Laboratory Evaluation of the Geotechnical Properties of Biochar-Amended Clay

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Acceptance of Senior Honors Thesis

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Abstract

The upkeep and rehabilitation of infrastructure damage related to the shrinking and swelling of expansive soils have cost the United States billions of dollars. Biochar, an innovative and eco-friendly additive proven to improve soil permeability, nutrient retention, and mechanical properties, is investigated as an additive to Mississippi chalk. The index properties of the chalk were determined and used to characterize its nature. The geotechnical engineering properties of the chalk amended with 6% and 12% biochar were evaluated via the Proctor compaction, compression, and direct shear tests. Results were analyzed to make comparative remarks on how the behavior of the chalk evolved with biochar percentage. The chalk's compactibility, compressibility, and shear strength increased as the biochar percentage increased. Overall, the cohesion coefficient decreased while the friction angle increased with increasing biochar percentage. The increased shear strength of biochar-amended soil is a promising observation of biochar's potential as a construction material in geo-transportation projects. Further investigation is warranted to look for ways to alleviate biochar's adverse effects on chalk's compression.

Laboratory Evaluation of the Geotechnical Properties of Biochar-Amended Clay

One of the most pervasive geotechnical hazards worldwide is expansive soils' shrinking and swelling behavior. Expansive soils are undesirable for any construction within or upon them. When the soil shrinks or swells, the changing soil properties can cause structures to heave or settle improperly, even causing irreversible damage in some cases (Jones et al., 2002). Even a mere 3% volume expansion of the soil can cause cracking in a structure (Jones et al., 2002). Fat clay, or clay with a liquid limit of greater than 50%, is a prevalent example of this (Bennett et al., 2011). Under moist conditions, fat clay absorbs water and attaches a thick layer of water onto its surface, weakening its structure and classifying it as an expansive soil. Furthermore, Nelson and Miller (1997) found that expansive soils can increase volume by more than 10%.

Additionally, the continental United States has experienced the pervasive effects of expansive soil behavior. An estimated 25% of U.S. homes are built on some type of expansive soil, and these soils cause over $15 billion in infrastructure damage annually (Nelson & Miller, 1997). Improving the geotechnical properties of expansive clays could significantly reduce this expense and increase the lifespan of infrastructure.

This research aims to investigate using biochar as an innovative soil amendment to improve a soil's geotechnical properties. Many previous studies have explored biochar, a carbon-rich charcoal-like product produced by heating biomass at low oxygen levels, for its environmental benefits, especially for increased agricultural yield and reduced soil emissions (Hunt et al., 2010). Biochar is an excellent candidate for expansive soil amendment because it has been shown to increase soil microporosity significantly (Castellini et al., 2014), theoretically improving soil drainage and reducing a soil's shrinking and swelling behavior.

This experimental research aims to assess the effect of biochar amendment on the geotechnical properties of clay. After a preliminary literature review of previous biochar research, the Mississippi clay (i.e., chalk) was selected for assessment. It is hypothesized that biochar will improve the engineering behavior of Mississippi chalk. Laboratory characterization tests of specific gravity, Atterberg limits, and grain size distribution will be performed per the ASTM procedures. Triplicate specimens of Mississippi clay will be prepared with no, 6%, and 12% biochar (by volume) amendment. The implications of biochar amendment on the mechanical properties of the chalk will be assessed using compaction, compression, and direct shear tests. Concluding remarks are made by contrasting the observed behavior of the specimens during the laboratory investigations.

Literature Review

Engineering Problems Associated with Expansive Clays

The shrinking and swelling behavior of expansive clays can cause many problems for engineers, sometimes even years after a structure has been built (Jones & Jefferson, 2012). Shrinking or swelling of soils occurs when the forces between soil particles change. When these forces change, an imbalance with the external stress on the soil is created, causing the soil's volume to change to achieve equilibrium (Nelson & Miller, 1997). This internal force imbalance can be caused by sudden changes in moisture content (Nelson & Miller, 1997).

Expansive clays are often characterized by montmorillonite, a clay mineral with a 2:1 structure with two silica layers surrounding a layer of magnesia or alumina (Suter et al., 2007). When the moisture content of montmorillonite increases, the inner layer of the 2:1 structure becomes hydrated, and the inner structure expands the two outer layers (Suter et al., 2007). This behavior allows montmorillonite to be the most expansive clay material, and because it is common in the United States, it can cause many problems in infrastructure development (Nelson & Miller, 1997; Chen, 2012). Additionally, highly expansive clays exhibit a high plasticity index, lower shrinkage limit, and high liquid limit, all characteristic behaviors of montmorillonite clay (Kalantari, 2012).

The shrinking and swelling behavior correlate directly with the water content of the soil. Expansive clays can absorb large amounts of moisture during rainfall and expand. As the clay dries out and the moisture leaves, the soil shrinks, often causing cracks to form in the soil and causing settling (Jones & Jefferson, 2012). Exacerbating this problem, the soil does not return to its original geometry. This allows improved access for water to swell the soil during the following rainfalls. If cracks are filled with sediment or other materials, the pressure and swell potential of the soil during the subsequent rainfall increase even more (Jones & Jefferson, 2012).

The presence of expansive clays around or beneath specific structures increases the potential for damages due to soil volume change. First, expanding soils can buckle pavement, damaging sidewalks, roads, and even parking lots. The soil can swell in the middle of the pavement and cause visible cracking. However, it can also swell on the sides, causing the pavement to bow inwards and forming cracks underneath and inside the pavement that weaken its structural integrity (Kalantari, 2012). Even airports can suffer significant damage from swelling and shrinking soils (Chen, 2012).

Second, residential houses can suffer damage in several different ways. Floor slabs can crack due to a deformation called hogging (Kalantari, 2012). Similarly, basement foundations can fall victim to cracking, and walls can shift horizontally and vertically (Kalantari, 2012). In large buildings, the soil around the perimeter of a foundation can become saturated. In contrast, the soil in the middle maintains a constant moisture level, causing cracking due to end lift (Jones

& Jefferson, 2012). Commercial and multi-story buildings are also affected by the same damages that residential houses endure from expansive soils (Chen, 2012).

Third, underground utilities, piping, and similar services can be damaged and even broken due to soil swelling (Chen, 2012). If a pipe lies near a water source or a depression where water can settle, the surrounding soil can expand and contract, contorting the pipe (Kalantari, 2012). Furthermore, expansive soils can contribute to urban landslides, causing damage where careful erosion control is absent (Chen, 2012). The potential dangers of expansive soils can also be intensified by trees near structures (Jones & Jefferson, 2012). Root growth of trees can disturb the soil and distort the moisture content within the soil. The impacts of root growth can extend to both the settling and cracking of buildings and damage to utilities, especially when older pipes lie near trees in highly expansive soils (Jones & Jefferson, 2012).

Expansive soils clearly can cause many engineering problems for infrastructure built on, in, or around them. As previously noted, an estimated 25% of homes have some expansive soil damage, and expansive soils are estimated to cause over $15 billion in annual damage costs in the United States (Nelson & Miller, 1997). In an earlier study, Jones and Holtz (1973) approximated the annual damage from expansive soils to be about $2.25 billion annually, with damage highways and streets, single-family homes, and commercial buildings being the costliest. While some of these damages result from improper construction techniques or earth pressure, the problem of expansive soils is still one of the greatest threats to modern infrastructure (Chen, 2012).

