the sand cone. As previously discussed in Chapter 3, the Photomodeler test on the dry test pad was poor due to the dusty nature of the soil.

Table 5.2. Total unit weight, dry unit weight and moisture content comparison for dry conditions on the environmentally controlled compacted clay pad.

	Photomodeler	Nuclear Density Gauge	Sand Cone	EDGe Gauge
Total Unit Weight [pcf]	90.91	98.70	100.87	103.01
Dry Unit Weight [pcf]	89.76	97.00	99.59	104.14
Moisture Content [%]	1.28	1.80	1.28	-1.08

Table 5.3. Total unit weight, dry unit weight and moisture content comparison for wet conditions after one day of wetting on the environmentally controlled compacted clay pad.

	Photomodeler	Nuclear Density Gauge	Sand Cone	EDGe Gauge
Total Unit Weight [pcf]	105.71	111.30	107.16	114.73
Dry Unit Weight [pcf]	94.03	102.00	95.33	107.87
Moisture Content [%]	12.41	9.10	12.41	6.42

Table 5.4. Total unit weight, dry unit weight and moisture content comparison for wet conditions after 10 days of wetting on the environmentally controlled compacted clay pad.

	Photomodeler	Nuclear Density Gauge	Sand Cone	EDGe Gauge
Total Unit Weight [pcf]	105.55	108.00	108.19	114.19
Dry Unit Weight [pcf]	96.03	100.30	98.43	107.67
Moisture Content [%]	9.92	7.70	9.92	6.05

5.6. Conclusion

The results obtained with the Humboldt EDGe electric density gauge were relatively precise when the clay within the test pad was not dry. However, the accuracy of the device was low, especially for moisture content results. Even with a laboratory calibration for the soil tested, the devices consistently overestimated total unit weight and dry unit weight. Additionally, the device consistently underestimated the water content when compared to the values obtained from the nuclear density gauge and the oven soil moisture content. The tests were performed on clay; thus, it might be possible that the accuracy of the results would improve on sands or other larger particle soils. Overall, while the device showed promise, it requires improvement to compare to methods such as the nuclear density gauge and the sand cone. While the method was able to provide a base reference it requires an additional method to confirm the in-situ results.

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CHAPTER 6: CONCLUSIONS

6.1. Chapter Overview

The overall conclusions of the investigation are reported herein. The limitations of the investigation are presented in Section 6.2. The summary of the conclusions is presented in Section 6.3. Recommendations for further research related to the topic are presented in Section 6.4.

6.2. Limitations

The main limitation with the photogrammetry method for use in obtaining soil dry unit weight is that it requires an external test to determine soil moisture. Other limitations are derived from the Photomodeler software experiencing difficulties with highly reflective surfaces or shadowed areas. Mobile phone cameras of lower quality that the iPhone 12 camera used for testing may lower the quality of the results obtained in this investigation.

The Humboldt EDGe electrical density gauge that was tested proved to have multiple limitations. As other investigations have determined for electrical gauges, the EDGe gauge required soil specific calibrations. Furthermore, the electrical gauge had difficulties with obtaining results in stiff soils and under very dry conditions. Additionally, the calibration performed in the laboratory may not be directly related to in-situ conditions.

The capacitance sensor had limitations of very small areas being tested around the sensor. The sensor would also require soil specific calibrations. The microwave oven method has difficulties with saturated clays and dusty clays. As for the Hydromix HM-08 sensor, flat surfaces are required to obtain consistent measurements on compacted soils. When the hydromix HM-08 sensor was used in the laboratory the soil depth must be at least 3 to 4 inches.

6.3. Summary

Overall, the photogrammetric method was determined to be versatile and convenient to measure total unit weight, and dry unit weight. The accuracy achieved was within 4 [pcf] and could be improved under more controlled conditions. The simplicity of the method required almost no training. The processing was relatively simple through the use of the Photomodeler software. This method should be combined with the Hydromix HM-08 method to obtain moisture content to develop dry unit weight on a short period of time. The combination of these methods would not require any level of certification or specialized training. The Hydromix HM-08 sensor was able to achieve an excellent linear relationship for all compacted soils and can be used in the field to obtain accurate moisture content measurements. The Hydromix HM-08 method presented no problems with measuring moisture content at dry conditions. If a flat surface is achieved, the method is effective.

The EDGe, while being versatile in providing total unit weight, dry unit weight and moisture content, constantly overestimates the unit weight values while undermining moisture content. The variations are fairly irregular; therefore, a correction might not be able to provide accurate measurements. Additionally, if the soils tested are stiff, the method becomes cumbersome as the darts are difficult to drive into the soil and remove from the soil. The capacitance sensor was determined to be too cumbersome and the calibration for all soil types is extensive.

6.4. Recommendations

The recommendations mentioned below refer mostly to possible future research on the methods described herein.

- Further research on different types of compacted clay and sand will reveal if the method is appropriate for all types of soil and lighting consitions. Advancements in mobile phone cameras will significantly increase the quality of the results of the method. Furthermore, a computer with high processing power will significantly decrease the time currently required.
- Research regarding microwave oven testing of moisture content is recommended to be performed at lower power settings as discussed herein. Additional moisture content measurements using the microwave sensor Hydromix HM-08 on different types of compacted soils will lead to the development of a linear relationship for all soils without the need of further calibrations depending on the soil types.
- Additional testing with the Humboldt EDGe electrical gauge is recommended to determine if the overestimation trend of total unit weights is consistent among different types of soils. Further investigations of laboratory calibration is recommended to determine if the accuracy on the field can be improved.
- The development of a prototype to automate and standardize the image acquisition for the Photomodeler method is recommended. The prototype recommended is a track for cameras and lights to be placed over the hole. This method will allow for photographs to be acquired in the same locations each time, increasing the usability of the method. Images before and after the excavation will be obtained at the same locations and a more accurate analysis may be performed.

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APPENDIX

APPENDIX A: PHOTOGRAMMETRIC RESULTS

A.1. Chapter Overview

This chapter contains a detailed description of the Photomodelere image analysis in Section A.2. Additionally, it contains records of all the measurement performed in conjunction with the photogrammetry analysis in Section A.3.

A.2. Detailed Description on Photomoldeler Image Analysis Method

The "Automated Point Clouds & Meshes (Smart Points)" as shown in Figure A.1, was used for this method. The "Dense Point Cloud Creation - MSV", "Surface Creation – Triangulation" and "MSV Higher Density" options (Figures A.2 and A.3) were selected, and the remaining settings were left on default mode. After the photos were uploaded into the program, the uncalibrated camera option was selected, and the program automatically began processing. Following processing of the images, the surface appeared as presented in Figure A.4. The model was then scaled by using the "Scale/Rotate Wizard" (Figure A.5) tool and using the measurement guide as a reference in centimeters. After the scales were determined, the model was trimmed around the hole by using the "Point Mesh Edit Region Mode" (Figure A.6) as observed in Figure A.7. The final model is presented in Figure A.8. The trimming of the model included rotating the model in three-dimensions (3D) to ensure that the edge of the hole was being selected.

Figure A.1. Automated point clouds and meshes (SmartPoints).

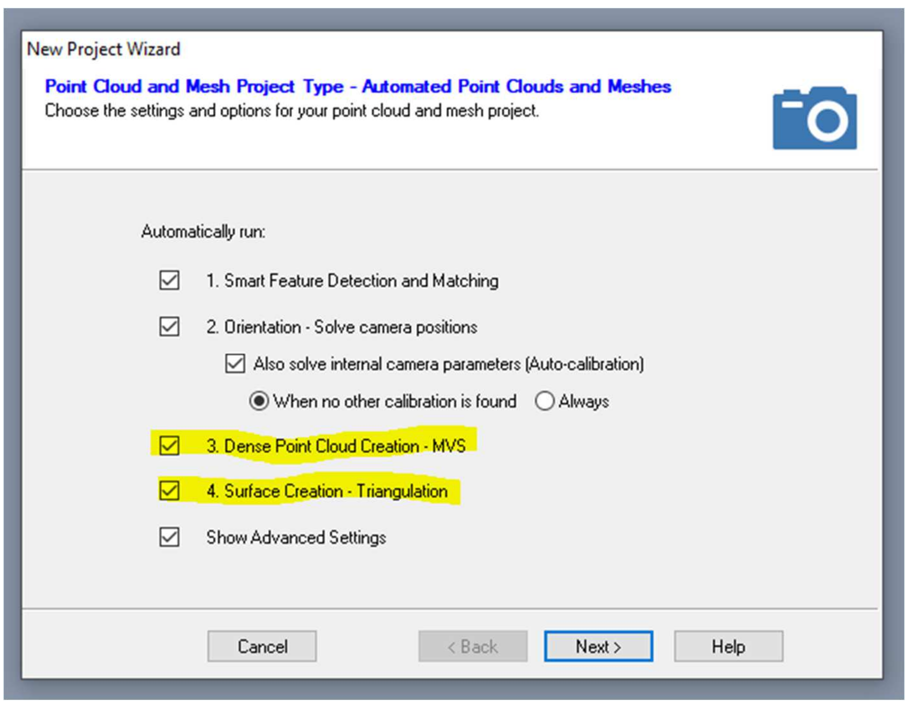


Figure A.2. Dense point cloud creation and surface creation – triangulation.

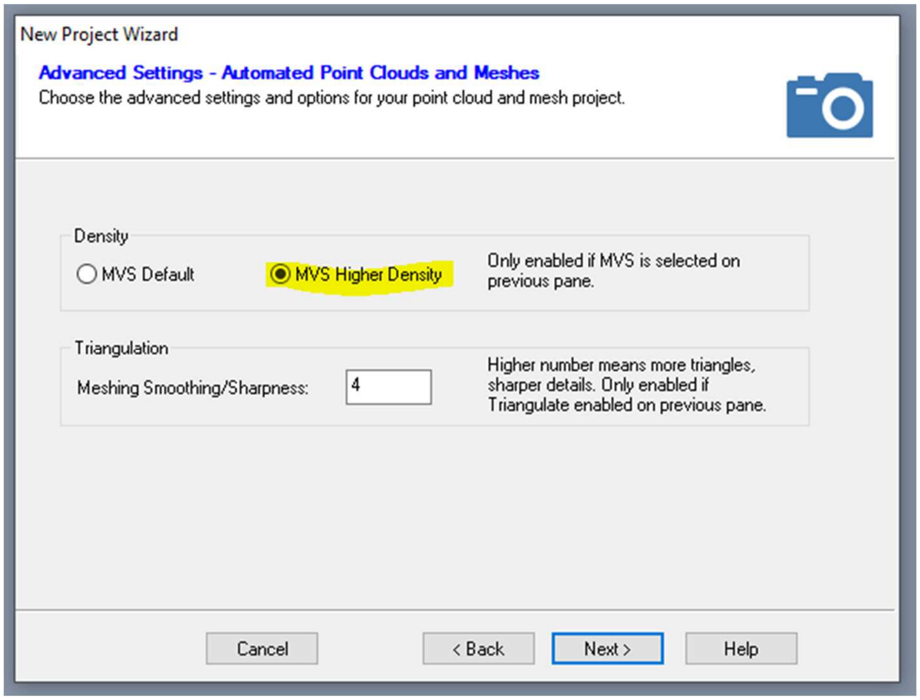


Figure A.3. Advanced settings: MSV higher density.

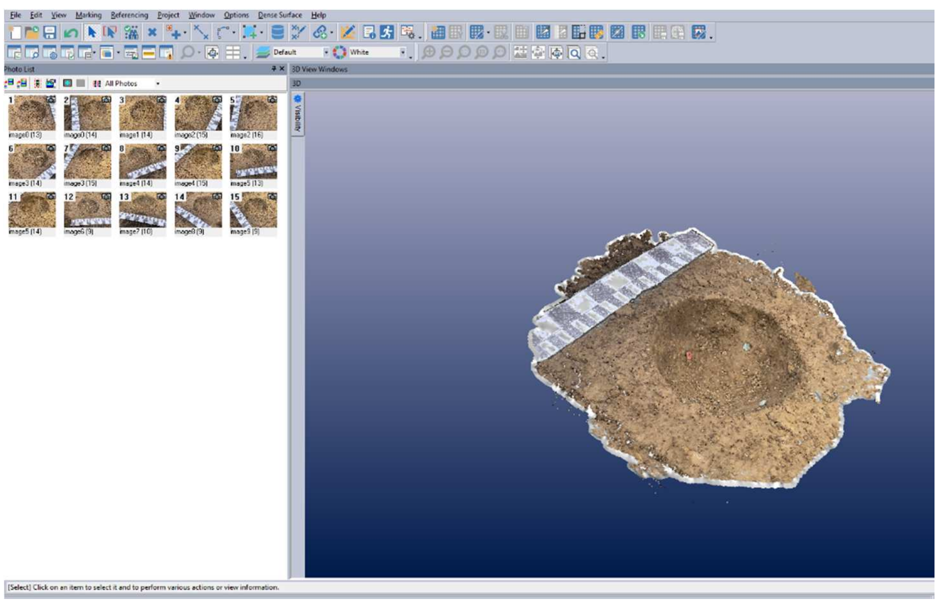


Figure A.4. Results from initial surface model creation of the dug hole.

