POTENTIAL IMPACTS OF SOIL AGING ON TDR CALIBRATIONS OF BIOCHAR AMENDED URBAN AND COASTAL SOILS

by

Ryan McCune

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Honors Degree in Environmental Engineering with Distinction

Spring 2022

POTENTIAL IMPACTS OF SOIL AGING

ON TDR CALIBRATIONS OF BIOCHAR AMENDED

URBAN AND COASTAL SOILS

by

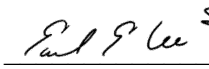
Ryan McCune

Approved: 

Paul T. Imhoff, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: 

Jules Bruck, Ph.D.
Committee member from the Department of Department Name

Approved: 

Earl Lee II, Ph.D.
Committee member from the Board of Senior Thesis Readers

Approved: _____

Michael Chajes, Ph.D.
Dean, University Honors Program

ACKNOWLEDGEMENTS

I would like to offer my sincere gratitude to my advisors, Dr. Jules Bruck and Dr. Paul T. Imhoff. It was a wonderful opportunity to be able to join Dr. Imhoff's research group to gain experience as an undergraduate researcher. As a member of this group, I was able to develop my skills and the space provided a catalyst for my passions in research to grow. My work with Dr. Bruck and the Coastal Resilience Design Studio at the University of Delaware was a fundamental experience in my undergraduate career. The interdisciplinary experience and coastal focus inspired my future goals and was a deeply enriching supplement to my academic pursuits.

I would also like to offer my thanks to my mentors within the Department of Civil & Environmental Engineering at the University of Delaware. Dr. Jack Puleo, Dr. Daniel Cha, Dr. Allen Jayne, Dr. Jennie Saxe, and Dr. Earl Lee were excellent instructors, but also went above and beyond to offer advice and a warm presence within the Department.

Finally, I wish to thank my family and friends for all of their support. My success would not be possible without the consistent support from my loved ones and for their generosity and kindness I am forever grateful.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Biochar, biomass pyrolyzed at high temperatures in low oxygen environments, is added to soils to improve physiochemical properties including stormwater runoff reduction, saturated hydraulic conductivity , and plant growth. The measure of these physiochemical properties is related to the amended soil's volumetric water content. Time domain reflectometry is a quick and cost-effective method of measuring volumetric water content of soils. However, this method requires calibration for use in biochar-amended soils.

This study determined calibration curves for soil samples from six field sites from Maryland and Delaware. The actual biochar content within these samples was also measured. These results were then analyzed to investigate the potential impacts of the aging of biochar on the resulting TDR calibration curve.

TDR calibration curves were found to definitively vary with measured biochar content. Higher mass percentages of biochar generally resulted in higher measured TDR periods. Biochar contents of field samples were also found to vary significantly from the assumed biochar contents by mass. It is suggested by the results from two field sites that aging of biochar samples in the field may impact the TDR calibration results.

Chapter 1

INTRODUCTION

1.1 Overview

Biochar is a material that results from biomass pyrolysis at high temperatures in an oxygen-depleted environment. This material has many unique properties compared to other organic matter, including a high proportion of fused aromatic rings (Lehmann et al., 2011). Biochar has a low particle density, high internal porosity, and significantly improves soil hydraulic properties when used as a soil amendment (Landers, 2018).

Time domain reflectometry (TDR) measures soil water content using the relationship between soil water content and dielectric constant (Ju et al., 2010). This method for the determination of porous water content and electrical conductivity is advantageous over traditional volumetric water content determinations due to its high accuracy and simplicity (Jones et al., 2002). The instrumentation infers water content using empirical and dielectric mixing models that relate dielectric permittivity to water content (Jones et al., 2002). TDR can determine the electrical conductivity from the signal attenuation through the medium. Although TDR has many advantages, certain soils reduce the accuracy of TDR measurements. For example, organic matter, such as biochar, and clays bind significantly large amounts of water. This creates larger signal attenuation, therefore reducing the measured bulk dielectric constant. Cases such as these require individual calibration (Jones et al., 2002).

1.2 Objectives

This study aims to quantify the amount of biochar contained within several soil types, create a TDR calibration curve for each soil, and compares these varying soils to determine if curve variation exists due to the aging of the sample. Investigating this potential dependency will allow us to gain a better understanding of the effect of biochar applications over time, and whether these effects have the potential to degrade.

The first objective of this study is to quantify the mass percentage of biochar within each sample to understand biochar consistency throughout the field site and to compare this true biomass percentage when analyzing samples for further objectives. The second objective is to create a TDR calibration curve comparing the recorded period and volumetric content of each sample over time. The results of these objectives paired with the site information for each sample will allow for further investigation of the relationships between various soil samples.

1.3 Site Descriptions

This study reviews information collected from six different field sites containing separate plots of biochar-amended soils. These sites will be referred to as Church site, Slack site, Site 1, Site 2, Exit Ramp site, and Toll Plaza site. Each of the field sites are currently the focus of other research efforts to understand the impact of biochar-amendment on saturated hydraulic conductivity, soil aggregation properties, stormwater runoff reduction, plant growth, and other physiochemical properties.

This study also includes a brief description of a recent biochar amendment to soils in the Angola by the Bay community near Rehoboth Beach, DE (Figure 1.1).

This site was amended with the same biochar as all other listed sites and will serve as a comparison site for the future.

Figure 1.1: Google Earth satellite imagery of the Angola by the Bay site location.

The Church site and Slack site are located in Ellicott City, Maryland (Figures 1.2 and 1.3, respectively). The Church site is adjacent to the parking lot of St. Peters Episcopal Church (39°26'N 76°80'W). The Slack site is adjacent to Slack Funeral Home's parking lot (39°27'N 76°81'W). Sites 1 and 2 (Figures 1.4 and 1.5) are both located in Delaware with Site 1 along the Route 299 exit of Route 301 (39°26'N 75°45'W) and Site 2 near the Bunker Hill Road overpass of Route 301 (39°27'N 75°44'W). The Exit Ramp site (Figure 1.6) is in Cecil County, Maryland, along the exit ramp of Interstate I-95 southbound toward MD 279 northbound (39°64'N 75°80'W). The Toll Plaza site (Figure 1.7) is along I-95 northbound adjacent to the Tydings Bridge Toll Plaza (39°59'N 76°07'W).