Kalantari (2012) suggested three methods to mitigate the damages caused by expansive clays' swelling and shrinking behaviors. First, structures could be isolated from areas with swelling soil. This method involves deep foundations that make the structure immune from any shrinking or swelling. Second, Kalantari (2012) suggested that stronger structures can be built to resist the cracking from shrinking and swelling clays. Lastly, the mitigating action could involve expelling the swelling behavior of the soil. This can be done by controlling soil moisture levels, replacing the soil entirely, or changing the soil properties (Kalantari 2012). While many methods have been proposed to reduce expansive soil damage, this research will use biochar to reduce soil expansivity and control soil moisture content.

Biochar as a Soil Amendment

Biochar is the byproduct of biomass heating with constricted oxygen levels (thermal decomposition), often through pyrolysis or gasification, which produces carbon-rich charcoal that can be made from many different biomass materials, including biomass waste (Castellini et al., 2015). Unlike charcoal, biochar is not produced for use as an energy source. Instead, biochar is commonly used for soil amendment and carbon sequestration (Kloss et al., 2012).

Because biochar is made from different types of biomasses, it can be sustainably sourced from everyday biological waste products (Sadasivim & Reddy, 2015). Common sources of biochar include forest fire char, hardwoods, food waste, litter, grass, rice hulls, etc. The biomass source, referred to as feedstock, should be selected depending on the specific purpose of the biochar, as biochar properties can vary based on feedstock and thermal decomposition methods (Lamprinakos & Manahiloh, 2019). Additionally, biochar feedstocks' general availability eliminates high costs and has a positive impact on the environment, especially when sourced from waste products (*Biochar*, 2018). The conditions of pyrolysis and the type of feedstock used in the formation of biochar can also greatly influence its properties, and careful note should be taken of biochar sourcing whenever it is applied, especially in a research setting (Singh et al., 2010). Furthermore, the environmental impacts and risk of biochar amendment must be investigated before biochar is amended to soil outside the laboratory to avoid possible pollution (Lamprinakos & Manahiloh, 2019).

One of the most essential and unique properties of biochar is its low degradation rate. Many other organic soil additives are unstable compared to biochar, as biochar's total degradation is estimated to take several hundred years (Castellini et al., 2015). For some biochar applications, such as climate change management, biochar may only need to be applied to the soil once (Deveraux et al., 2012).

Biochar's carbon-rich nature makes it a valuable resource for many different applications, specifically as a soil amendment. When added to different soils, biochar has been shown to increase soil nutrient and water retention/filtration, increase carbon sequestration, and reduce landfill methane emissions, and its increased porosity increases oxygen supply to the soil at different moisture levels (Reddy et al., 2015). Biochar amendment also increases the surface area of the soil, making room for microorganisms to grow and improve soil nutrients. (Hunt et al., 2010).

Moreover, biochar's unique properties can be used for more than just environmental benefits, as biochar can improve the hydraulic conductivity and structural stability of soil (Jin et al., 2017). When used as a soil amendment, these improved soil properties have been shown to increase crop yield (Barnes et al., 2014). In fact, many countries need to amend their soil to get any crop yield (Lehmann & Joseph, 2012). Biochar is an accessible soil additive that can be used to increase soil nutrients, but further research must be done to prove its effectiveness as some studies have shown that biochar adversely affects yield (Baiamonte et al., 2015). Additionally, the potential of biochar-amended soil as a construction material has not been extensively investigated.

Existing literature on biochar confirms the usefulness of biochar as a soil additive. Nakhli et al. (2021) found that biochar size and shape can affect pore structure, and moistening biochar before soil amendment can inhibit segregation. Reddy et al. (2015) researched biochar-amended soil as a landfill-covering material and discovered that increased biochar amendment and decreased particle size resulted in increased hydraulic conductivity, decreased soil compressibility, and increased shear strength. Jin et al. (2017) found that biochar addition to a bioretention medium increased porosity and decreased dry bulk density, even with varied particle size. Xie et al. (2015) and Mukherjee and Lal (2013) found that biochar is useful in inhibiting greenhouse gas emissions and combat climate change, and Sadasivam and Reddy (2015) tested the compressibility and shear strength properties of biochar.

While biochar has generally been shown to improve soil properties when used as an additive, biochar amendment must be investigated in different soil types to confirm its usefulness. Several articles have investigated the effects of biochar amendment on clay soils. In sandy soils, the addition of biochar increases the soil's drainage capabilities. On the other hand, clay soils amended with biochar display the opposite effect: biochar-amended clays drain more rapidly (Barnes et al., 2014). Baiamonte et al. (2015) explored the effects of biochar amendment on sandy clay. This study found that increasing biochar percentages correspondingly increased the stability of the soil. Additionally, Ghorbani et al. (2019) studied the soil properties of biochar-amended loamy sand in contrast with biochar-amended clay. The biochar-amended clay displayed significantly improved results compared to the sand, even at small biochar percentages of 1 and 3 percent. Wong et. al. (2017) found that biochar amendment in clay can increase soil water retention. Moreover, Castellini et al. (2015) investigated the physical and hydraulic properties of biochar-amended clay, reporting several significant findings. When large amounts of biochar are added to the clay, gaseous and liquid imbalances can form within the soil. The study found that increased biochar percentages increased both air capacity and macroporosity. However, the hydraulic conductivity of the biochar-amended clay was unaffected.

An abundance of research is present on the benefits of biochar amendment, and the effect of biochar amendment on clays has also been investigated in several studies. However, most research to date focuses on the agricultural applications and environmental impacts of biochar amendment. Although several studies have investigated the geotechnical properties of biochar-amended soils, these studies do not explore biochar's effect on expansive clays. As expansive soils cause billions of dollars in damage each year, biochar-amended clay serves as an excellent starting point for biochar's potential in mitigating its shrinking and swelling behavior.

Several characteristics of biochar suggest that it has the potential to diminish the effects of expansive clays. First, the increased porosity of the biochar-amended soils, especially in clays, indicates that biochar could reduce the swelling nature of clays when they become saturated with moisture. Second, the improved geotechnical stability of biochar-amended soil could inhibit excessive soil settling or displacement. Lastly, biochar is a relatively inexpensive, renewable soil amendment with a low degradation rate. Thus, biochar amendment may be an inexpensive and long-lasting solution to the problem of expansive clays. The following experimental tests will investigate if biochar amendment to clay improves properties that correlate with the shrinking and swelling of expansive clays.

Laboratory Experiments

Materials

To experimentally investigate the properties of expansive clays and the improvement that biochar can have on the soil properties, the first step was to obtain clay that displayed expansive properties and to purchase biochar for use as a soil additive. The biochar used in the following experiments was 100% wood- based Soil Reef PURE™ biochar.

Additionally, the clay used in the experiment was sourced from Oktibbeha County, Mississippi. The index classification was not known prior to experimental testing, but textual observation suggested that the soil was fine-grained and most likely clay. Furthermore, the grayish hue and fine grain size of the soil led to the hypothesis that the Mississippi clay consisted of montmorillonite. However, before the geotechnical properties of the biochar-amended soil could be investigated, the Mississippi clay had to be classified using the Unified Soil Classification System (USCS).

Test Matrices

The process of testing the Mississippi clay and the biochar-amended clay specimens was broken into two major categories: soil classification tests and geotechnical engineering property evaluation tests. The test matrices for both categories are shown in Table 1 and Table 2, with the number under each heading corresponding to the number of tests performed.

Table 1

Soil Classification Test Matrix

Specific Gravity	Liquid Limit	Plastic Limit	Shrinkage Limit
2	9	3	2

Table 2

Geotechnical Engineering Property Test Matrix

% Biochar	Compaction	Compression	Direct Shear
0%	1	1	1
6%	1	1	1
12%	1	1	1

The soil classification tests were only performed on the Mississippi clay with 0% biochar amendment. As seen in Table 1, the soil classification tests performed consisted of specific gravity tests and Atterberg limit tests (liquid, plastic, and shrinkage limit tests). The Atterberg limit tests inform the creation of the plasticity chart, where the plasticity index and liquid limit of the soil are plotted to determine the final USCS classification.

