USING FOOD-INDUSTRY BYPRODUCTS TO TREAT EXPANSIVE CLAY

by

Nicole L. Shaw

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Nicole L. Shaw

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The following individuals read and discussed the thesis submitted by student Nicole L. Shaw, and they evaluated the student's presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

Arvin Farid, Ph.D., P.E.	Chair, Supervisory Committee
Nick Hudyma, Ph.D., P.E.	Member, Supervisory Committee
Dan Gado, M.S., P.E.	Member, Supervisory Committee

The final reading approval of the thesis was granted by Arvin Farid, Ph.D., P.E., Chair of the Supervisory Committee. The thesis was approved by the Graduate College.

DEDICATION

I would like to dedicate this work to my loving family – who all have been so influential throughout my life and supportive during this journey.

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ABSTRACT

Lime stabilization has proven to be a valuable method in improving the properties of expansive clays under light structures such as those in transportation projects where ground improvement methods are often necessary over a large area. Hydrous and quick lime products are also utilized in various types of food processing operations to remove impurities from agricultural products. During this purification, waste is produced consisting of precipitated calcium carbonate, organic debris, and trace amounts of soil and agricultural contaminants. This food-processing waste typically contains commercially available unspent lime products, which are still viable for construction applications. Hence, this type of waste could be viewed as a byproduct to be reused or recycled.

The waste is generated in excess of 100,000 tons per year per site when produced in large-scale operations. The volume produced is too large to be sent to landfills and is not compostable due to its chemical composition. Therefore, the waste is typically stockpiled on land adjacent to food processing facilities. There is potential to save capital on construction projects as well as significantly save in land investment by food processing facilities if a more environmentally and economically sustainable solution is found to utilize, reuse, or recycle this material. This paper studies the potential to use agricultural and food industry waste in construction applications where the organic content by weight is consistently measured at lower than 5%. Using a series of geotechnical and environmental laboratory testing procedures, several engineering properties (e.g., swell potential, permeability, and strength properties) of various blends of this waste and expansive clay are measured to find the right series of tests to evaluate this potential. Preliminary testing on a series of blends with an expansive clay suggests decreased swelling potential, increased density, and potential leachate immobilization. Once more blends have been studied and procedures have been standardized, these materials may also produce a secondary revenue stream for certain food processing facilities when utilized in construction applications.

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LIST OF ABBREVIATIONS

CaO	Calcium Oxide
Ca(OH)	Calcium Hydroxide
CaCO3	Calcium Carbonate
DDL	Double-Diffuse Layer
DST	Direct Shear Test
FIBP	Food Industry Byproduct
HDPE	High-Density Polyethylene
PCC	Precipitated Calcium Carbonate
SEM	Scanning Electron Microscope
UCS	Unconfined Compressive Strength

CHAPTER ONE: INTRODUCTION

The coauthors' research team was introduced to a sponsor facility located at multiple sites in Idaho (henceforth referred to as the 'sponsor') that wishes to remain anonymous. A nondisclosure agreement is in place to protect their anonymity. The materials discussed in this paper that are generated on their sites will generally be referred to as FIBP, not identifying the specific food products being processed and the sponsor.

This research investigates the relationship between an agricultural food-industry byproduct (FIBP) and a local expansive clay when blended to improve engineering properties for both materials in construction applications. The FIBP is a calcium-carbonate-based waste that has proven to be problematic to the sponsor due to its large quantity and trace of toxic or impure chemicals. On the other hand, expansive clays are also problematic underneath construction sites and light infrastructure due to their swelling properties, among other issues.

The goal of this research is to combine these two problematic materials and create an engineered product that utilizes the calcium-rich waste to reduce swelling in the clay, utilizes the low permeability of the clay to immobilize potential leachates out of the FIBP, and improves strength and density properties of both materials. The following chapters exemplify the processes followed to prove that FIBP has potential as a construction material.

This waste is produced through a common agricultural purification process that utilizes hydrated lime (calcium hydroxide) mixed with a juiced form of an impure food product. When the charged calcium ions of Calcium hydroxide encounter the agricultural impurities (i.e., trace amounts of fertilizers, pesticides, heavy metals) in the juice, they pull these away from the organic juice, flocculate, and precipitate as a waster/byproduct, leaving a purified food product). The waste consists of precipitated calcium carbonate with trace levels of various contaminants.