Figure 1.2: Google Earth satellite imagery of the Church site location.

Figure 1.3: Google Earth satellite imagery of the Slack site location.

Figure 1.4: Google Earth satellite imagery of the Site 1 location.

Figure 1.5: Google Earth satellite imagery of the Site 2 location.

Figure 1.6: Google Earth satellite imagery of the Exit Ramp site.

Figure 1.7: Google Earth satellite imagery of the Toll Plaza site.

All sites were amended using a commercial Rogue Biochar™ produced by Oregon Biochar Solutions in White City, Oregon. This biochar was created using tops and limbs from Douglas fir and Ponderosa pine trees which were pyrolyzed at 950°C at a high heating rate. The physiochemical properties of this biochar are present in Appendix A.

All sites were designed as long treatment strips which were segmented to contain different mass percentages of biochar treatment. The Church site, Slack site, Site 1 and Site 2 all contained a 0% tilled section as well as a tilled section containing approximately 4% biochar by mass. The Toll Plaza and Exit Ramp sites contained 0%, 2% and 4% biochar segments. The soil properties for these sites are presented in Appendix B.

Chapter 2

METHODS

2.1 Loss on Ignition Testing

Although biochar was added in the field to reach the appropriate percentage by mass, it is very difficult to evenly disperse the biochar throughout the medium. Therefore, two temperature loss on ignition (LOI) testing was conducted on soil samples from each site to accurately determine their biochar content.

The two-temperature method is an inexpensive and simple method to determine biochar content in field soils (Nakhli et al., 2019). Using this method, the mass fraction of biochar is computed from the dry mass of the soil/biochar mixture after sequential heating to a low temperature (LH) and high temperature (HT) (Nakhli et al., 2019). This method does require the LOI profile for both the native soil and the biochar representative of that in the field (Nakhli et al., 2019). It was determined that using the same LT and HT for all site soils would be appropriate because of similar burn characteristics of the native soils and the fact that all sites used the same biochar.

For each soil, three replicates were oven dried at 110℃ for 24 hours. Sample masses ranged from approximately 14.7 to 24 grams. These samples were then weighed and heated to a higher temperature value of 200℃ (LT) for 24 hours. Before weighing, samples were placed in a desiccator until they reached room temperature. Samples were then heated to a higher temperature value of 400℃ (HT). Final masses were recorded, and biochar content could then be determined.

2.2 TDR Instrumentation

All TDR calibration curves were constructed using measured values obtained with a Fieldscout TDR 150 from Spectrum Technologies, Inc. Although the name

"TDR 150" suggests that it purely uses time domain reflectometry as the method of water content determination, this is a misnomer (Kim et al., 2020). This device is a water content reflectometer (WCR) which relates a period average to a quadratic expression to determine soil water content (Kim et al., 2020). Both WCR and TDR relate soil dielectric properties to volumetric water content. However, WCR uses lower frequencies (typically 15-45 MHz) whereas TDR uses much higher frequencies–up to 1 GHz (Chandler et al., 2004). WCR calibration is more sensitive to soil property variations because these properties have a greater effect on dielectric properties at lower frequencies (Chandler et al., 2004). In comparison to TDR instruments, this device is still highly accurate. As compared to five other field sensors, the Fieldscout TDR had the lowest error after site-specific correction (Kim et al., 2020).

The need for this correction to reduce error as determined by Kim et al. further reinforces the need for calibration. For this study, the three-inch stainless-steel soil probes were used. The sampling volume of this sensor is an elliptical cylinder which extends approximately 3 cm from the rods (Spectrum Technologies, Inc., 2018). The generated signal travels down the rods and back to return an average value across the distance of the rods (Spectrum Technologies, Inc., 2018).

2.3 TDR Calibration

The TDR calibration was conducted for roadway soils from Delaware and Maryland (Church, Slack, Exit Ramp, and Toll Plaza sites) both with and without biochar. The following methodology was developed by a graduate research assistant, Derya Akpinar.

2.3.1 Packing of Field Samples

Samples from the field were collected by first removing the top layer of vegetation and some topsoil in a circle approximately 30 cm in diameter. The soil was then removed to a depth of approximately 30 cm and placed in a five-gallon bucket which was sealed to prevent changes in water content. Cores were also taken from the site to determine the dry bulk density of the soil.

The TDR calibration began by adding enough water to loosen hard soil pieces and by separating all large natural materials (e.g. plant roots) and rocks from the soil. Samples near the approximate mass necessary for packing according to the measured bulk density were then placed in an oven at 105°C for at least 24 hours. These samples were then assumed to be at or nearly zero water content.

Multipurpose plastic buckets were purchased and adapted for use in sample packing. The bucket dimensions were 15.5 cm inner diameter and 15 cm height (approximate volume of 2.4 liters). Specific volumes for each bucket were determined by adding water to the bucket to the inner lip at a height of 13.5 cm. This amount of water was weighed and, using the temperature of the water to determine its density, a final volume was calculated and recorded for each bucket. Seven 10 mm diameter holes were drilled into the bottom of the bucket for future soil saturation and drainage and a nylon mesh was secured with adhesive over the bottom of the bucket.

Using the measured bucket volume and the soil's dry bulk density, the mass of dry soil needed to obtain the bulk density was then slowly added to the bucket. As the soil was incrementally added, it was compacted and wetted with a spray of DI water. This continued until the entire mass was compacted to reach the 13.5 cm height within the bucket. These packed samples were then set into larger vessels for saturation. DI

water was slowly added to each outer vessel over the course of several hours to fully saturate each sample from below.

Each sample was considered fully saturated when the water pooled above the soil surface. This method minimized air entrapment within each sample, but the potential for air contained within the sample is still present. After each sample was fully saturated, it was removed from the outer vessel and any pooling water above the soil surface was allowed to drain. The sample was then weighed, and the first TDR measurement was taken on "Period Mode" with the soil type "Standard". The TDR was inserted vertically into the center of the sample. The period, temperature, and electrical conductivity were recorded.