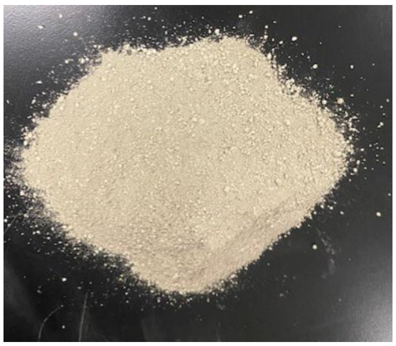
A grain-size distribution analysis using a sieve was not performed on the soil because the grains were fine enough to pass through the smallest sieve. A hydrometer analysis could have been performed to further classify the fine-grain soil, but it was not necessary for the USCS classification. Multiple tests were performed for most soil classification tests to ensure consistent results and accurate classification of the Mississippi clay for a total of 15 soil classification tests. The soil's USCS classification was complete with the finalization and analysis of all the soil classification tests listed. The geotechnical property evaluation of the classified soil shown in Table 2 was also performed on the Mississippi clay amended with 0%, 6%, and 12% biochar by volume. Furthermore, compaction, compression, and direct shear tests were selected to provide insight into the effect of varied biochar percentages on the geotechnical engineering properties of the soil. At least one test was performed for each of test type and biochar percentage for a total of 15 geotechnical tests.

Index and Soil Classification Tests

The first tests performed were the soil classification tests to determine the USCS classification of the Mississippi clay. The results of these tests are discussed in this section, as soil classification is an important prerequisite for the geotechnical property testing discussed in the following section. As seen in Table 1, the tests necessary for soil classification were specific gravity tests and Atterberg limit tests (liquid limit, plastic limit, shrinkage limit). Before testing could begin, however, the soil had to be air-dried and broken up into individual grains. The soil was broken down using a Gilson soil grinder, and the soil is shown in Figure 1 below.

Figure 1

Mississippi Clay



Specific Gravity Test

The first test performed on the Mississippi clay was the specific gravity test. Not only is the specific gravity of a soil important for soil classification, but it also reflects the weight-volume relationship of the soil, as it identifies the ratio of the soil density to the density of distilled water (Lamprinakos & Manahiloh, 2021). Because the Mississippi clay was hypothesized to consist largely of montmorillonite clay, it was expected to have a specific gravity in the range of 2.65-2.80 (Das, 2015).

The specific gravity of the Mississippi clay was determined by following the ASTM D-854 standard procedure, except for tap water was used instead of distilled water (ASTM International, 2014; Das, 2015). First, water was deaired in a 500 mL volumetric flask using a vacuum pump to ensure that none of the water's volume was due to dissolved air. The temperature of the water was taken to ensure it was at room temperature. When the water was sufficiently deaired, the mass of the 500 mL of water and the flask was recorded in Table 3.

Table 3

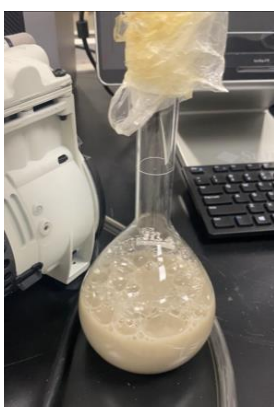
Specific Gravity Test Results

Item	Test Number	
	1	2
Mass of Flask + Water, M_1 (g)	644.91	644.91
Mass of Flask + Soil + Water, M_2 (g)	671.85	680.71
Mass of Dry Soil, M_s (g)	42.44	55.47
Mass of Equal Volume of Soil and Water, M_w (g)	15.50	19.67
G_s at 20 C	2.738	2.820
Average Specific Gravity	2.78	
R_g (Check for Error)	1.03	

Next, 40-50 grams of dried soil was mixed with water to form a paste. This was necessary because of the cohesiveness of the soil, further indicating its clay-like behavior. The paste was then added to another volumetric flask and mixed with more water. The vacuum pump was attached to the flask, and the soil/water mixture was deaired for several minutes. The mixture inside the flask was agitated during this process, which released gas bubbles and formed a foamy layer on top of the volumetric flask as seen in Figure 2.

Figure 2

Dearing by Vacuum



When the mixture was completely deaired, the vacuum pump was removed from the flask, and deaired water was added until it reached the 500 mL mark on the flask. The flask with then soil/water mixture was weighed and recorded in Table 3 once it was reduced to room temperature, and the contents of the flask were poured into an evaporating pan with a known mass. A plastic squeeze bottle was used to rinse the inside of the flask into the pan to ensure no particles were left inside. The evaporating pan was placed into the oven to dry the soil, and the dried mass was then calculated and recorded in Table 3. Finally, the specific gravity of the soil was calculated by dividing the mass of dry soil by the mass of the equivalent volume of water. This test was completed twice, and the results are shown in Table 3.

The average specific gravity of the soil was 2.78. The ratio R_g of the larger value to the smaller value of the test results was only 1.03, which was less than the required value of 1.2 (Das, 2015). Therefore, only two tests were sufficient to determine the specific gravity of the soil. Furthermore, the specific gravity was within the estimated range of 2.65-2.80, indicating that the specific gravity was consistent with the hypothesis that the soil was montmorillonite clay. However, other clay minerals such as illite also have specific gravities near or equal to 2.8 (Das, 2015). The Mississippi clay was likely a combination of clay and other minerals, and further investigation was required to classify the soil and determine its degree of expansivity.

Liquid Limit Test

The next step in soil classification after the completion of the specific gravity test is the Atterberg limit tests, consisting of the liquid limit, plastic limit, and shrinkage limit tests. The liquid limit test determines the percentage of soil moisture content in which a cohesive soil's behavior moves from its plastic state to its liquid state. The estimated value of the liquid limit of the Mississippi clay was 100-800 assuming it was montmorillonite, but similar, less expansive clay minerals would reflect a liquid limit below 100 (Das, 2015).

The procedure for this liquid limit test followed the ASTM D-4318 standard procedure using the Casagrande percussion bowl method (ASTM International, 2017; Das, 2015). First, about 200 grams of air-dried soil was placed into an evaporating dish, and water was added from a squeeze bottle and mixed with the soil. When the soil formed a paste and appeared to be near its liquid limit, the mixture was placed into the Casagrande percussion bowl. An example of the soil paste and Casagrande device is shown in Figure 3 below.

Figure 3

Liquid Limit Soil Paste and Casagrande Percussion Bowl

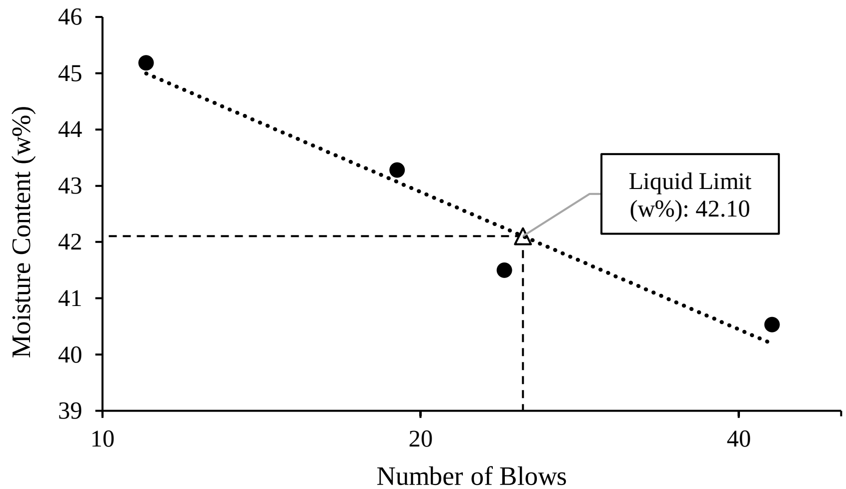
Next, the surface of the paste within the bowl was smoothed with the spatula. A groove 2 mm wide was cut down the center of the soil pat with the grooving tool. The bowl was calibrated so that each turn of the handle raised and dropped the bowl 10 mm. The handle was turned at a rate of about 2 revolutions per second, causing the soil to settle slightly with each turn. When the soil groove had closed completely over a length of 13 mm, the number of turns was recorded. The test was repeated with an adjusted moisture content until the number of turns, N, was between 25 and 35. Once the desired value of N was achieved, a sample of the soil was placed in evaporating dish with a known mass (M_1), and the mass of the moist soil and dish (M_2) was found. The soil was then dried in the oven, weighed again, and the mass of the dry soil (M_3) was also determined. This was repeated for several different moisture contents resulting in several different values for N. The percussion cup was thoroughly cleaned between each repetition. The test was also repeated three times to ensure consistent results.