Currently, the generated waste at each site is stockpiled, sprawling for areas larger than city blocks and as tall as buildings, creating nuisance and dust issues. If ways are found to reuse this waste, these stockpiles no longer need to be maintained with significant personnel and equipment, the sponsor will see a significant reduction in spending. This land can also be utilized for other production purposes as needed or sold. Because these stockpiles can be very unsightly and the fine-grained nature of the material creates a great deal of dust, their removal would likely please communities neighboring the sponsor facilities. If an acceptable application for this byproduct is found, both the sponsor and the surrounding community will receive a multitude of benefits. In construction projects, this material may have the potential to introduce cost-savings where imported commercial products would have otherwise been used.

This thesis is manuscript-based and consists of two manuscripts originating from different stages during the research presented. While both chapters present similar information, the first consists of a conference paper submitted at an early stage of laboratory testing focused on the background, literature review, and methodology with few preliminary results, and the second, a journal article, consisting of complete results and analysis.

CHAPTER TWO: SOIL-STABILIZING POTENTIAL OF USING FOOD INDUSTRY BYPRODUCTS

Manuscript 1:

Abstract

Hydrous and quick lime is utilized in various types of food processing operations to remove impurities from agricultural products. During this process, the waste that is produced consists of precipitated calcium carbonate, organic debris, and trace amounts of soil and contaminants. When used in large-scale operations, the waste can exceed 100,000 tons of waste per year per site. This waste material is not compostable due to its chemical composition and is of too large volume to be sent to landfills. Hence, the waste is typically stockpiled on land adjacent to food processing facilities, which is not an environmentally or economically sustainable solution. Finding an environmentally and economically sustainable solution to utilize this waste material has the potential to save capital on construction projects as well as significantly save in land investment by food processing facilities. The food-processing waste described above usually contains commercially available unspent Lime products, which are viable for construction applications. Lime stabilization using relatively pure quick or hydrous lime has been successfully used to improve the strength and swelling properties of expansive clays. This paper studies the utilization of the above-mentioned waste in construction where the organic content by weight is consistently measured at lower than 5%. Using a series of geotechnical and

environmental laboratory testing procedures, several engineering properties (e.g., swell potential, permeability, leachate potential) are measured to find the right series of tests and appropriate target blends of construction material and food processing waste. Preliminary testing points to reduced swelling potential and increased density when a sample of the food-processing waste is mixed with an expansive clay. Once procedures have been standardized, using these materials in construction applications may also produce a secondary revenue stream for certain food processing facilities.

Introduction

This research team was introduced to a sponsor facility located at multiple sites in Idaho (henceforth referred to as the 'sponsor') that wishes to remain anonymous. A nondisclosure agreement is in place to protect their anonymity, and the materials discussed in this paper that are generated on their sites will not identify the specific food products being processed.

The sponsor operates as an agricultural processing facility and produces the primary material this paper studies, hereafter referred to as Food Industry Byproduct (FIBP). This FIBP is produced in several food purification processes and typically involves converting calcium carbonate to hydrated lime to be mixed with the juiced form extracted from impure plant material. The hydrated lime extracts impurities out of the juice. The resulting materials are a purified plant juice that can continue through processing and the remainder of FIBP—a precipitated calcium carbonate mixed with trace soil, organic impurities, fertilizers, pesticides, herbicides, and heavy metals—is disposed of on-site. This waste is generally white to gray, very fine-grained, and has a high moisture retention capacity. It can be described as having a consistency like that of all-purpose flour.

Due to the ever-changing nature of the FIBP with varying soil conditions and agricultural practices, it became extremely difficult for the sponsor to utilize this material. Similar facilities in some parts of the United States can sell their FIBP materials back to local farmers to fertilize their fields, however, this does not work well in Idaho due to the relatively high pH encountered in the native soils. Because the FIBP cannot be transported to a landfill, the current practice is stockpiling the material on-site. While we do not have data on the combined national or worldwide stockpiled waste at these private facilities, we were informed that our sponsor produces greater than 100,000 tons of FIBP annually that must be stockpiled in Idaho alone. The land cost, combined with equipment and personnel to maintain stockpiles and mitigate dust hazards makes this inefficient from an economic standpoint. The potential for leachates paired with unknown factors presents an environmental risk. The need for dust mitigation of this fine-grained waste, odor, and unsightly stockpiles presents social challenges for the sponsor. It is apparent that finding a way to *dispose* of the FIBP is necessary; however, finding a way to *repurpose* the FIBP is preferred, and finding a way to *profit* from the FIBP is desired.