Samples were then placed in a hot room at 35°C to maintain constant and equal drying conditions. These samples were revisited every 12-24 hours and their mass and TDR measurements were recorded until the samples were determined to have a volumetric water content near zero.

2.3.2 Packing of Samples with Laboratory Biochar

For the Church and Slack sites, the process was repeated for an additional trial. For this additional trial, a mass of biochar was added to a dry sample of the native site soil to reach an exact dry mass percentage of 4%. This total mass was then packed following the procedure outlined above. This was done to simulate the assumed conditions in the field directly after installation of the biochar amendment and serves as a comparison for the aged samples. For this study, further reference of aged samples refers to biochar which was present within field soils whereas new or laboratory biochar refers to biochar which has never been exposed to natural soil processes. This biochar is stored with minimal interaction with the atmosphere and its

properties are assumed to remain constant over time. This same laboratory packing was also performed by Derya Akpinar and the results of these samples are further presented as the results for Site 1 and Site 2.

2.4 Angola by the Bay Soil Amendment

The Angola by the Bay site was chosen because it is currently the site of a living shoreline project managed by the Delaware Center for the Inland Bays. As part of this living shoreline project, there are several areas designated as “no mow” areas to become future wildflower meadows. One of these areas near Marina Drive has been subdivided and amended with biochar.

The selected area has a total length of 60 feet. This length has been separated into five sections, each 12 feet in length and five feet in width. The first plot, furthest to the west, is the first amended plot. The pattern of amendment is then alternating with the third and fifth plots also amended with biochar and the second and fourth serving as 0% biochar sections.

Each section containing biochar was amended to 4% biochar by mass. The contractor amended the soil by lifting the bulk bag of biochar with a skid steer and cutting along the bag to release the material (Figure 2.1). The cut was placed based on height within the bag to release an approximate volume of biochar needed to reach 4% for each section. After release, this biochar was then mixed into the soil to a 30 cm depth by both tilling the soil (Figure 2.2) and using the skid steer’s blade to knead the biochar into the native soil. Several test holes were dug to determine the depth of biochar amendment and the material seemed to reach the requested 30 cm.

Figure 2.1: Release of biochar into soil section for amendment to approximately 4% by mass.

Figure 2.2: Biochar and soil section being tilled by contractor.

The five plots were finally covered in rye grass seeds and straw for the winter. These plots will be tilled and replanted in the late spring of 2022 for the desired wildflower meadow mixture.

Chapter 3

RESULTS

3.1 Loss on Ignition

Results of two-temperature LOI testing are presented in Table 3.1. Although significant masses were used to minimize error, the measured biochar percentages varied significantly from the approximate amounts assumed to be homogeneous throughout the field samples. The smallest observed difference was a measured mass percentage of 3.29% for the Church site. This is an approximate difference of 17.75% lower than the expected value of 4% by mass. The largest difference was the Toll Plaza site with a value of 4.32% rather than 2%, an increase of 116%.

Table 3.1: Tabulated two-temperature loss on ignition results. Approximate field mass percentage of biochar is provided with the actual measured LOI result and the relative error between the two.

	Mass Percentage		
	Approximate (%)	Measured (%)	Relative Error (%)
Sample Site:			
Church	4	3.29	17.8
Slack	4	2.48	38.0
Exit Ramp	2	4.13	106.5
	4	7.95	98.8
Toll Plaza	2	4.32	116.0
	4	5.46	36.5

3.2 TDR Calibration

The measured results for all sites revealed nonlinear behavior for soils containing biochar at low water contents. Native soils displayed linear behavior throughout the entire trial.

The calibration curves of volumetric water content versus measured period for Site 1 and Site 2 are provided in Figure 3.1 and Figure 3.2, respectively. These are the result of soil packing and lab measurements performed by Derya Akpinar. These samples were ideal packings using fresh biochar and a sample of the native soil as described for the additional trials of the Church and Slack sites. These curves show a definite distinction of each percentage of biochar, mainly altering the intercept values rather than the regression slopes. A summary table of regression slopes and intercepts for all curves is provided in Appendix C.

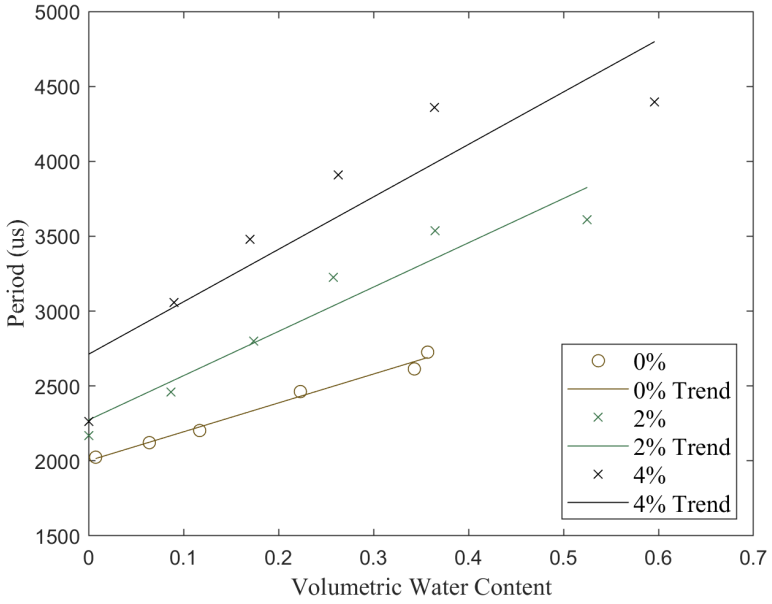


Figure 3.1: TDR calibration curves for Site 1 at 0%, 2%, and 4% biochar by mass. Green and black crosses denote recorded measurements for 2% and 4% amendments, respectively. Brown circles indicate measurements for the native soil.