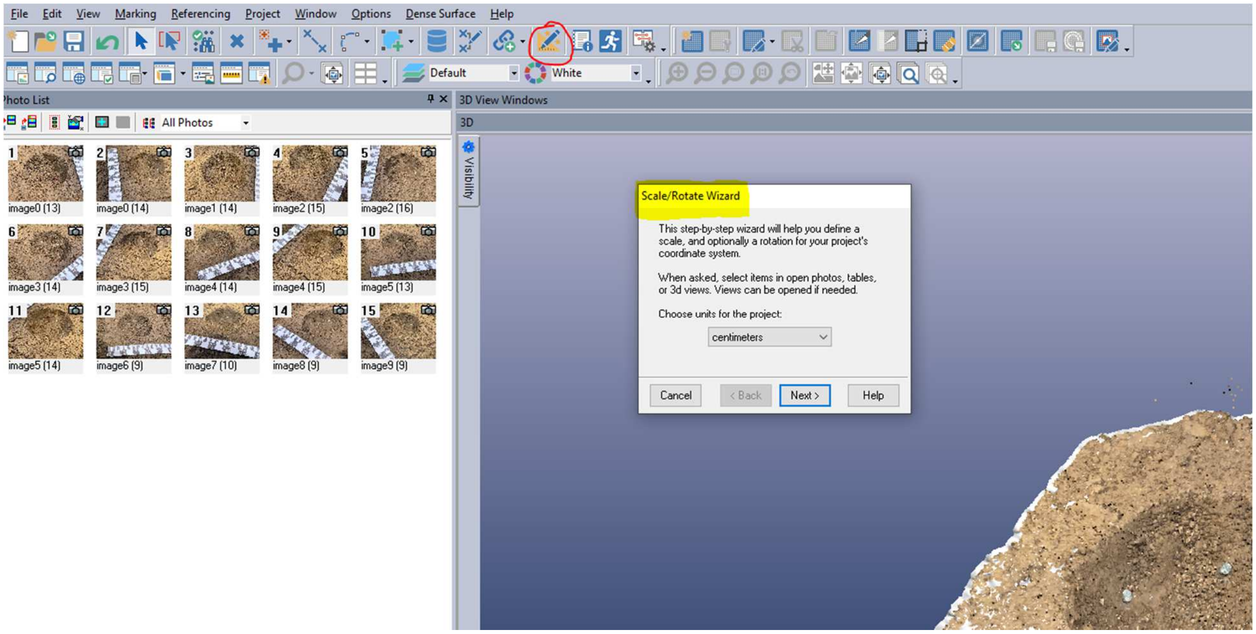


Figure A.5. Scale/rotate wizard.

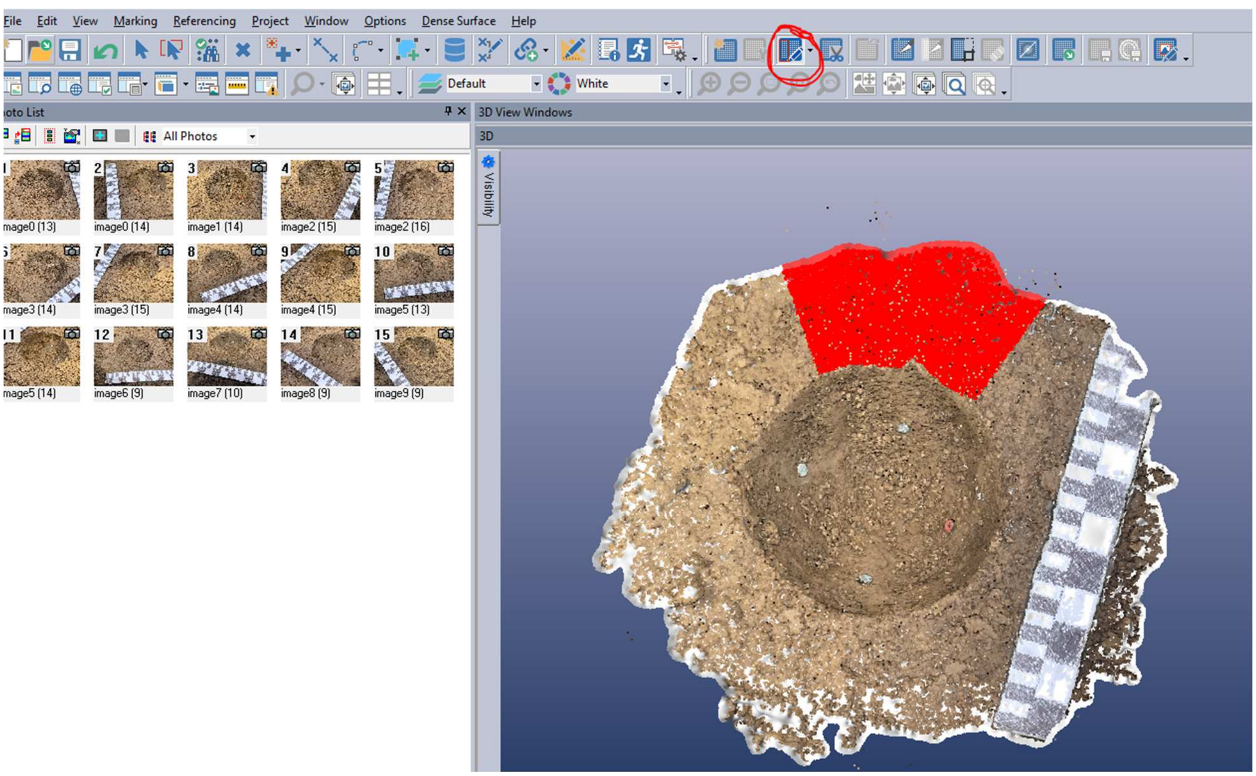


Figure A.6. Point mesh edit region mode.

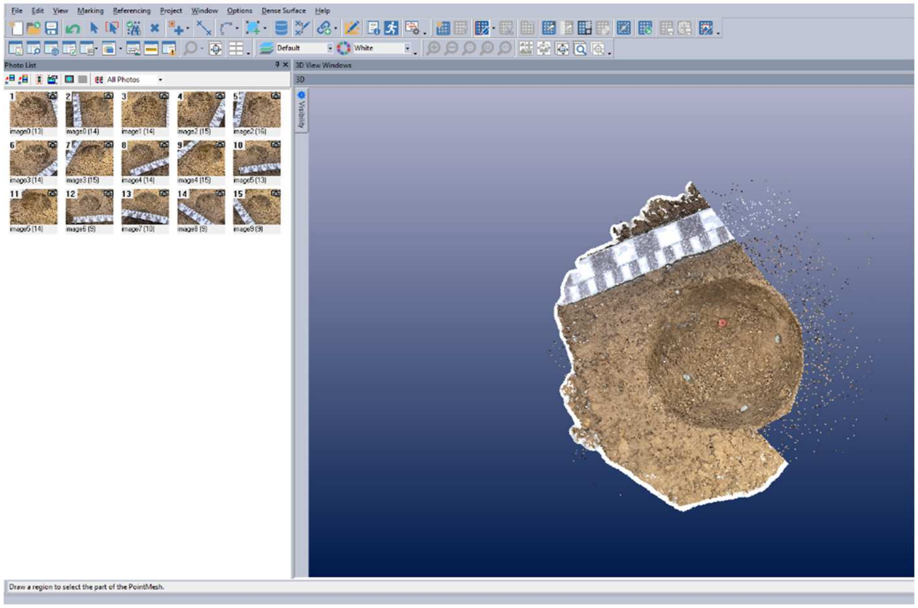


Figure A.7. Trimming of the model around the outside edges of the hole.

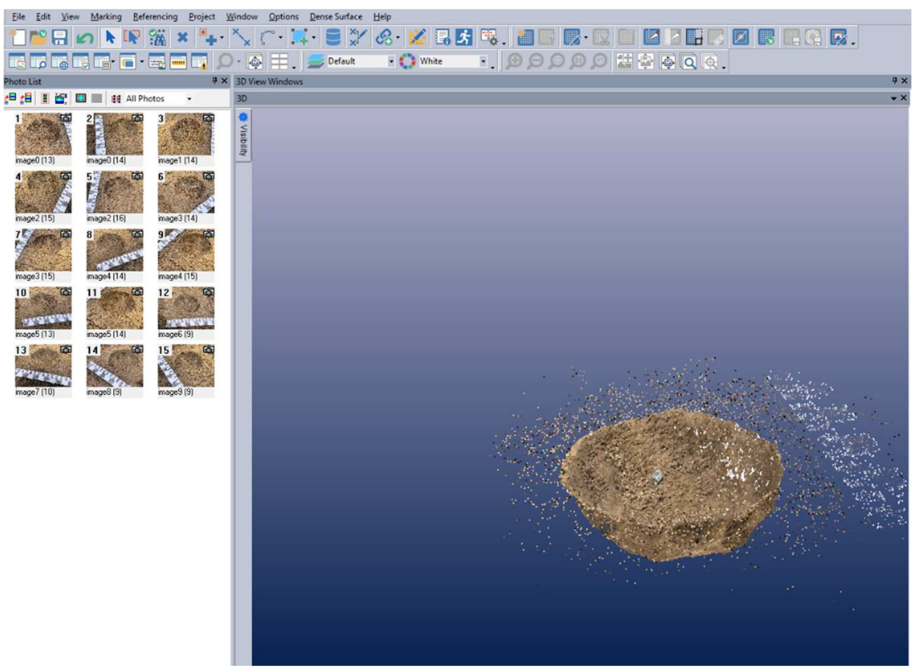


Figure A.8. Model trimming completed.

Following trimming, the remaining surface is the hole itself, 8-10 smart points on the ground level around and above the hole were selected and a flat plane was placed through these points by the use of the "Create Best Fit Plane From Selected Objects" (Figure A.8). After the plane is fitted, the "measurements" tool becomes activated. The hole surface and the flat plane surface were selected at the same time and the final volume was displayed, in cubic centimeters, on the right side as "Volume Above the Plane" (Figure A.9). The processing took 8 minutes and 50 seconds.

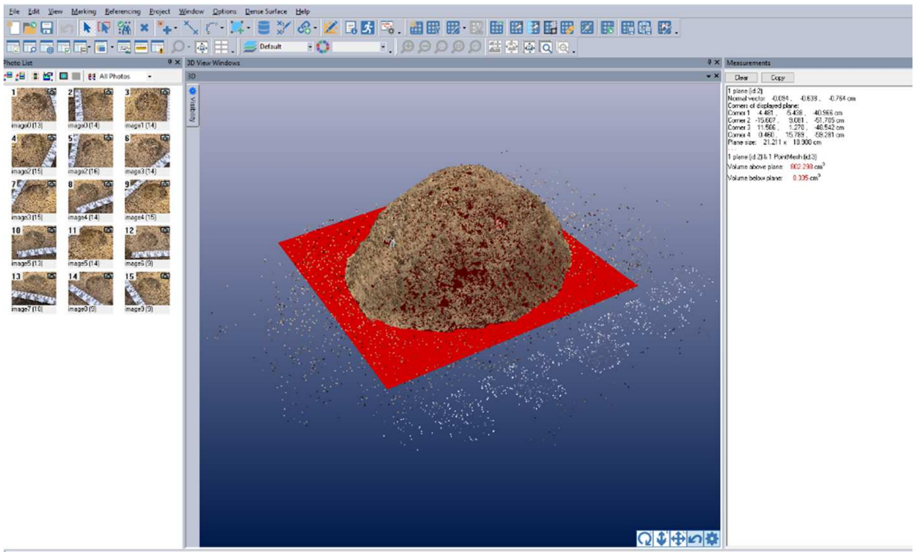


Figure A.9. Model surface selection and volume measurement reported.

A.3. Total Unit Weight and Dry Unit Weight Tests Performed

The results of the tests performed utilizing various methods are presented in the tables below.

Table A.1. Photomodeler and sand cone total and dry unit weight comparison on outer compacted clay pad.

	Photomodeler	Sand Cone
Volume [cm3]	802.3	813.74
Total Unit Weight [pcf]	117.63	115.98
Dry Unit Weight [pcf]	98.71	100.12

Table A.2. Simultaneous tests for Photomodeler and sand cone total and dry unit weight comparison on outer compacted clay pad.

