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Experimental evaluation of the engineering behavior of soil-biochar mixture as a roadway construction material

FINAL REPORT

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16. Abstract Past studies have investigated the influcendes of biochar addition on the nutrient removal and saturated conductivity properties of soils. Literature survey showed that there is a gap in the amount of work devoted to studying the effects of biochar addition on strength and volume change properties of soils. If biochar amended soils are to be used as geo-environmental construction materials, their mechanical behavior needs to be examined in depth. This project describes a laboratory-based experimental program that was conducted to study the mechanical properties of a mid-atlantic native intermediate silty sand that was amended with different biochar volume percentages. The effect of compactive effort is specially scrutinized on biochar amended soils. Results are interpreted and comparative discussions are made with respect to the limited studies found in the literature. Speculations are made on biochar's potential as a viable ground improvement material for geo-environmental engineering applications.			
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BACKGROUND

Introduction

The objective of this work was to advance a fundamental and mechanistic understanding of biochar's influence on soil strength and deformation behaviors. This understanding is critical in achieving the following goals: The development of procedures for laboratory and field testing of biochar-soil mixtures and models that predict the influence of biochar on upscaled hydro-mechanical soil properties; The identification of areas of application for soil-biochar mixture on a mid- to large-scales; The development of practical ways of implementation for soil-biochar mixture as a qualifying engineered-geomaterial; and Devising quality check/control mechanisms.

The results of this project will provide preliminary work and data that will become invaluable inputs for a federally funded larger long-term research. Such research, in turn, will enable doing a robust investigation of the potential benefits of soil-biochar mixtures and answering essential fundamental questions before widespread biochar application can occur.

Biochar is one of the innovative "construction materials" that has gained popularity in recent years. It is a carbon rich product obtained when plant-based or poultry-based biomass is heated in a closed container with little or no oxygen. Its positive attributes include carbon dioxide removal (sequestration) from the atmosphere, increasing plant fertility, decreasing nutrient leaching, enhancing moisture retention capacity in soils (i.e. reduced irrigation needs). More or less, all of the listed benefits circle around improving our environment and are all related to the effects biochar impose on the flow-related behavior of soils. It should be noted that, the moisture retention and/or conduction of biochar-amended soil affects not only their flow-related behavior but also their inherently coupled shear strength- and volume change-behaviors. No robust study has been done to look at the all-round effects of biochar addition on soils. Past studies singled out and investigated the flow-related aspects of biochar addition and a very few studies looked at how other geotechnical engineering properties got affected.

In agriculture, biochar has been applied to soils to enhance their fertility. In engineering, the current application of soil-biochar mixtures is limited to using them as stormwater management, bio-retention, and landfill cover media, applications that heavily depend on the flow-related properties of the mixture. In practice, each soil-biochar mixture is tested for hydraulic properties before field application, a time-consuming and expensive process. In addition, since biochar particles are expected to physically degrade into smaller carbon particles through time, it seems likely that soil-biochar engineering properties will change with time too. Furthermore, biochar particles are expected to undergo a physical change due to daily and/or seasonal temperature fluctuations that include multiple freeze-thaw cycles. Therefore, it becomes imperative to investigate how the inter-related flow-, deformation-, and strength properties of soil-biochar mixture evolve as a function of time and/or temperature in addition to the changes in the physically imposed loads.

Background

Biochar is a charcoal made from biomass via pyrolysis, which is a process that heats biomass in the absence of or very little oxygen [1]. The specific characteristics of the biochar depend on the source used and the specific pyrolysis process. There are many biochar sources, and some include hardwood, switch grass, rice, food wastes, or poultry litter. Lei and Zhang [2] reported that the pyrolysis conditions might differ in temperature, duration of combustion, and air exposure. The different sources can alter the biochar's carbon to nitrogen ratio. In the same work, it was also reported that when the pyrolysis temperature is higher, biochar tends to have a higher specific surface and porosity.

Reports indicate that humanity discharges 43 gigatonnes of carbon dioxide annually.

This discharge is 25% greater than just a decade ago. Studies indicate that converting forestry and agricultural waste into biochar could remove 4 gigatonnes of carbon dioxide each year. Biochar soil amendment has gained strong research interest because of the significant benefits biochar might provide, including carbon dioxide sequestration, increased plant fertility, decreased nutrient leaching, and enhanced soil moisture retention capacity (reduced irrigation). The application of biochar in storm water management is also gaining attention by the state and federal transportation agencies. Even though biochar has been shown to provide these benefits in some soils, in others the benefits have been minimal and sometimes even detrimental. An example is soil hydrology, where biochar sometimes increases and sometimes decreases hydraulic conductivity, the maximum rate of water infiltration under a unit hydraulic gradient. Without models that predict biochar's influence on soil's engineering properties, its large-scale application is severely limited.

Biochar has been used as a soil amendment in agricultural and environmental engineering applications. Its ability to improve soil fertility, to reduce carbon dioxide, methane and nitrous oxide emissions, and to enhance soil microbial life have made biochar a viable soil amendment material [1]. Biochar is composed of stable aromatic forms of organic carbon. This enables it to not degrade to CO_2 easily when it is applied to the soil to absorb pollutants. Because of this stable form, biochar may not require replacement for a very long time once added to the soil [3]. Biochar's ability to resist microbial and chemical decomposition makes it a sustainable soil amendment option. The efficiency of enhancing soil quality is higher in biochar than other organic soil amendments [4].

Biochar amendment has the ability to change the soil's structure, porosity, density, and texture [1]. The high charge density of biochar allows for high nutrient retention [5]. The high surface area and porosity of biochar allow it to increase soil water-holding capacity, cation exchange, and surface sorption capacity of the soil it is added to [1]. Because biochar will change a soil's porosity and density, it also affects the behavior of compacted soil.

Soil compaction enables the soil particles to pack closer together by reducing the air voids through mechanical means [6]. During the standard Proctor test, the addition of water expels the air, so that a higher density can be achieved. The highest density is achieved at the optimum water content [7].

This project evaluated the compacted behavior of a biochar-amended silty sand that is native to the mid-atlantic region. Procedures specified in the standard Proctor test were adopted for the compaction of specimens and results were scrutinized by allowing and preventing remixing of compacted specimens to the source material.

PROPOSED APPROACH

General

Literature survey indicated a shortage of past studies that studied the effect of biochar addition on the engineering properties of soils other than the flow-related ones. One shortcoming of past studies is that their approach towards investigating the effects of biochar addition is not robust. Apparently, the strength and volume change (deformation) behavior of soils are inherently coupled with their hydrological (flow-related) properties. Looking at the flow-related effects only, thus, would be a mistaken approach. In this study it is proposed to investigate the influence of biochar on the strength and volume change properties of soils.

This study proposed a laboratory investigation in which multiple samples were prepared from soil-biochar mixtures (by varying biochar content from none, to 6%, and 10% by volume) and the physicochemical (moisture content, density, specific gravity etc) and mechanical (deformation- and strength-related) properties of the soil only, soil + 6% biochar, and soil + 10% biochar were investigated using standard testing procedures. The unified soil classification system (USCS) was used to classify the soil. Tests such as

Atterberg limit tests [8], sieve analysis [9], hydrometer analysis [10], proctor compaction [11, 12], oedometer [13], and triaxial shear test [14] were conducted for the characterization of the mechanical behavior of the soil and soil-biochar mixtures.

LABORATORY EXPERIMENTS

Materials

The soil used in this project was obtained from a site off of route 301 in Delaware. To complete the soil classification five tests were performed. These tests included specific gravity of soils, liquid limit, plastic limit, sieve analysis, and hydrometer analysis. Using the Unified Soil Classification System (USCS), the soil was classified as a silty sand (SM). More than 50 percent of soil was retained on the number 200 sieve. 50 percent or more of the coarse fraction passed through the number 4 sieve. The sand had fines more than 12 percent. The plasticity index was less than 4. The gradation curve, seen in Figure 1, showed the silty sand was well graded with 13 percent fines.