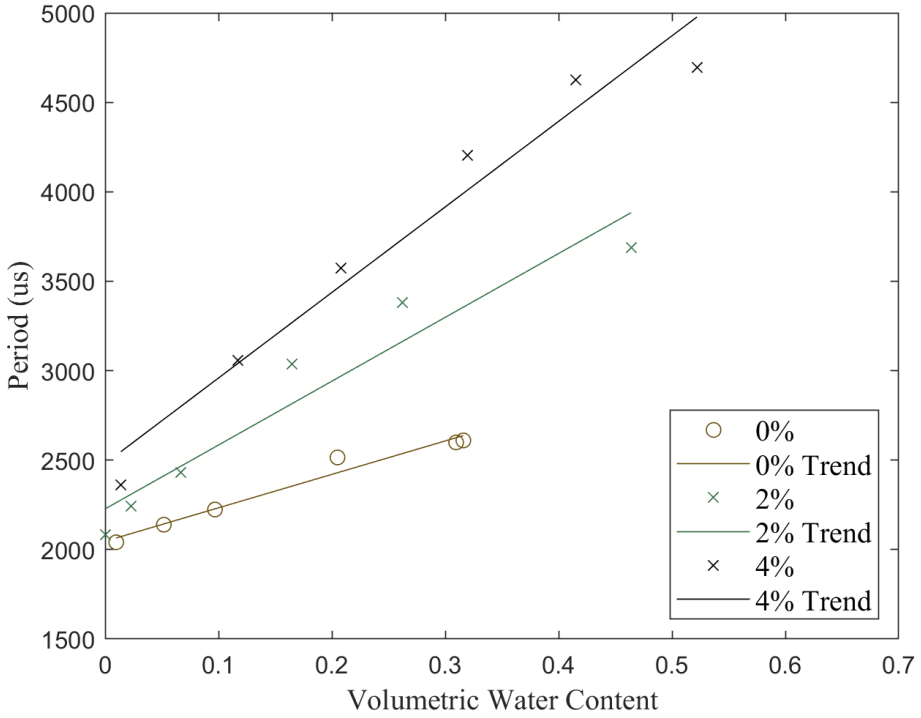


Figure 3.2: TDR calibration curves for Site 2 at 0%, 2%, and 4% biochar by mass. Green and black crosses denote recorded measurements for 2% and 4% amendments, respectively. Brown circles indicate measurements for the native soil.

Similar to the calibration results of Site 1 and Site 2, the Exit Ramp (Figure 3.3) site shows distinct differences between the produced curves. However, the Toll Plaza (Figure 3.4) site does not. There is a very noticeable overlap of the lines corresponding to 2% and 4% biochar by mass. Interestingly, the line for the sample assumed to be containing 2% biochar has a steeper slope value than the 4% sample and falls above the 4% line for the majority of observed water contents.

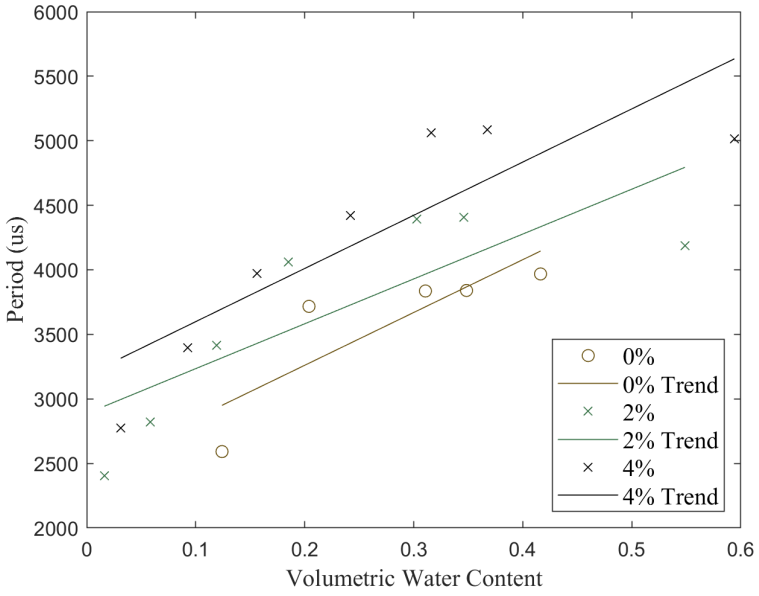


Figure 3.3: TDR calibration curves for Exit Ramp site at 0%, 2% (4.13% actual), and 4% (7.95% actual) biochar by mass. Green and black crosses denote recorded measurements for 2% and 4% amendments, respectively. Brown circles indicate measurements for the native soil.

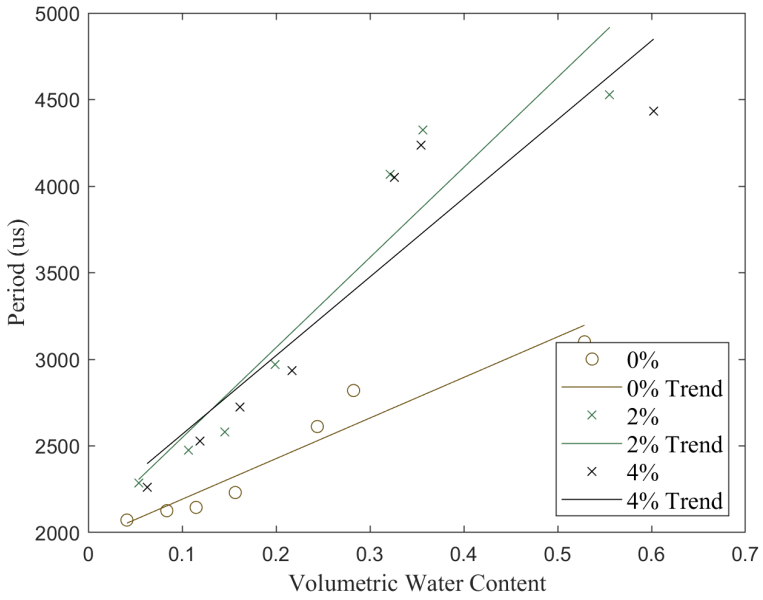


Figure 3.4: TDR calibration curves for Toll Plaza site at 0%, 2% (4.32% actual), and 4% (5.46% actual) biochar by mass. Green and black crosses denote recorded measurements for 2% and 4% amendments, respectively. Brown circles indicate measurements for the native soil.