	Photomodeler Test 1	Photomodeler Test 2	Sand Cone
Volume [cm3]	695	678	632.49
Total Unit Weight [pcf]	136	139	149.21
Dry Unit Weight [pcf]	116	118	127.42

Table A.3. Repetition of simultaneous tests for Photomodeler and sand cone total and dry unit weight comparison on outer compacted clay pad.

	Photomodeler Test 1	Photomodeler Test 2	Sand Cone
Volume [cm3]	908	905	881.5
Total Unit Weight [pcf]	103.94	104.28	107.06
Dry Unit Weight [pcf]	90.45	90.75	93.17

Table A.4. Simultaneous tests for Photomodeler and sand cone total and dry unit weight comparison on base coarse.

	Photomodeler Test 1	Photomodeler Test 2	Sand Cone
Volume [cm3]	961.85	1128.62	1409.08
Total Unit Weight [pcf]	95.59	81.44	65.22
Dry Unit Weight [pcf]	90.45	81.38	65.17

Table A.5. Repetition of simultaneous tests for Photomodeler and sand cone total and dry unit weight comparison on base coarse.

	Photomodeler Test 1	Photomodeler Test 2	Photomodeler Test 2	Sand Cone
Volume [cm3]	1161.52	1036.45	1076.51	1157.85
Total Unit Weight [pcf]	95.37	106.97	102.9	95.72
Dry Unit Weight [pcf]	92.63	103.89	99.98	92.96

Table A.6. Photomodeler and sand cone total and dry unit weight comparison on base coarse with and without spray rubber coating.

	Photomodeler Test 1	Photomodeler Test 2 (Rubber)	Sand Cone
Volume [cm3]	648.98	617.24	672.11
Total Unit Weight [pcf]	108.92	116.33	106.79
Dry Unit Weight [pcf]	103.28	110.31	101.26

Table A.7. Time of processing analysis based on the number of images uploaded to the Photomodeler software.

Number of Photos Taken	Model Feasability	Time for model processing [min]	Volume processing time [min]
1	No	-	8:30
2	No	-	
3	No	3:13	
4	No	3:35	
5	No	4:04	
6	No	3:49	
7	No	6:00	
8	No	5:21	
9	No	5:46	
10	No	6:08	
11	No	5:14	
12	No	7:43	
13	No	7:17	
14	No	8:14	
15	Yes	8:50	
16	Yes	11:55	
17	Yes	12:40	
18	Yes	13:42	
19	Yes	14:06	
20	Yes	15:16	

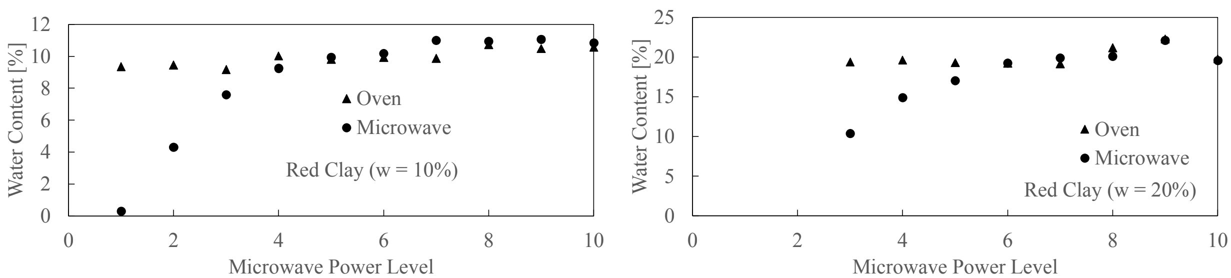
APPENDIX B: MOISTURE CONTENT TESTING

B.1. Chapter Overview

The full set of tests performed on different soils using the microwave oven method at different power levels are presented in Section B.2. The results obtained from the microwave sensor HydroMix HM-08 on outputs "V" and "E" are presented in Section B.3. The methods and results to measure moisture content of a compacted sample with the HydroMix sensor for the "F" output are presented in Section B.4.

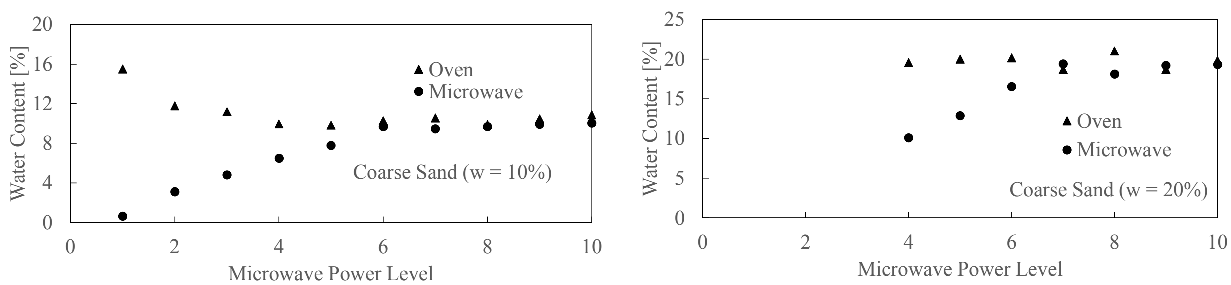
B.2. Microwave Oven Testing at Different Power levels

The figures presented on this chapter represent different soils being tested at different power levels of the microwave oven:



(a)

Figure B.1. Red clay microwave results at different power levels. (a) 10 % moisture, (b) 20 % moisture.



(a) (b)

Figure B.2. Coarse sand microwave results at different power levels. (a) 10 % moisture, (b) 20 % moisture.

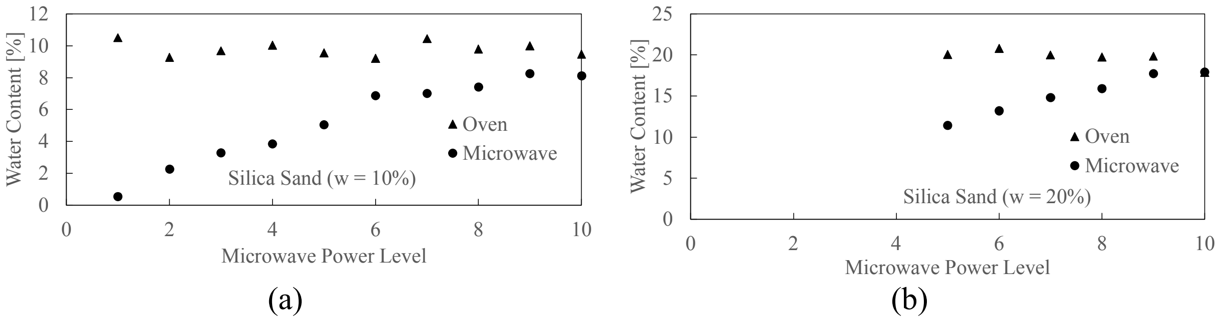


Figure B.3. Silica sand microwave results at different power levels. (a) 10 % moisture, (b) 20 % moisture.

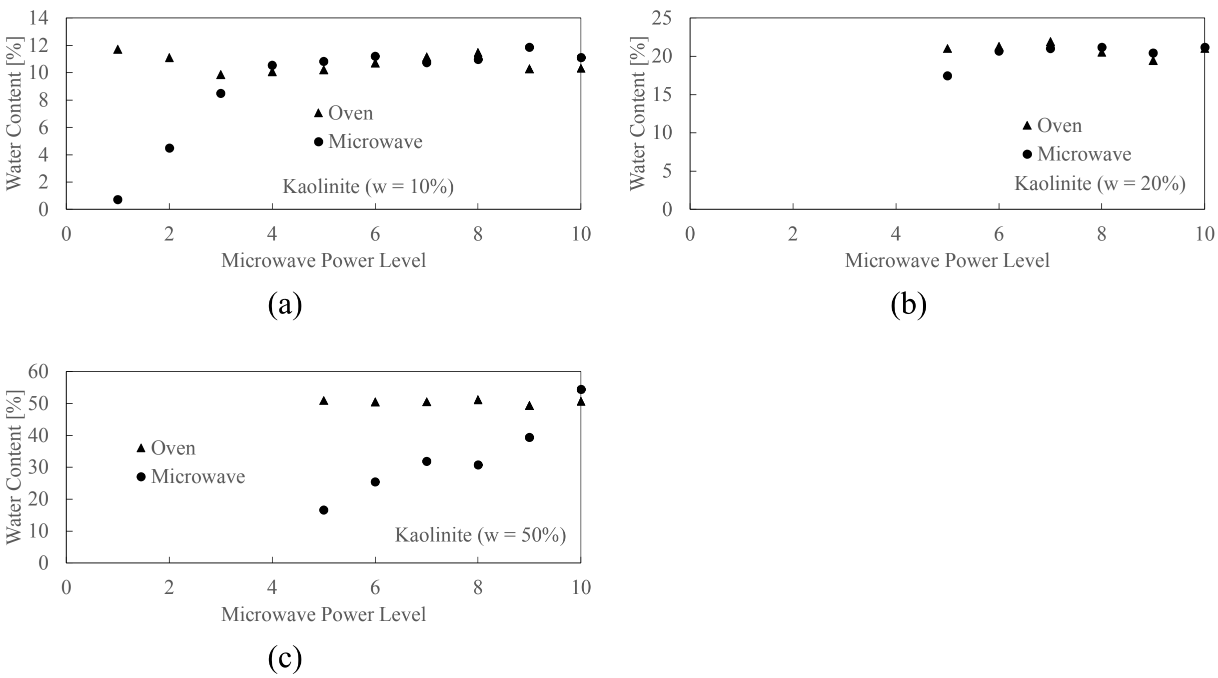


Figure B.4. Kaolinite microwave results at different power levels. (a) 10 % moisture, (b) 20 % moisture (c) 50 % moisture

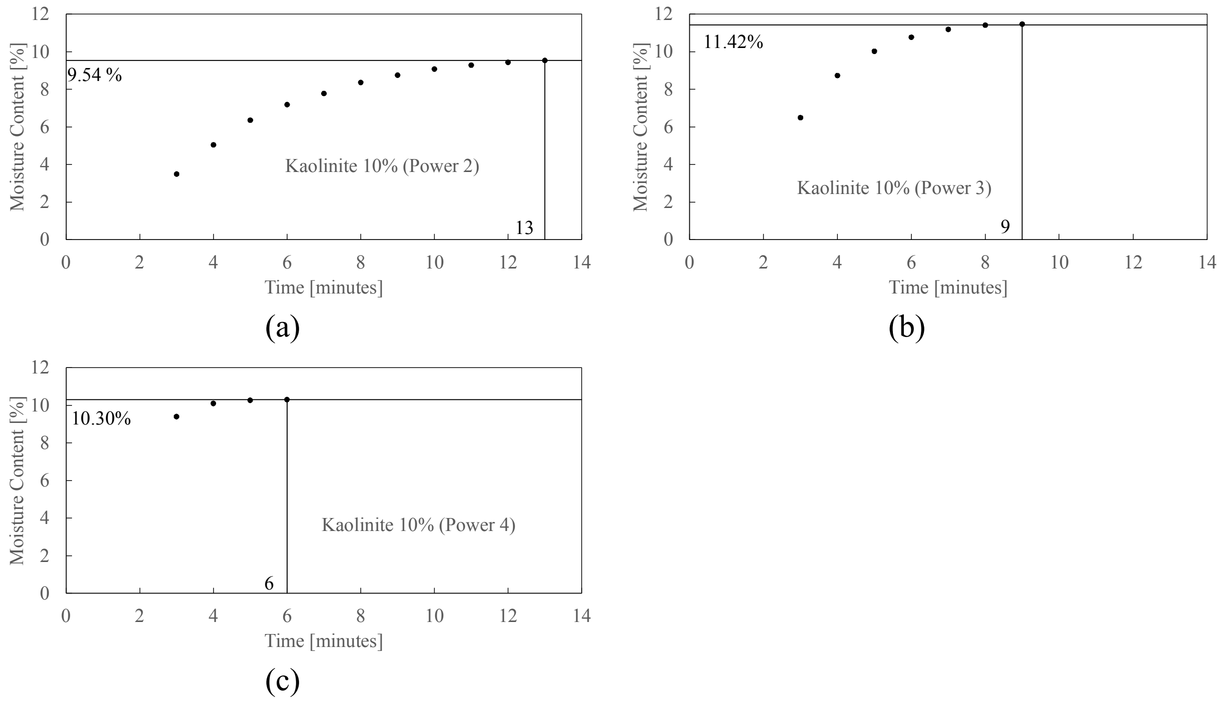


Figure B.5. Kaolinite microwave results at power 2, 3 and 4. (a) Power 2 and 10% moisture content, (b) power 3 and 10% moisture content, (c) power 4 and 10% moisture content.