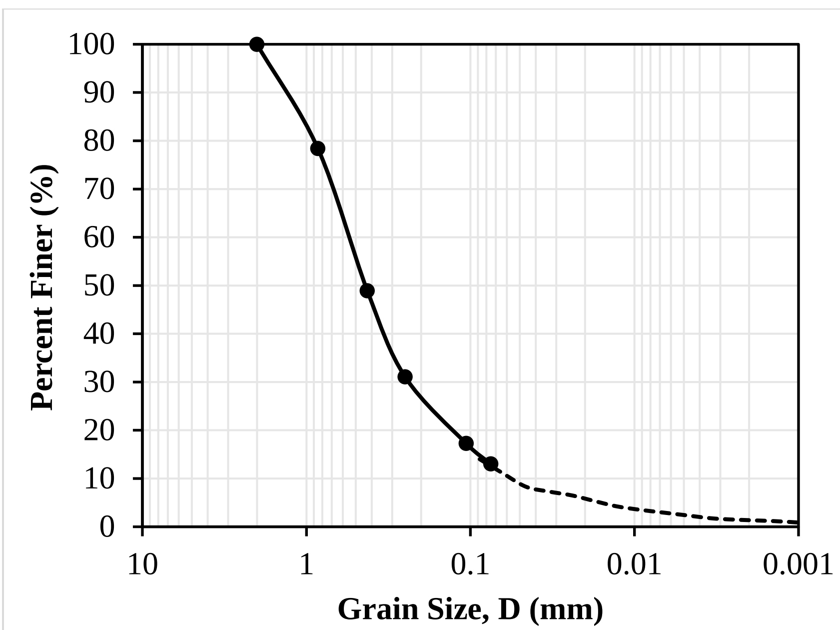

Figure 1 Gradation curve for silty sand from sieve and hydrometer analysis

The biochar used for this research was produced by Soil Reef™ biochar (The Biochar Company, Berwyn, PA). The biochar was made from Southern Yellow Pine by pyrolysis at 550 degrees Celsius for 10 minutes. The biochar that passed through the No. 4 sieve was used for the compaction experiments. The biochar-soil mixtures were created by adding either 6 or 10 percent biochar by volume to the soil.

Specific Gravity of Solids

The procedures stipulated in ASTM D854 were followed to obtain the specific gravity of the soil [15]. Some of the apparatuses involved in the test are shown in Figures 2 and 3. In the estimation of the specific gravity of the soil soilids, the volumetric flask was filled with distilled water up to the 500 ml mark. Then the flask was weighed (M1). The temperature of the water was measured and recorded in a separate graduated cylinder (All distilled water used was at room temperature). Next, distilled water was poured out of the volumetric flask into the beaker so the flask is about one half full. Then, about 50 grams of soil was placed in an evaporating dish and then put into the volumetric flask using the funnel.

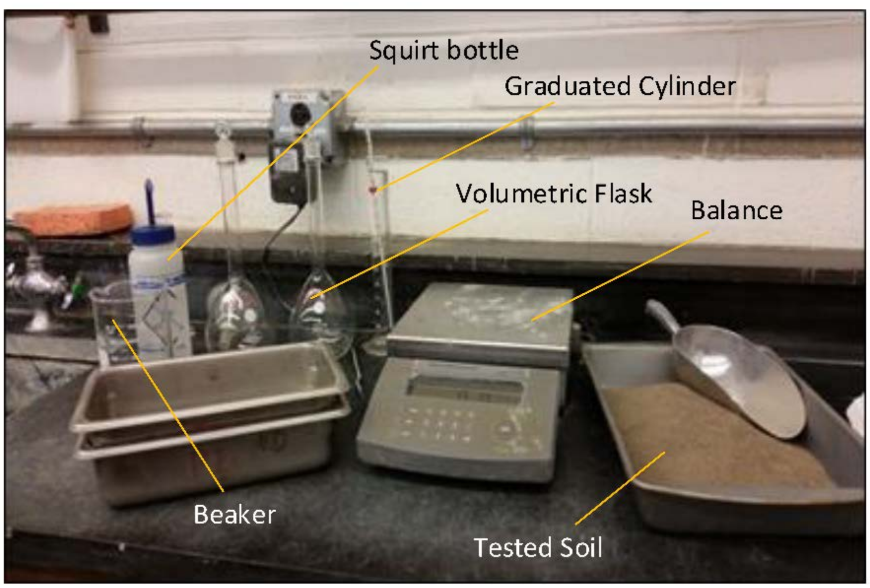

Figure 2 Test setup and materials

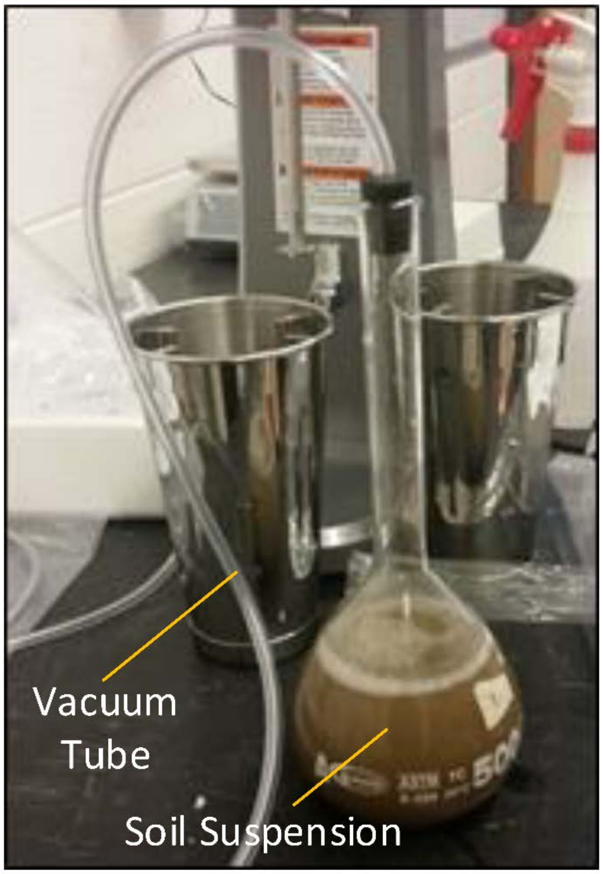

Figure 3 Vacuum system in use

Squirt bottle was used to wash any soil into the flask. Air was then removed from the water-soil mixture using a vacuum. The vacuum tube and stopper were used in order to create a seal. Before applying the vacuum, the flask was swirled to help the air escape. While the vacuum was being applied, the top of the soil-water mixture became foamy. The foam subsided after the entrapped air was removed. Then, distilled water was added to the volumetric flask up to the 500 ml mark and the flask was weighed (M2). Next the empty pan was weighed, then the soil-water mixture was poured into the pan using a swirling technique to get out all of the soil. Water was squirted to remove any remaining soil grains out of the flask and into the pan. After that, the pan was placed in an oven to dry the soil suspension. After the soil dried, the pan (with dry soil inside) was weighed. The mass of the dry soil was calculated from subtracting the pan weight from the pan plus the dry soil weight. This test was completed twice.

Table 1 Specific gravity data

Item	Test 1 (grams)	Test 2 (grams)
Mass of Pan	186.93	540.26
Mass of flask + water (M1)	665.6	647.42
Mass of flask + water + sand (M2)	697.51	679.58
Mass of dry soil + pan	237.81	592.6
Mass of dry soil (Ms)	50.88	52.34

Table 2 Specific gravity calculations

Formula	Test 1	Test 2
Mw(g)=M1+Ms-M2	18.97	20.18
Gs(@T1)=Ms/Mw	2.682	2.59
Gs=Gs(@T1)*A	2.679	2.593

The temperature during this test was 26 degrees Celsius and the value of "A" was 0.9986 from Table 3-4 in the "Soil Mechanics Lab Manual" by Das [16]. The average specific gravity of solids was 2.64, from equation 1.

$$G_{s\,average} = \frac{1}{2}(G_{s1} + G_{s2}) \tag{1}$$

Liquid Limit

The procedures stipulated in ATSM D4318 were followed [8]. Summary of what was done in this project is presented below.

- The moisture can masses were determined.
- About 100 grams of dry soil that passed through the no. 40 sieve was placed in an evaporating dish.
- Water from a squeeze bottle was added to the soil and mixed with the spatula to create a uniform paste.
- Soil paste was placed in the Casagrande liquid limit device (Figure 4). The grooving tool was used to smoot the soil surface to about 8 mm. Then the grooving

tool was used to create a centerline in the soil. Next the crank of the Casagrande liquid limit device was turned at about 2 revolutions per second. The number of blows, corresponding to a 0.5 inch (13 mm) groove closure was recorded.

Figure 4 Casagrande liquid limit device

- A sample of the soil on the device was collected in a moisture can and then weighed. Next it was placed in an oven to dry and then the dry can plus soil was weighed. This process was repeated 3 times and the number of blows (log-scale) was plotted against the moisture content. This plot is commonly referred to as the Flow curve and is shown in Fiugre 5.
- From the flow curve, the liquid limit was determined as the water content corresponding to the number of blows of 25. As such, it was found that the liquid limit of the soil is 27.