The Church and Slack sites were the oldest sites studied having been amended with biochar several years ago. Interestingly, they also provided the least distinction between the native soil and the soil amended with biochar. In all other results, the greatest distinction was between the regression line for the 4% biochar and the native soil. However, the intercepts for the 4% biochar and native soil in these cases were relatively similar. As shown in Figure 3.5 (a) and (b), there was a large difference observed between the results for the aged biochar-amended soils from the field and the soils which were packed with fresh biochar in the laboratory for the Church site. This same result for the Slack site is shown in Figure 3.6 (a) and (b).

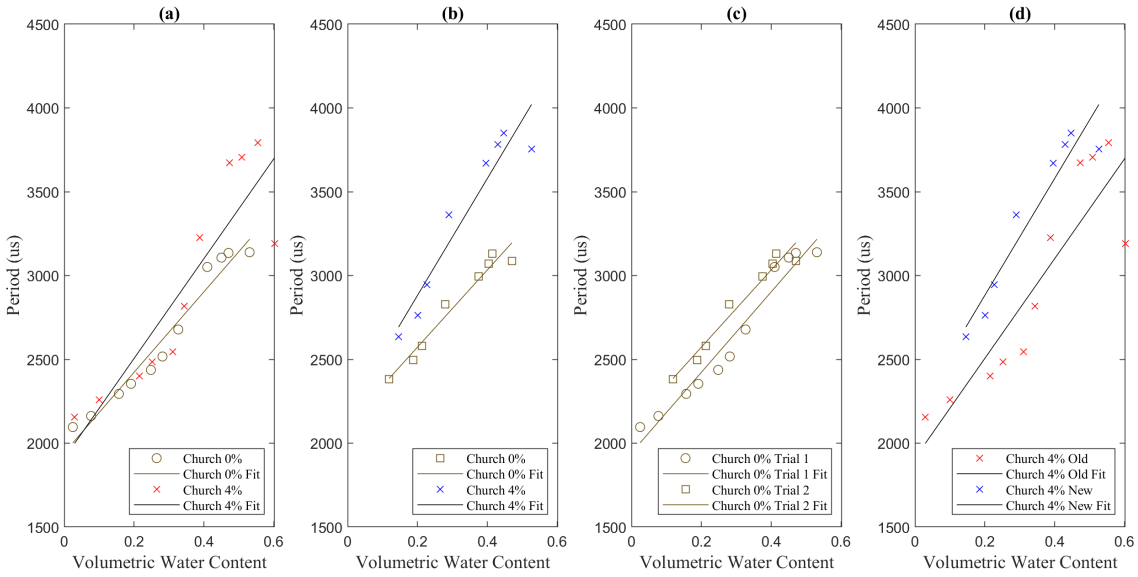


Figure 3.5: Red and blue crosses denote measurements for old and fresh biochar, respectively. Brown circles and squares mark measurements for native soil. (**a**) TDR calibration curves for the Church site comparing the native (0%) soil and biochar amended (4%, 3.29% actual) soil. (**b**) TDR calibration curves for the Church site comparing the native (0%) soil to laboratory-packed amended soils containing 4% biochar by mass. (**c**) TDR calibration curves for only the repeat trials of the 0% biochar soil. (**d**) TDR calibration curves for only the repeat trials of the 4% biochar soil.

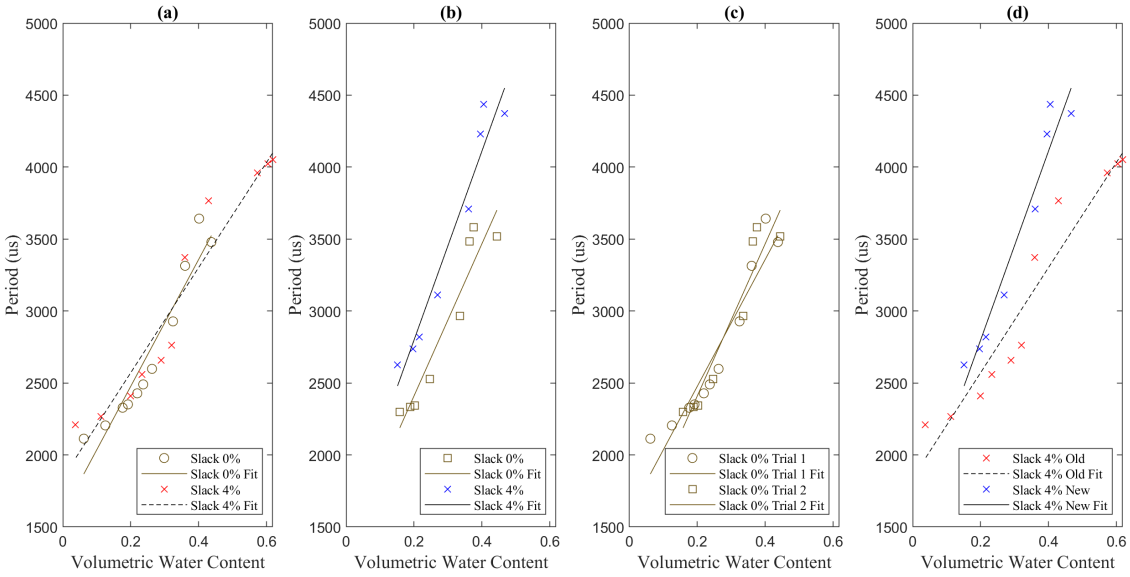


Figure 3.6: Red and blue crosses denote measurements for old and fresh biochar, respectively. Brown circles and squares mark measurements for native soil. (**a**) TDR calibration curves for the Slack site comparing the native (0%) soil and biochar amended (4%, 2.48% actual) soil. (**b**) TDR calibration curves for the Slack site comparing the native (0%) soil to laboratory-packed amended soils containing 4% biochar by mass. (**c**) TDR calibration curves for only the repeat trials of the 0% biochar soil. (**d**) TDR calibration curves for only the repeat trials of the 4% biochar soil.