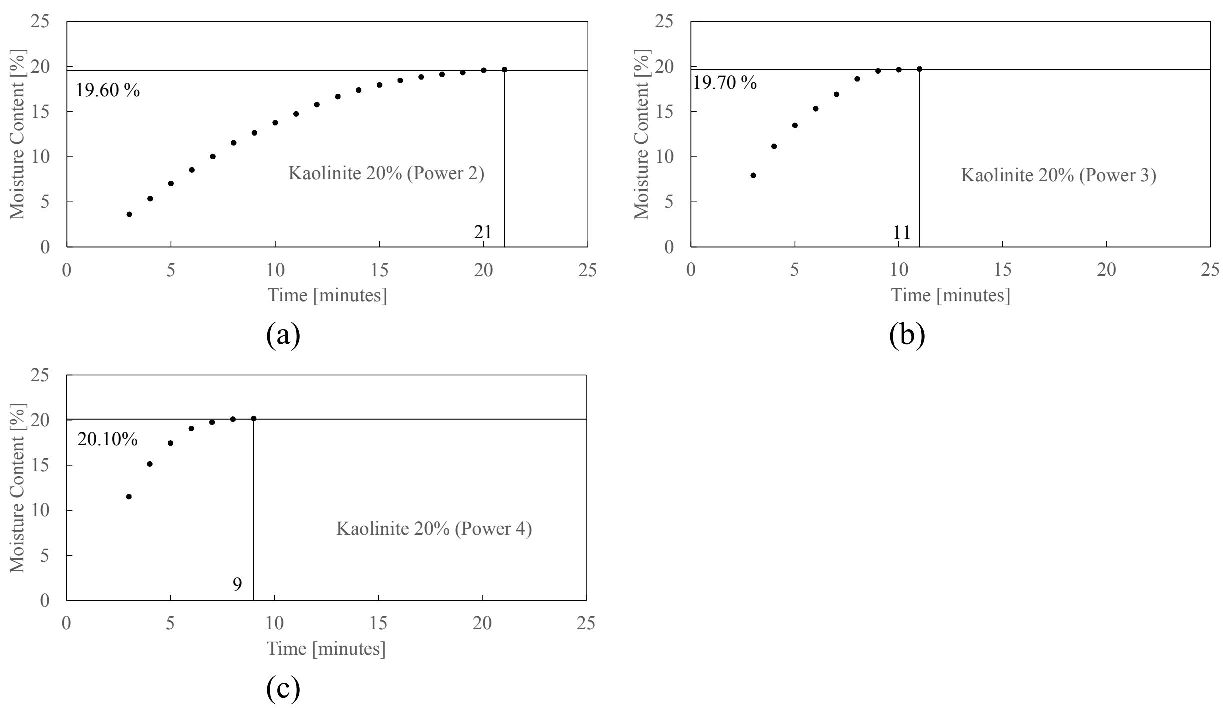


Figure B.6. Kaolinite microwave results at power 2, 3 and 4. (a) Power 2 and 20% moisture content, (b) power 3 and 20% moisture content, (c) power 4 and 20% moisture content.

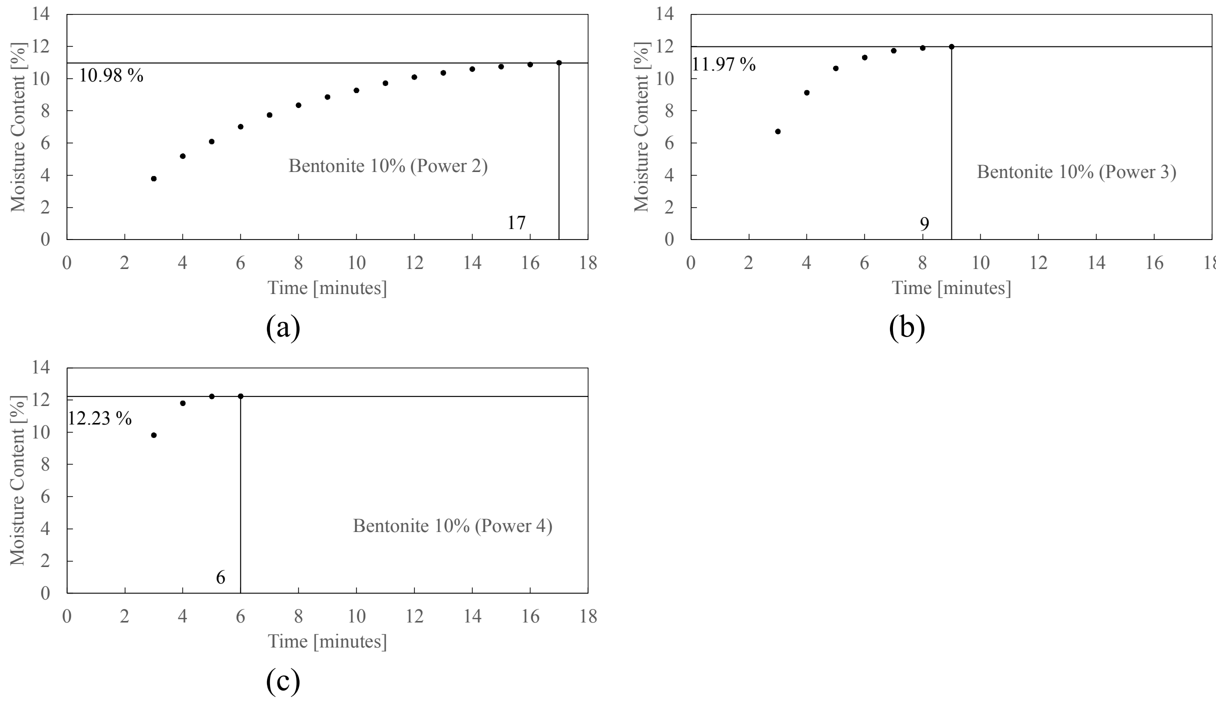


Figure B.7. Bentonite microwave results at power 2, 3 and 4. (a) Power 2 and 10% moisture content, (b) power 3 and 10% moisture content, (c) power 4 and 10% moisture content.

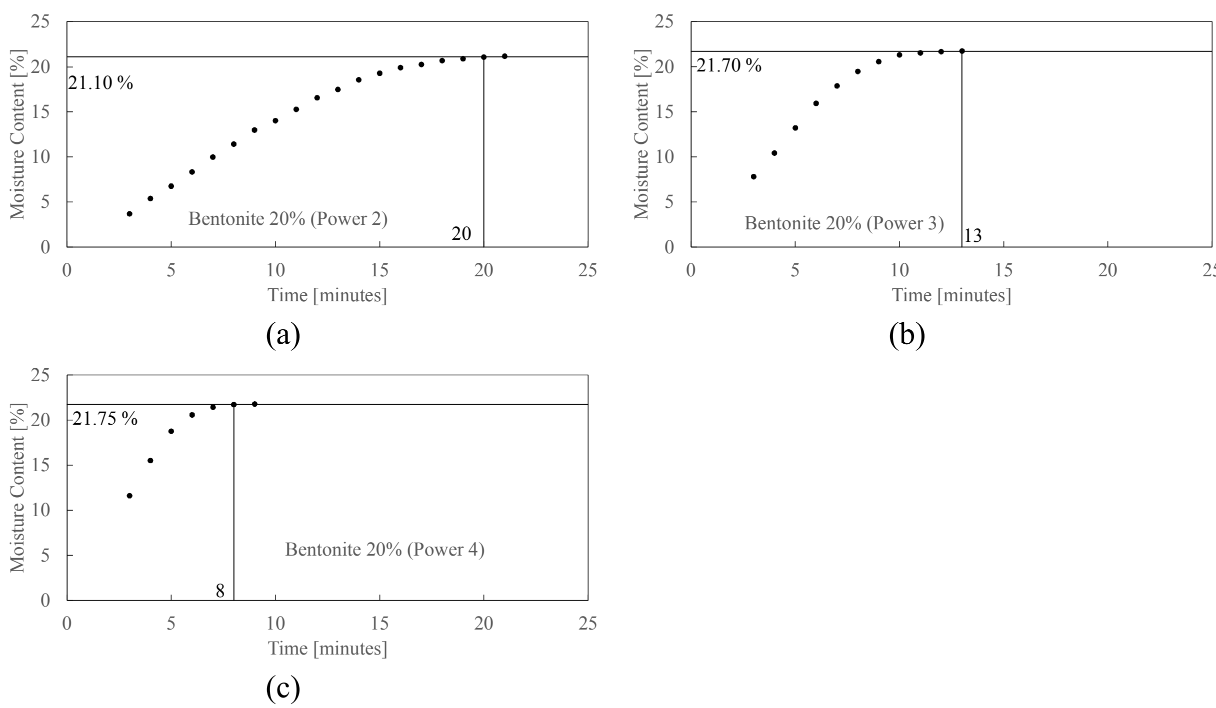
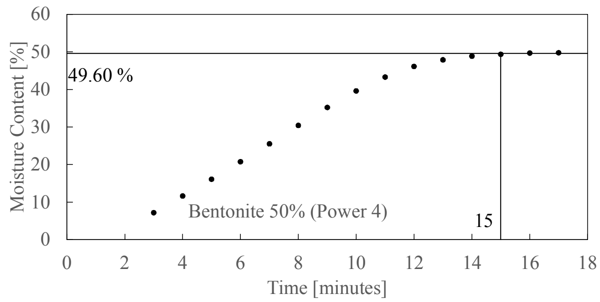
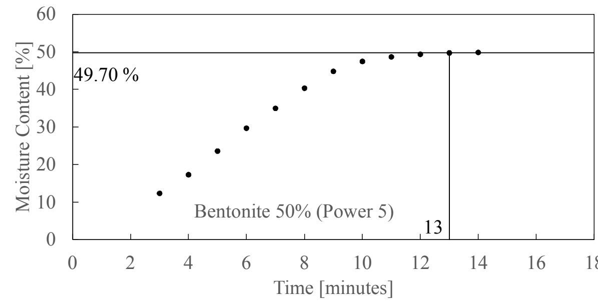


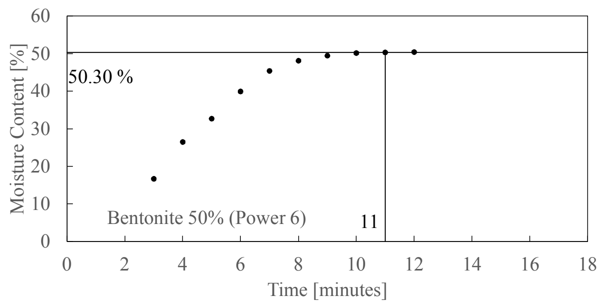
Figure B.8. Bentonite microwave results at power 2, 3 and 4. (a) Power 2 and 20% moisture content, (b) power 3 and 20% moisture content, (c) power 4 and 20% moisture content.



(a)

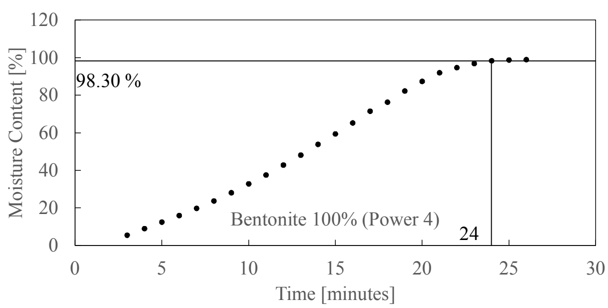


(b)

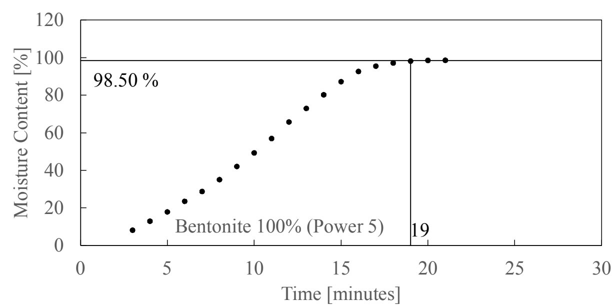


(c)

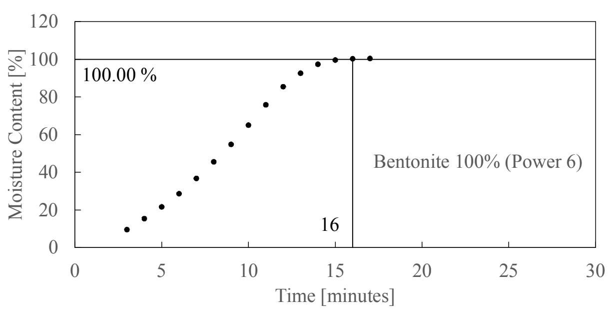
Figure B.9. Bentonite microwave results at power 4, 5 and 6. (a) Power 4 and 50% moisture content, (b) Power 5 and 50% moisture content, (c) Power 6 and 50% moisture content.



