Investigation of Sand-Biochar Mixtures as a Potential Roadway Fill Material

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INVESTIGATION OF SAND-BIOCHAR MIXTURES AS A POTENTIAL ROADWAY FILL MATERIAL

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science in Civil Engineering

in

The Department of Civil and Environmental Engineering

by
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Dedicated to my parents and my siblings who have offered
their unconditional love and support throughout this process.
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ABSTRACT

Biochar is a sustainable and lightweight carbon-rich material with a high surface area and porosity. Previous studies reported that biochar can reduce soil erosion and cracking, retain contaminants, and enhance soil aggregation. Given these favorable properties, soil-biochar mixtures have the possibility to serve as a multifunctional lightweight fill material for roadway embankment applications. The purpose of this research is to develop sand-biochar mixtures as a sustainable and multifunctional lightweight fill material for roadway embankment applications.

This research investigated the consolidation and hydraulic properties of sand-biochar mixtures by (1) performing 1D consolidation tests, (2) performing permeability tests, and (3) assessing the optimal mixing ratio of the sand-biochar mixtures and lightly cemented sand-biochar mixtures. 1D consolidation tests instrumented with bender elements were performed to investigate the shear modulus and compressibility of the sand, sand-biochar mixtures, and lightly cemented sand-biochar mixtures with different mixing ratios of sand, biochar, and cement.

Next, the hydraulic conductivities of different mixtures were measured using an automated permeameter. Based on these results, an optimal mixing ratio of sand, biochar, and cement (i.e., high mechanical strength and excellent drainage properties) was determined for lightweight fill applications. Finally, the micro-scale morphologies and pore structures of the lightly cemented sand-biochar mixtures were investigated using a Scanning Electron Microscope combined with energy-dispersive X-ray spectroscopy. Satisfying mechanical and hydraulic properties of the sand-biochar mixtures were observed at low biochar percentages.
CHAPTER 1. INTRODUCTION

1.1. General Information

The design and construction of roadway embankments is often challenged by the possibility of bearing failure, slope instability, excessive total and differential settlements, or a weak foundation. To mitigate these issues, several ground improvement techniques (e.g., column supported embankment and deep replacement) have been suggested to enhance foundations. An alternative mitigation method is the reduction of the weight of the embankment by using a lightweight fill material, particularly if soft soil is present beneath the embankment. In the United States, the available lightweight fill materials include Expanded Polystyrene (EPS) commonly known as “geofoam”, foamed concrete, and expanded shale, clay, and slate lightweight aggregate (LWA). The use of these materials has proven that lightweight materials are able to improve the performance of embankments by reducing load and facilitating the replacement of problematic old fill materials. However, these lightweight fill materials could be costly, and their production energy intensive.

Biochar is a sustainable and carbon-rich material obtained from the slow and incomplete combustion of agricultural and forestry wastes at extremely high temperature (~500 °C) in an oxygen-free environment, through a process called pyrolysis. Biochar has a low density, a high surface area and porosity, as well as an excellent ability to absorb contaminants. Given these favorable properties, biochar amended soils have the potential to serve as a multifunctional lightweight fill material. For this study, sand-biochar mixtures of varying biochar contents (0, 2, 4.8, 9.1, 16.7, 28.6, 37.5, 44.4 and 50%) were tested to determine their consolidation and hydraulic properties, to investigate an optimal mixing ratio for roadway embankment fill applications.
The maintenance of states’ highway embankment systems is a strenuous task with serious impacts on the limited budgets of state Departments of Transportation (DOT). In Region 6, embankments present on soft soils often rely on pile installation and ground improvement techniques that require complex and expensive construction. Also, with increasingly stringent stormwater regulations, DOTs across the country are required to remediate stormwater for metals, bacteria, water runoff and other pollutants. The development of a new sustainable and multifunctional lightweight fill material with a potential for erosion and cracking reduction, contaminant retention, and reduction of stormwater runoff is beneficial and much needed for DOTs in their mission for sustainable design of roadway embankments.

1.2. Objectives

The objective of this study is to evaluate the suitability of sand-biochar mixtures as a multifunctional lightweight fill material. To this end, sand-biochar mixtures of varying biochar contents were subjected to 1D consolidation tests and permeability tests to determine the optimal mixing ratio of sand and biochar. Cement (5% by weight) was also added to the mixtures (i.e., lightly cemented sand-biochar mixtures) to improve their consolidation and hydraulic properties.

Specifically, this research aims to:

- Provide a sustainable alternative for fill materials used in the United States by introducing sand-biochar mixtures.
- Assess the mechanical properties of sand-biochar mixtures and lightly cemented sand-biochar mixtures such as consolidation, permeability, and small-strain shear modulus.
• Study the behavior of sand-biochar mixtures and lightly cemented sand-biochar mixtures with different biochar contents.

1.3. Thesis Organization

The objectives and results of this study are presented in the thesis as follows:

Chapter 2 reviews previous studies conducted on biochar and soil-biochar mixtures and presents the concepts applied for this research.

Chapter 3 introduces the different materials used in this study and the characterization tests performed on each material.

Chapter 4 presents the equipment, experimental procedures, and results obtained for the consolidation and hydraulic conductivity properties of sand-biochar mixtures.

Chapter 5 presents the experimental procedures and the results obtained for the consolidation and hydraulic conductivity properties of lightly cemented sand-biochar mixtures.

Chapter 6 presents an analysis and discussion of the behavior of sand-biochar mixtures and lightly cemented sand-biochar mixtures.

Chapter 7 summarizes the important conclusions drawn from analysis and discussions and recommends an optimal sand-biochar mixing ratio.
CHAPTER 2. LITERATURE REVIEW

2.1. Lightweight Fill Materials

A lightweight fill material is any material used to replace heavy in-situ soil to alleviate the load on subgrade soils. In the United States, the use of lightweight fill materials has become widespread over the years for road construction by Departments of Transportation (DOTs) and other transportation agencies. Roadway embankments constructed on soft soil are susceptible to excessive settlements and slope stability failure. To prevent such failures, two main solutions were proposed: (1) improving the mechanical properties (e.g., shear strength and compressibility) of foundation soils; and (2) reducing the weight of the embankment.

The most significant characteristic of lightweight fill materials is their range in density, which can vary from 1% to as much as 70% of the density of the soil or rock (Stark et al., 2004). Lightweight materials also have a wide range in material costs, construction costs, and engineering properties. Therefore, two categories are used to classify lightweight fill materials: lightweight fill materials with inherent compressive strength (i.e., EPS-block geofoam and foamed concrete geofoam) and granular lightweight fills (wood fiber, blast furnace slag, fly ash, boiler slag, expanded clay or shale and shredded tires). From 1998 to 2001, in preparation for the 2002 Winter Olympic Games held in Utah, the Utah Department of Transportation and a large construction consortium completed the widening of the freeway, Interstate Highway 15 (I-15), in the Salt Lake Valley. This project required the placement of large embankments on soft clayey foundation soils. Expanded polystyrene (geofoam) was chosen as the fill material. The placement of about 100,000 m$^3$ of this extremely lightweight material (density of 18 kg/m$^3$) allowed for the rapid construction of full-height embankments in a short period of time, without costly utility relocations (Newman et al., 2014). In North Carolina, for the widening and raising of the TranterS Creek Bridge Approach
in Washington, NC, the state DOT used LWA to replace the old embankment as part of the bridge replacement project to mitigate settlement (Wall and Castrodale, 2013). These two examples validated the assumption that lightweight fill materials improved the performance of embankments and could mitigate settlement.

Unfortunately, most lightweight fill materials are considered expensive with prices ranging from $65 to $130/yd³ (Loux, 2018). At these prices, these materials often have limited applications in projects due to often restrained budgets. Furthermore, the production of these materials is energy intensive as it can account for very high carbon dioxide (CO₂) emissions. Incidentally, biochar amended soils or soil-biochar mixtures have been introduced as an alternative lightweight fill material. Biochar can also sequester carbon that is beneficial in the reduction of greenhouse gas emissions. Thus, biochar is a potentially cost-effective and durable material as compared to other lightweight fill materials.

2.2. **Types of Biochar**

Biochar is an organic material that is produced by the slow and incomplete combustion of biomass in an oxygen-limited environment. This process is known as pyrolysis. Biochar can also be obtained through gasification of biomass residues such as wood chips and cereal straw (Hansen et al, 2015). The primary sources of biochar are agricultural and forestry residues, wood processing waste, animal manure, and municipal sewage sludge (Duku et al., 2011). Figures 1 and 2 show biochars obtained from wood feedstock, switchgrass, and hardwood.
Figure 1. Wood feedstock material (left) and biochar product (right), Basiri et al. (2019)

Figure 2. Switchgrass biochar (left) and hardwood biochar (right), both produced at ~1,000°C (Basiri et al. 2019).