Table 3 Liquid limit data

Test Number	1	2	3
Mass of Can (m1)	13.38	13.38	13.61
Mass of Can + Moist Soil (m2)	27.09	22.75	23.93
Mass of Can + Dry Soil (m3)	24.5	21.1	22.1
Moisture Content	23.29	21.37	21.55
Number of Blows (N)	28	35	25

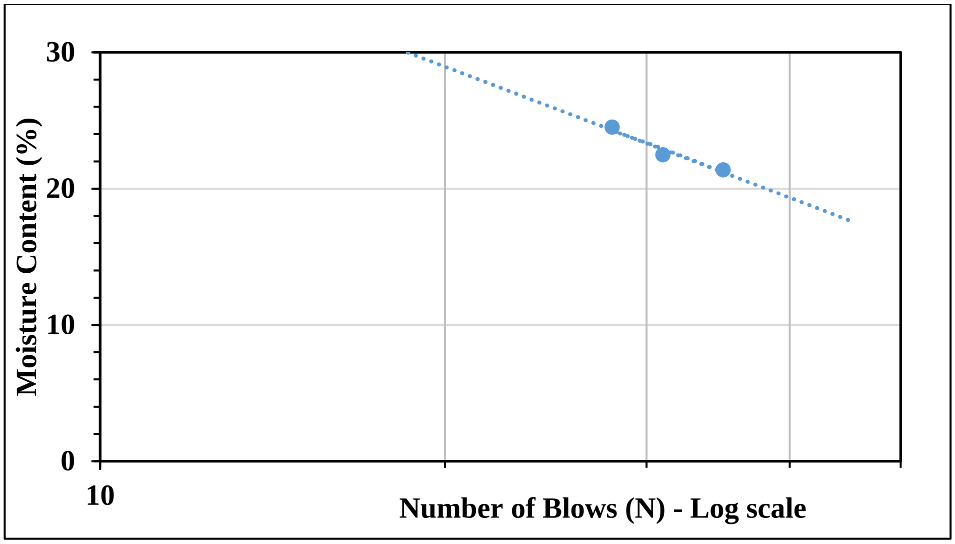

Figure 5 Flow Curve

Plastic limit

The procedures stipulated in ATSM D4318 were followed[8]. Summary of what was done in this project is presented below.

- The moisture cans were weighed.
- About 30 grams of dry soil that passed the no. 40 sieve was placed in an evaporating dish.
- Water was added to the soil with a plastic squeeze bottle and mixed with a spatula.
- A few ellipsoidally shaped soil masses were created and placed on the glass plate. The piece of soils was rolled, using the palms, back and forth until the diameter was about 1/8 inches (3.2 mm).
- This process was repeated until the soil crumbled at that diameter.
- The rolled soil pieces were placed in a moisture can and weighed.
- The can was placed in the oven to dry the soil. The can plus dry soil was then weighed. This procedure was repeated three times.

From the data, the plastic limit was computed as the water content on which the soil started to crumbling when rolled to a diameter of the 1/8 inches (3.2 mm).

Table 4 Plastic Limit data and results

Test number	1	2	3
Mass of can (m1)	13.56	13.47	13.66
Mass of can + moist soil (m2)	18.52	17.26	16.7
Mass of can + dry soil (m3)	17.5	16.5	16.1
PL = (m2-m3)/(m3-m1)	25.89	25.08	24.59
PI=LL-PL	1.112	1.917	2.409

By averaging the results obtained from three tests, the plastic limit was determined as 25.19. With knowledge of the liquid and plastic limits, the plasticity index (PI) of the tested soil was found to be 1.81. This PI is small indicating that the fine fraction of the tested soil is silt.

Grain Size Distribution Analysis (GSD)

For the grain size distribution a combination of the sieve analysis [9] and the hydrometer analysis [10] was used. The following procedures were used to perform the GSD analysis. In the sieve analysis, each sieve and the pan were weighed. Next the sieves were stacked from smallest opening to the largest (bottom to up) with a pan on the bottom (Figure 6a). The sieves were then placed in the mechanical sieve shaker (Figure 6b).

(a) (b)

Figure 6 (a) Sieve stack, (b) Mechanical sieve shaker

Then about 500 grams of soil was weighed and poured into the top sieve. The cover was placed on top and the sieve shaker was turned on for about 15 minutes. Next, each sieve and the pan were weighed with the soil still inside the sieves (see Fig 7). Lastly, the calculations shown below (Table 5) and the grain size distribution graph (solid line in Figure 9) were completed.

Table 5 Sieve analysis data

	Sieve #	Particle Diameter (mm)	Percent Finer (100-Σrn)
Sand	4	4.75	99.99324
	10	2	99.95815
	20	0.85	78.35257
Fine Sand	40	0.425	48.87681
	60	0.25	31.04727
	140	0.106	17.24376
Silt + Clay	200	0.075	13.89012
	pan	N/A	0

Figure 7 Sieves – grain sizes

For the hydrometer analysis, 50 grams of soil that has passed through the No. 200 sieve was put in a beaker. Next the deflocculating agent was prepared by adding 40 grams of sodium hexametaphosphate (Calgon) to a 1000 cm^3 of distilled water and mixing to create a 4 percent Calgon solution. Then 125 cm^3 of the mixture was added to the 50 grams of soil, which was left to soak for 12 hours. 875 cm^3 of distilled water was added to a graduated cylinder along with 125 cm^3 of the Calgon solution and mixed thoroughly.

Next a thermometer was placed in the graduated cylinder to record the temperature. A hydrometer was then placed in the graduated cylinder and the zero and the meniscus correction factors were recorded by looking at the location of the zero mark the bottom of the meniscus, respectively. Then a spatula was used to mix the soil/Calgon mixture that was left to sit for 12 hours. Next the mixture was poured into the mixer cup (distilled water from a squeeze bottle was used to squirt the remaining soil stuck to the beaker into the cup). Distilled water was poured into the cup to make it two-thirds full and the mixture was mixed for two minutes. Then the mixture was poured into the second graduated cylinder and distilled water was used to fill the rest of the cylinder up to the 1000 cm^3 line (see Figure 8).

Figure 8 Soil mixture in graduated cylinders

A number 12 stopper was then placed on top of the second graduated cylinder and turned up and down several times. Then the stopper is removed and hydrometer readings are taken from the upper level of the meniscus at specified times. In between readings the hydrometer was placed in the first graduated cylinder so it is clean before the next reading. The results of the Hydrometer analysis are tabulated in Table 6 and the corresponding grain size distribution curve is shown with the dotted line in Figure 9.

Table 6 Hydrometer analysis data

Particle Diameter (mm)	Percent Finer (%)
0.087828	14
0.064306	11.2
0.045906	8.3
0.033292	7.3
0.023908	6.481981
0.017412	5.303439
0.013025	4.272215
0.009353	3.535626
0.006688	2.946355
0.004782	2.357084
0.00343	1.767813
0.002434	1.473177
0.001415	1.178542
0.001007	0.883906

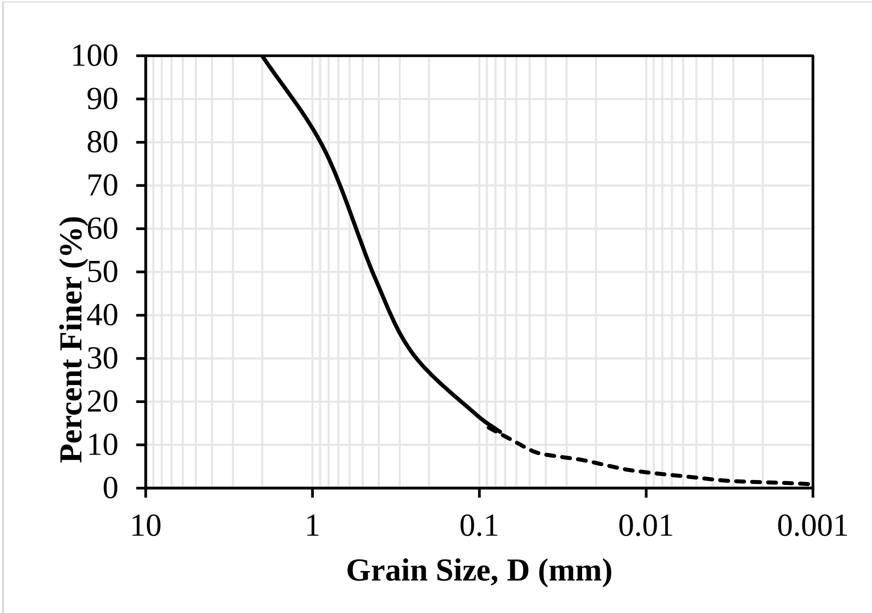

Figure 9 Grain-size distribution curve

Compacted behavior of Soil-biochar mixtures

The soil-biochar mixtures were prepared by hand mixing after the appropriate masses of the biochar and soil were measured. During the standard Proctor compaction test [11], water was added by a squirt bottle to ensure even distribution throughout the mixture. A typical moist soil-biochar mixture can be seen in Figure 10. Compaction tests were completed for the soil itself, a 6 percent (by volume) biochar-soil mixture, and a 10 percent (by volume) biochar-soil mixture. Figure 11 shows the hammer and mold that were used for the standard Proctor compaction test.