(a)



(b)



(c)

Figure B.10. Bentonite microwave results at power 4, 5 and 6. (a) Power 4 and 100% moisture content, (b) power 5 and 100% moisture content, (c) power 6 and 100% moisture content.

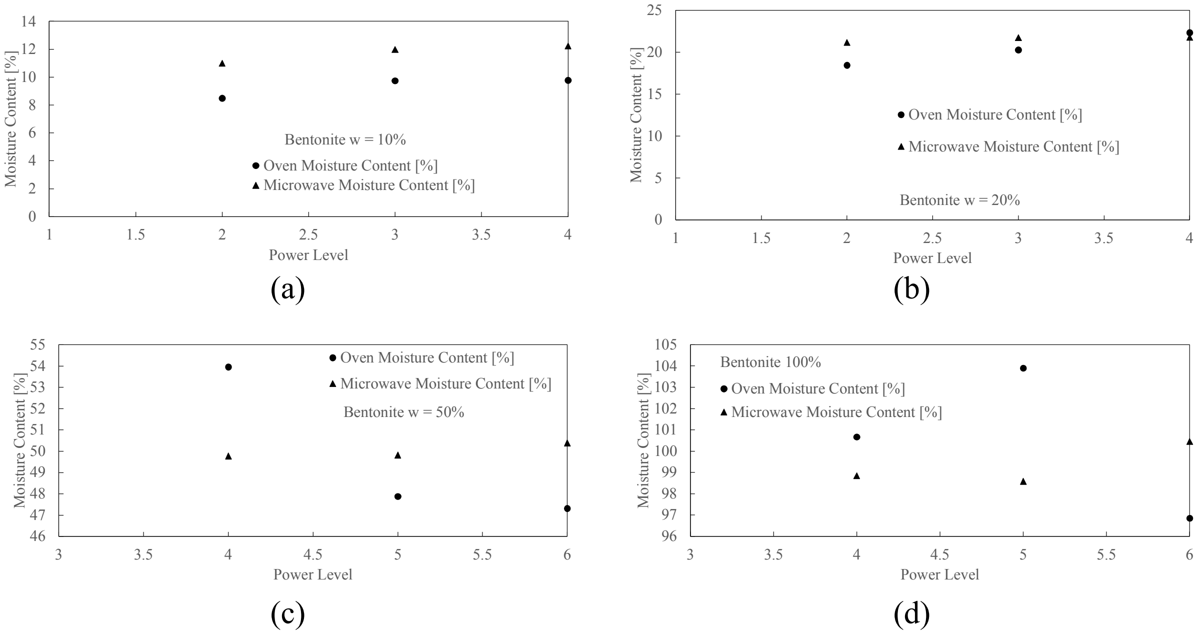


Figure B.11. Bentonite microwave results compared to the oven method. (a) Sample at 10% moisture aim, (b) sample at 20% moisture aim, (c) sample at 50% moisture aim, (c) sample at 100% moisture aim.

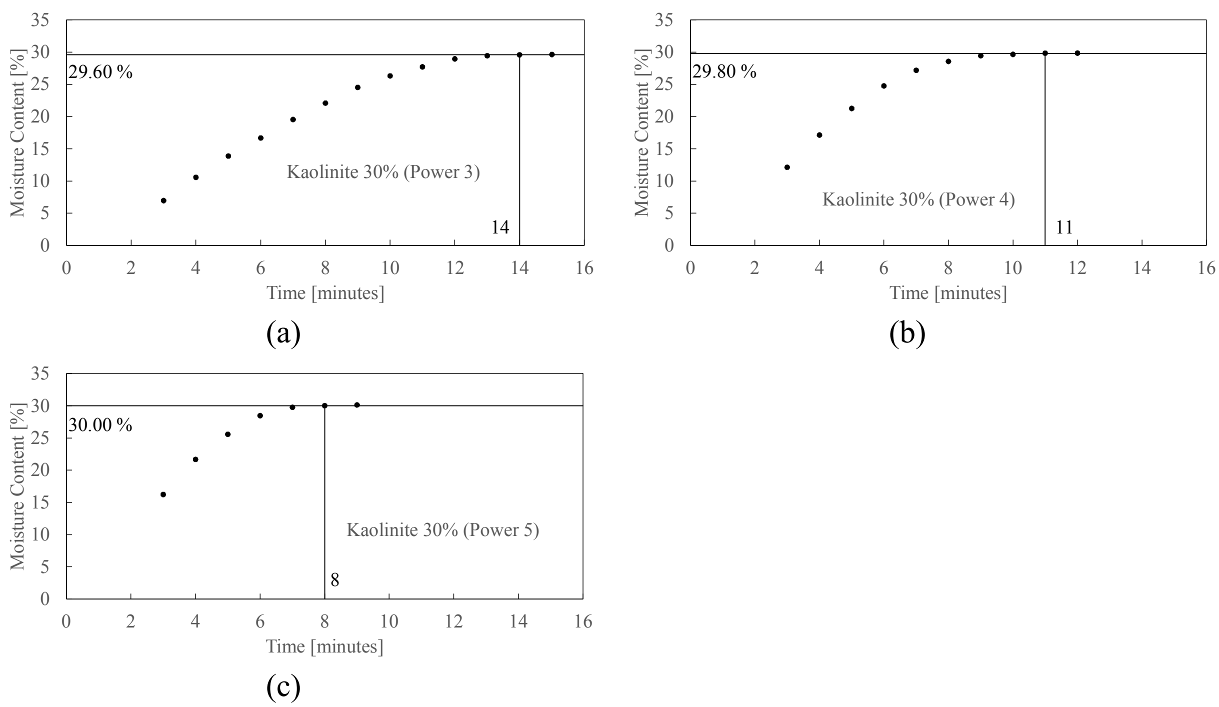
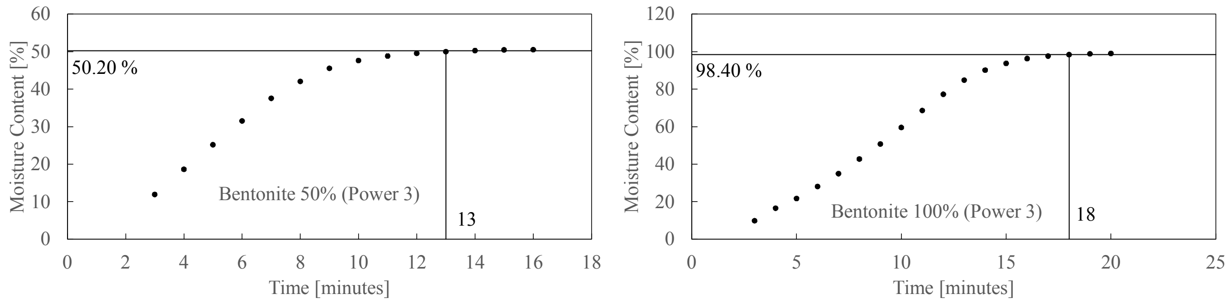


Figure B.12. Kaolinite microwave results at power 3, 4 and 5. (a) Power 3 and 30% moisture content, (b) power 4 and 30% moisture content, (c) power 5 and 30% moisture content.



(a) (b)

Figure B.13. Bentonite microwave results at (a) power 5 and 50% moisture content, (b) power 5 and 100% moisture content.

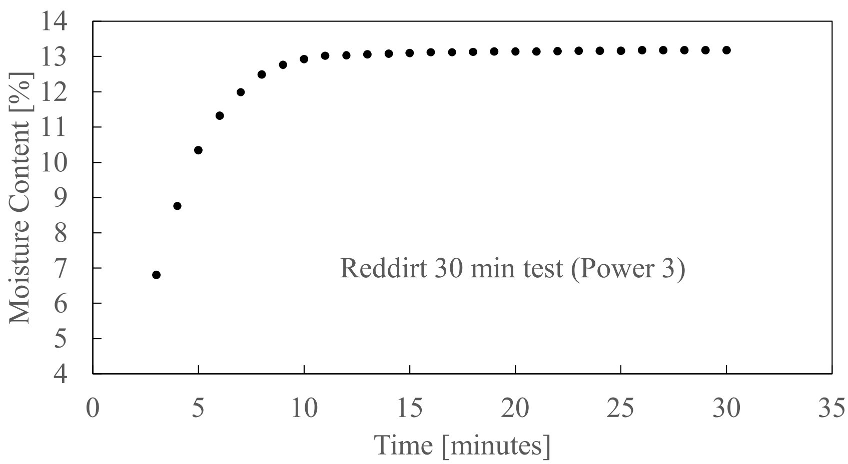
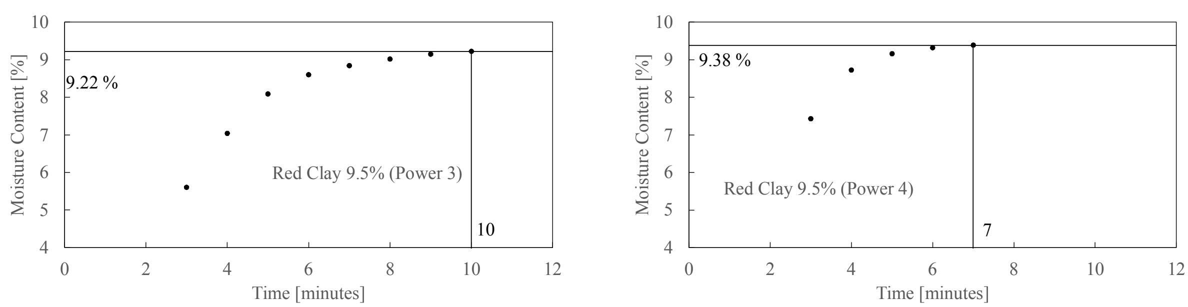
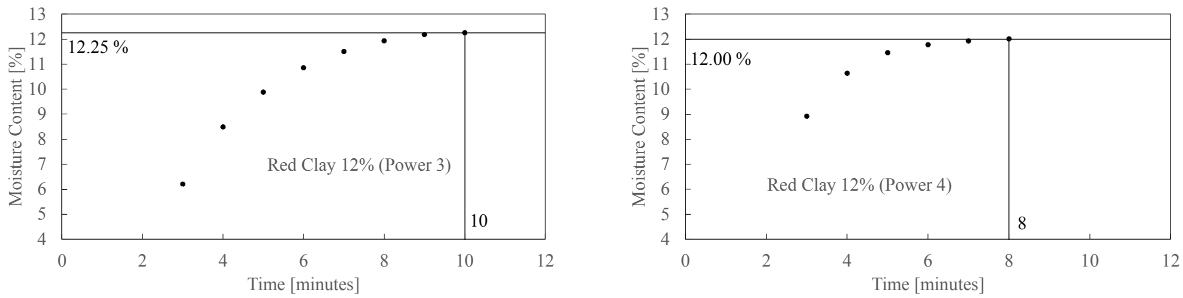


Figure B.14. 30-minute test on red clay on microwave power 3.



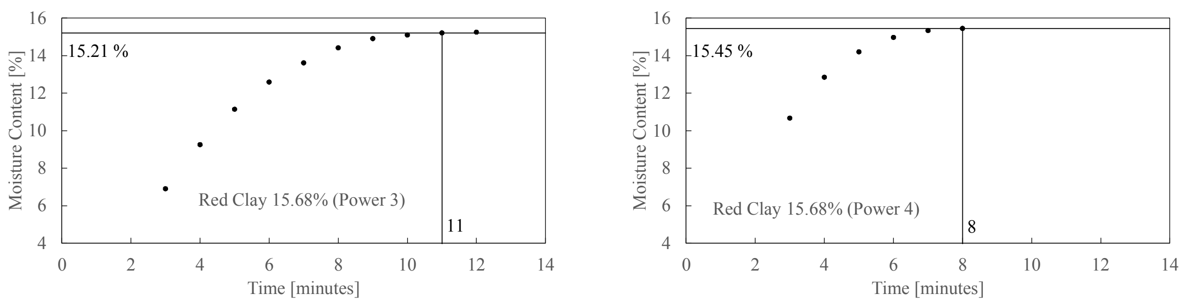
(a) (b)

Figure B.15. Compacted red clay microwave results at power 3 and 4. (a) Power 3 and 9.5% moisture content, (b) power 4 and 9.5% moisture content.