During these processes, the biomass transforms into a highly porous, stable, and carbon-rich material called biochar. In recent years, biochar has attracted a lot of attention from the scientific community, given its positive attributes such as high carbon content, high cation exchange capacity, large surface area and structure stability (Wang and Wang, 2019). Biochar is reported to be comprised of more than 65% carbon and smaller amounts of oxygen, nitrogen, and hydrogen (Wijitkosum et al., 2019). Depending on the temperature and time used for pyrolysis, the resulting biochar will have varying properties. Basiri et al. (2019) reported that biochar produced through fast pyrolysis and higher temperature (> 650 °C) had finer and porous particles, higher pH, and greater surface area, while biochar produced through slow pyrolysis and at low temperature (450 to 650 °C) resulted in larger biochar particles and smaller surface area, as well as lower pH.
2.3. **Use of Biochar as Construction Material**

Greenhouse gases (GHG) emissions are a serious concern in the construction industry due to the energy intensive processes and the release of carbon dioxide (CO$_2$) involved in the manufacturing of cement. It is estimated that about one ton of CO$_2$ is released in the atmosphere during the manufacturing of one ton of Portland Cement (Worrell et al., 2001). In the United States, cement is responsible for nearly 1% of all CO$_2$ emissions (Choi et al., 2012). One of the newest approaches to climate change mitigation is the development of technologies for direct air capture of CO$_2$. Biochar, with its strong affinity for nonpolar substances and high surface area, can be a potential material to capture and store CO$_2$ from air (Gupta et al., 2017). Thus, the use of biochar as a construction material can contribute to the lowering of carbon emissions in the building industry.

In recent years, biochar has been increasingly used as an additive for building materials (e.g., panel, bricks, plaster, and tile adhesives) because of its favorable properties which include low thermal conductivity, high chemical stability, and low flammability. In Switzerland, the Ithaka Institute building was partially restored using plaster containing biochar. Biochar was used to replace up to 50% of plaster mixture, with the rest of the mixture being made of clay, cement mortar, and lime (Schmidt, 2013). The addition of biochar to concrete and asphalt has also been investigated. Gupta et al. (2018) showed that the addition of wood derived biochar to cement mortar improves its compressive and flexural strengths. The compressive strength results of the cement mortar with 2% biochar demonstrated that the initial setting time was reduced and the 7-day and 28-day compressive strengths of the cement mortar increased by 15% and 17%, respectively. This improvement was attributed to the ability of biochar to adsorb water in micropores during mixing, which promoted internal curing during the hydration process. On the other hand, flexural strength
tests showed that the flexural failure was more ductile and the value of flexural strength was almost unchanged. Similar results that demonstrated increased compressive strengths and ductile flexural failures with biochar addition were also reported in other studies (Ahmad et al., 2015; Khushnood et al., 2016; Restuccia & Ferro, 2016; Choi et al., 2012).

Zhao et al. (2014) performed multiple binder and performance tests on hot-mix asphalt (HMA) using modified binders containing biochar (obtained from switchgrass). Results demonstrated that the use of biochar increased the rutting resistance, reduced moisture susceptibility, and enhanced the cracking resistance of HMA. The improvement was attributed to the reduction of the temperature susceptibility when biochar was present in the modified binder. Other studies (Chebil et al., 2000; Walters et al., 2014) reported similar results in which the addition of biochar enhanced the durability of asphalt, therefore preventing aging and cracking due to brittleness. The case studies mentioned above prove the positive impacts that biochar can have in the construction industry and its potential for GHG emission reduction.

2.4. Beneficial Properties of Biochar for Soil Improvement

2.4.1. Effect on Physical and Mechanical Properties of Soils

2.4.1.1. Bulk density

Blanco-Canqui (2017) reported that biochar application reduced bulk density by 3 to 31% in 19 out of 22 soils and by 12% on average, which suggests that bulk density generally decreases with biochar application. It was observed that bulk density would linearly decrease with an increase in biochar content. However, Rogovska et al. (2016) reported that the bulk density would decrease quadratically. Additionally, Blanco-Canqui (2017) found that the potential for biochar to reduce bulk density was found to be more pronounced in coarse-grained than in fine-grained soils, suggesting that the effects of biochar should be assessed on a site-to-site basis. Indeed, a 14.2% density decrease in coarse-grained soils and 9.2% density decrease in fine-grained soils were
observed. This could be explained by two mechanisms. First, given biochar’s low bulk density, its application is likely to reduce the soil bulk density through the mixing or dilution effect especially if the difference in densities of the two materials is large. Second, the interaction of biochar with soil particles and subsequent improvement of aggregation and porosity could reduce the bulk density in the long term.

2.4.1.2. Particle Density

Particle density is an important property that affects not only porosity, but also particle sedimentation, specific surface area, thermal properties, and others. Biochar’s particle density ranges from 1.5 to 2 g/cm³ while the particle density of soil is often assumed to be 2.65 g/cm³. It was reported that changes in soil carbon concentration could significantly reduce particle density (Blanco-Canqui et al., 2006). This means that the addition of biochar, which is rich in carbon (>60%), could induce changes in particle density and affect soil porosity. Githinji (2014) found that the particle density of a loamy sand decreased linearly with biochar content (at 0, 25, 50, 75, and 100% by volume), with a 64% particle density reduction at 100% biochar content by volume.

2.4.1.3. Porosity

Biochar, with a porosity of 70 to 90%, can increase soil porosity, which will reduce soil bulk density, increase soil aggregation, interact with mineral soil particles, and reduce soil packing (Blanco-Canqui, 2017). Andrenelli et al. (2016) reported that the porosity of biochar is dependent upon the temperature used for pyrolysis and could increase with an increase in temperature. It was also reported that the effects of biochar on soil density and porosity seem to occur regardless of biochar type, the duration of the study, and soil type. However, sandy soils appear to be more susceptible to be affected by biochar than clayey soils.
2.4.1.4. Tensile Strength

The tensile strength of soil refers to the inherent ability of a soil to resist the tensile forces responsible for fracture or rupture of the soil. Changes in soil tensile strength strongly depend on soil porosity, interparticle bonds, internal friction, clay content, and mineralogy. Blanco-Canqui (2017) reported that biochar application reduces tensile strength by 42 to 242%, regardless of soil type. Thus, the decrease in tensile strength following biochar application is an indicator of the weakness of interparticle bonds and reduction in density and cohesiveness of the soil. Additionally, the reduction in tensile strength is more pronounced when biochar is applied at rates greater than 2% (Zong et al., 2016). This indicates that low biochar contents have limited or no effects on tensile strength reduction.

2.4.1.5. Shear Strength

Shear strength refers to the internal resistance of soil against sliding as a function of cohesion and friction angle. Unlike other soil properties, there are not many extensive studies that examined changes in shear strength following biochar application. However, it was suggested that the effects of biochar can vary depending on soil type and biochar type, and that biochar application consistently reduced shear strength of clayey soils. Zong et al. (2014) found that the application of three types of biochar (woodchip, straw, and wastewater sludge) at 0, 2, 4, and 6% biochar content reduced the shear strength of a clayey soil by reducing cohesion and internal friction angle. Reddy et al. (2015) reported that wood biochar had higher shear strength than a silty clay. Therefore, the application of 5, 10, and 20% biochar to silty clay resulted in an increase in shear strength of the mixture.

2.4.2. Effect on Hydraulic Properties of Soils

2.4.2.1. Hydraulic Conductivity
Several studies have shown that biochar addition can influence saturated and unsaturated hydraulic conductivities, as well as water infiltration. Blanco-Canqui (2017) studied the hydraulic conductivities of 28 soils. Out of 15 coarse-grained soils, the decrease of saturated hydraulic conductivity with biochar addition was observed in 13 coarse-grained soils. This decreased ranged from 7% to 2270%. Out of 13 fine-grained soils, it was found that biochar addition increased the saturated hydraulic conductivity of 8 fine-grained soils. The increase in this case ranged from 25% to 328%, indicating that biochar has a greater impact on coarse-grained soils than on fine-grained soils. Similar results were obtained for the unsaturated hydraulic conductivity of biochar amended soils (Uzoma et al., 2011; Kameyama et al. 2012).

Blanco-Canqui (2017) attributed the decrease in hydraulic conductivity to the clogging of macropores by fine biochar particles. Biochar particles are often very small in diameter (< 2 mm) and can fill the pore space and interact with soil particles. It should be noted that the decrease of soil permeability also depends on the types of biochar. While biochar with hydrophobic properties can induce water repellency, plate-like biochar particles are more likely clog micropores than spherical biochar particles (Githinji, 2014; Novak et. 2016). Blanco-Canqui (2017) attributed the increase in permeability of fine-grained soils to biochar particles having a bigger diameter than the fine-grained soils. This caused an increase in porous space and water seepage in the soil matrix.

2.4.2.2. Water Retention

Biochar particles have a good water absorption capability. Imhoff et al. (2017) reported that biochar amendment increased water retention of loamy sand by 6%. This increase was attributed to the increase of soil porosity with addition of biochar. For the three types of soils (silt loam, loamy sand, and sandy loam) tested in their study, biochar proved to be more efficient in the increase of water retention of coarse-grained soils.
Blanco-Canqui (2017) found similar results as reported in the study conducted by Imhoff et al. (2017) when comparing the water retention of 19 biochar amended soils. This comparison indicated that biochar application increased the water retention (even at low biochar contents), for 17 out of 19 soils (both coarse and fine-grained). Large amounts of biochar should then be applied for a more consistent improvement of water retention of a soil. It should be noted that there were no changes of water retention in 2 fine-grained soils. This indicates that fine-grained soils might require greater amounts of biochar to increase water retention than coarse-grained soils.

2.5. Maximum Shear Modulus ($G_{max}$)

Shear wave (S-wave) is a wave motion in which the particle motion is perpendicular to the direction of the propagation. The maximum shear modulus ($G_{max}$), also known as small-strain shear modulus, is defined as the linear-elastic response to S-wave propagation in granular soils, which is controlled by the interparticle forces at particle contacts and state of stress (Santamarina et al., 2001). It is the ratio of shear stress to the shear strain in a material. $G_{max}$ is an important soil parameter in the design of foundations subjected to dynamic loading, liquefaction assessment, process monitoring, and soil improvement (Lee et al., 2005). The maximum shear modulus can be obtained by measuring S-wave velocity using piezoelectric transducers (bender elements) as shown in Equation (1).

$$G_{max} = \rho \cdot v_s^2$$  \hspace{1cm} (1)

where $\rho$ = density of the soil specimen and $v_s$ = S-wave velocity.