3.3 Angola by the Bay Site Installation

The Angola by the Bay site was visited on March 18th and one sample was taken from the first site plot. It appeared that vegetation growth was thicker in areas amended with biochar. There were no observed issues with the site and this site will continue to be monitored in the future.

Chapter 4

DISCUSSION

4.1 LOI Results

Considering the LOI results for each site, it is important to consider potential factors which may have resulted in biochar mass percentages so much higher than those assumed to be present in the field. Laboratory error is certainly a potential source of these unexpected data. However, the ignited mass was within the ranges specified by Nakhli et al. (2019) to minimize error. It may also be important to consider the movement of biochar temporally and spatially in the field. It is known that biochar may be lost in the field over time and that it can move vertically and horizontally in soil (Nakhli et al., 2019). It is possible that the biochar may have become more or less concentrated throughout the area of the field installation, therefore impacting biochar content results from the single sampling location.

Interestingly, the LOI results for the Exit Ramp were nearly twice as much as anticipated for both the 2% and 4% sections. This could suggest incomplete mixing in the field or the accidental addition of a higher mass of biochar. Additionally, the TDR curves for the Exit Ramp showed a similar distribution in slope and intercept between the 2% and 4% lines (which were more truly 4% and 8% lines) as compared to the 2% and 4% lines observed for the Site 1 and Site 2 soil samples packed in the laboratory. This could potentially suggest a predictable relationship between mass percentage and the TDR calibration curve.

4.2 TDR Calibration Results

Visual inspection of the TDR curves for the Church and Slack sites shows seemingly significant differences between the soils which were exposed to natural

field conditions versus those which were packed in the laboratory. Figure 4.1 and Figure 4.2 display all testing results of the Church and Slack sites, respectively.

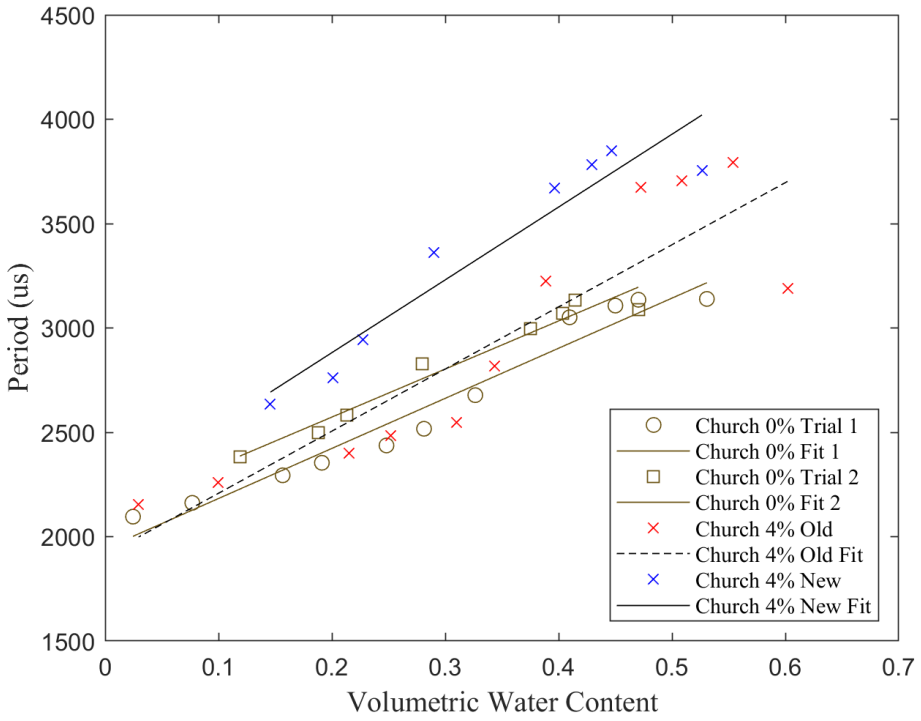


Figure 4.1: TDR calibration curves representing all four samples (Trials 1 and 2 of the native soil, 4% (3.29% actual) biochar by mass from the field, and "new" 4% biochar by mass) for the Church site. Red and blue crosses denote measurements for old and fresh biochar, respectively. Brown circles and squares mark measurements for native soil.

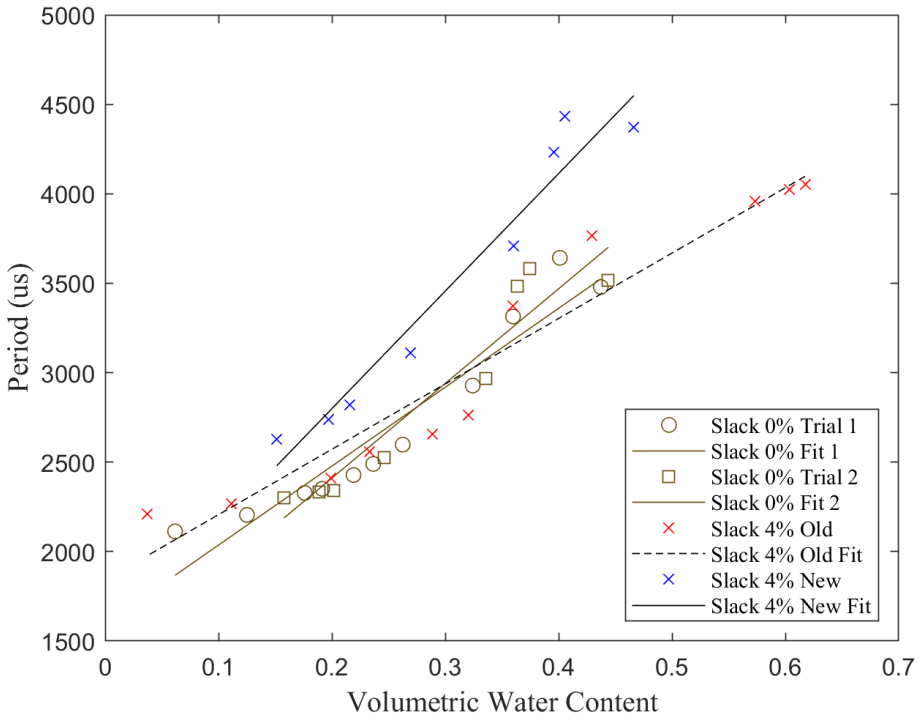


Figure 4.2: TDR calibration curves representing all four samples (Trials 1 and 2 of the native soil, 4% (2.48% actual) biochar by mass from the field, and "new" 4% biochar by mass) for the Slack site. Red and blue crosses denote measurements for old and fresh biochar, respectively. Brown circles and squares mark measurements for native soil.