Initially, the compaction tests were done following the Das' soil mechanics lab manual [7]. Method A was used because less than 20 percent, by mass, of soil was retained on the number four U.S. sieve (4.75 mm). Therefore the mold had a 4-inch diameter and a volume of 943 cubic centimeters. The hammer weight was 5.5 pounds with a drop height of 12 inches. Three soil layers were created with 25 blows per layer. The manual clearly states that once a sub specimen is created, the remaining soil in the mold can be broken up and added to the leftover soil. Then more water is added to raise the water content to create the next specimen [7].

Figure 10 Moist soil-biochar mixture

Figure 11 Standard Proctor hammer and mold

It was found that the reuse of soil during the test did not work well for the soil-biochar mixtures due to biochar particle breakage. Therefore, this procedure was altered so that once a subsample was created the rest of the compacted mixture would be discarded and the next sample would be comprised of a mixture that had not previously been compacted. It is noteworthy that ASTM D698 does not allow the use of a previously compacted material. This clarification and modification of the Das procedures fixed the problems faced with including altered biochar particles in the estimation of compaction curves. The compaction curves for the soil only did not change when compaction procedures followed Das [16] and ASTM D698. It was concluded that this observation is related to the soil particles not breaking during compaction.

Once the data was collected, a curve fitting was used to plot the compaction curves. A log Gaussian function [17] given in Equation 2 was applied for this purpose. In Equation 2, *A*, *B*, *C*, and *D* are curve fitting parameters that were determined using solver in Excel. The dry unit weight is expressed as γ, the water content is expressed as w, and Euler's constant is shown as e.

$$\gamma_{dry} = Ae^{-\frac{[Ln(w)-B]^2}{C}} + D \qquad (2)$$

The curve fitting parameters that matched the data well are presented in Tables 7 and 8. Tables 9 and 10 present the optimum water content and maximum dry density obtained using compaction tests in which compacted soil was reused and discarded, respectively.

Table 7 Curve Fitting Parameters (Soil reused)

Parameters	Soil	Soil + 6% biochar	Soil + 10% biochar
A	17.65	16.105	14.98
B	2.62	2.78	3.02
C	1.72	1.40	0.93
D	0.099	0.00	0.0099

Table 8 Curve Fitting Parameters (No soil reused)

Parameters	Soil + 6% biochar	Soil + 10% biochar
A	15.87	14.61
B	2.62	2.94
C	3.53	1.28
D	0.10	0.099

Table 9 Unaltered Procedure (Soil reused)

Properties	Soil	Soil + 6% biochar	Soil + 10% biochar
w_{opt} (%)	13.8	16.3	20.3
$\gamma_{d,\,max}$ (kN/m^3)	17.8	16.1	15.0

Table 10 Modified Procedure (No soil reused)

Properties	Soil + 6% biochar	Soil + 10% biochar
w_{opt} (%)	14.0	19.0
$\gamma_{d,\,max}$ (kN/m^3)	16.0	14.7

Figure 12 shows the compaction and zero air void curves obtained for the standard Proctor procedure. In the figure, the cases of soil reuse and no reuse are compiled. The zero air void curves did not change with the addition of biochar or differing of procedure. The curves moved down and to the right with increasing biochar percentage for both approaches. Accordingly, the maximum dry unit weight decreased with increasing biochar percentage and the optimum water content increased with increasing biochar percentage. It is clearly seen that the procedure that allowed soil reuse had compaction curves with a higher maximum dry unit weight and a higher optimum water content than the modified procedure with no soil reuse. When comparing the soil's maximum dry density and optimum water content to the 6 and 10 percent biochar-soil mixtures without soil reuse, a significant change was observed as can be seen in Tables 9 and 10. The change in maximum dry unit weight had a 1.8 kN/m^3 decrease from the soil to the 6 percent soil-biochar mixture. Between the soil and the 10 percent biochar-soil mixture a 3.1 kN/m^3 difference is displayed. The change in optimum water content had a 0.2 percent increase from the soil to the 6 percent soil-biochar mixture. Between the soil and the 10 percent biochar-soil mixture a 5.2 percent difference is shown.

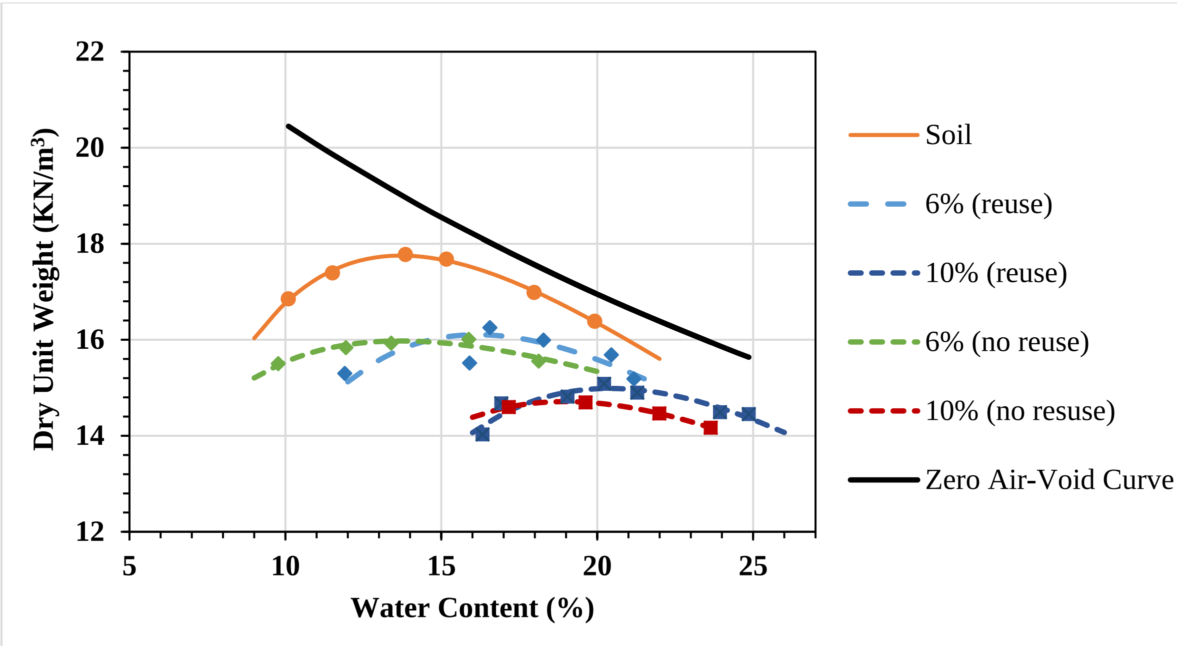

Figure 12 Standard Proctor compaction curves

As can be seen in Figure 13, an almost linear trend is shown between increasing biochar percentage and the maximum dry unit weight. The slope is about -0.3, which indicates a steady decline in maximum dry unit weight with increasing biochar percentage.

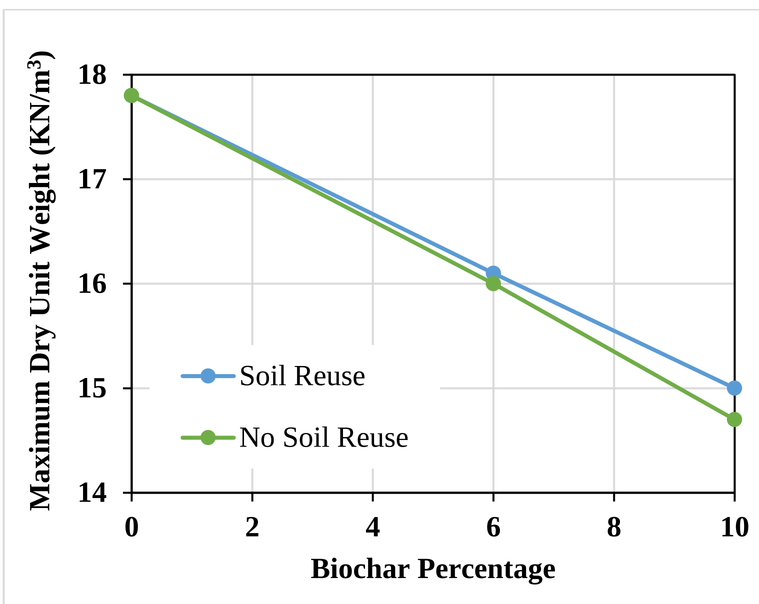

Figure 13 Effect of increasing biochar on maximum dry unit weight

Figure 14 presents the trend displayed by the optimum water content as biochar percentage increases. The change in optimum water content was only 0.1 to 2.3 percent from 0 to 6 percent biochar. From 6 to 10 percent biochar, the change in the optimum water content was 4 percent. It appears that biochar affects the optimum water content of soil non-linearly, closer to a polynomial or exponential trend.