Bender elements have been widely used in soil and rock S-wave testing because of their good wave directivity and suitable coupling with soil (Lee and Santamarina, 2005). A bender element consists of two sheets of piezoelectric ceramic material with center shim of brass in
between, which is an electromechanical transducer capable of converting mechanical energy into electrical energy and vice versa (Leong et al., 2005). The polarization and propagating direction of a signal depends on the position of the bender element. In a typical test, a pair of bender elements is installed in-line at two ends of a soil sample. One will serve as the S-wave sender and the other as the S-wave receiver. At the beginning of the test, the sender is input with a square wave signal through a function generator. The sender then converts this electrical signal into mechanical S-wave vibration which will travel through the soil sample and be collected by the receiver. The receiver converts the received mechanical S-wave vibrations to electrical signal. The electrical signal is then filtered by a band pass filter. The input and output signals are then displayed on a digital oscilloscope, from which the travel time of the S-wave (Δt) will be determined. To calculate the S-wave velocity (v_s), the tip-to-tip distance (L) between the two bender elements is determined and divided by the travel time, Δt as shown in equation (2).

\[ v_s = \frac{L}{\Delta t} \]  

(2)

To determine the travel time (Δt), the two most commonly used methods are the peak-peak method and the start-start method. The peak-peak method consists of calculating the time difference between the first peak on the departing sine wave and the equal point on the arriving sine wave, as shown in Figure 3.
Figure 3. Peak-peak method for the determination of the wave travel time with bender elements (Santamarina et al., 2001).

Figure 4. Typical S-wave signal): (A) first deflection, (B) first bump maximum, (C) zero after first bump, and (D) major first peak. (Lee and Santamarina, 2005)

The start-start method, however, is about the difference of travel time between the start of the sending wave and the start of the following receiving wave. In Figure 4, point C is considered the point of first arrival at which the travel time is measured.
CHAPTER 3. CHARACTERIZATION OF BIOCHAR, SAND, AND SAND-BIOCHAR MIXTURES

3.1. Samples

Figure 5 depicts the three materials used in this research. The biochar was provided by Chip Energy, Inc located in Goodfield, Illinois and produced from wood pellets using an updraft gasifier operated at 520°C. These biochar particles were cylindrical in shape with an approximate height and diameter of 1 cm and 0.5 cm, respectively. To obtain uniform sand-biochar mixtures, the cylindrical biochar particles were grinded for 15 seconds using a Hamilton Beach electric coffee grinder and sieved using sieve #50 (0.3 mm opening size). These biochar particles were not dried upon arrival because they were already dry from gasification. The sieved biochar particles were then mixed with Ottawa 20-30 sand to obtain uniform samples. Ottawa 20-30 sand, standardized by ASTM C778, was used for this study given that its physical properties are known. Biochar was added to Ottawa 20-30 sand at weight contents of 2, 4.8, 9.1, 16.7, 28.6, 37.5, 44.4 and 50% (weight contents equal to the weight of biochar divided by the total weight of biochar and dry Ottawa 20-30 sand). These tests will ultimately determine the optimal mixing ratio between sand and biochar for roadway fill application.

To use the sand and biochar in the experiments, their main physical properties had to be determined. Thus, sieve analyses were conducted on Ottawa 20-30 sand and biochar, in accordance with ASTM C136. Additionally, specific gravity tests in accordance with ASTM D854 were run on biochar and sand-biochar mixtures. Finally, Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray spectroscopy (EDS) was conducted to determine the micro-scale morphologies and pore structures of biochar.
3.2. Particle Size Distribution

Figure 6 shows the particle size distribution curves of Ottawa 20-30 sand, biochar before grinding, and biochar after 15 seconds of grinding. Hydrometer analyses were not conducted in this instance due to the low percentage of fines (less than 2%) in biochar.

According to the Unified Soil Classification System (USCS), Ottawa 20-30 sand is classified as poorly graded sand (SP), with a coefficient of uniformity \(c_u\) of 1.38 and a coefficient of gradation \(c_c\) of 1.01. The particle diameters defining 10%, 30%, and 60% finer from the grain size distribution curve are estimated as: \(D_{10} = 0.66\) mm, \(D_{30} = 0.78\) mm, and \(D_{60} = 0.91\) mm. Biochar, in the form obtained from the manufacturer, was tested by sieve analysis. The results showed that 35.28% of biochar was retained on sieve #4 (4.75 mm opening size), while only 0.40% of fines were collected in the pan. Also, 64.32% of biochar particles size ranged between 0.075 and 4.75 mm in diameter. Using USCS, this biochar is classified as poorly graded sand (SP) and the particle diameters defining 10%, 30%, and 60% finer are estimated as: \(D_{10} = 0.24\) mm, \(D_{30} = 0.85\) mm, and \(D_{60} = 4\) mm. The \(c_c\) and \(c_u\) parameters are 0.75 and 16.67, respectively.
For the biochar grinded for 15 seconds, the results showed that 1.01% of biochar particles were retained on sieve #10 (2 mm opening size) and 1.37% passed sieve #200 (0.075 mm opening size). This means that biochar grinded for 15 seconds is classified in the sand range. The parameters $D_{10}$, $D_{30}$, and $D_{60}$ were estimated as 0.18, 0.24, and 0.4 mm, respectively. The coefficient of gradation, $c_c$ and coefficient of uniformity, $c_u$ are 0.80 and 2.22, respectively. According to USCS, this biochar is classified as poorly graded sand (SP).

3.3. **Specific Gravity**

Specific gravity tests were performed according to ASTM D854 to determine the specific gravities ($G_s$) of biochar, Ottawa 20-30 sand, and sand-biochar mixtures. A 500 mL pycnometer and electric vacuum pump were used to ensure no air was present in the pycnometer during testing. Figure 7 shows the specific gravities of sand-biochar mixtures versus biochar content.
Figure 7. Specific gravities of sand-biochar mixtures.

After completion of the specific gravity tests, the specific gravity of biochar was found to be 1.49 while the specific gravity of Ottawa 20-30 sand is equal to 2.65. The specific gravity of sand-biochar mixture with a biochar content of 2% was equal to 2.61. As the biochar content increased in the mixtures, the specific gravity decreased. At 4.8% biochar content, the mixture’s specific gravity decreased to 2.56 and to 1.90 at 50% biochar content. The specific gravity of materials, using the pycnometer method, is dependent upon the chemical composition and particle structure of the tested materials. In that sense, denser materials tend to have higher specific gravities. Therefore, the decrease in specific gravity with increase in biochar content can be attributed to the increase of carbon content and decrease in density as more biochar was added to the samples.

3.4. SEM Imaging

Scanning Electron Microscopy (SEM) was used to assess the micro-scale morphologies and pore structures of biochar. The FEI Quanta 3D FIB-SEM (shown in Figure 8), located in the Shared Instrumentation Facility (SIF) of the Chemistry and Material Building on the Louisiana
State University main campus, was used for SEM imaging of biochar. This device combines a Focused Ion Beam (FIB) with a high-resolution Field Emission Gun Scanning Electron Microscope (FEG-SEM), which allows to obtain enhanced 2D and 3D materials characterization and analysis for a wide range of samples. Featuring three imaging modes, high vacuum, low vacuum, and ESEM, this device accommodates the widest range of samples of any SEM system. The integrated EDAX Pegasus EDS & EBSD system allows to determine the chemical composition, element distribution, crystallographic orientation, and grain size distribution.

To prepare biochar for SEM imaging, a sample was carefully placed on a carbon adhesive previously installed on top of a SEM pin stub. The sample was then transported and placed into a Sputter Coater device (model EMS550X) as shown in Figure 9. Because biochar is not a conducive material, it needed to be coated with a gold alloy to improve the sample imaging. Platinum is an excellent coating material because it creates a conductive layer on the sample, which inhibits charging, reduces thermal damage, and improves the secondary electron signal required for
topographic imaging in the SEM. Once sample coating was completed, the pin stub was removed from the coating device and placed on the specimen stage inside the SEM.

![Sputter Coating Device, Model EMS550X](image)

Figure 9. Sputter Coating Device, Model EMS550X

The images obtained from SEM imaging are depicted in Figures 10 and 11. First, an image with 250x of magnification was taken. The magnification was increased to find interesting spots that best showed the microstructure of biochar. Biochar samples was captured at magnifications of 250x, 500x, 650x, 1000x, 1200x, and 2000x. As expected, the images show that biochar particles were small and porous. Figures 10 and 11 show biochar particles captured in the sizes ranging from 20 μm to 200 μm, exhibited honeycomb like pore structures and large surface areas.
Figure 10. SEM images showing pore structure of biochar.

Figure 11. Pores structures of biochar
3.5. Chemical Composition

To determine the chemical composition of biochar, EDS was performed after SEM imaging. The results are shown in Figure 12, where the x-axis shows the elements present in biochar and the y-axis represents the count number of elements.

![Biochar EDS analysis results](image)

Figure 12. Biochar EDS analysis results.