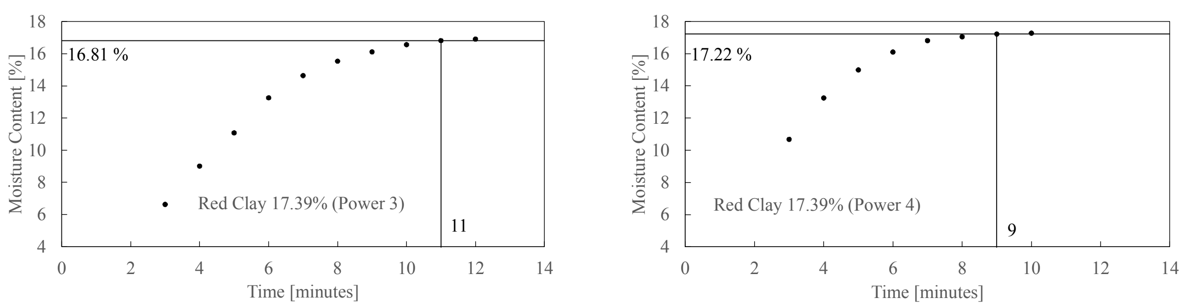
(a) (b)

Figure B.16. Compacted red clay microwave results at power 3 and 4. (a) Power 3 and 12% moisture content, (b) power 4 and 12% moisture content.



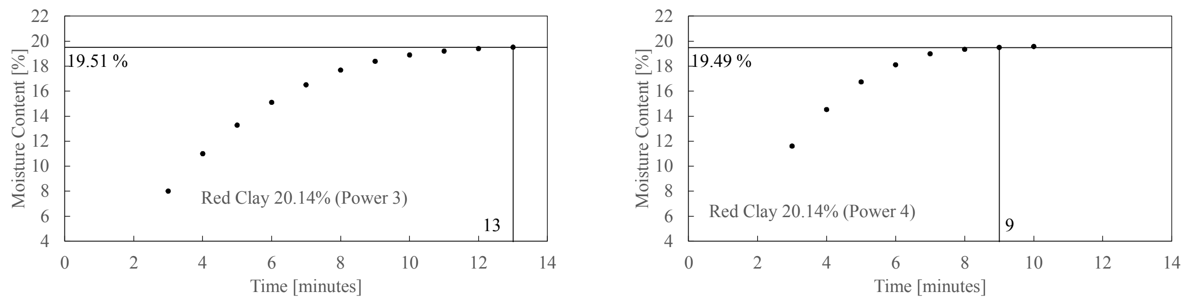
(a) (b)

Figure B.17. Compacted red clay microwave results at power 3 and 4. (a) Power 3 and 15.68% moisture content, (b) power 4 and 15.68% moisture content.



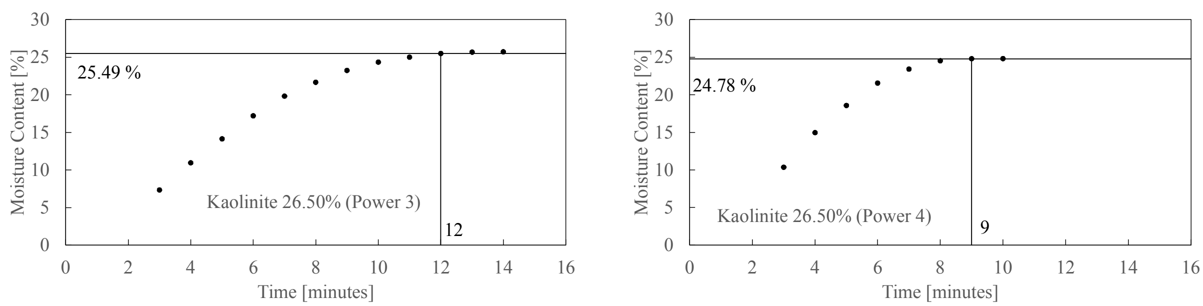
(a) (b)

Figure B.18. Compacted red clay microwave results at power 3 and 4. (a) Power 3 and 17.39% moisture content, (b) power 4 and 17.39% moisture content.



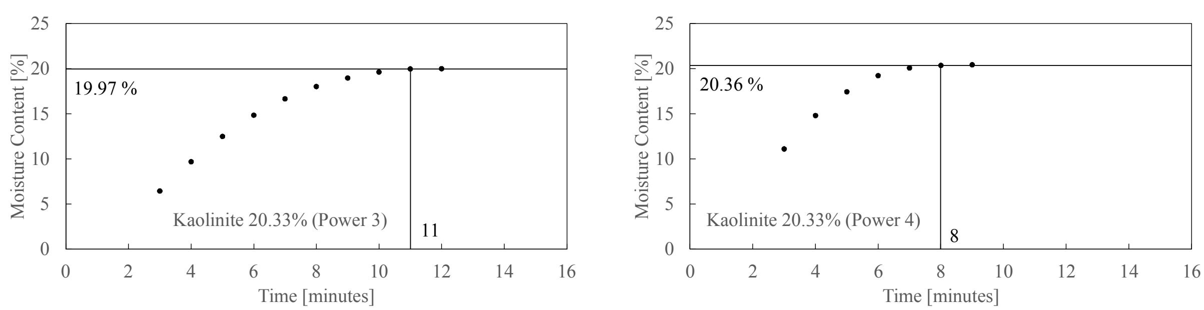
(a) (b)

Figure B.19. Compacted red clay microwave results at power 3 and 4. (a) Power 3 and 20.14% moisture content, (b) power 4 and 20.14% moisture content.



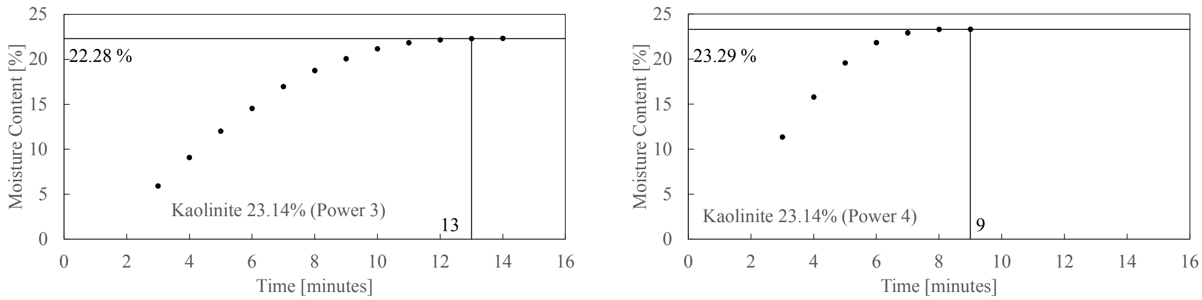
(a) (b)

Figure B.20. Compacted kaolinite microwave results at power 3 and 4. (a) Power 3 and 26.5% moisture content, (b) power 4 and 26.5% moisture content.



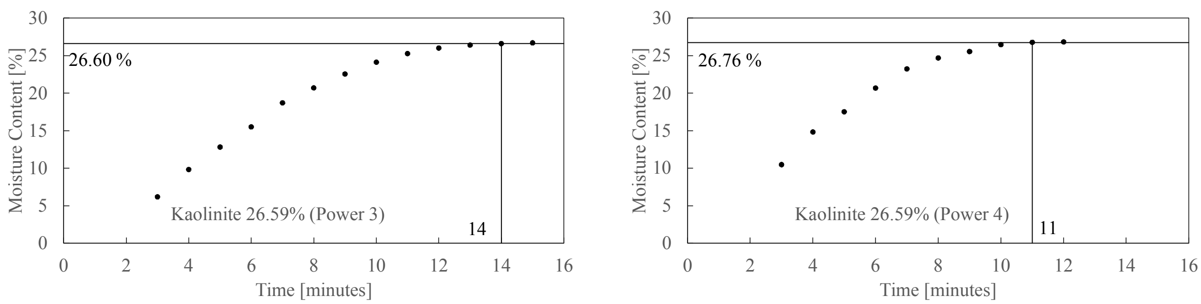
(a) (b)

Figure B.21. Compacted kaolinite microwave results at power 3 and 4. (a) Power 3 and 20.33% moisture content, (b) power 4 and 20.33% moisture content.



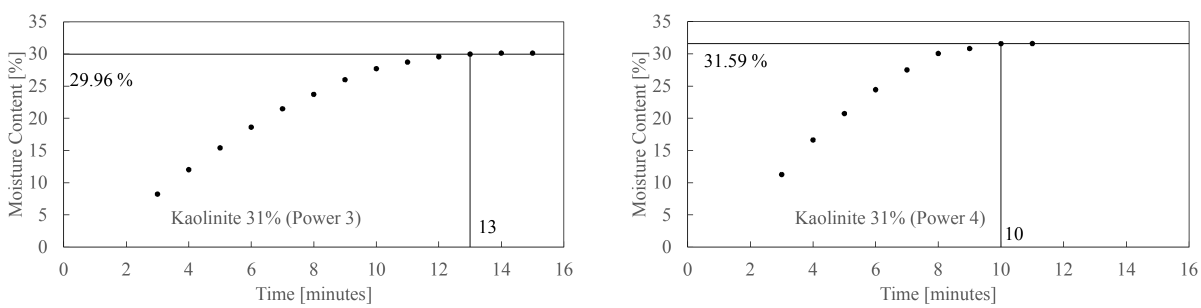
(a) (b)

Figure B.22. Compacted kaolinite microwave results at power 3 and 4. (a) Power 3 and 23.14% moisture content, (b) power 4 and 23.14% moisture content.



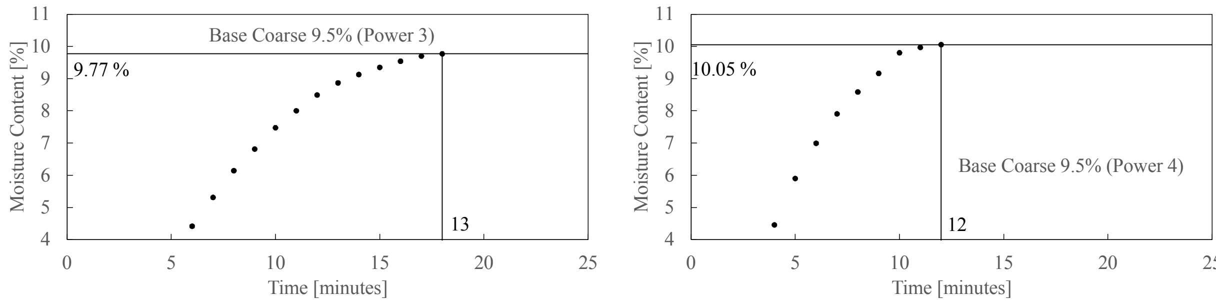
(a) (b)

Figure B.23. Compacted kaolinite microwave results at power 3 and 4. (a) Power 3 and 26.59% moisture content, (b) power 4 and 26.59% moisture content.



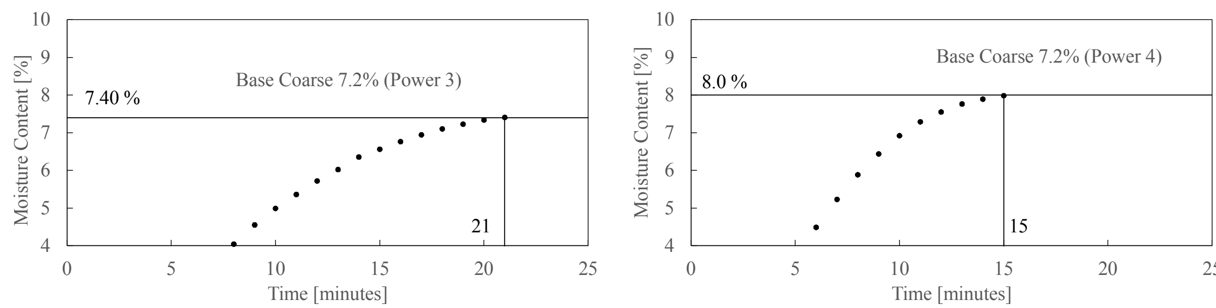
(a) (b)

Figure B.24. Compacted kaolinite microwave results at power 3 and 4. (a) Power 3 and 31% moisture content, (b) power 4 and 31% moisture content.



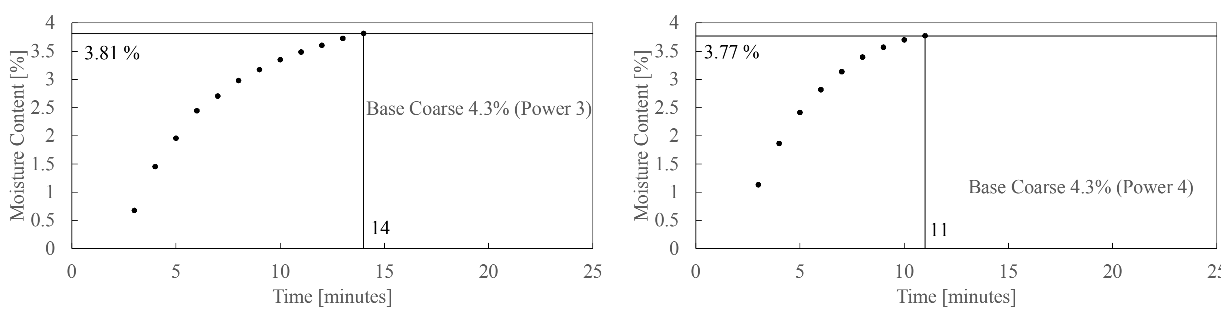
(a) (b)

Figure B.25. Compacted base coarse microwave results at power 3 and 4. (a) Power 3 and 9.5% moisture content, (b) power 4 and 9.5% moisture content.