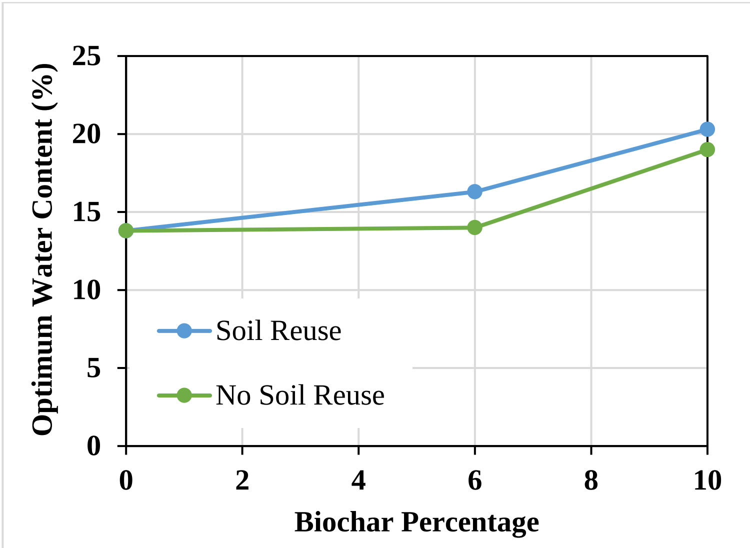

Figure 14 Effect of increasing biochar on the optimum water content

Summarizing the observations made from Figures 12 through 14, it can be said that the compaction procedures in which soil remixing was avoided led to lower maximum dry unit weights and optimum water contents compared to those that allowed remixing. The re-compacted biochar particles would be able to compact to a higher density because the particle structure would be modified by the crushing that followed the impact from the Proctor hammer.

The effect of compaction [11, 12] on the relevant engineering properties of the mixtures was first investigated. Stress strain curves were developed and material variables such as the angle of internal friction and coefficient of cohesion were determined using existing failure criteria (e.g. Mohr-coulomb). The data obtained from a series of physical testing will play a pivotal role in assessing multiple unanswered and unasked questions of the future. Obtained results will be compared amongst each other and engineering discussion/interpretation of results will be made.

Conclusions drawn from compaction testing

Standard Proctor compaction tests were completed using soil only, a 6 percent biochar-soil mixture, and a 10 percent biochar-soil mixture. Two compaction approaches were scrutinized. One, which allowed soil remixing and the other not so. The soil used was a silty sand (SM), and the biochar was produced from an organic source. The following conclusions can be drawn from this experimental study:

1. The addition of biochar to silty sand did impact the soil's compacted behavior. Through the addition of 6 and 10 percent of biochar (by volume) to the soil, the data showed a decreasing maximum dry unit weight and an increasing optimum water content trend.

2. The change in the optimum water content was greater from 6 percent biochar-soil mixture to 10 percent biochar-soil mixture compared to the soil-only and 6 percent biochar-soil mixture. Therefore, with a greater amount of biochar, the optimum water content will increase in a non-linear fashion.

3. The change in maximum dry density between the biochar-soil mixtures was almost linear. Therefore there is a direct correlation between the amount of biochar added to the soil and the maximum dry density. This linear relationship makes predictions of maximum dry density with other biochar percentages simple.

4. The optimum water content was higher when soil remixing was allowed. Therefore, a lower percentage of water was needed to reach a maximum density in the procedure where remixing was not allowed. The compaction procedures for biochar-soil mixtures need to be carefully considered to ensure the biochar particle structure is not broken. A crushed biochar particle will not have as helpful geo-environmental benefits as an intact particle.

Overall, the standard proctor data showed consistent trends with biochar addition. The data can be extrapolated to predict how higher biochar percentages will impact compaction as well as biochar percentages between 0 and 6 and 6 and 10. This data could be used for design if biochar is to be implemented in an area that will be compacted, like the side of a roadway. The density does decrease significantly with 10 percent biochar. Therefore, a balance needs to be reached of having enough biochar to benefit from its geo-environmental uses, while also not using so much that the soil density is too greatly diminished. Biochar is a viable, sustainable option that can be used in compacted soil if the altered soil behavior is considered.

Compressibility

Compressbility behavior of the tested soil, in the presence and absence of biochar, was examined by modifying the ASTM consolidation testing [13]. Here, it was intended to get a relative sense of compression when biochar is added at varied amounts. The following procedure was followed.

First the soil was compacted in the compression ring to s specified density. Next the filter paper and porous stones were added to either side of the ring. These components were assembled onto the oedometer. The loading schedule as shown in Table 11 was adopted. As can be seen, after each 24 hour period, the weight applied to the device was be doubled.

Table 11 Weight added to Oedometer

Day 1	Day 2	Day 3	Day 4	Day 5
2 kg	4 kg	8 kg	16 kg	32 kg

Observing the axial compressions of the specimen (Table 12), it can be concluded that the compressibility of the natural soil increased with the percentage of biochar added. In another study [1], it was reported that the compressibility decreased when biochar percentage was increased. It should be noted that the natural soil investigated in this study was silty sand while that examined by Reddy et al [1] wasn't. From these contrasting observations, it can be hypothesized that depending on the grain size distribution of the soil and the biochar, the effect of adding biochar could be different and therefore, attention should be given to the type and size of the components that make the soil-biochar mixture.

Table 12 Change in specimen height (inches)

Biochar Percentage	0	6	10
Test 1	0.140	0.161	0.133
Test 2	0.110	0.125	0.190
Test 3	0.116	0.144	0.172
Average	**0.122**	**0.143**	**0.165**

Shear Strength Testing

To examine how the shear strength of soil-biochar mixtures change, consolidated undrained (CU) triaxial tests were performed on soil only, 6% biochar, and 10% biochar specimens. The standard procedures stipulated by ASTM [14] were adopted for all tests. The samples were created in a split mold by compacting them to a target density. A typical specimen has a diameter to height ratio of 1:2. One such specimen is shown in Figure 15. The figure on the left shows the soil as compacted inside a split mold and the one on the right shows half of the mold removed.

Figure 15 Silty sand specimen in split mold after tamping

A Trautwein® S-500 panelboard, cell, and GeoJac load frame were utilized for the CU triaxial tests. The panelboard is used to supply required back and cell pressures and the water needed for sample saturation.

In general in Triaxial testing, after the sample is prepared it undergoes the steps of saturation, consolidation and shearing. Saturation and consolidation are performed while the sample (inside a triaxial cell) is connected to the panel board was used for the saturation and consolidation phases. A quick check namely, Skempton's B-check, is done to verify the saturation of specimens. Figure 16 shows the specimen undergoing a B-check. Skempton's B compares how much of the added cell pressure is transferred to the pore-water. If all void spaces are filled with water, any additional cell pressure (σ_3) is transferred to the pore-water (U) and the ratio of the two (see Equation 3 defining B) becomes one. When B is equal (or very close to one), it is believed that the specimen has saturated fully.

$$B = \frac{\Delta U}{\Delta \sigma_3} \quad (3)$$

In this study, two confining pressure values were utilized, 12 psi and 22 psi. To prevent overstressing of the sample and build up of excess pore pressure, 5 psi was added over a 5 minute interval (ramped saturation) to the cell and pore (also referred to as back) pressures until the desired saturation pressure was reached. The cell pressure was always kept 2 psi higher than the sample's pore pressure to avoid sample bulging before shearing. When using a 22 psi confining pressure, during saturation the cell pressure was kept at 60 psi and the pore pressure at 58 psi. During the consolidation phase, the cell pressure was increased to 80.0 psi. When using a 12 psi confining pressure, during saturation the cell pressure was kept at 70 psi and the pore pressure at 68 psi.

During the consolidation phase, the cell pressure was increased to 80.0 psi. Once consolidation was complete, the triaxial cell was moved to the loading frame, where an axially compressive load was applied at a rate of 1 %/hour. The shearing rate was calculated by following the steps in [14]. Shearing was stopped once the specimen's strain reached 15 %.

Figure 16 Triaxial device during a B-check

During shearing the axial displacement is monitored and reported by an axial strain transducer (see Figure 17). The cell and back pressures were monitored with pore-ressure transducers (Figure 17). The axial load is monitored by a sensor fitted to the loading ram (load cell see Figure 17).