As expected, the results of the EDS analysis showed the presence of carbon, oxygen, and potassium in biochar. The samples presented with an 84.5% weight percentage of carbon and an atomic percentage of 91.2%. Oxygen was found in the sample with a 10.2% weight percentage and an atomic percentage of 8.3%. Smaller amounts of potassium and platinum were also found. Although potassium was expected in biochar, the presence of platinum found was likely caused by the coating agent. These results were found to be in accordance with similar analyses reported in the literature (Wijitkosum et al., 2019).
CHAPTER 4. CONSOLIDATION AND HYDRAULIC PROPERTIES OF SAND-BIOCHAR MIXTURES

To investigate the compressibility of sand-biochar mixtures at different biochar contents, one-dimensional (1D) consolidation tests equipped with bender elements were conducted. To assess the permeability of sand-biochar mixtures, falling head permeability tests were conducted using an automated permeameter. SEM imaging and EDS spectroscopy were used to assess and compare the microscale morphologies and pore structures of sand-biochar mixtures.

4.1. 1D Consolidation Tests

The compressibility of a soil is crucial to the design and construction of roadway embankments. Compressibility is defined as the ability of soil to decrease its volume under mechanical loads. Knowing the compressibility parameters (e.g., compression index and recompression index) allows to estimate the settlement of the soil and keep it within a tolerable range to avoid significant settlement. 1D consolidation tests were conducted on dry and saturated sand-biochar samples to compare their behavior when subjected to incremental loading at different mixing ratios. Each test comprised a loading stage, an unloading stage, and a reloading stage to obtain the virgin consolidation curve, rebound curve, and recompression curve for each sample.

4.1.1. Apparatus

The equipment used for all 1D consolidation tests was an automated loading system called GeoJac™. The main component is the GeoJac™ automated loader which has a 2000-pound load capacity and a Direct Current Displacement Transducer (DCDT). The entire system also includes four channels with 22-bit analog data acquisition system and a data acquisition software called Sigma-1 ICON. The software allows to monitor the tests and display results, such as the stress
versus strain and the deformation versus time curves at each loading stage in real time. The complete setup is shown in Figure 13.

![Figure 13. 1D consolidation test setup.](image)

The samples were placed inside a steel cell embedded with bender elements which were used to measure the S-wave velocities inside the samples during the 1D consolidation tests. This cell is 57 mm high with a diameter of 64 mm, as shown in Figure 14. The base plate is connected to a hose to allow drainage. The top cap of the cell is a thick plate with holes to allow drainage from the top of the cell. Both the base plate and the cap were embedded with a bender element at the same location, so that both bender elements were perfectly aligned with each other when the cell was assembled. A small mesh was also used to prevent sand and biochar particles from clogging the drainage system of the cell. This mesh was placed at the middle of the base plate before sample preparation.
4.1.2. Sample Preparation

To determine an optimal mixing ratio for sand-biochar mixtures, samples containing 0, 2, 4.8, 9.1, 16.7, 28.6, 37.5, 44.4, and 50% of biochar were obtained and subjected to 1D consolidation tests. For dry and saturated samples, the first step consisted of grinding biochar particles for 15 seconds. The grinded biochar was then sieved using sieve #50 until the targeted mass of biochar was collected. The biochar content of all samples was calculated as the mass of biochar divided by the combined masses of Ottawa 20-30 sand and biochar. For each sample, 250 g of sand was measured and the targeted amount of biochar was calculated based on the targeted biochar percentage and weight of sand. Sand and biochar were then thoroughly mixed inside a bowl for 5 minutes.

For the dry samples, the mixture was poured into the steel cell using a 5 mL small scoop. The samples were prepared in eight (8) layers with equal thickness of 5 mm. Each layer was compacted using a 1 kg tamper with a 48 mm diameter. Ten (10) blows were applied to compact
each layer and to ensure uniformity throughout the samples. The final samples were measured and had approximately 40 mm in height and 50 mm in diameter. A digital caliper was used to measure the height of each sample.

When preparing saturated soil samples, the drainage hose was closed and about 60 mL of deionized water were poured into the steel cell. Each layer of the mixture was then poured in the same fashion as previously described for dry samples. Ten (10) minutes were allotted to allow biochar particles to settle before compaction. For samples with biochar content higher than 16.7%, a small spatula was used to submerge biochar particles floating at the water surface. It is worth noting that, as the biochar content increased (over 16.7%), the majority of biochar particles floated on the surface and settle at a very slow rate. After 10 minutes, each layer of the saturated samples was compacted using the 1 kg tamper. The same compaction energy (10 blows per layer) was applied to each of the saturated layers as for the dry samples. The final height of the samples was measured using a digital caliper after compaction of the eighth layer.

4.1.3. Test Procedure

1D consolidation tests were conducted for pure sand and sand-biochar mixtures at biochar contents of 2, 4.8, 9.1, 16.7, 28.6, 37.5, 44.4, and 50%, and at dry and saturated conditions. Once the sample preparation was completed, the top cap was placed on top of the sample. The two embedded bender elements were aligned. The use of the steel cell is to restrain lateral deformation during load application, thus ensuring 1D consolidation condition. The loading schedule was divided in three steps: initial loading, unloading, and reloading. The initial loading phase consisted of applying incremental consolidation pressures of 12, 24, 48, 96, and 192 kPa. During unloading, pressures of 96, 48, and 24 kPa were applied to the sample. During reloading the samples were recompressed to pressures of 48, 96, 192, 384, and 768 kPa. Each load was applied to the samples
for 15 minutes, except for pure sand sample for which the loads were applied for only 10 minutes. The loading schedule was the same for the tests conducted on dry and saturated samples.

4.1.4. 1D Consolidation Test Results

Figures 15 and 16 show the results from 1D consolidation tests conducted on sand-biochar mixtures with biochar contents of 0, 2, 4.8, 9.1, 16.7, 28.6, 37.5, 44.4, and 50%. Figures 15a and b show the strain versus applied stress for dry and saturated samples. In both dry and saturated conditions, strains increased with the applied loads. Also, at the same applied load, the strains increased with increasing biochar content. The lowest maximum strains (1.16% in dry condition and 1.58% in saturated condition) were measured from the samples without biochar (i.e., Ottawa 20-30 sand). The samples with 50% of biochar content were found to have the highest maximum strains (6.20% in dry condition and 6.55% in saturated condition). Overall, the strains measured in saturated conditions were higher than those in dry conditions at the same applied loads and same biochar contents.

Figures 16a and b show the void ratio versus applied stress for dry and saturated samples. For all samples, the void ratio decreased as the applied stress increased. Furthermore, the addition of biochar to Ottawa 20-30 sand showed that the slopes of the void ratio versus stress curves increased with increasing biochar content. The samples containing 2% and 4.8% biochar contents decreased the mixtures’ initial void ratio. The lowest initial void ratio of all sand-biochar mixtures was measured at the biochar content of 4.8%. In dry conditions, the initial void ratio for the sample with 4.8% of biochar was equal to 0.325. The initial void ratio was 0.309 in saturated condition. As the biochar content increased over 4.8%, the void ratio linearly increased with the biochar content. The highest void ratios were equal to 0.78 (dry condition) and 0.76 (saturated condition) for the sample containing 50% of biochar.
Figure 15. Strains versus applied stress for (a) dry samples and (b) saturated samples.
Figure 16. Void ratio versus applied stress for (a) dry samples and (b) saturated samples.
4.2. Shear Wave Velocities

4.2.1. Apparatus

To measure the shear wave (S-wave) velocities during the 1D consolidation tests, the bender elements used were made in-house and installed in the base top plates of the consolidation cell. A function waveform generator, a filter and amplifier, and a digital oscilloscope were used to control and process waveforms generated from bender elements.

Two sets of data acquisition systems were used to measure S-wave velocities from two consolidation cells. Thus, two function generators were used including the Agilent Function Waveform Generator (model 33220A) and the FeelElec™ DDS Signal Generator/Counter (model FY6800) as shown in Figure 17. This device modulated an electrical signal that was sent to the bender element located at the base of the consolidation cell and considered as S-wave sender. Using the signal generator, one can set the waveform, frequency, and amplitude parameters for the S-wave velocity test. For all the 1D consolidation tests, the wave function “square” was used to generate a square waveform. The maximum amplitude of the square signal was ± 3 volts (V) and the peak-to-peak signal amplitude was 6 V. The frequency was 50 Hertz (Hz), which corresponds to 50 cycles per second.

Figure 17. Agilent Function/Arbitrary Waveform Generator (left) and DDS Signal Generator (right).
Two filters were used in conjunction with the signal generators and the digital oscilloscopes. Two Krohn-Hite Multi Channel Filters (model 3944) shown in Figure 18 were used to filter out the noise that would affect the travel time measurements. In channel 2.1, a high-pass frequency of 300 Hz was selected, and a low-pass frequency of 50 Hz was selected in channel 1.1. This low-pass frequency often had to be lowered when higher stresses (i.e., 384 and 768 kPa) were applied on the sample due to the apparition of P-waves (compression waves). After filtration, the signal was amplified and sent to the oscilloscope.

![Figure 18. Krohn-Hite Multi Channel Filter (model 3944).](image)

Two oscilloscopes were used to display the electrical signals received by the bender elements (both sender and receiver). A Hantek Digital Storage Oscilloscope (model DSO5102P) and a SIGLENT Digital Storage Oscilloscope (model SDS 1104X-E) were used for the tests as shown in Figure 19. These devices provided a real time display of the sending and receiving signals on the screen, allowing to measure the travel time of the S-waves. At the end of each load increment (i.e., 10 minutes for Ottawa 20-30 sand and 15 minutes for sand-biochar mixtures), the travel time of the S-waves in the samples was measured in the oscilloscope. Figure 20 shows the setup of the consolidation test as well as the instruments of the S-wave velocity tests.
Figure 19. Hantek Digital Storage Oscilloscope (left) and SIGLENT Digital Storage Oscilloscope (right).