The moisture content of each soil specimen was calculated using Equation 1 (Das, 2015). Each calculated moisture content was plotted against number of blows on a log scale in Figure 4.

$$w\% = \frac{M_2 - M_3}{M_3 - M_1} \quad (1)$$

Figure 4

Liquid Limit Plot



Furthermore, the flow curve approximates the behavior of these points with a straight line on the semi-logarithmic plot. The liquid limit was calculated by finding the equation of the flow line and solving for the moisture content corresponding to an input of 25 blows. The liquid limit of the soil was found to be 42 (see Figure 4), and the results were confirmed by the two other tests which were within acceptable error. The liquid limit was significantly lower than expected for montmorillonite clay, indicating that the Mississippi clay was probably made of different types of clay molecules. Moreover, Kalantari (2012) defined soils with a liquid limit from 35 to 50 to correlate with medium expansivity behavior. This indicates that the Mississippi clay may not exhibit the expansive behavior desired, but it should still be affected by biochar addition.

An important note on the liquid limit testing procedure is that similar results can be obtained without drying the soil in an oven. The test was repeated using the exact same procedure, except the masses of the water and air-dried soil were taken before testing. This modified procedure resulted a liquid limit of 39. The liquid limit value was slightly lower because the air-dried soil likely had a small amount of moisture content. However, this modified process could be used when an oven is not available with only a small decrease in accuracy. When an oven is available, the traditional ASTM method should be used because of greater accuracy and the ability to modify the soil's moisture content after the specimen has been prepared.

Plastic Limit Test

The second Atterberg limit test and final test necessary for the formation of the plasticity chart is the plastic limit test. The plastic limit of a soil is the moisture content in which its behavior moves from a plastic state into a semisolid state. According to the ASTM D-4318 standard, this point is defined as when a 3.2 mm diameter rolled soil specimen will crumble (ASTM International, 2017). The traditional procedure used when performing this test involves the rolling of the specimen with the human hand. However, a very similar procedure was used for the Mississippi clay where a plastic rolling device was used instead of a hand as seen in Figure 5.

Figure 5

Plastic Limit Rolling Device

To perform the test, the first step was to mix a sample of soil, about 35 grams, with a weight percentage of water less than that of the liquid limit by about 15 percent. Next the soil was formed into an ellipsoidal shape and rolled at rate of about 80 rolls per minute (Das, 2015). When the soil had been rolled into a diameter of 3.2 mm, the specimen was checked from crumbling. If crumbling had not yet occurred, the steps were repeated until the soil crumbled at that diameter. Moreover, the plastic rolling device conveniently had a ledge that was 3.2 mm in height, so rolling the specimen to a smaller diameter was not possible.

Three rolled soil specimens were weighed immediately after crumbling (M_2) and weighed in a can with a known mass (M_1). The specimens were then dried in an oven and weighed again (M_3). These measurements were recorded in Table 4 below. The plastic limit was calculated using Equation 1, the same equation used in determining the moisture percentages in the liquid limit test. Lastly, the plasticity index was found by subtracting the average plastic limit from the liquid limit.

Table 4

Plastic Limit Test Results

Bowl (g)	Bowl with Soil	Dry Mass of Soil	PL (%)
14.42	17.46	16.9	22.58
14.36	17.91	17.26	22.41
14.36	19.24	18.33	22.92
		Average	22.64
		PI (%)	19.47

As seen in Table 4, the plastic limit of the Mississippi clay was 22.64 and the plasticity index was 19.47. Kalantari (2012) correlated a plasticity index of 15-28 with a medium potential for volume change, further indicating that the Mississippi clay was a medium expansivity clay and not montmorillonite like originally hypothesized.

When the procedure was performed with the plastic rolling device, results were much more consistent and did not depend as much on the technique of the person performing the test. However, an experienced individual may still wish to perform the plastic limit test with their hands. The plastic rolling device did not perform well if the specimens were not inserted completely straight. The specimens often stuck to the plastic roller or became squished so that they did not roll well. Using a hand allows for finer adjustments and prevents sticking. With the plastic limit test, liquid limit test, and specific gravity test completed and the plasticity index calculated, all the necessary information for the USCS soil classification had been found. However, the Atterberg limit tests also require the shrinkage limit test to be performed, which would also help to inform the expansivity of the Mississippi clay.

Shrinkage Limit Test

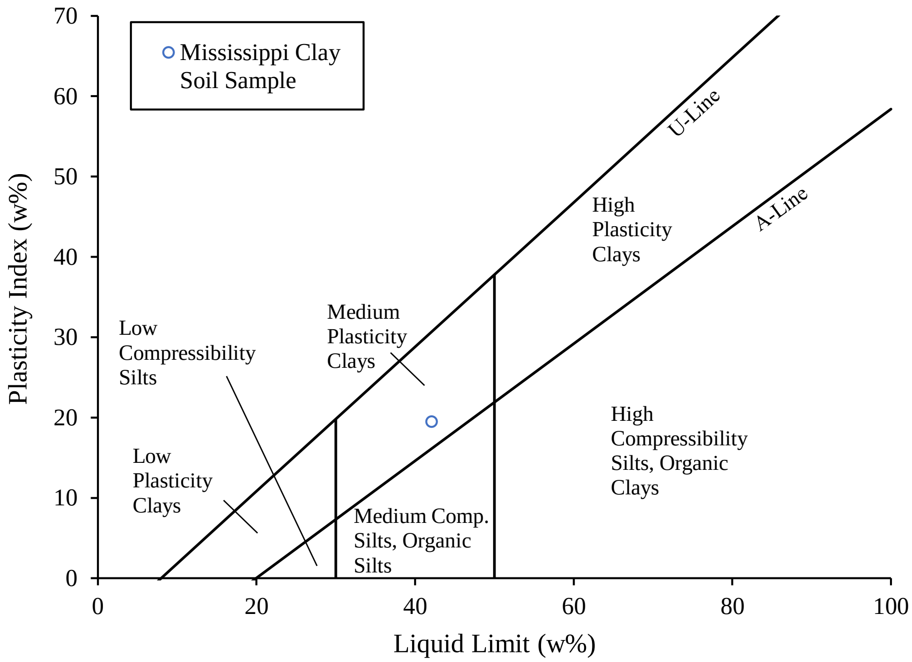
The shrinkage limit of soil describes the moisture content at which the volume of the soil no longer changes. For the Mississippi clay, the ASTM D-4943 procedure was followed, as the shrinkage limit was determined using wax instead of mercury (ASTM International, 2018). First, a sample of the Mississippi clay was mixed with water to a moisture content greater than the liquid limit. A shrinkage limit dish was weighed, coated with petroleum jelly, and weighed once more. The dish was filled with the prepared soil specimen, and the excess soil was cleaned before the filled dish was weighed again. The specimen was tied to a fishing line and coated in hot wax. After cooling, the specimen was weighed once more. Next, the specimen was submersed in water to determine the volume of the soil after shrinkage. The shrinkage limit of the soil was found to be 23.3%, and the shrinkage ratio was 1.44. This indicates that the soil exhibits low swelling potential (Kalantari 2012).