For both sites, data for native soils are similar in both slope and intercept. The consistency in these results further reinforce the potential interest in the observed difference between new and aged biochar in the 4% by mass samples. However, it is also important to consider other factors which may be impacting these curves.

The main consideration for potential error in comparing these curves is the fact that the LOI testing for the aged sample did not result in a biochar mass percentage of exactly 4%. Rather, as discussed previously, it was approximately 3.29% for the Church site and 2.48% for the Slack site. These correspond to errors of 17.75% and

38%, respectively. These amounts of biochar are significantly lower than their assumed values and could potentially be the source of the difference in these TDR curves. However, as better illustrated in Figure 4.3, the aged biochar still did not graphically appear to significantly differ from the native soil. This is in direct contrast to the laboratory packings of Site 1 and Site 2 which showed clear distinction even at only 2% biochar content. This behavior also contrasts that observed in the Exit Ramp and Toll Plaza sites which also showed more varied behavior as opposed to the native soil curve.

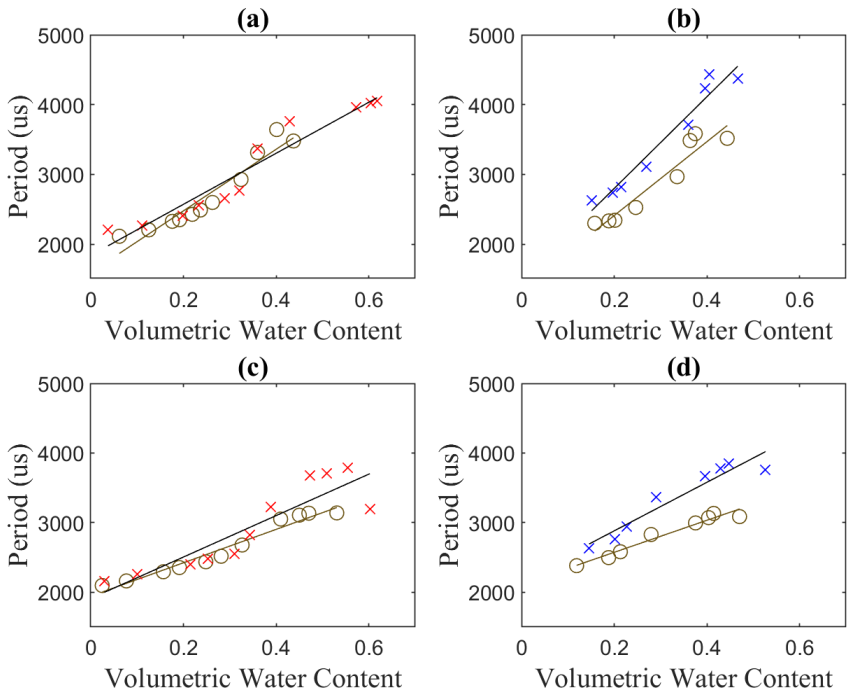


Figure 4.3: Red and blue crosses denote measurements for old and fresh biochar, respectively. Brown circles and squares mark measurements for native soil. (**a**) TDR curve for the Slack site including the native soil data in brown and aged biochar data in red. (**b**) TDR curve for the Slack site including the native soil data in brown and new biochar in blue. (**c**) TDR curve for the Church site including the native soil data in brown and aged biochar data in red. (**d**) TDR curve for the Church site including the native soil data in brown and new biochar in blue.

Chapter 5

CONCLUSIONS

A total of 16 soil samples from six different sites were used to develop time domain reflectometry calibration curves and to perform two-temperature loss on ignition testing. In performing these tests, it was illustrated both that the assumed field concentration of biochar in percent by mass is not accurate for these sites and that the TDR curves for most sites showed a distinct relationship between biochar content and increased TDR period readings.

The impact of biochar aging is suggested by the differing results of Church and Slack sites TDR curves comparing the amended soils from the field to those amended within the laboratory. This is further reinforced by further observed contrasts between these sites and the other four. The results of the TDR analysis of the Exit Ramp site in comparison to Site 1 and Site 2 may also suggest the ability to further develop a relationship between biochar percentage by mass and the expected TDR calibration.

Further work should quantify the significance of the observed differences between samples containing aged versus laboratory biochar. This work should also compare results of the other four field site calibrations to laboratory packings using new biochar. Finally, the relationship between biochar mass and TDR readings should be further explored to potentially develop a prediction model.

REFERENCES

Chandler, D. G., Seyfried, M., Murdock, M., & McNamara, J. P. (2004). Field calibration of water content reflectometers. *Soil Science Society of America Journal, 68*(5), 1501–1507. https://doi.org/10.2136/sssaj2004.1501

Jones, S. B., Wraith, J. M., & Or, D. (2002). Time domain reflectometry measurement principles and applications. *Hydrological Processes, 16*(1), 141–153. https://doi.org/10.1002/hyp.513

Ju, Z., Hu, C., Liu, X., & Ren, T. (2010). Measuring soil water content with time domain reflectometry: an improved calibration considering soil bulk density. *Soil Science, 175*(10), 469–473. https://doi.org/10.1097/SS.0b013e3181f55aa3

Kim, H., Cosh, M. H., Bindlish, R., & Lakshmi, V. (2020). Field evaluation of portable soil water content sensors in a sandy loam. *Vadose Zone Journal, 19*(1). https://doi.org/10.1002/vzj2.20033

Landers, J. (2018). Adding biochar to soils beside highways could reduce runoff, report says.(transportation research board of the national academies of sciences, engineering and medicine's report)(civil engineering news / stormwater). *Civil Engineering, 88*(1), 31–32.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota - a review. *Soil Biology and Biochemistry, 43*(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Nakhli, S. A. A., Panta, S., Brown, J. D., Tian, J., & Imhoff, P. T. (2019). Quantifying biochar content in a field soil with varying organic matter content using a two-temperature loss on ignition method. *Science of the Total Environment, 658*, 1106–1116. https://doi.org/10.1016/j.scitotenv.2018.12.174

Spectrum Technologies, Inc. (2018). *Fieldscout TDR 150: Product Manual*. Aurora, IL: Publisher.