Figure 20. 1D consolidation and S-wave velocity tests setup.
4.2.2. Results

The S-wave velocities were calculated by dividing the wave travel distances by the travel time (measured from the digital oscilloscope). The wave travel distance corresponds to the tip-to-tip distance between the sender and receiver bender elements. To calculate the tip-to-tip distance, the height of each bender element protrusion was measured with a digital caliper. The sum of the protrusion heights was subtracted from the measured height of the sample inside the consolidation cell. Furthermore, the cumulative settlement of the sample at each load increment was considered and subtracted from the initial height of the sample to calculate the tip-to-tip distance at different load increments. The travel time at the end of each load increment was determined according to the start-start method described in Chapter 2.

Figure 21 shows the S-wave velocities of sand-biochar mixtures in dry and saturated conditions. For clarity, the S-wave velocities measured during the unloading stage were not included. Figure 21 shows that in both dry and saturated conditions, the S-wave velocities of sand-biochar mixtures increased with increasing applied stress. The initial S-wave velocities of the sand biochar mixtures also decreased as biochar content increased. Additionally, with the increase in biochar content, the slopes of the S-wave velocity curves decreased for dry sand-biochar mixtures. The overall S-wave velocities ranged from 99 to 552 m/s in dry condition and from 88 to 522 m/s in saturated condition, which indicates that S-waves traveled faster in dry samples than in saturated samples. This can be attributed to the lower void ratios encountered in the dry sand-biochar mixtures than in the saturated mixtures. In dry condition, pure Ottawa 20-30 sand presented with the highest initial S-wave velocities, and the sample with 50% biochar content had the lowest S-wave velocities. This could be attributed to the increase of void ratio with increasing biochar content and to the properties of biochar itself in the samples. Furthermore, the initial S-wave
velocities of pure Ottawa 20-30 sand increased by 314 m/s while the initial S-wave velocity of the sample containing 50% biochar content increased by 92 m/s, at the end of the tests.

Similar results were obtained from the S-wave velocity measurements in saturated consolidation tests. Pure Ottawa 20-30 sand showed the highest initial S-wave velocity, while the sample with 50% biochar content showed the lowest initial S-wave velocity. However, the decrease of the slopes of S-wave velocities is less pronounced than in dry samples. This is likely due to the fact that S-wave velocities traveled at slower rates in saturated conditions. Figure 22 shows the small-strain shear modulus, calculated using Equation (1), of sand-biochar mixtures in dry and saturated conditions.

![Figure 21 S-wave velocities of sand-biochar mixtures in (a) dry condition.](a)
Figure 21 (cont.). S-wave velocities of sand-biochar mixtures in (b) saturated conditions.

Figure 22: Small-strain shear modulus of sand-biochar mixtures in (a) dry and (b) saturated conditions.
Figure 22 (cont.). Small-strain shear modulus of sand-biochar mixtures in (a) dry and (b) saturated conditions

4.3. Hydraulic Conductivity Tests

Hydraulic conductivity tests were conducted on sand-biochar mixtures with 0, 2, 4.8, 9.1, 16.7, 28.6, 37.5, 44.4, and 50% biochar contents. Falling head permeability tests were conducted using an automated permeameter called KSAT produced by Meter Group. This device measures the hydraulic conductivity \( K_s \) of saturated sand-biochar samples. These measurements are based on Darcy’s equation as shown in Equation 3.

\[
K_s = \frac{L V}{H A t} \tag{3}
\]

where \( L \) is the length of the sample, \( V \) is the percolated volume of water, \( H \) is the height of the water column, \( A \) is the area of the probe, and \( t \) is the time.
4.3.1. Apparatus and Procedure

The KSAT automated permeameter comprises a burette, a measuring dome with a water discharge, a gasket with a lower porous plate, a stainless-steel sample ring, a gasket with upper porous plate, a crown, and a screw cap. The device is also equipped with a pressure sensor that can be connected to the computer for data acquisition. The software KSAT VIEW® for Windows was used for data acquisition. For each test, the sample was prepared in the specimen ring that is 5 cm in height and 8 cm in diameter. A schematic view of the falling-head apparatus is shown in Figure 23.

![Schematic view of the KSAT automated permeameter (KSAT user manual).](image)

To conduct permeability tests and to obtain accurate and consistent results during the falling-head tests, the samples were prepared following the same procedure used for 1D consolidation tests. However, given the differences in equipment and specimen sizes between the
permeability and 1D consolidation tests, the sample preparation procedure was adjusted. Ideally, samples with the same void ratios and the same sand-biochar mixing ratios should be used for both consolidation and permeability tests for consistent results. However, it proved extremely difficult to obtain such specimens. Thus, an error margin of ±0.05 in void ratios was deemed acceptable for the sand-biochar samples used for hydraulic conductivity tests as compared to the dry samples used for 1D consolidation tests.

To prepare the permeability samples in the 5 cm high specimen ring, about 420 g of Ottawa 20-30 sand was used. The required amount of biochar based on the biochar content was calculated and measured. The sand and biochar were then mixed in a bowl for 5 minutes. Next, a sealing cap was placed on the bottom of the specimen ring so that only the top was open to allow the sample to be prepared. Using the 5 mL scoop, 4 scoops of soil mixture were poured in a circular manner inside the specimen to form a 5 mm high layer. Ten (10) layers of mixture were compacted to obtain the final specimen. Each layer was compacted by 30 blows from a 1 kg tamper. The gasket with lower porous plate was carefully placed on top of the specimen. Next, the specimen ring was turned upside down so that the sample stood on the gasket. The sealing cap, previously on the bottom and now on top of the ring, was removed. Then, the sample was placed in a desiccator and partially saturated with deionized and deaired water for at least 6 hours. Figures 24a and b show the sample preparation equipment used and a final Ottawa 20-30 sand specimen. To fully saturate the samples inside the desiccator, the gasket with the upper porous plate was placed on top of the specimen ring to avoid sample disturbance. Then, using the line connected to the water tank, the water elevation was raised to such that the sample was completely submerged. Each sample was fully saturated for at least one hour before the test. The permeameter was then connected to a
computer to start the KSAT View software. After calibration, the sample was removed from the desiccator, placed on the measuring dome, and secured with the screw cap (see Figure 24c).

![Photos of sample preparation equipment, prepared Ottawa 20-30 sand sample, and prepared sample inside KSAT automated permeameter connected to water tank.](image)

Figure 24. (a) Permeability test sample preparation equipment, (b) prepared Ottawa 20-30 sand sample, (c) prepared sample inside KSAT automated permeameter connected to water tank.

For every sample, the permeability was measured at different hydraulic gradients. Water was filled in the burette at different elevations (3, 4, 5, 7.5, 10, 12.5 and 15 cm) and flowed through the specimen. The software was used to monitor the real time measurement of hydraulic conductivity. Knowing the height of the specimen, the hydraulic gradient was calculated by dividing the water elevation in the burette by the length of the samples. At the end of each test, the hydraulic conductivity normalized at 10 °C was measured by the automated permeameter and displayed on the software.

4.3.2. Results

The saturated hydraulic conductivities of the different mixtures were plotted against the applied hydraulic gradients. Figure 25 shows that pure Ottawa 20-30 sand had the highest hydraulic
conductivities which were averaged at $8.70 \times 10^{-4}$ m/s. The hydraulic conductivities consistently decreased by almost two orders of magnitude from $8.70 \times 10^{-4}$ m/s at 0% biochar content to $1.09 \times 10^{-5}$ m/s at only 9.1% biochar content. When the biochar content was greater than 9.1%, the hydraulic conductivities ranged between $1 \times 10^{-6}$ and $1 \times 10^{-5}$ m/s with no apparent trend. Figure 25 also shows that, for samples with biochar contents ranging from 9.1% to 50%, the hydraulic conductivities decreased with increasing hydraulic gradient. This is attributed to the clogging of pores caused by the displacement of biochar particles in the pore channels. The sample with a 4.8% biochar content, showed an increase in hydraulic conductivity from $1.15 \times 10^{-4}$ m/s at the hydraulic gradient of 1.5 to $2.13 \times 10^{-4}$ m/s at the hydraulic gradient of 2. This was likely due to sand boiling during testing. Samples with 0% (pure Ottawa 20-30 sand) and 2% biochar contents did not exhibit a significant fluctuation in hydraulic conductivity with increasing hydraulic gradient.

Figure 25. Hydraulic conductivities of sand-biochar mixtures versus hydraulic gradient.
CHAPTER 5. LIGHTLY CEMENTED SAND-BIOCHAR MIXTURES

To improve the consolidation behavior of sand-biochar mixtures, cement addition was proposed to maximize the performance of sand-biochar. Portland cement (5% by weight) was added to the sand-biochar mixtures. These lightly cemented mixtures were subjected to the same series of tests as described in the previous chapter for sand-biochar mixtures. Given the time and resources limitations, it was not possible to conduct the same tests for 9 mixing ratios. Thus, lightly cemented sample with 5 mixing ratios were used for 1D consolidation tests and hydraulic conductivity tests. Additionally, SEM imaging and EDS analysis were conducted to analyze the effect of cementation on the microstructures of sand-biochar mixtures.