(a) (b)

Figure B.26. Compacted base coarse microwave results at power 3 and 4. (a) Power 3 and 7.2% moisture content, (b) power 4 and 7.2% moisture content.



(a) (b)

Figure B.27. Compacted base coarse microwave results at power 3 and 4. (a) Power 3 and 4.3% moisture content, (b) power 4 and 4.3% moisture content.

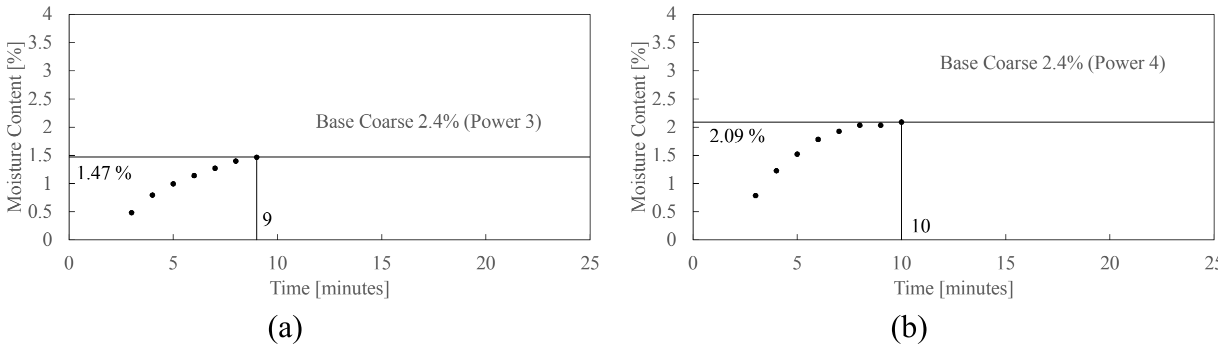


Figure B.28. Compacted base coarse microwave results at power 3 and 4. (a) Power 3 and 2.4% moisture content, (b) power 4 and 2.4% moisture content.

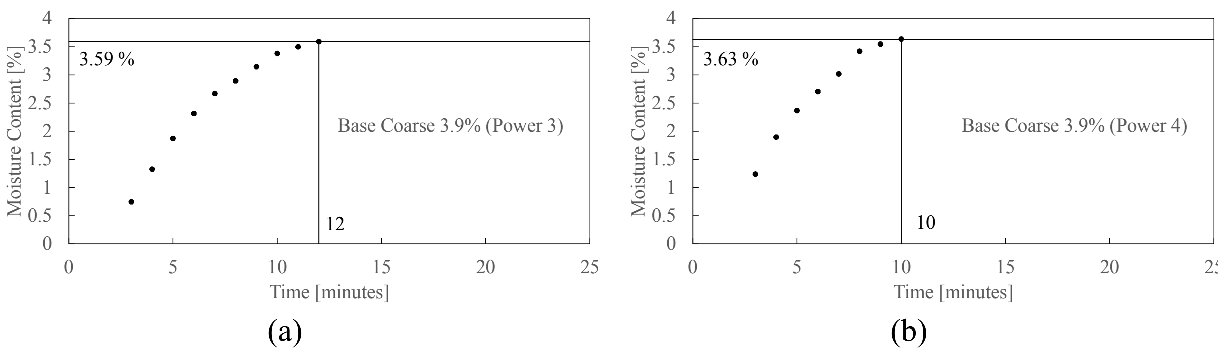


Figure B.29. Compacted base coarse microwave results at power 3 and 4. (a) Power 3 and 3.9% moisture content, (b) power 4 and 3.9% moisture content.

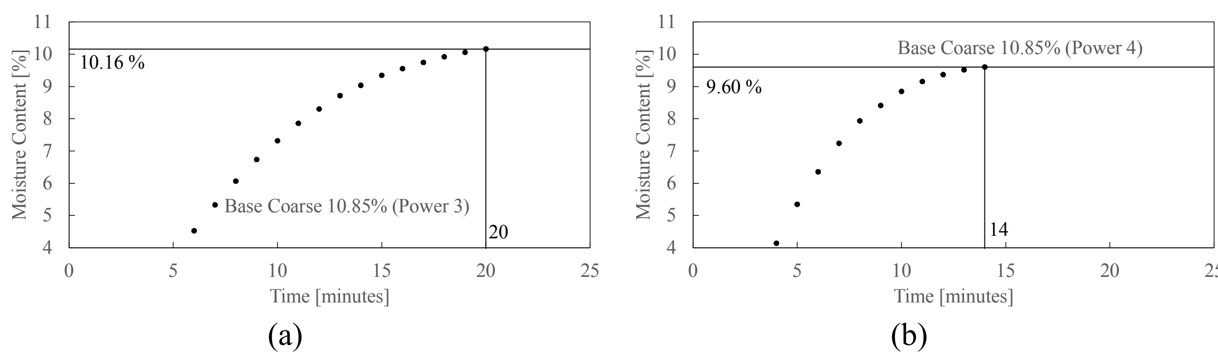


Figure B.30. Compacted base coarse microwave results at power 3 and 4. (a) Power 3 and 10.85% moisture content, (b) power 4 and 10.85% moisture content.

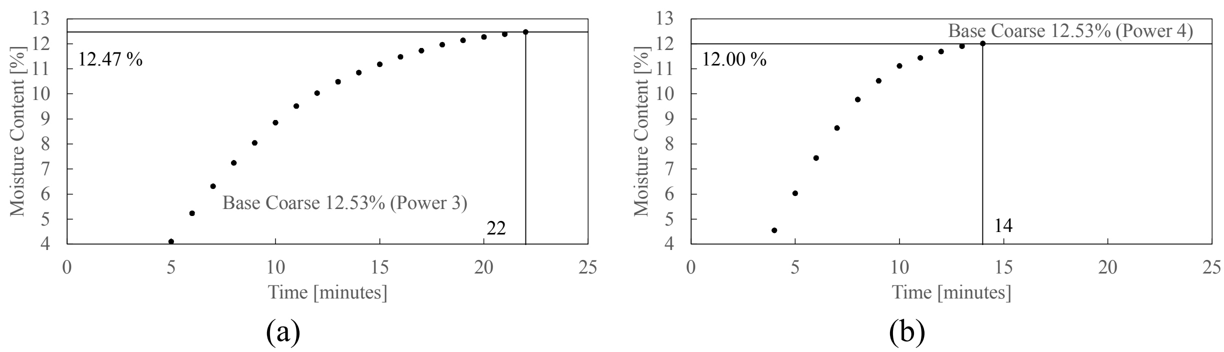


Figure B.31. Compacted base coarse microwave results at power 3 and 4. (a) Power 3 and 12.53% moisture content, (b) power 4 and 12.53% moisture content.

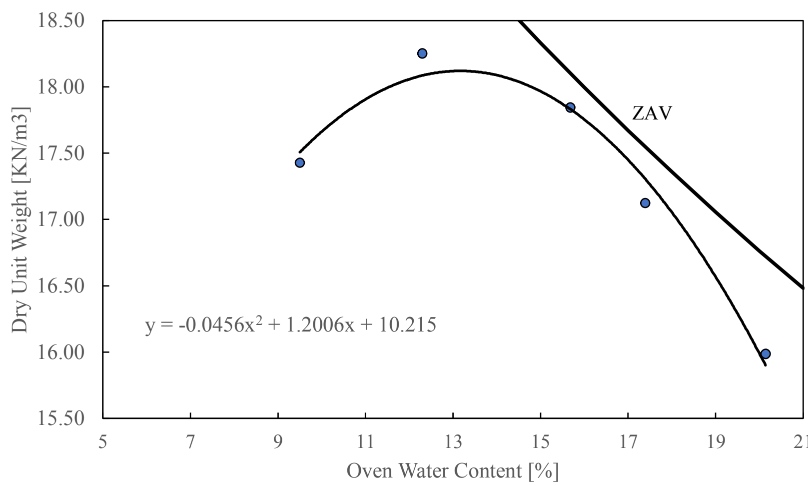


Figure B.32. Red clay oven method compaction curve.

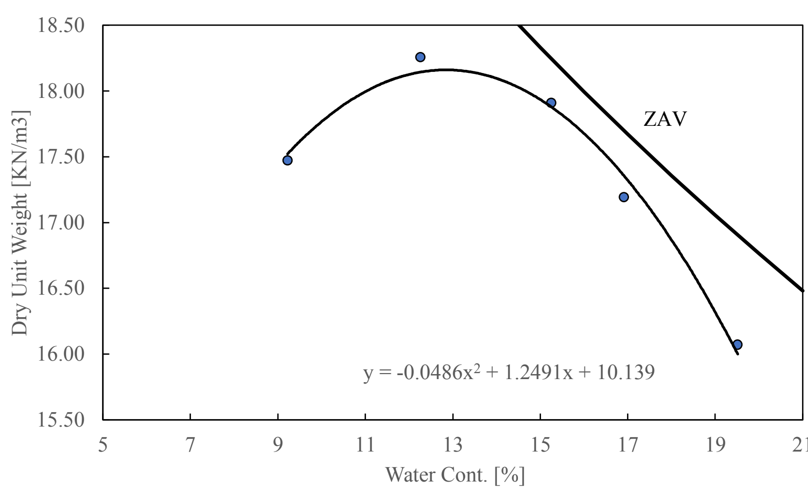


Figure B.33. Red clay microwave method power 3 compaction curve.

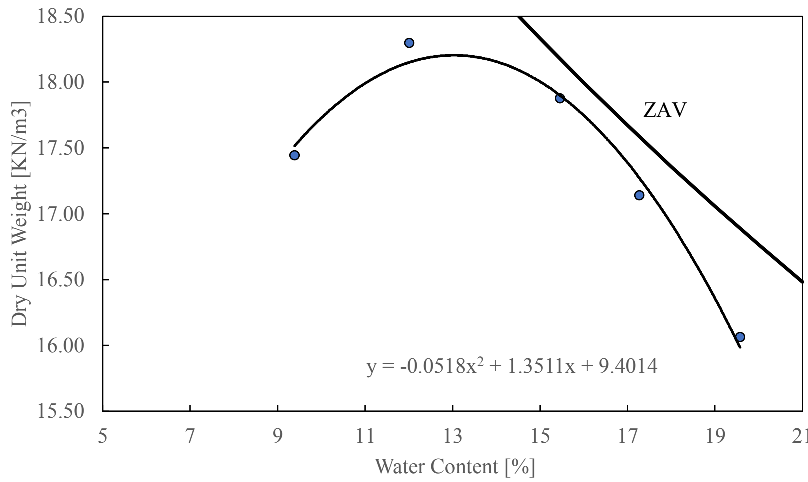


Figure B.34. Red clay microwave method power 4 compaction curve.

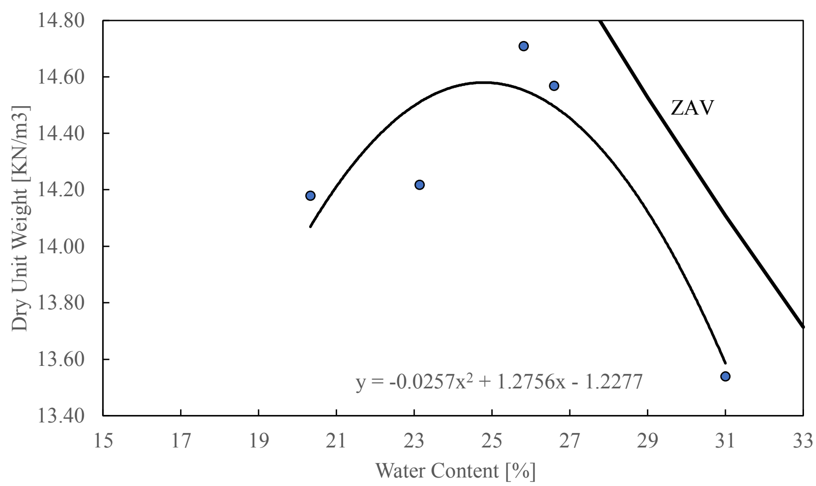


Figure B.35. Kaolinite oven method compaction curve.