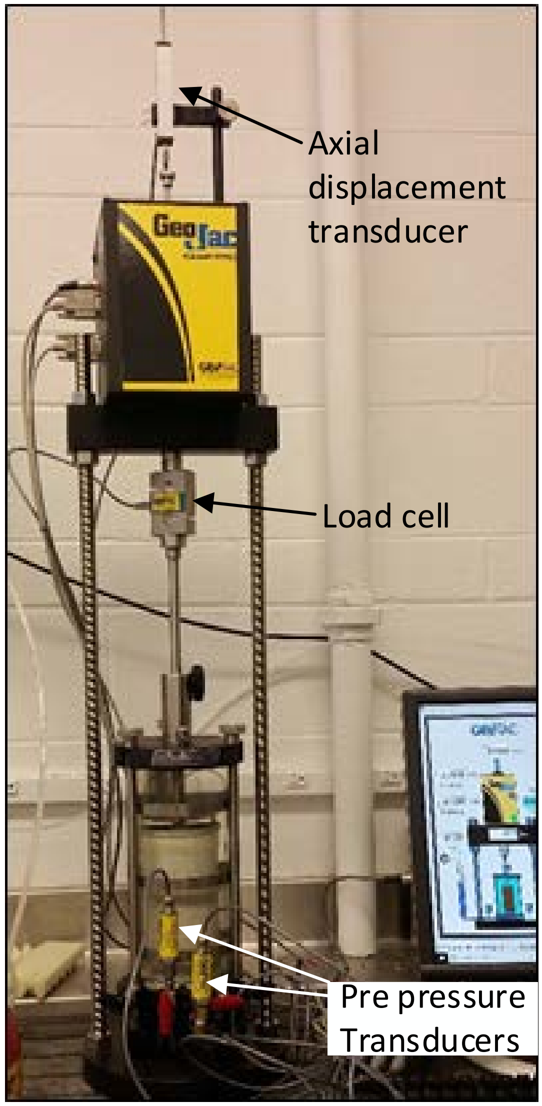

Figure 17 Various sensors in a triaxial system

Figure 18 shows a picture of a specimen that was sheared to failure. The failed specimen is shown in Figure 19, along with the specimen before test begun.

Figure 18 Failed specimen in loading frame

Figure 19 Specimen after (left) and before (right) shearingfore (right) shearing

Shear strength test results and discussion

The silty sand, silty sand + 6% biochar, and silty sand + 10% biochar were used to prepare triplicate identical specimens. The specimens were sheared with axial compression under consolidated undrained conditions. The results of the shear tests are summarized in Table 13. Plots of the deviatoric and excess pore pressure versus the axial strain are presented in Figures 20 through 25. Appropriate additional information is provided in the Figures. By defining failure at peak formation in the stress-strain space, the Mohr circles and the corresponding Mohr-Coulomb (M-C) envelopes are developed and presented as shown in Figures 26 through 28. As can be seen as the biochar fraction increased the friction angle (ϕ') decreased while the coefficient of cohesion (c) increased.

Table 13 Axial compression constrained undrained triaxial results

Biochar fraction (%)	**0**	**6**	**10**
Friction Angle, ϕ' (degrees)	34	32	31
Cohesion coefficient, c (psi)	0.0	1.06	1.50
σ_f(psi)	11.0	10.47	11.87
τ_f(psi)	7.42	7.60	8.63