5.1. 1D Consolidation Tests

5.1.1. Apparatus and Sample Preparation

The equipment used for 1D consolidation tests of lightly cemented sand-biochar mixtures was the same as the equipment used for sand-biochar mixtures. The sample preparation process was essentially the same except for cement addition. First, 250 g of Ottawa 20-30 sand was mixed with the targeted amount of biochar, the needed percentage of biochar. For lightly cemented mixtures, samples with biochar contents of 0, 4.8, 16.7, 37.5, and 50% were prepared. Next, the targeted amount of cement (5% by weight of sand and biochar) was measured and added to the mixture. The water to cement ratio was chosen as 1:1 so an equal amount of deionized water was also added. The materials were thoroughly mixed inside a bowl for 10 minutes using a spatula. Once the mixture was ready, a 5 mL scoop was used to prepare 8 layers of mixture with a height of 5 mm in the consolidation cell. 10 blows were applied to each layer using a 1 kg tamper. Then, a digital caliper was used to measure the height of the sample inside the consolidation cell. The final height of the samples was about 40 mm in height.
5.1.2. Procedure

After sample preparation, the top cap was placed on the sample so that the two embedded bender elements were aligned. The test schedule consisted of four steps. Initially, the samples were allowed to cure for 7 days inside the consolidation cell under an applied seating load of 12 kPa. The strains and S-wave velocities were monitored during curing. After curing, the same incremental loading schedule adopted for sand-biochar mixtures was followed for lightly cemented sand-biochar mixtures. The initial loading phase consisted of applying incremental consolidation pressures of 12, 24, 48, 96, and 192 kPa followed by unloading at pressures of 96, 48, and 24 kPa. During reloading, the samples were then subjected to pressures of 48, 96, 192, 384, and 768 kPa. Every load increment was applied to the samples for 15 minutes. At the end of each load increment the settlement and S-wave velocities were measured.

5.1.3. Results

The results of the consolidation tests are shown in Figures 26 and 27. The stress-strains curves of five lightly cemented sand-biochar samples were plotted in Figure 26. The void ratios of each sample at each loading stage can be seen in Figure 27. Figure 26 shows that strains increased in lightly cemented sand-biochar mixtures with the increase in applied stresses and increase of biochar content. Also, for the samples with biochar contents of 16.7, 37.5, and 50%, strains were much higher than those measured for the samples with 0 and 4.8% biochar contents. This indicates that cement addition might not be effective for strain reduction at higher biochar contents as compared to the 1D consolidation tests of sand-biochar mixtures without cement. At biochar contents of 0 and 4.8%, however, the resulting maximum strains were 0.95 and 1.63%, respectively. This demonstrates that cement addition had positive impacts on samples with low biochar contents.
Figure 26. Strains versus applied stress for lightly cemented sand-biochar mixtures.

Figure 27 shows the void ratios at initial loading, unloading, and reloading of the lightly cemented sand-biochar mixtures. The sample without biochar (pure Ottawa 20-30 sand sample) showed very little variation of void ratios. With the increase of biochar contents, the differences between initial and final void ratios increased. For the sample with a biochar content of 4.8%, the difference between initial void ratio ($e_i = 0.36$) and the final void ratio ($e_f = 0.34$) was equal to 0.02. However, the sample with a 50% biochar content showed a decrease in void ratio. The difference between initial and final void ratios ($e_i = 0.80$ and $e_f = 0.68$) was equal to 0.12.
5.2. Shear Wave Velocities

The S-wave velocities of lightly cemented sand-biochar mixtures were calculated following the calculation procedure detailed in section 4.2.2. Figure 28 shows the variation of S-wave velocities with the increase of applied vertical stress. During cement curing lightly cemented sand-biochar mixtures, S-wave velocities were monitored under a sitting load of 12 kPa. As cementation occurred within the samples, S-wave velocities gradually increased. The lightly cemented mixture containing 4.8\% of biochar experienced the greatest increase in S-waves velocity during curing (from 715 m/s to 817 m/s in seven days). Cemented Ottawa 20-30 sand, however, showed the smallest change in S-wave velocity with a small increase of 0.224 m/s in seven days. The remaining samples showed an average increase of S-wave velocities of about 23 m/s during curing.
The loading and unloading stages of sand-biochar mixtures followed the same trendline. In other words, there was no change in the S-wave velocity slope for initial loading and unloading. However, with cement addition, S-wave velocities either remained constant or showed a slight increase with vertical stress during initial loading, and then considerably decreased during unloading suggesting loss of cementation. This level of decrease of S-wave velocities during unloading was less pronounced as the biochar content increased. Also, the level of cementation of the samples decreased with increasing biochar content. With cement addition, the Ottawa 20-30 sand sample showed minimal changes in S-wave velocities with the increase of applied stress, thus yielding a curve with a slope close to zero. The measured S-wave velocities of Ottawa 20-30 sand were higher than those of other samples.

A similar behavior is exhibited by the sample with 4.8% biochar content (as shown in Figure 28), however, there was a slight decrease in S-wave velocities at 192 and 384 kPa. For the lightly cemented samples with biochar contents greater than 4.8%, the S-wave velocities increased with applied stress, indicating that the effect of cement did not significantly improve the responses of S-wave velocities under loading. Also, the increase in biochar content caused the decrease of S-wave velocities.

The maximum shear moduli of lightly cemented sand-biochar mixtures were calculated using equation (1) and plotted in Figure 29. The variations of shear moduli were similar to the S-wave velocities.
Figure 28. S-wave velocities for lightly cemented sand-biochar measured during curing, loading, unloading, and reloading.

Figure 29. Small-strain shear modulus versus applied stress for lightly cemented sand-biochar mixtures

### 5.3. Hydraulic Conductivity Tests

Permeability tests were conducted on lightly cemented sand-biochar mixtures to measure their hydraulic conductivities and compare them to those of sand-biochar mixtures. These
permeability tests were conducted using the same apparatus and procedure as described in section 4.3.

5.3.1. Sample Preparation

Before sample preparation, Vaseline was used to grease the inside wall of the specimen ring and the two sealing caps were used to ensure the samples remained undisturbed during curing. About 420 g of sand-biochar mixtures with 0, 4.8, 16.7, 37.5, and 50% biochar contents were collected in a bowl. Then, 5% cement by weight of sand and biochar was calculated, measured, and added to the sand-biochar mixture. Water, as an equal amount of cement, was added to the mixture to achieve a 1:1 water to cement ratio. The contents of the bowl were then thoroughly mixed for 10 minutes. Next, one of the sealing caps was placed on the bottom of the specimen ring so that only the top of the sample was open. Using the 5 mL scoop, 10 layers of equal thickness (5 mm thick) were compacted in the specimen ring. Each layer received 30 compaction blows by a 1 kg tamper. After specimen preparation, the second sealing cap was placed on top of the specimen ring. The sample was allowed to cure for 7 days before testing. After curing, the top sealing cap was removed from specimen ring and replaced with a gasket with the lower porous plate. The sample was then turned upside down so that it stood on the gasket and the second sealing cap was removed. Next, the sample was partially saturated inside a desiccator filled with deionized and deaired water for at least 6 hours.

After partial saturation, the gasket with the upper porous plate was placed on top of the specimen ring. Using the line connected to the water tank, the water elevation inside the desiccator was raised so that the sample was submerged. Each sample was fully saturated for an hour before the test. Following sample preparation, the automated permeameter was connected to the computer.
and the data acquisition software (KSAT View) was launched. The specimen was then removed from the desiccator, placed on the measuring dome, and secured with the screw cap to begin testing.

5.3.2. Results

The hydraulic conductivities normalized at 10 °C for every lightly cemented mixture were plotted against the hydraulic gradient. Figure 30 showed less variability of hydraulic conductivities with an increase in hydraulic gradient for the lightly cemented mixtures. As opposed to sand-biochar mixtures, the hydraulic conductivities of lightly cemented sand-biochar mixtures did not decrease but rather remained constant or showed a slight increase. Indeed, hydraulic conductivities for lightly cemented Ottawa 20-30 sand ranged from $1.55 \times 10^{-4}$ m/s at $i = 0.6$ to $2.86 \times 10^{-4}$ m/s at $i = 3$, with an average of $1.99 \times 10^{-4}$ m/s. Similarly, the hydraulic conductivities for the lightly cemented sample with 50% biochar content were $3.05 \times 10^{-6}$ m/s at $i = 0.6$, $2.52 \times 10^{-6}$ m/s at $i = 0.8$, and $4.19 \times 10^{-6}$ m/s at $i = 3$. The hydraulic conductivities of lightly cemented samples with 4.8, 16.7, and 37.5% biochar contents remained almost constant with minimal fluctuation. An important observation was that the sample with a biochar content of 4.8% showed higher hydraulic conductivities than the lightly cemented sand sample without biochar as shown in Figure 30.
Figure 30. Hydraulic conductivities of lightly cemented sand-biochar mixtures normal at 10°C

5.4. SEM Imaging

After the 1D consolidation tests of lightly cemented sand-biochar mixtures, samples were conserved for SEM imaging. The effects of cement addition on sand-biochar mixtures were

Figure 31. SEM images of lightly cemented Ottawa 20-30 sand at (a) magnification of 50x
analyzed through SEM imaging. Figure 31 shows the SEM images of the lightly cemented sand sample at magnifications of 50x and 100x. The cemented Ottawa 20-30 sand particles were highly cemented. Strong cementation bonds were created between sand particles.