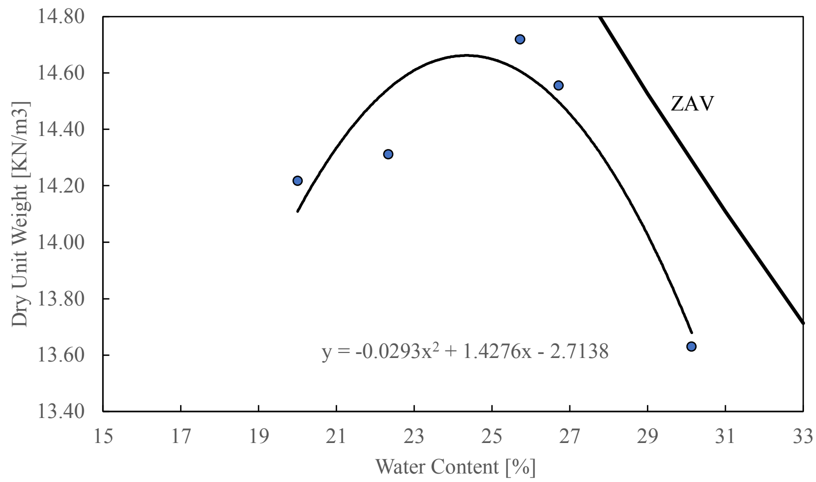


Figure B.36. Kaolinite microwave method at power 3 compaction curve.

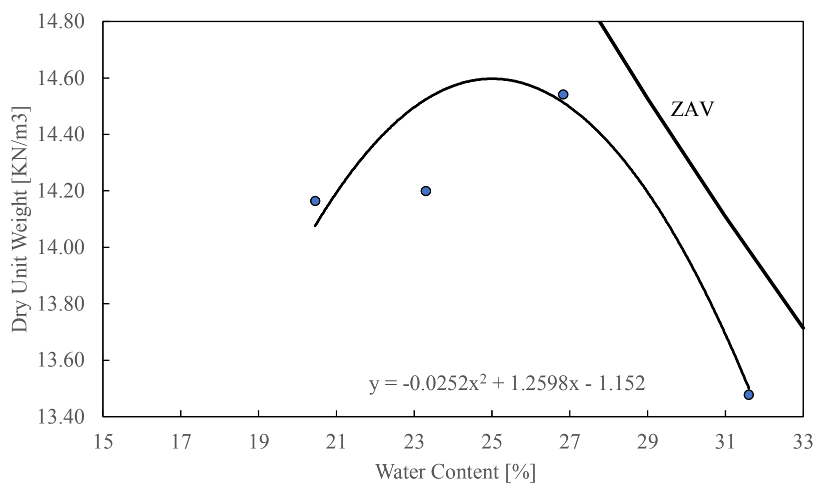


Figure B.37. Kaolinite microwave method at power 4 compaction curve.

B.3. HydroMix HM-08 Output "V" and Output "E"

The figures presented in this chapter are the same soils used in output "F" of the HydroMix Hydro-Com software. However, the alternative outputs "V" and "E" were recorded:

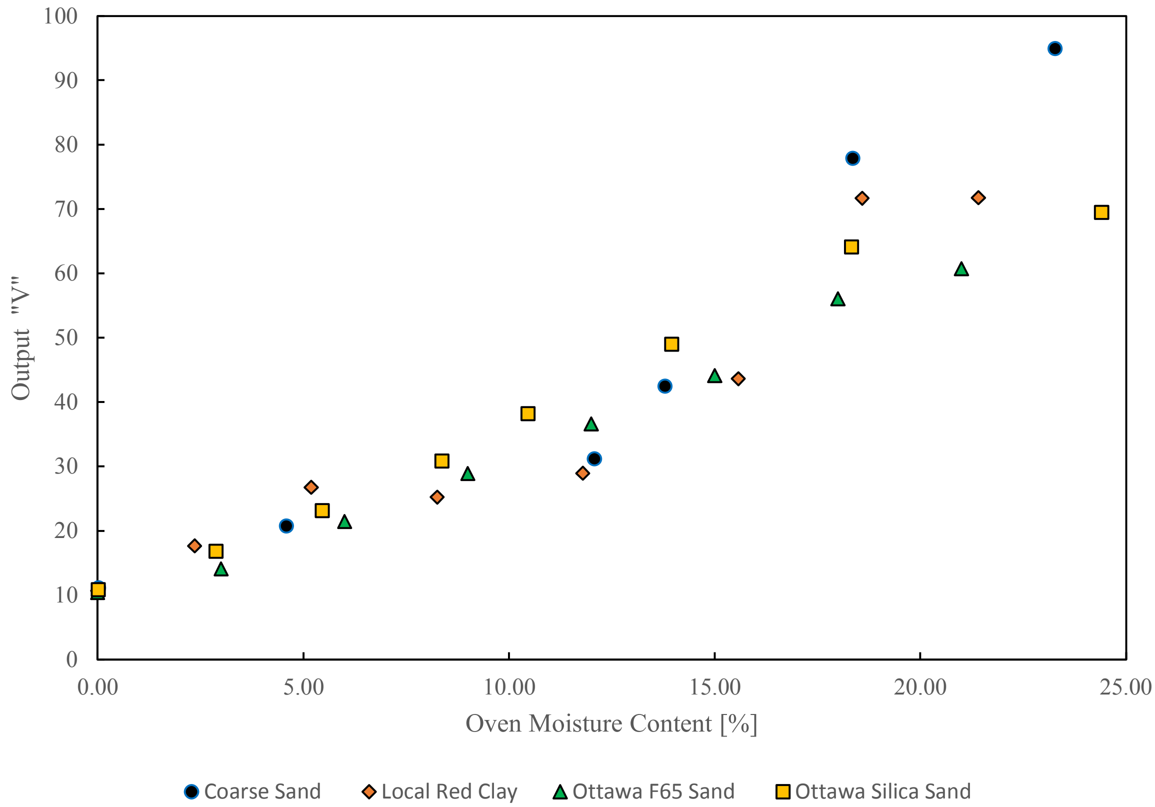


Figure B.38. HydroMix testing using output "V".

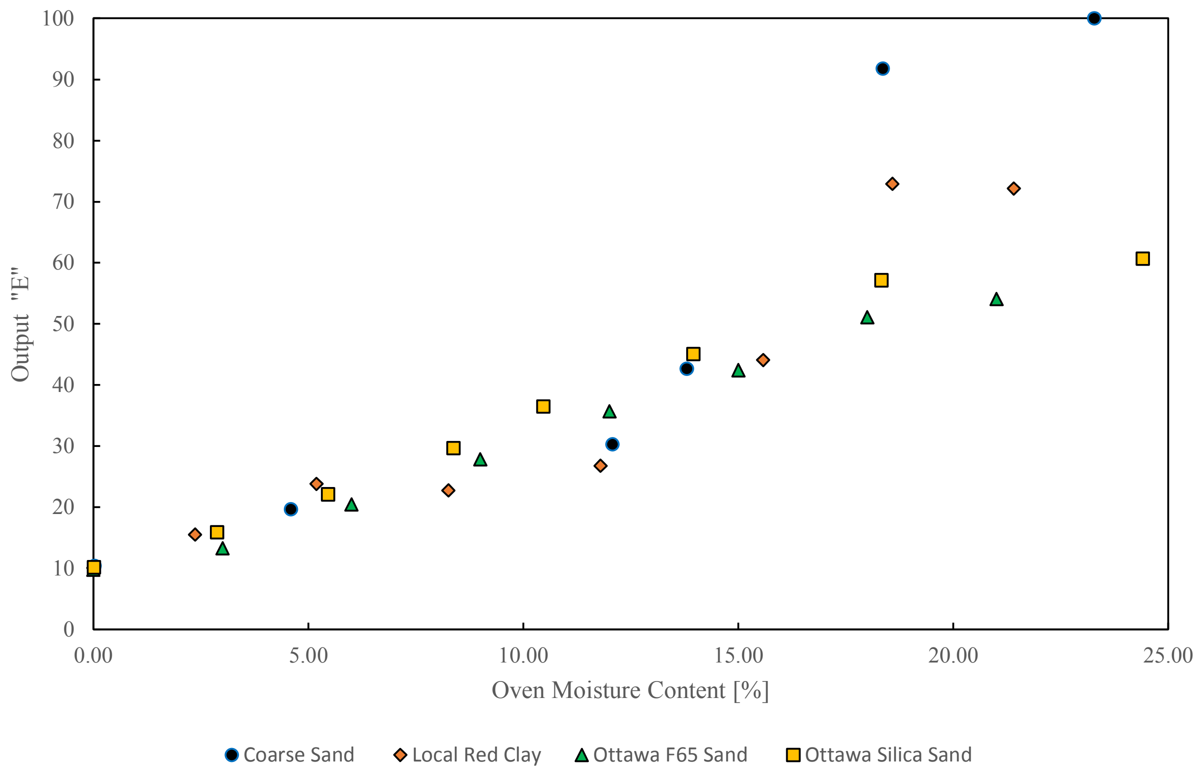


Figure B.39. HydroMix testing using output “E”.

B.4. HydroMix Compacted Sample Testing Using Different Methods

The figure presented in this section displays the linear relationships for different parts of the compacted sample.

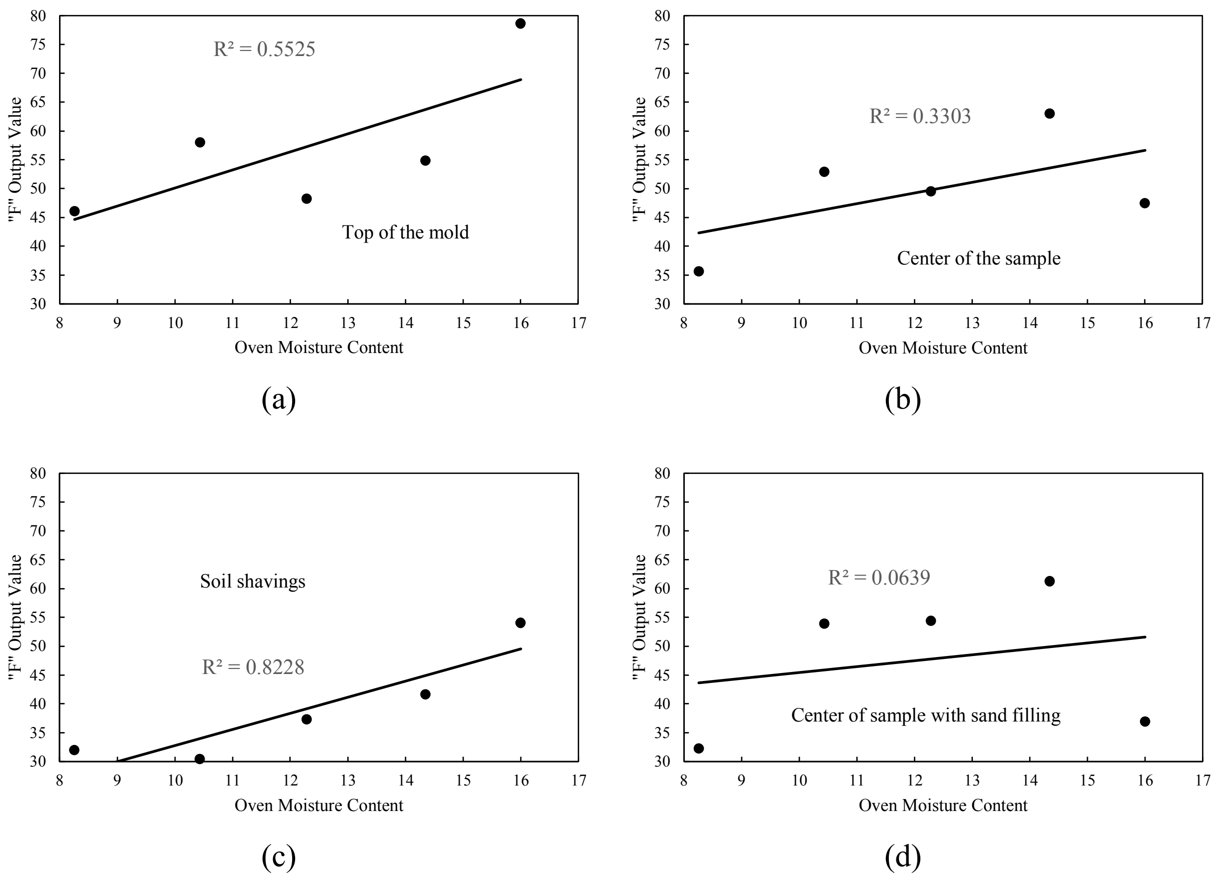


Figure B.40. HydroMix compacted sample measurements at (a) the top of the mold (b) center of the sample (c) soil shavings obtained from the center of the sample (d) sample center filled with silica sand.