USCS Soil Classification

The final step in classifying the soil was compiling the results from the previous tests and creating a plasticity chart. The plasticity chart plots the plasticity index of a fine-grain soil versus its liquid limit and was used according to the standard ASTM D-2487 to classify the soil (ASTM International, 2017; Das, 2015). The U-line on the chart represents the approximate upper limit of the chart, and the A-line separates inorganic silts and clays. The plasticity chart for the Mississippi clay is shown in Figure 6.

Figure 6

Plasticity Chart for Mississippi Clay



Note: Adapted from Soil Mechanics Laboratory Manual (9th edition, p. 75), by B. M. Das, 2015, New York: Oxford University Press. Copyright 2015 by Oxford University Press. Adapted with permission.

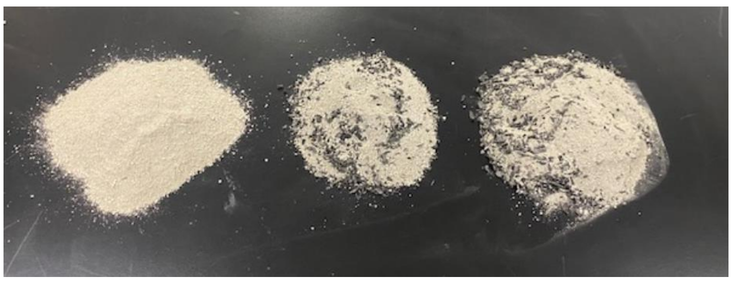
According to Figure 6, the Mississippi clay datapoint is located between the A-line and U-line and between a liquid limit of 30 and 50. Therefore, the Mississippi clay is classified as a medium plasticity clay, also known as a lean clay (Moreno-Maroto et al., 2021). This means that the Mississippi clay possesses the designation CL, as it is also a considered a fine-grained soil. With this designation, the USGS soil classification of the Mississippi clay was complete. While the Mississippi clay was classified as a lean clay, the effect of biochar amendment on its expansive properties should have a similar effect as on fat clays.

Geotechnical Engineering Property Evaluation Tests

Before testing could begin, three specimens of biochar-amended clay were mixed according to the test matrices. The three specimens are shown in Figure 7 below. As previously stated, all biochar percentages were calculated as volume percentages of biochar compared to the volume of the Mississippi clay.

Figure 7

Zero Percent, 6%, and 12% Biochar-Amended Samples



Note: On the left is the 0% biochar specimen made solely of the CL Mississippi clay. The middle shows the 6% biochar mixture, and the 12% specimen is on the right.

Standard Proctor Compaction Test

The first geotechnical test performed on all three soil specimens was the Proctor compaction test. The standard compaction test involves generating a compaction curve comparing dry unit weight to the water content of a compacted specimen, but in this analysis, only points at about 20-25% water content were investigated for the three biochar-amended specimens. This was due to the limited soil supply in the lab, as the soil could not be reused because biochar does not behave the same once compacted (Lamprinakos and Manahiloh, 2019). The standard Proctor compaction test investigates the compactibility of the soil, which increases as the optimum moisture content, or the peak of the compaction curve, moves downward and to the right. The compaction mold and metal rammer used for the test are shown in Figure 8 below.

Figure 8

Proctor Compaction Test Equipment

The standard used to inform the procedure of this test was ASTM D698-21 (ASTM International, 2021; Bardet, 1997). However, this procedure was modified to a one-point Proctor compaction test to estimate the optimum moisture content of each soil sample (*MT-7,* 2005). First, a specimen of approximately 20-25% moisture content was prepared for the test. The compaction mold assembly was placed on a concrete floor, and the soil mixture was added to the mold until it was filled halfway. Next, the soil inside the mold was compacted with 25 rammer blows from a 300 mm height. The blows were varied across the surface of the mold for relatively even compaction.

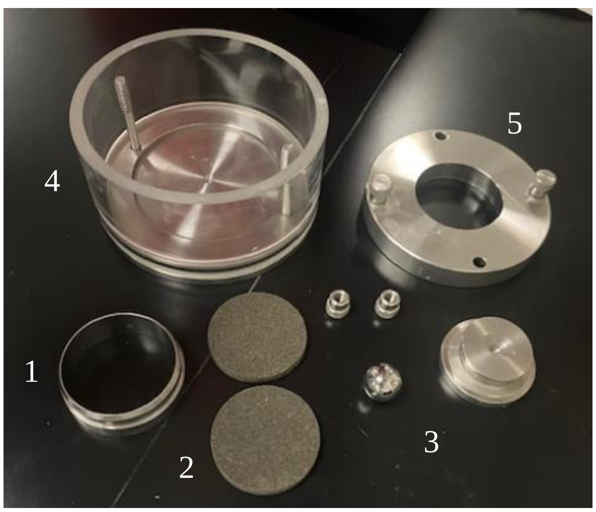
After the first round of compaction, a second layer of soil was added on top of the first layer and compacted using the same procedure. Finally, a third layer was added, and the same procedure was repeated once more. The extension collar was removed, excess soil cut away, and base plate removed. The soil and mold were weighed, and the soil was extracted from the mold. This process was repeated for the 6% and 12% biochar-amended specimens. The dry unit weight was calculated based on the weights and volumes recorded. The plot of dry unit weight versus the final water content of the soil is displayed in the Results and Discussion section, including the predicted the optimum moisture content of the soil determined by Mississippi Test Method 7: Moisture-Density Relations of Soils Using Family of Curves (*MT-7*, 2005).

Compression Test

The second test performed to evaluate the effects of biochar amendment on the Mississippi clay was the compression test. For compressible clays, the compression behavior is evaluated by performing consolidation tests in accordance with standard ASTM D-2435. This test can be used to determine the compression index and swell index of the soil (ASTM International, 2020; Das, 2015). The consolidometer used is shown in Figure 9.

Figure 9

Fixed Ring Consolidometer Assembly



Note: The consolidometer assembly includes the consolidation ring (1), porous stones (2), loading head and ball (3), base plate (4), and metal ring (5).

In this thesis, since a relative compression behavior is sought, a modified compression test (i.e., not purely consolidation) was performed on the specimens, prepared by varying the biochar content of the control clay and subjecting them to similar loading conditions. For the compression test, a specimen was put in a consolidation ring with a determined mass (M_1), and the specimen was trimmed to fit the ring so that it was flush on the top and bottom. The height and diameter of the specimen and the mass of the ring and specimen (M_2) were recorded. The initial moisture content of the soil was determined, and the specimen was placed inside a fixed ring consolidometer between two porous stones. Water was added to completely saturate the soil, and the consolidometer was placed inside the load frame. The strain gauge was set in place to measure the vertical displacement of the soil.

A normal load of 1/2 ton/ft^2 was applied to the specimen, and the vertical deflection was recorded at 16 different times within a 24-hour period. This process was repeated with the applied load being doubled every 24 hours until a load of 16 ton/ft^2 was achieved. The specimen was also unloaded to 8 and 4 ton/ft^2 to determine the swell index, and the load was again doubled until a load 32 ton/ft^2 was reached. This test was not only repeated for the different loads but also for the three different biochar mixtures. The plots of void ratio versus pressure and a table reporting the compression index and swell index are found in the Results and Discussion section.