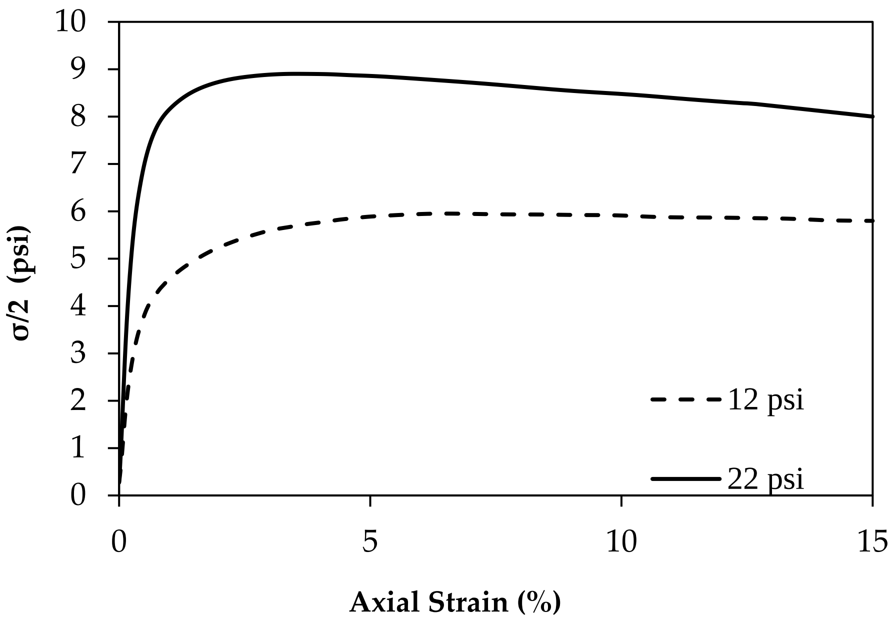

Figure 20 Stress-strain curve, no biochar

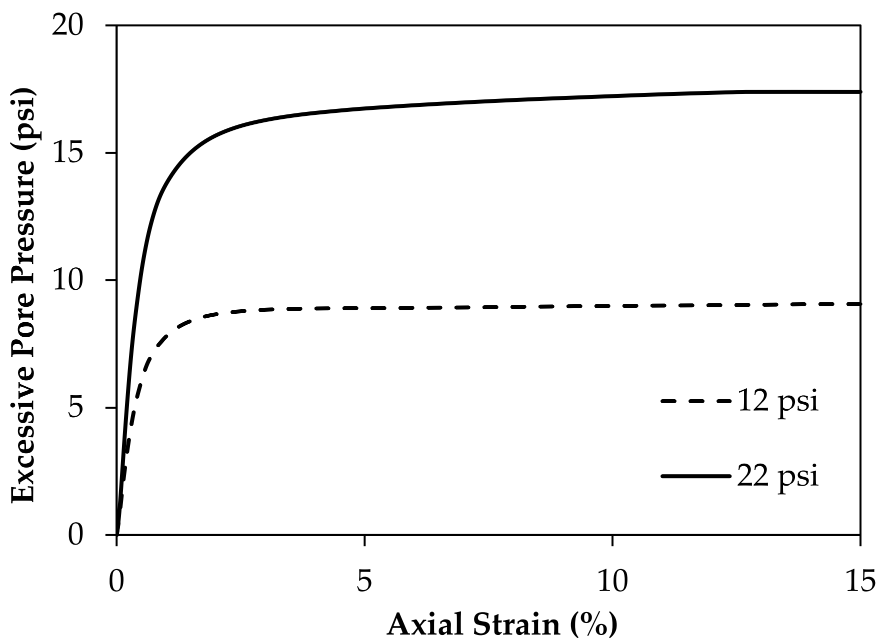

Figure 21 Excess pore-pressure Vs. Axial Strain, no biochar

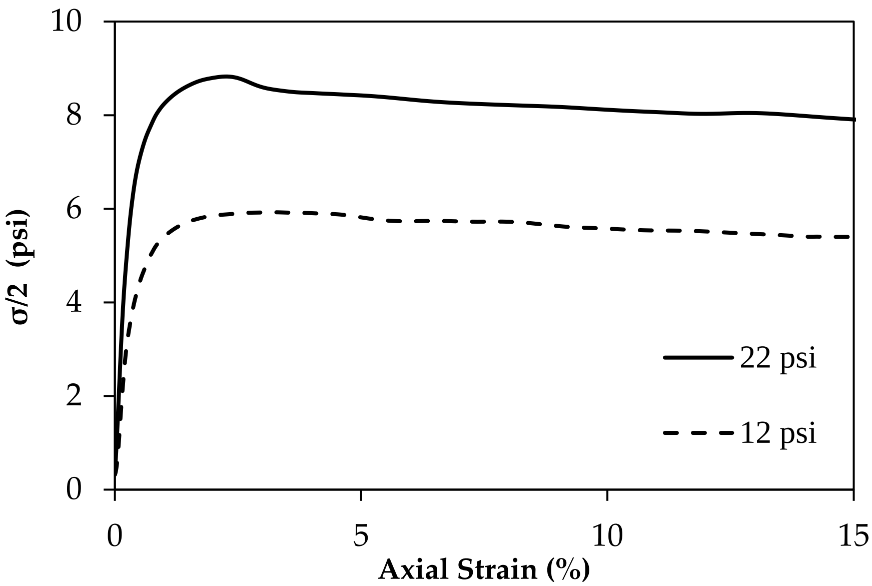

Figure 22 Stress-strain curve, 6% biochar

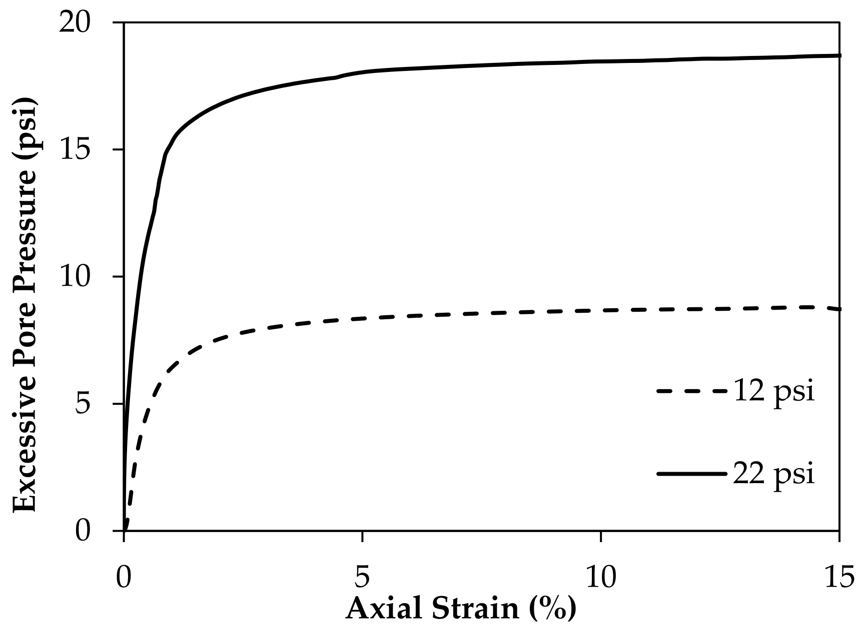

Figure 23 Excess pore-pressure Vs. Axial Strain, 6% biochar

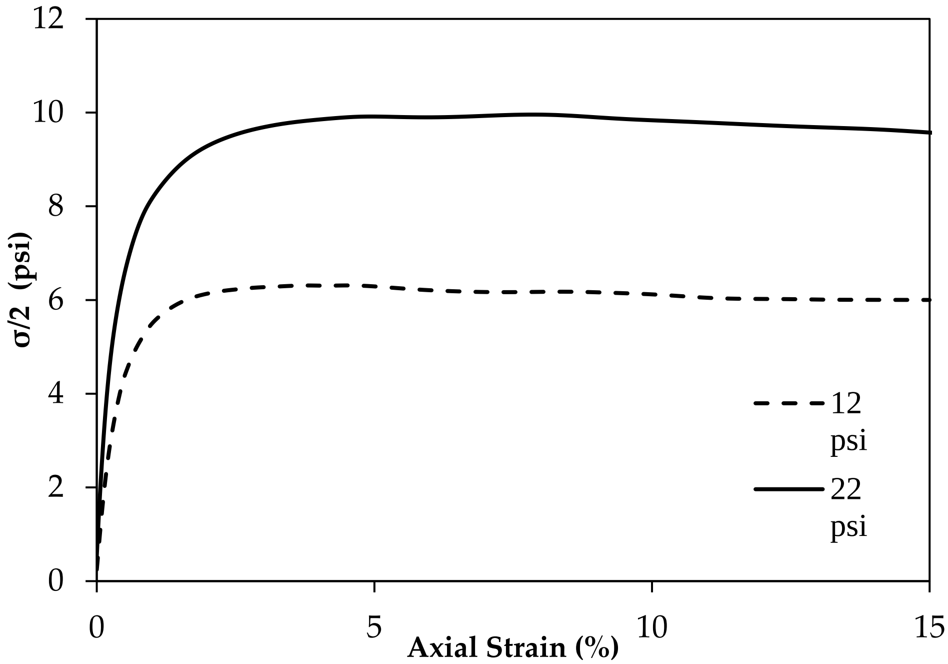

Figure 24 Stress-strain curve, 10% biochar

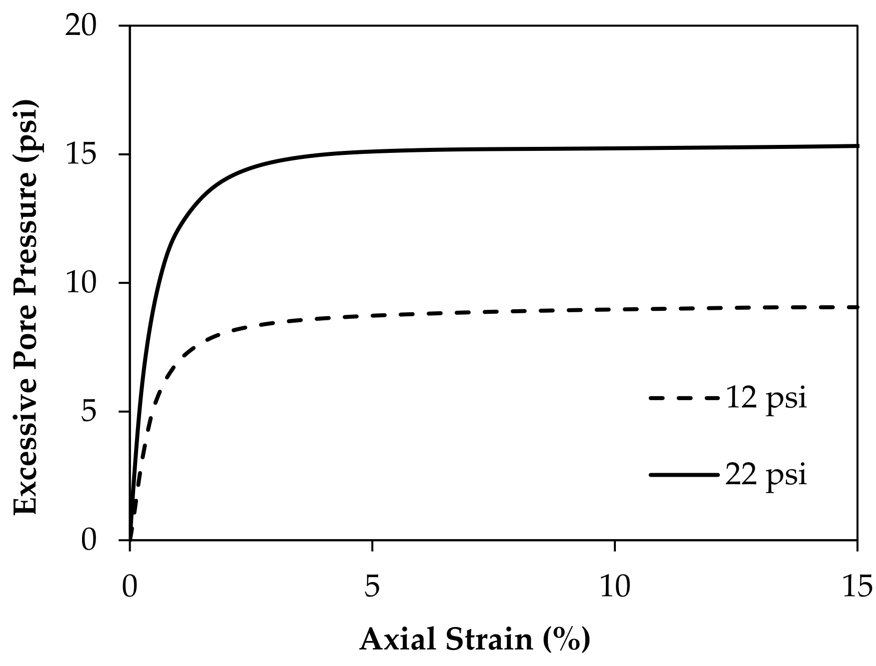

Figure 25 Excess pore-pressure Vs. Axial Strain, 10% biochar

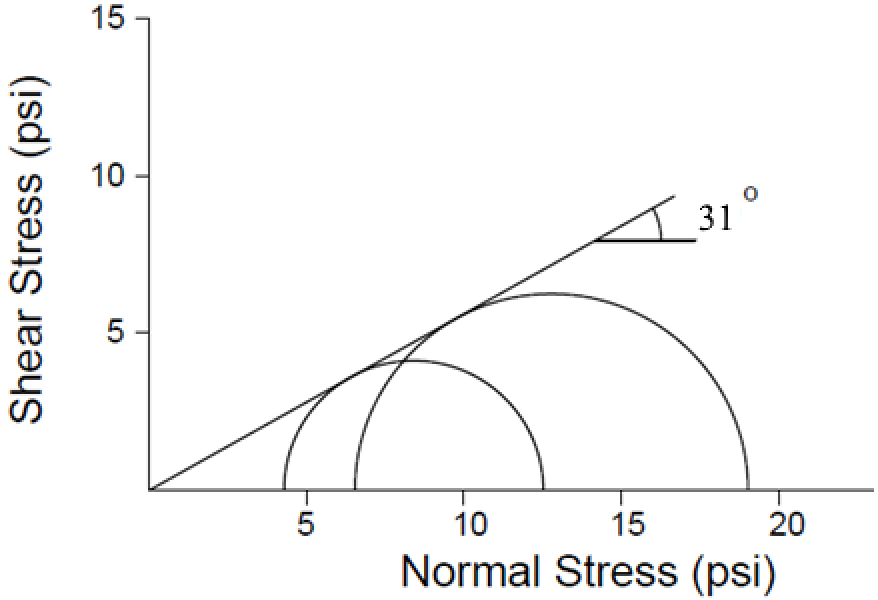

Figure 26 CU triaxial results for silty sand soil with no biochar

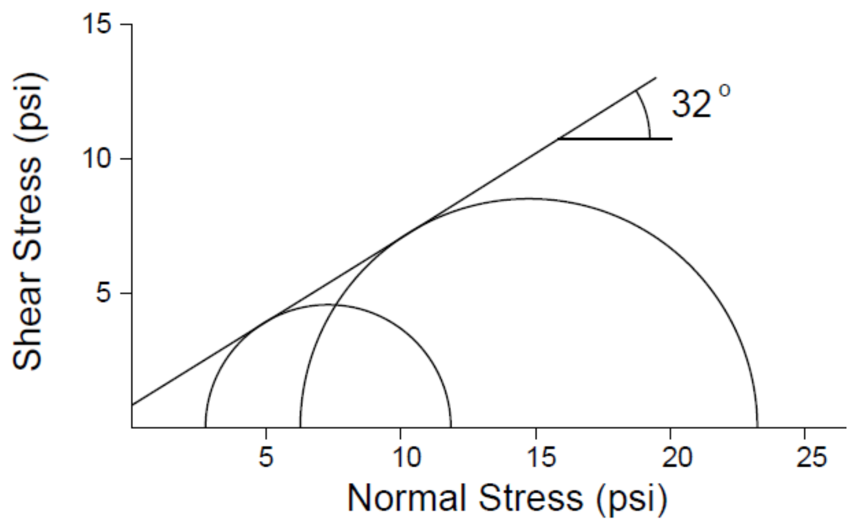

Figure 27 CU triaxial results for soil +6% biochar

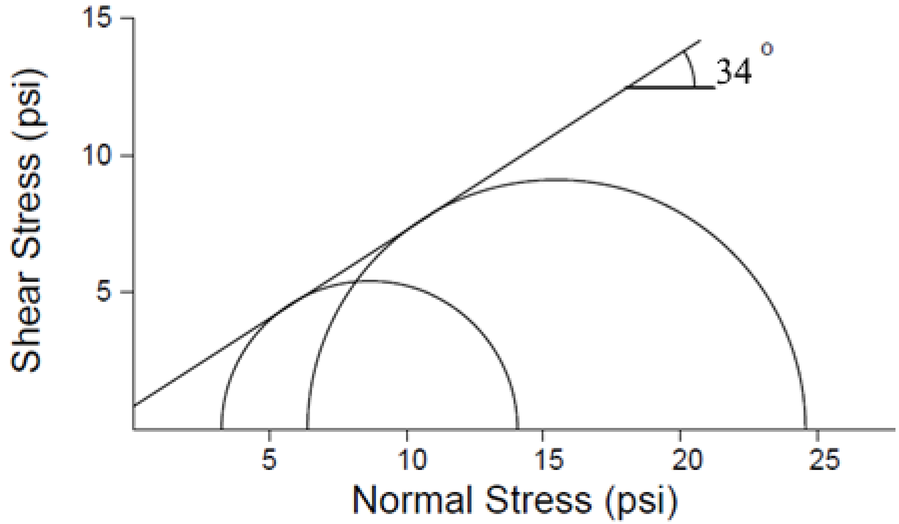

Figure 28 CU triaxial results for soil +10% biochar

In Table 13, $\boldsymbol{\sigma_f}$ gives the normal stress that was obtained at failure. Employing the M-C failure criterion (Equation 4) to calculate the shear strength at failure ($\boldsymbol{\tau_f}$) of the specimens, it can be seen that the shear strength increased with biochar fraction. It can be said that, while the strength contribution from the frictional effect decreased (as manifested in the decreasing angle of friction values), the over all strength of the mixture increased due to the compensating effect of the contribution from cohesion.

$$\tau_f = c + \sigma_f \tan(\phi') \qquad (4)$$

With a constant value of σ_{con}, shear stress increases with increasing biochar percentage due to the increase in cohesion. Therefore, biochar increase the silty sand's shear strength not because of the change in friction angle, but due to the increase in cohesion.

CONCLUSIONS

Standard Proctor compaction tests were completed using soil only, a 6 percent biochar-soil mixture, and a 10 percent biochar-soil mixture. Two compaction approaches were scrutinized. One, which allowed soil remixing and the other not so. The soil used was a silty sand (SM), and the biochar was produced from an organic source. The following conclusions can be drawn from this experimental study:

1. The addition of biochar to silty sand did impact the soil's compacted behavior. Through the addition of 6 and 10 percent of biochar (by volume) to the soil, the data showed a decreasing maximum dry unit weight and an increasing optimum water content trend.

2. The change in the optimum water content was greater from 6 percent biochar-soil mixture to 10 percent biochar-soil mixture compared to the soil-only and 6 percent biochar-soil mixture. Therefore, with a greater amount of biochar, the optimum water content will increase in a non-linear fashion.

3. The change in maximum dry density between the biochar-soil mixtures was almost linear. Therefore there is a direct correlation between the amount of biochar added to the soil and the maximum dry density. This linear relationship makes predictions of maximum dry density with other biochar percentages simple.

4. The optimum water content was higher when soil remixing was allowed. Therefore, a lower percentage of water was needed to reach a maximum density in the procedure where remixing was not allowed. The compaction procedures for biochar-soil mixtures need to be carefully considered to ensure the biochar particle structure is not broken. A crushed biochar particle will not have as helpful geo-environmental benefits as an intact particle.

Overall, the standard proctor data showed consistent trends with biochar addition.

The data can be extrapolated to predict how higher biochar percentages will impact compaction as well as biochar percentages between 0 and 6 and 6 and 10. This data could be used for design if biochar is to be implemented in an area that will be compacted, like the side of a roadway. The density does decrease significantly with 10 percent biochar. Therefore, a balance needs to be reached of having enough biochar to benefit from its geo-environmental uses, while also not using so much that the soil density is too greatly diminished. Biochar is a viable, sustainable option that can be used in compacted soil if the altered soil behavior is considered.