Figure 32 shows the SEM images of the lightly cemented sample containing 4.8% biochar content obtained at magnifications of 28x, 65x, 350x, and 2000x. It is observed that at 65x magnification, sand and biochar particles were cemented with apparent pores. At 350x magnification, the sand particles are seen covered with cement. At 2000x magnification, cementation was observed on the surface of biochar particles, but not inside the pores. Due to cementation, some of the pores within biochar appear to be closed as shown in Figure 32.
Figure 33 shows the SEM images obtained for the lightly cemented sand-biochar mixture containing 16.7% of biochar, at magnifications of 1000x, 1500x, 2500x, 5000x, and 35000x. At magnifications of 1000x and 1500x, pores are visible, and there is less cement on the surface of sand and biochar particles compared to the previous sample (i.e., lightly cemented sand with 4.8% biochar content). At 2500x magnification, cement particles are observed on the surface of biochar particles but not inside pores. At magnification of 35000x, the microstructure of cemented biochar resembles the hexagonal shape of honeycomb as seen in Figure 33.

Figure 34 shows the SEM images for the lightly cemented sand-biochar sample at 37.5% biochar content. At 350x magnification, cementation appears to be weak within the sample. Cement particles are dispersed on the surface of sand and biochar particles and pores are visible. At 650x and 2000x magnifications, fewer cement fibers and particles are seen on the surface of biochar particles. The biochar pores also appear unobstructed.
Figure 32 (cont.). SEM images of lightly cemented sand containing 4.8% of biochar at magnifications of 28x, 65x, 350x, and 2000x.

Figure 33. SEM images for lightly cemented sand-biochar with 16.7% biochar.
Figure 33. (cont.) SEM images for lightly cemented sand-biochar with 16.7% biochar.

Figure 34. SEM images of lightly cemented sand with 37.5% biochar content.
Figure 35 shows the SEM images for a lightly cemented sand-biochar sample at 50% biochar content. At 65x magnification, the image shows sand and biochar particles separated from each other, with cement covering a sand particle. The bonds between sand, biochar and cement are inexistent indicating there is almost no cementation in the sample. At magnification of 200x, cement is seen dispersed on the surface of some biochar particles and the amount of pores in the sample is significant.
5.5. **EDS Results**

The EDS analysis on lightly cemented sand-biochar mixtures was conducted after SEM imaging on the samples with a biochar contents of 0 and 16.7%. Figures 36 and 37 show the EDS results. The lightly cemented Ottawa 20-30 sand showed high amounts of silicon (Si) and oxygen (O) with weight percentages equal to 37.4% and 22.1%, respectively. Calcium (Ca), aluminum (Al), and sulfur (S) typically found in cement were detected in the sample, but at lower weight percentages of 16.6%, 5.4%, and 3.6%, respectively. A very small amount of carbon (C) detected (3.8% weight percentage), which was expected as the sample did not contain biochar. The platinum (Pt) detected was likely from the coating agent used to prepare the sample.

![Figure 35. EDS Results for lightly cemented sand with 5% cement.](image)

Figure 37 shows the EDS results for sand with 16.7% of biochar content. The predominant element in the mixture is silicon (Si) with a weight percentage of 34.5%, followed by oxygen (O) at 33.1%. Compared to the lightly cemented Ottawa 20-30 sand mixture, the sample with 16.7% biochar content contained more carbon (C) due to biochar, but fewer amounts of calcium (Ca) and aluminum (Al). Platinum (Pt) from the coating agent was also detected in the mixture.
Figure 36. EDS results for lightly cemented sand with 16.7% biochar content.
CHAPTER 6. ANALYSIS AND DISCUSSIONS

In this chapter, the results of the different laboratory tests performed in chapter 4 and 5 were compared and discussed to determine the suitability of sand-biochar and lightly cemented sand-biochar mixtures for roadway fill applications.

6.1. 1D Consolidation Tests

6.1.1. Sand-Biochar Mixtures

Sand-biochar mixtures were subjected to 1D consolidation tests at different biochar contents in dry and saturated conditions and their consolidation parameters were compared. The strains and void ratios of sand-biochar samples at biochar contents of 0, 2, 4.8, 9.1, 16.7, 28.6, 37.5, 44.4, and 50% were plotted against applied stress, as shown in Figures 15 and 16.

Figure 38 shows the initial void ratio of sand-biochar mixtures against biochar content. The lowest initial void ratio value \(e_i = 0.325\) was achieved at 4.8% biochar content, and the highest void ratio \(e_i = 0.817\) was at 44.4% biochar content. This suggests that in the sample with 4.8% biochar content, biochar particles filled the voids thus yielding a low void ratio value.

The compression and recompression indices \((C_c\) and \(C_r)\) were calculated for each sample and plotted in Figure 39. Figures 39a and b show there is a good agreement between dry and saturated conditions in terms of compressibility. Sand-biochar samples became more compressible as biochar content increased. For tests conducted in dry condition, \(C_c\) was equal to 0.007 at 0% biochar content (i.e., pure Ottawa 20-30 sand), and almost doubled at 4.8% biochar content \((C_c\) was equal to 0.012). At 50% biochar content, \(C_c\) was equal to 0.04, approximately 3.5 times that of the sample with 4.8% biochar content, and 6 times that of pure Ottawa 20-30 sand. The recompression index \((C_r)\), on the other hand, showed less variation between samples with different biochar contents. The recompression indices \((C_r)\) were equal to 0.003, 0.004, and 0.014 for samples
with 0, 4.8, and 50% biochar contents, respectively. Similar results were obtained in saturated conditions, as shown in Figures 39a and b.

![Figure 37. Initial void ratio versus biochar content.](image)

![Figure 38. (a) Compression index of sand-biochar mixtures versus biochar content, (b) recompression index of sand-biochar mixtures versus biochar content.](image)

6.1.2. Lightly Cemented Sand-Biochar Mixtures

The addition of 5% cement (weight of cement divided by the weight of the sand-biochar mixture) to sand-biochar mixtures was expected to improve the consolidation properties of sand-
biochar mixtures. As shown in Figure 40a, lightly cemented samples had lower maximum strains than sand-biochar mixtures when the biochar content is less than 4.8%. At 4.8% biochar content, the maximum strain achieved for the lightly cement mixture was 1.63%, indicating a 24% decrease compared to the maximum strain of sand-biochar at 4.8% biochar content. However, after 16.7% biochar content, lightly cemented mixtures sand-biochar mixtures showed higher maximum strains than sand-biochar mixtures. A 43% increase in strains is observed with cement addition for the sample with 16.7% biochar content.

Figure 39. (a) Maximum strains of sand-biochar and lightly cemented sand-biochar mixtures versus biochar content, (b) initial void ratio of sand-biochar mixtures and lightly cemented sand-biochar mixtures versus biochar content.

The initial void ratios of lightly cemented mixtures are shown in Figure 40b. There is a good agreement between dry and saturated void ratios for sand-biochar mixtures. It should be noted that, for lightly cemented sand-biochar mixtures, initial void ratios were computed without accounting for cement in the samples. Cement particles were considered as voids so the real void ratios of lightly cemented mixtures might be slightly smaller.
Figure 40. (a) Compression index $C_c$ versus biochar content and (b) recompression index $C_r$ versus biochar content for sand-biochar and lightly cemented sand-biochar mixtures.

The consolidation parameters ($C_c$ and $C_r$) of lightly cemented mixtures were also computed and plotted for comparison, as shown in Figure 41. Lightly cemented mixtures show a lower compressibility than sand-biochar mixtures without cement addition at biochar contents less than 16.7%. At 4.8% biochar content, $C_c$ was equal to 0.0097, indicating a 19% decrease compared to the sand-biochar mixture at the same biochar content without cement. However, at biochar contents greater than 16.7%, the compression index is higher for lightly cemented mixtures than sand-biochar mixtures without cement. At 37.5% biochar content, the $C_c$ increased from 0.037 to 0.063 with cement addition.

Cement addition had more pronounced effects on the recompression index, $C_r$. As seen in Figure 41b, the recompression index doubled from 0.006 to 0.012 with cement addition for samples with 16.8% biochar contents. At 50% biochar content, the recompression index showed the greatest increase from 0.014 to 0.031 with cement addition. This suggests that cement addition did not significantly improve the consolidation properties of sand-biochar mixtures for samples with biochar contents greater than 4.8%.

6.2. Shear Wave Velocities Results
6.2.1. Sand-Biochar Mixtures

Figures 21 and 22 presented the results of S-wave velocities and shear moduli for sand-biochar mixtures. Samples with less than 16.7% biochar content had the highest initial S-wave velocities and initial small-strain shear moduli. These parameters decreased when the biochar content increased. The plotted S-wave velocities exhibited a power relationship with the applied stress, as shown in Equation (3).

\[ V_s = \alpha \left( \frac{\sigma'_{z}}{1 \text{kPa}} \right)^\beta \]  

(3)

where \(\alpha\) is the S-wave velocity in m/s at 1 kPa, \(\sigma'_{z}\) is the applied vertical stress and the exponent \(\beta\) reflects the sensitivity of S-wave velocity to changes in stress. Values of \(\alpha\) and \(\beta\) were determined for each sample by fitting a power function trendline to each data set. In dry conditions, \(\alpha\) values ranged from 55 m/s to 174 m/s and \(\beta\)-exponents ranged from 0.17 to 0.27. In saturated conditions, the \(\alpha\) and \(\beta\) values ranged from 46 m/s to 157 m/s and 0.13 to 0.36, respectively. Less compressible soils exhibited higher \(\alpha\) factors and lower \(\beta\) exponents. For instance, the \(\alpha\) factors for pure Ottawa 20-30 sand and samples with 2, 4.8, and 9.1% biochar contents were greater than 100 m/s (in both dry and saturated conditions). The \(\beta\) exponents ranged from 0.17 to 0.24 in dry conditions and from 0.13 to 0.30 in saturated conditions. These results are plotted and compared with the typical \(\alpha\) and \(\beta\) values for sands in Figure 41. As seen in Figure 41, the \(\alpha\) and \(\beta\) values of uncemented sand-biochar mixtures were in relatively good agreement with \(\alpha\) and \(\beta\) trends for natural sands and that uncemented sand-biochar samples have a behavior similar to natural sands relative to S-wave velocity.
6.2.2. Lightly Cemented Sand-Biochar Mixtures