Direct Shear Test

The direct shear test is used to determine the drained shear strength parameters (i.e., cohesion coefficient c' and angle of friction ϕ') of the soil and soil-biochar mixture. These parameters are employed in the assessment of how the shear strength of the control clay changes when amended with different biochar contents. The shear strength of a given soil can be determined by using the Mohr-Coulomb (M-C) shear strength equation as:

$$\tau = c' + \sigma_n' \tan(\phi') \quad (2)$$

Where:

τ = shear strength (kPa)

c' = the cohesion coefficient from a drained test (effective cohesion) (kPa)

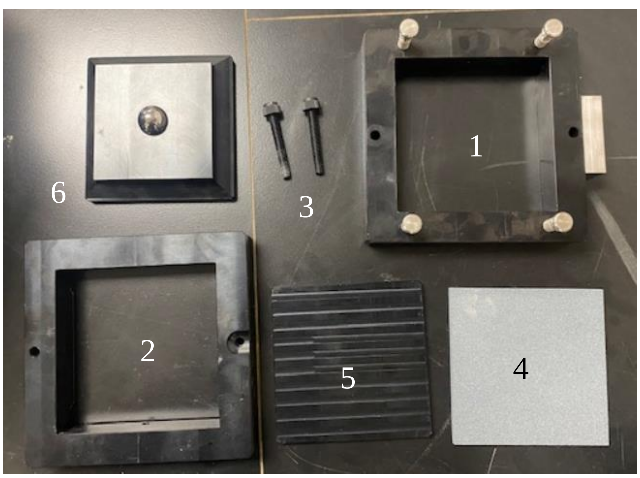
σ_n' = the effective normal stress (kPa)

and ϕ' = the friction angle from drained test (effective friction) (deg)

The testing procedure for fine-grained clays was used for the Mississippi clay, following ASTM D-3080 (ASTM International, 2011; Bardet, 1997). The direct shear box assembly is shown below in Figure 10.

Figure 10

Direct Shear Box Assembly



Note: The upper (1) and lower (2) portions of the direct shear box, the set screws (3), the porous stone (4), base plate (5), and loading head (6) of the direct shear box assembly are shown.

First, the depth and height of the box were recorded. An air-dried soil specimen was added into the shear box, and the initial soil height was measured. The direct shear box was assembled and mounted onto the direct shear load frame, and the set screws were inserted so that the shear box had no gaps. Next, a normal force was applied, and vertical settlement of the clay was recorded until primary consolidation had ceased. The shearing rate was then set to 5 mm/min, and the set screws were removed. The shear force, time, shear displacements, and normal displacements were recorded at several different times until the shear load frame reached maximum displacement and the shear force approached a maximum (Bardet, 1997).

The maximum shear stresses and applied normal stresses of 25, 50, and 100 kPa were plotted to create a plot of the Mohr-Coulomb failure envelope shown in the Results and Discussion section. This plot was used to determine the cohesion coefficient c' and angle of friction ϕ' for specimens of 0%, 6% and 12% biochar-amended clay. Furthermore, these parameters were used to compare the maximum shear strength of each of the soil specimens at different normal forces.

Results and Discussion

Standard Proctor Compaction Test Results

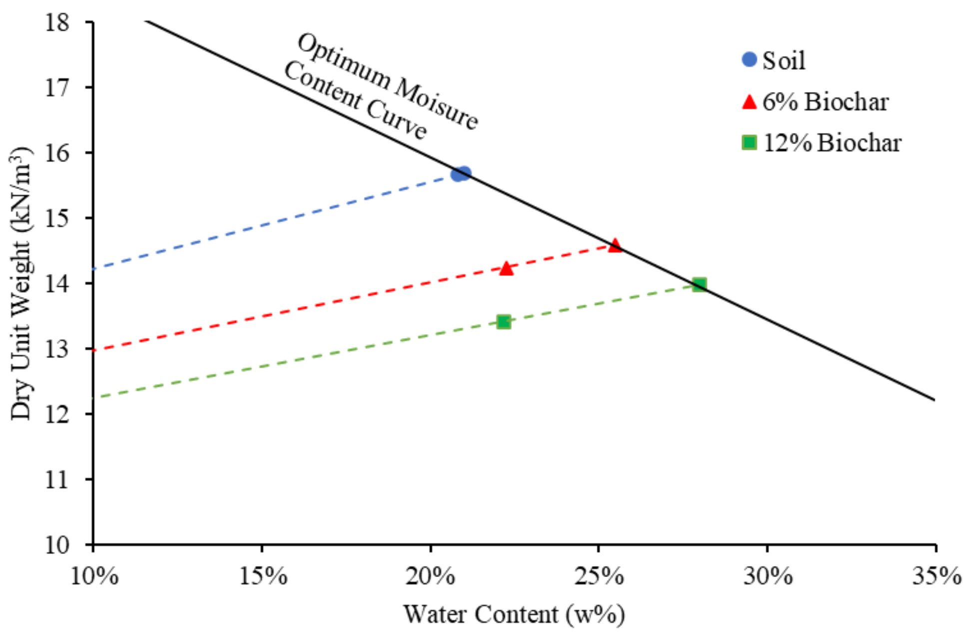
The standard Proctor compaction tests were performed at about 20-25% moisture content for the 0%, 6%, and 12% biochar-amended clay specimens. An example of a fully compacted specimen (12% biochar) is shown in Figure 11 after removal from the compaction mold. The dry unit weight for each specimen was plotted versus the specimen's exact moisture content in Figure 12 below. Additionally, the estimated optimum moisture content from the one-point Proctor compaction test is also plotted in Figure 11.

Figure 11

Fully Compacted Specimen (12% Biochar)

Figure 12

Proctor Compaction Test Results for Mississippi Clay Amended with 0%, 6%, and 12% Biochar



Note: Data for the estimated optimum moisture content taken from Mississippi Test Method 7: Moisture-Density Relations of Soils Using Family of Curves (*MT-7*, 2005).

As seen in Figure 12, an increase in biochar percentage in the soil corresponds to the decrease in dry unit weight, with the point of estimated optimum moisture content moving downward and to the right. Ahmed et al. (2017) found similar results with a silt loam soil, and Lamprinakos and Manahiloh (2019) also found the optimum moisture content of biochar-amended soil to move downward and to the right.

Although complete compaction curves were not generated for the Mississippi clay, the results from Figure 12 and these two studies suggest that as biochar percentage increases, the compaction curve moves downward and to the right. The greater compactibility of the soil with increased biochar percentage adversely affects the mechanical properties of the soil. The significant decrease in dry unit weight with increasing biochar percentage should be taken into account in structural applications, especially when soil is likely to be heavily compacted. Therefore, biochar amendment may not be a feasible solution with applications that experience repetitive compaction cycles.

Compression Test Results

Three different plots were created to visualize the results from the compression test on the three different soils specimens. Figure 13 shows the plot of void ratio versus input pressure on the Mississippi clay without biochar, and Figures 14 and 15 show similar plots with the soil amended with 6% and 12% biochar, respectively. The slope of the loading curve calculated from the higher data points where the graph is linear is called the compression index, while the slope of the unloading and recompression curve forms the swell index. These parameters are summarized in Table 5 for all three specimens.