Compressibility tests were conducted on soil only, a 6% biochar soil mixture, and a 10% biochar soil mixture. Results showed that as the biochar percentage (all fraction is by volume) increased the mixture showed increased compressibily. This was exhibited with the increasing vertical compression.

Consolidated Undrained (CU) axial compression triaxial shear tests were conducted on soil only, a 6% biochar soil mixture, and a 10% biochar soil mixture. Results showed that the angle of internal friction decreased as the biochar fraction increased. This was accompanied by an increase in the cohesion coefficient. The overall shear strength, as evaluated with the Mohr-Coulomb criterion, was found to increase with increasing biochar fraction.

The overall implication of this experimental study was that biochar could be used as a geo-environmenal construction material. Example applications include use of the biochar amended soil as a road-side backfill and its usage in bioswales. By combining the flow-related qualitites of biochar amended soils with their strength-related qualities, the could be used as effective geo-environmental construction material which removes nutrients from runoff while performing satisfactorily.

PRODUCTS

The finindings of this study were deissiminated using the following channels.

Conference Proceedings

Lamprinakos, R.*, and Manahiloh, K.N. (2019). “Examining the behavior of compacted soil-biochar specimens.” *Geotechnical Frontiers 2019,* March 24-27, Philadelphia. (https://doi.org/10.1061/9780784482117.013)

Magazine Articles

Manahiloh K.N., and Imhoff P. (2018). "Properties of biochar-amended highway soils." *GeoStrata*, Sept/Oct. 2018 Issue.

Invited seminars

“Biochar’s Effect on Soils Properties.” Geotechnical Engineering mini symposium, University of Delaware, March 22, 2019, Newark, DE. (Lamprinakos R.)

“Evaluation of the engineering behavior of soil-biochar mixtures as a roadway construction material”, Geo-transportation Engineering seminar, April 18, 2017, University of Delaware. (Manahiloh, K.N.)

Poster Presentations

Lamprinakos, R., and Manahiloh, K.N. (2019) “Examining the Behavior of Compacted Soil-Biochar Specimens.” 2019 Geotechnical Frontiers, March 26, Philadelphia, PA.

Lamprinakos, R., and Manahiloh, K.N. (2019) “Examining the Behavior of Compacted Soil-Biochar Specimens.” *ASCE Delaware valley Geotechnical Institute*, March 18, Villanova, PA.

Lamprinakos, R., Manahiloh, K.N. (2018) “Examining the behavior of compacted soil-biochar specimens.” *Engineering Advisory Council Meeting*, May 03, Newark, DE.

Lamprinakos, R., Manahiloh, K.N. (2018) “Examining changes in the compacted behavior of soil-biochar mixtures.” 8th Annual *Graduate Research Forum*, April 20, Newark, DE.

Lamprinakos, R., Manahiloh, K.N. (2018) "Effect of biochar on geotechnical properties of soils." *ASCE Delaware valley Geotechnical Institute*, 03/15, Villanova, PA.

Lamprinakos, R., Manahiloh, K.N. (2018) "Examining the behavior of compacted soil-biochar specimens." *ASCE Delaware valley Geotechnical Institute*, 03/15, Villanova, PA.

RECOMMENDATIONS

The study conducted in this work used only one soil and one type and size biochar. In order to have a robust understanding of how biochar amended soils behave, it is recommended to do further studies in which the soil type and the biochar type and size are varied adequately. Also, the cost aspects of amending soils with biochar need examination. It is also recommended that the time and temperature effects be investigated. From the basic analysis performed here, it was noticed that biochar could degrade with age and if subject to fluctuations in temperature.

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