The $\alpha$ and $\beta$ values for lightly cemented mixtures were also computed and shown in Figure 42. At 0 and 5% biochar contents, the $\beta$ values were close to zero indicating that their S-wave velocities were not susceptible to changes of applied stresses. The $\alpha$ factors, however, were higher compared to those of sand-biochar mixtures at the same biochar contents. The $\alpha$ factors are equal to 916 m/s for lightly cemented Ottawa 20-30 sand and 828 m/s for lightly cemented sand with 4.8% biochar content. At 16.7% biochar content, the $\alpha$ factor decreased to 267 m/s while the $\beta$ exponent increased to 0.05, indicating low susceptibility to changes of stress. Similarly, at 37.5% and 50% biochar contents, the $\alpha$ factors kept decreasing while the corresponding $\beta$-exponent increased. At 50% biochar content, where the compressibility indices are the highest among lightly cemented mixtures (Figure 41), the $\beta$-exponent was equal to 0.14. It can be concluded that lightly cemented sand-biochar mixtures had higher S-wave velocities and $\alpha$ factors, and the lower $\beta$-exponent values as compared to uncemented sand-biochar mixtures. This indicates that lightly cemented sand-biochar mixtures are less susceptible to stress-sensitivity than uncemented sand-biochar mixtures.

Figure 43 shows the comparison between uncemented and cemented sand-biochar mixtures. It is observed that S-wave velocities decrease with increasing biochar contents and that cement addition improved the overall responses of S-wave velocities. The initial S-wave velocities reduced from 817 m/s at 4.8% biochar content to 189 m/s at 50% biochar content (as shown in Figure 43), indicating that the effects of cement addition are more pronounced in samples with lower biochar contents.
Figure 41. $\alpha$ and $\beta$ values for sand-biochar and lightly cemented sand-biochar mixtures compared with typical values for sands.

Figure 42. Initial S-wave velocities of sand-biochar and lightly cemented sand-biochar mixtures versus biochar content.
6.3. Hydraulic Conductivity Results

6.3.1. Sand-Biochar Mixtures

Figure 25 showed the decrease of hydraulic conductivity with the increase of hydraulic gradient is observed, for samples with 9.1 to 50% biochar content. This can be explained by the fact that biochar particles are lightweight and can easily be transported through the samples, causing pore clogging in the samples. Samples with high biochar contents which looked dark (almost black) before the permeability test would have a light color (the color of sand) at the bottom and gradually darken along the length of the sample and be completely black at the top. This was evidenced by the color change of the effluent solutions at end of permeability tests, as shown in Figure 44. Biochar erosion also occurred during testing. Also, some biochar particles were transported out of the sample into the discharged water line. The decrease of hydraulic conductivities with increased hydraulic gradient indicated that clogging in the samples (i.e., decreasing hydraulic conductivities) had a greater impact than biochar erosion (i.e., increasing hydraulic conductivities).

The hydraulic conductivities measured at different hydraulic gradients and normalized at 10 °C of sand-biochar mixtures were averaged for each sand-biochar sample and plotted against biochar content in Figure 44. The average hydraulic conductivities of samples with 0% (i.e., pure Ottawa 20-30 sand) and 2% biochar contents were measured to be $8.7 \times 10^{-4}$ m/s, and $5.15 \times 10^{-5}$ m/s, respectively. From 4.8% to 9.1% biochar content, the average hydraulic conductivity of the sand-biochar mixture decreased by more than one order of magnitude from $1.54 \times 10^{-4}$ m/s to $1.09 \times 10^{-5}$ m/s. At the biochar contents greater than 16.7%, the measured hydraulic conductivities ranged from $1 \times 10^{-6}$ to $1 \times 10^{-5}$ m/s. Among all the sand-biochar mixtures, the samples with 2 and 4.8% biochar contents presented with the best drainage properties with average hydraulic conductivities equal to $5.15 \times 10^{-4}$ and $1.54 \times 10^{-4}$ m/s, respectively.
6.3.2. Lightly Cemented Sand-Biochar Mixtures

Figure 30 showed the variation of hydraulic conductivities with increasing hydraulic gradients for lightly cemented sand-biochar mixtures. Lightly cemented samples with biochar contents of 4.8, 16.7, and 37.5% did not exhibit significant changes in hydraulic conductivity with the increase of hydraulic gradient. The lightly cemented sand-biochar samples with 0 and 50% biochar contents, however, showed a slight increase in hydraulic conductivity with the increase of hydraulic gradient. It is unclear why this decrease occurred for the samples with 0 and 50% biochar contents.

Figure 45 shows the comparison of averaged hydraulic conductivities between sand-biochar mixtures and lightly cemented sand-biochar mixtures. While cement addition reduced the hydraulic conductivities of pure Ottawa 20-30 sand by 77%, lightly cemented samples with 4.8% and 16.7% biochar contents showed an increase in hydraulic conductivities as compared to uncemented sand-biochar mixtures. At 4.8% biochar content, the averaged hydraulic conductivities increased from $1.54 \times 10^{-4}$ m/s to $2.70 \times 10^{-4}$ m/s with cement addition. At 16.7% biochar content, the averaged hydraulic conductivities increased from $4.39 \times 10^{-6}$ m/s to $5.76 \times 10^{-5}$ m/s with cement
addition. At biochar contents of 37.5% and 50%, the measured hydraulic conductivities were similar between cemented and uncemented samples. It is important to note that, at 4.8% of biochar content, cement addition increased the hydraulic conductivity by 36% (from $1.99 \times 10^{-4}$ m/s to $2.70 \times 10^{-4}$ m/s). Thus, it can be concluded that cement addition to sand-biochar mixtures reduced the possibility of pore clogging in the samples and improved the hydraulic conductivities at biochar contents that ranged between 4.8% and 16.7%.

Figure 44. Hydraulic conductivities of sand-biochar mixtures and lightly cemented sand-biochar mixtures at different biochar contents.

6.4. **Optimal Sand-Biochar Mixing Ratio**

To achieve a sustainable fill material suitable for roadway applications, the use of cement is not recommended due to the energy-intensive processes associated with its production. Among the sand-biochar mixtures tested at different biochar contents, the samples with biochar contents up to 10% demonstrated a low susceptibility to deformation with maximum strains less than 2.5%,
S-wave velocities ranging from 183 to 553 m/s, small-strain moduli ranging from 61 MPa to 578 MPa, and good drainage properties with average hydraulic conductivities ranging from $1.09 \times 10^{-5}$ m/s to $5.15 \times 10^{-4}$ m/s. Therefore, sand-biochar mixtures with biochar contents up to 10% are recommended as a fill material for roadway applications.
CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

This thesis documented the comprehensive study of sand-biochar mixtures and lightly cemented sand-biochar mixtures to assess their suitability as a fill material for roadway application. Results from 1D consolidation tests, hydraulic conductivity tests, and S-wave velocity measurement were presented and discussed. The following conclusions were drawn:

- The densities and specific gravities of sand-biochar mixtures decrease with increasing biochar content. At 50% biochar content, a 28% decrease in density and specific gravity was observed.

- Sand-biochar mixtures were less compressible at low biochar contents (less than 4.8% biochar content). Biochar particles (which are smaller in diameter than sand particles) filled the voids within the sand matrix, causing a decrease of void ratio. Furthermore, cement addition improved compressibility of sand-biochar mixtures but only at biochar contents that were less than or equal to 4.8%.

- The S-wave velocities and small-strain shear moduli of sand-biochar mixtures decreased with biochar addition and increase with applied stresses. The improvement of S-wave velocities due to cement addition (5% by weight) ranged from 90% at 50% biochar content to 248% at 0% biochar content. Lightly cemented sand-biochar mixtures showed minimal variation of S-wave velocities with applied stresses compared to sand-biochar mixtures.

- The hydraulic conductivities of sand-biochar mixtures decreased with biochar content. However, sand-biochar mixtures with biochar contents lower than 4.8% still showed favorable drainage properties. Cement addition only improved the hydraulic conductivities of sand-biochar mixtures at 4.8% biochar content.
• Sand-biochar mixtures with biochar contents up to 10% showed satisfactory consolidation properties and drainage properties. This range of biochar contents is recommended for consideration in the design of fill material for roadway applications.

• Even though the addition of biochar to sand did not improve its consolidation and hydraulic properties, the use of biochar is recommended because of its carbon sequestration ability, and its potential for contaminant retention and water retention for stormwater runoff mitigation. From a sustainable design point of view, cement addition should not be considered given that its improvement of sand-biochar mixtures was not significant. However, more tests are needed to determine the applicability of sand-biochar mixtures as a sustainable fill material for roadway application.

• Future tests are needed to advance biochar application in roadway embankments, including (1) investigating the compaction and density requirements of sand-biochar mixtures for use as a roadway fill material according to the requirements of DOTs, (2) evaluating the potential of contaminants absorption for sand-biochar mixtures at different biochar contents, and (3) assessing the erodibility and durability of sand-biochar mixtures at different biochar contents.
REFERENCES


VITA

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