Figure 13

Compression Test Results of Mississippi Chalk (0% Biochar)

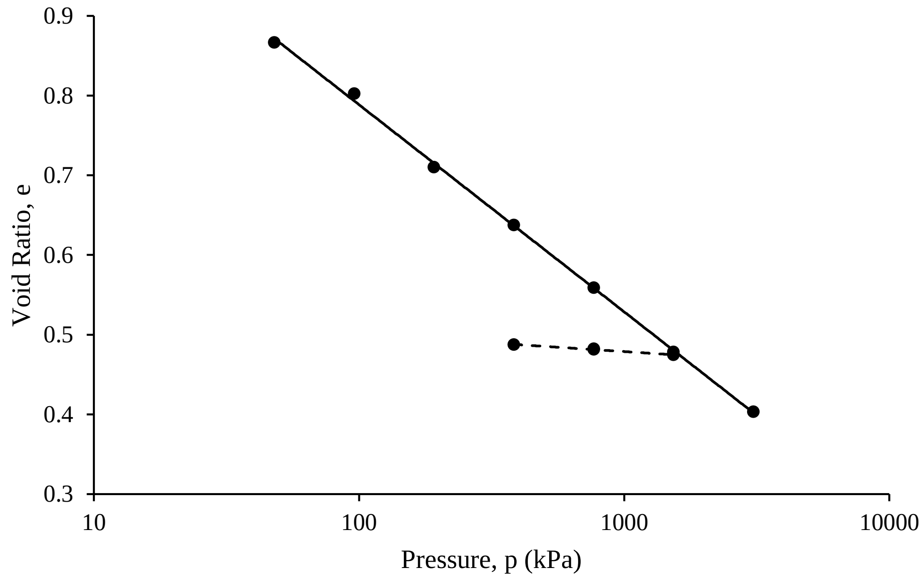


Figure 14

Compression Test Results of Chalk Amended with 6% Biochar

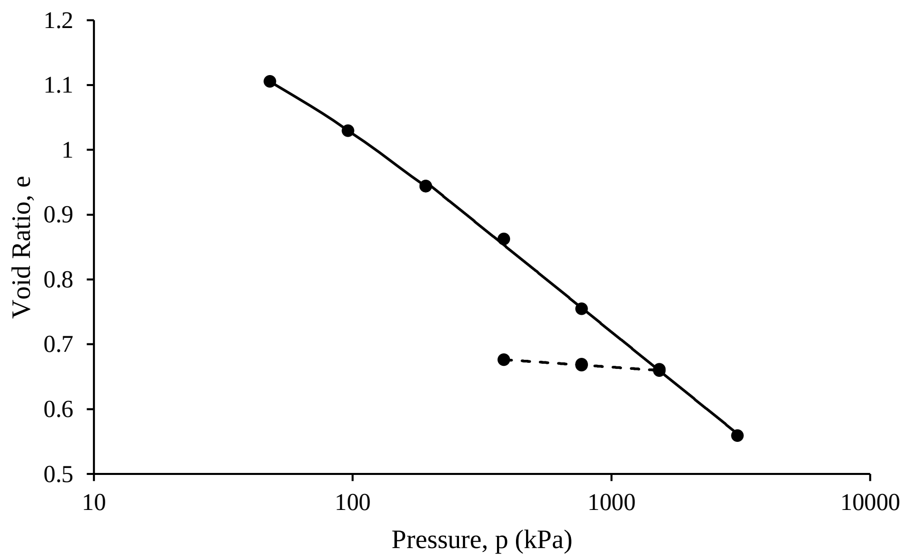


Figure 15

Compression Test Results of Chalk Amended with 12% Biochar

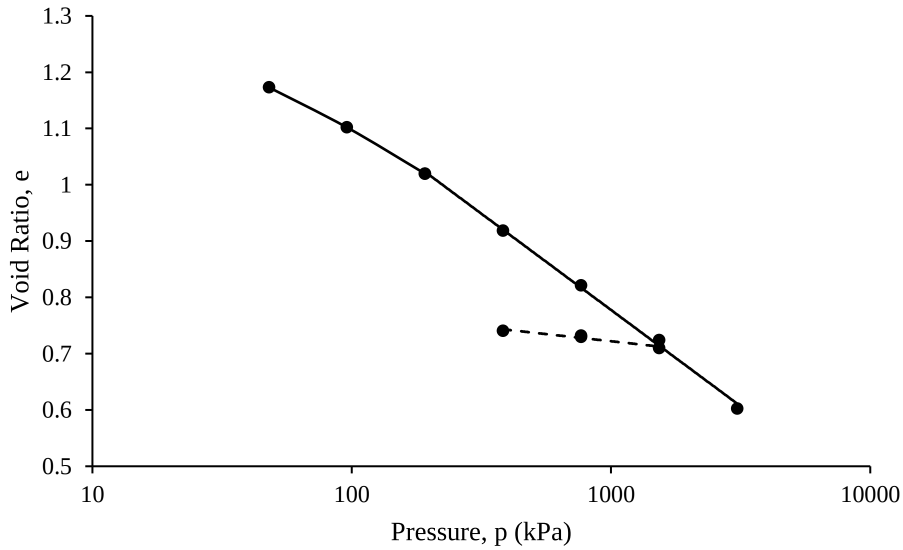


Table 5

Compression and Swell Index of Chalk Amended with 0%, 6%, and 12% Biochar

% Biochar	Compression Index C_c	Swell Index C_s
0	0.133	0.009
6	0.140	0.012
12	0.148	0.022

As seen in Figures 13 through 15 and Table 5, the compression index and swell index both increased with increasing biochar percentage. Furthermore, Figures 13 through 15 also illustrate that an increase in biochar percentage increases the void ratio at all compression pressures. The decrease in density and increase in porosity that results from biochar amendment likely contributed to the increase in compression and swell index. Lamprinakos and Manahiloh (2019) and Sadasivam and Reddy (2015) found similar trends with biochar amendment to well-graded silty sand and landfill cover soil, respectively.

The increase in compressibility of the soil is not a desirable property because a decrease in compression and swell index would improve the mechanical properties of the soil. Thus, the increase in compressibility with increased biochar percentage should be considered when used for improving the geotechnical properties of soil. However, the small change in compression and swell index does not modify the soil enough to drastically decrease its compressibility. Care should be taken to not use too high of a biochar percentage to avoid a significant decrease in compressibility.

Direct Shear Test Results

With the completion of the direct shear test, the Mohr-Coulomb failure envelope was plotted for each specimen with varied biochar percentages. Figure 16 shows the failure envelope of the Mississippi chalk without biochar amendment. Similarly, the failure envelopes of chalk amended with 6% and 12% biochar are shown in Figures 17 and 18, respectively. Additionally, the Mohr-Coulomb shear stress equation was used to predict the shear strength of the three soil specimens under a normal stress of 25, 50, and 100 kPa. The results for each of the three specimens are summarized in Table 6, including the friction angle and cohesion coefficient found from Figures 16 through 18.