Appendix A

PHYSIOCHEMICAL PROPERTIES OF ROGUE BIOCHAR™

Table A.1: Physiochemical properties of Rogue Biochar™ as measured by Sraboni Chowdhury for her Master's thesis. Presented values denote the mean (standard error of the mean) of duplicate measurements.

Parameter	**Rogue Biochar™**
Particle Size (% mass)	
Fine gravel	33.1 (1.3)
Sand	66.7 (1.2)
Silt	-
Clay	-
Particle Density (g/cm^3)	
Skeletal	0.98 (-)
Envelope	0.44 (-)
BET Surface Area (m^2/g)	553 (8)
Organic Matter (% mass)	88.8 (0.4)
Cation Exchange Capacity (meq/100 g)	54.6 (0.6)
Exchangeable Cations (meq/100 g)	
Ca	35.3 (0.1)
K	22.3 (0.1)
Mg	7.28 (0.01)
Na	11.18 (0.05)

Table A.1: *continued.*

Extractable Nutrient (mg/kg)		
	P	41.3 (0.5)
	K	1024 (14)
	Ca	749 (6)
	Mg	128.2 (1.9)
	Mn	29.9 (0.3)
	Fe	49.0 (0.7)
	S	32.7 (0.9)
	Na	280 (4)
	Al	53.6 (1.5)
pH		
	Initial	9.5 (0.03)
	Final 0%	-
	2%	-
	4%	-

Appendix B

PHYSIOCHEMICAL PROPERTIES OF SITE SOILS

Table B.1: Physiochemical properties of site soils as measured by Sraboni Chowdhury for her Master's thesis. Presented values denote the mean (standard error of the mean) of duplicate measurements.

Parameter	Church Site	Slack Site	Ramp Site	Plaza Site
Particle Size (% mass)				
Fine gravel	6.5 (0.1)	25 (10)	10.9 (0.5)	9.5 (0.8)
Sand	54 (3)	44 (6)	39.5 (1.3)	42 (3)
Silt	28.0 (1.8)	19 (5)	37.8 (1.5)	32 (2)
Clay	11.4 (0.9)	11 (5)	11.8 (0.4)	16.0 (0.3)
Particle Density (g/cm^3)				
Skeletal	2.63 (0.01)	2.66 (0.01)	2.71 (0.01)	2.64 (0.02)
Envelope	-	-	-	-
BET Surface Area (m^2/g)	3.35 (0.01)	3.20 (0.01)	5.72 (0.01)	9.94 (0.03)
Organic Matter (% mass)	3.13 (0.02)	5.54 (0.03)	3.32 (0.01)	6.76 (0.02)
Cation Exchange Capacity (meq/100 g)	13.5 (0.2)	18.2 (0.5)	8.3 (0.4)	13.1 (0.1)
Exhangeable Cations (meq/100 g)				
Ca	11.1 (0.3)	17.2 (0.1)	1.89 (0.07)	3.31 (0.08)
K	0.13 (-)	0.24 (-)	0.07 (-)	0.07 (-)
Mg	0.84 (0.02)	1.13 (0.01)	0.29 (-)	1.21 (0.02)
Na	0.34 (-)	0.03 (0.01)	3.4 (0.2)	3.9 (0.2)

Table B.1: *continued.*

Extractable Nutrient (mg/kg)				
P	27.20 (0.07)	17.9 (0.4)	16.8 (0.1)	9.1 (0.1)
K	37.8 (1.2)	86 (2)	29.5 (0.5)	24.6 (0.2)
Ca	1635 (21)	3381 (42)	369 (4)	574 (6)
Mg	96.1 (1.1)	136.7 (1.6)	41.1 (0.8)	134.6 (1.6)
Mn	24.7 (0.1)	37.2 (1.1)	39.7 (0.4)	30.2 (1.1)
Fe	127.4 (1.2)	71.7 (0.1)	114.8 (1.1)	91.3 (-)
S	17.02 (0.21)	26.9 (0.3)	21.2 (0.3)	19.6 (0.2)
Na	40.4 (0.5)	8.8 (0.1)	704 (2)	708 (4)
Al	492 (3)	215 (3)	401 (5)	626 (4)
pH				
Initial	6.82 (0.02)	7.54 (-)	6.39 (0.01)	6.09 (0.01)
Final 0%	6.49 (0.01)	6.96 (0.01)	-	-
2%	-	-	6.78 (0.04)	6.44 (0.02)
4%	6.06 (0.04)	6.92 (0.02)	7.03 (0.02)	6.76 (0.03)

Appendix C

SUMMARY TABLE OF LINEAR REGRESSION PARAMETERS

Table C.1: Linear regression slope and intercept values for each TDR curve as listed by site and biochar mass percentage.

	Linear Regression Summary	
	Slope	Intercept
Sample Site:		
Church		
0% - Trial 1	1942.7	2400.2
0% - Trial 2	2112.4	2302.7
4% - Aged	1910.2	2976.7
4% - New	2184.0	3488.0
Slack		
0% - Trial 1	1595.4	4410.7
0% - Trial 2	1352.7	5290.5
4% - Aged	1840.8	3655.0
4% - New	1485.0	6569.8
Site 1		
0%	2001.5	1928.9
2%	2273.2	2957.2
4%	2711.9	3501.4
Site 2		
0%	2046.6	1868.7
2%	2227.5	3568.7
4%	2480.9	4781.5
Exit Ramp		
0%	2442.4	4090.7
2%	2886.9	3475.9
4%	3186.5	4121.1
Toll Plaza		
0%	1957.6	2344.9
2%	2026.8	5204.0
4%	2112.5	4544.3