Figure 16

Failure Envelope of Mississippi Chalk (0% Biochar)

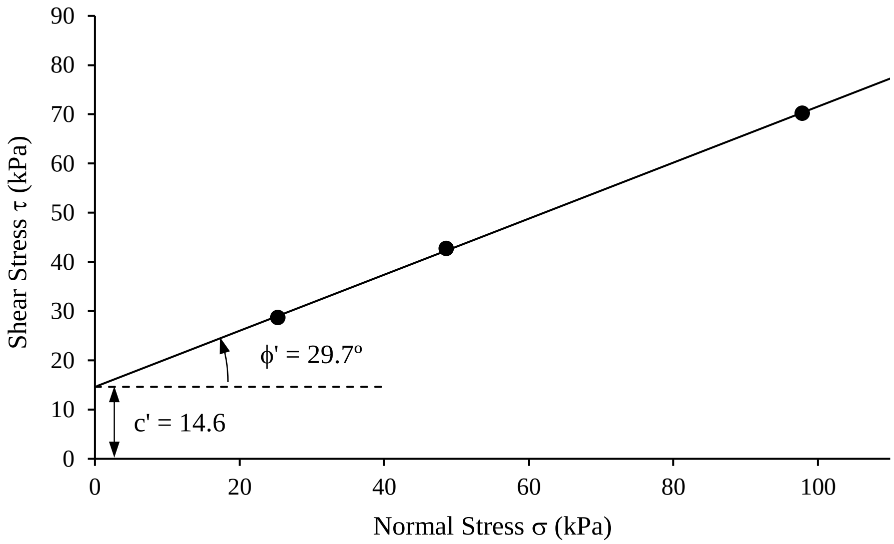


Figure 17

Failure Envelope of Chalk Amended with 6% Biochar

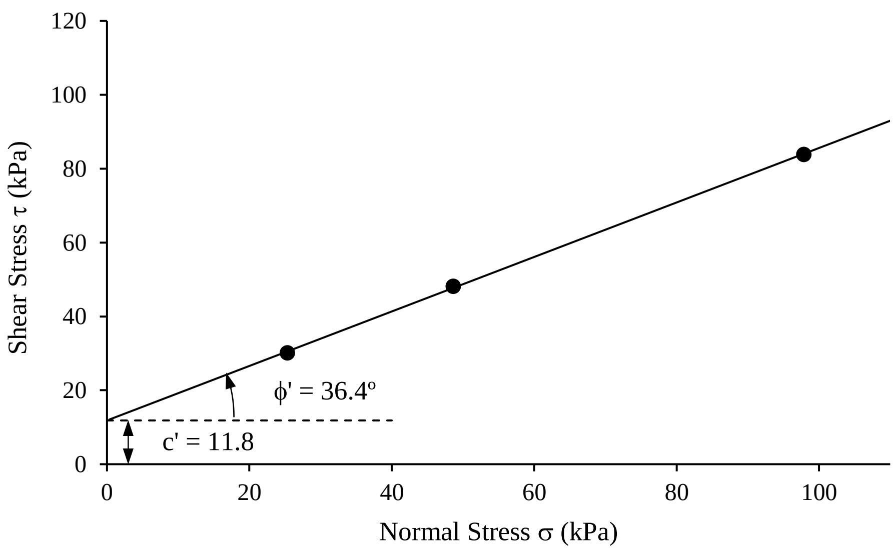


Figure 18

Failure Envelope of Chalk Amended with 6% Biochar

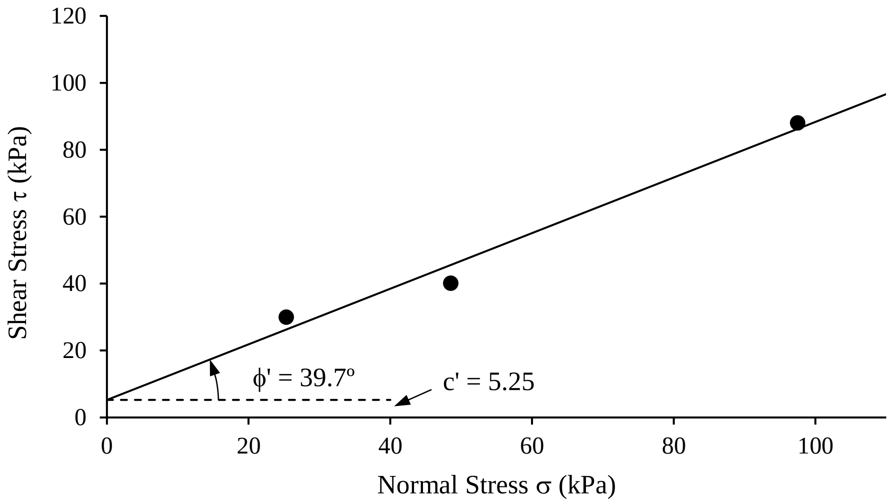


Table 6

Direct Shear Test Results for Chalk Amended with 0%, 6%, and 12% Biochar

% Biochar	Friction Angle ϕ' (deg)	Cohesion Coefficient c' (kPa)	Shear Strength τ (kPa) at σ = 25 kPa	at σ = 50 kPa	at σ = 100 kPa
0	29.7	14.6	28.9	43.1	71.6
6	36.4	11.8	30.2	48.7	85.5
12	39.7	5.25	26.0	46.8	88.3

As seen in Figures 16-18 and Table 6, the friction angle increases, and the cohesion coefficient decreases with increasing biochar percentage. An increase in friction angle has a positive increase effect on the shear strength of the soil, while the decrease in cohesion coefficient has a negative effect. The results of the direct shear test were similar to the expected results. The cohesion coefficient was expected to decrease with increased biochar percentage because of the large grain size and incohesive nature of biochar relative to the Mississippi chalk. On the other hand, the friction angle was expected to increase with increased biochar percentage because biochar was hypothesized to increase the shear strength of the soil under a higher normal force.

For all three chosen normal stresses, the 6% biochar amendment increased the shear strength of the soil. However, the 12% biochar showed no improvement at 25 kPa, less improvement at 50 kPa, and only slightly more improvement than the 6% biochar at 100 kPa. Therefore, amending the Mississippi chalk with 6% biochar shows improvement to the shear strength over a wide range of normal loads. However, chalk amended 12% biochar does not show significant improvement of the shear strength of the soil unless high normal loads are experienced. The improvement of soil shear strength with increasing biochar percentage agrees with the results found by Reddy et al. (2015). Furthermore, Lamprinakos and Manahiloh (2019) found that biochar amendment improves shear strength properties on soils with greater fine contents. The Mississippi clay confirms these results, as the clay was a very fine-grained soil.

Conclusions

The index properties of the Mississippi chalk, such as soil classification, specific gravity, and Atterberg limits, were determined following ASTM protocols, and the Mississippi clay was classified as a medium plasticity (CL) clay. The mechanical behavior of the chalk and chalk amended with 6% and 12% biochar was evaluated in the laboratory via the Proctor compaction, compression, and direct shear tests performed per the ASTM guidelines. Results showed that as the biochar percentage increased, the optimum point on the compaction curve moved downward, showing that the biochar amendment decreased soil compactibility. Furthermore, as the percentage of biochar increased, the compressibility of the specimens increased. Using the shear strength parameters obtained from direct shear test and employing the M-C failure criterion, it also was concluded that the shear strength of the chalk increased with biochar percentage.

In summary, the shear strength of the Mississippi chalk was improved by biochar amendment, especially at high normal stresses, while biochar adversely affected the compactibility and compressibility of the soil. The increased shear strength of biochar-amended clay could provide useful for applications in infrastructure and soil retention, as well as providing improved stability when implemented for environmental applications. However, the significant decrease in soil compactibility in biochar-amended clay would prove to be detrimental in infrastructural applications. The swelling and shrinking behavior of expansive soils could be exacerbated with high biochar amendment percentages. The small decrease in soil compressibility should also be considered at higher biochar percentages. Biochar amendment may not be a feasible solution with applications that endure large compressive stresses or repetitive compaction. The benefits of biochar amendment on the shear strength of the Mississippi clay should be balanced with the drawbacks of increased compressibility and compactibility. The feasibility of biochar amendment should be evaluated on a case-by-case basis, and large biochar amendment percentages should be avoided.

Further research should be done to determine the optimum biochar percentage under different practical loading scenarios. Moreover, the effect of biochar amendment on other soils, especially fat clays, should also be investigated. The results of similar tests on biochar-amended field specimens should be compared with laboratory results to check for consistency. Different biochar sources should continue to be researched on various soil types to observe if results are universally applicable or soil specific. Furthermore, the behavior of biochar-amended soil under higher loads or longer duration loads should be investigated. The effect of the grain size of biochar on the mechanical behavior of soils should also be explored.

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