Literature Review

Based on a review of similar waste materials, it can be assumed that there is potential for the FIBP in geo-structural applications, soil remediation, ground improvement, agricultural applications, and others yet to be considered. This paper has focused on ground improvement applications by mixing the FIBP with problematic soils used as pavement subgrades, specifically expansive clays.

Some comparisons can be drawn between the FIBP material analyzed in this paper and several prior studies on ash from coal combustion and other similar waste materials.

In comparing the FIBP with coal-combustion fly ash, some similarities between the materials exist such as their alkalinity, impurity content, and cementitious properties of the unspent lime (Kolias 2005). Their unsustainable land use and transportation costs have also presented parallel problems for society to solve.

In preparation for this paper, the goal of the literature review was to find evidence suggesting that this material may be successful in ground improvement applications. The research began with measuring various properties and determining which properties should be evaluated to prove potential. The properties selected included grain-size distribution, Atterberg limits, maximum dry density, optimum moisture content, unconfined compressive strength, and permeability. The next step is to find the best blend of FIBP and expansive clay based on those properties. Once a range of blends is evaluated and determined which blend(s) maximize(s) beneficial properties, ways to maximize utilization of the FIBP will be investigated.

The literature and studies presented in this paper are each included for a specific purpose. Some background studies performed at a nonacademic level by the sponsor and their subcontractors are first explained below. These studies show that this material can perform the desired functions. Next, a paper that studies a very similar material but investigates slightly different parameters and applications is visited. This study provides a glimpse of what is expected from the FIBP under study. Finally, a paper that goes through a very similar process, but on a different material, is reviewed.

Trials by Sponsor

Because the sponsor has access to practically unlimited FIBP, it has been in their interest over the years to experiment with utilizing this material on their private property for small-scale construction activities. During our team's travel to the sponsor's multiple sites, two projects that have been performing well and were able to utilize a significant portion of the FIBP waste on-site were visited. While these projects demonstrate that the FIBP may have construction applications, this material needs to be studied much more closely before implementation on civil engineering projects that are utilized by the public.

The first project involved building up an above-grade 18-foot-high embankment around a settling pond used to store wastewater from on-site processes. The embankment was designed to be completely lined with a High-Density Polyethylene (HDPE) liner to prevent seepage of wastewater. At the time of construction in the year 2015, the sponsor also had a considerable stockpile of coal combustion fly-ash waste. By partnering with a local geotechnical engineering firm to develop a testing program consisting of grain-size distributions, moisture-density curves, direct shear, and consolidation tests, a blend of materials was established to build the embankment. The blend consisted of varying percentages of native silt, fly ash, and FIBP. This was the first project to utilize their FIBP waste, and it was able to contribute to making an on-site project more economical while reusing what would have been a stockpiled waste costly to maintain. To this day, the settling pond embankment has been performing with success.

The second project was a 2020 rehabilitation of a gravel road on the property of one of their sites. The sponsor had the same issue every spring—snow melt would wash away large sections of this gravel road. However, the stretch of road was not used enough to justify a flexible pavement investment. Rather than placing a traditional crushed aggregate base for the road, a blend of native silt, fly ash, and FIBP was placed in an 8-inch lift, followed by a 4-inch gravel section. In a conversation during spring 2022, it was stated that, even though not perfect, this section of the road is apparently performing better than it had previously. Picture 2.1 shows the blend that was placed in lieu of the road base, and Picture 2.2 shows the finished gravel road. Although both projects seem to be performing with success, a deeper understanding of the role FIBP plays in combination with native soils for construction applications is necessary for safety and environmental reasons at the minimum. A better understanding of this union can also help to ensure the success of future engineering projects.

Picture 2.1 FIBP Road Base

Picture 2.2 Finished Gravel Road

Academic Literature Review

Langroudi et al. (2019) studied the use of waste material, like the subject of our research, to address a different problem. They studied different precipitated calcium carbonates (PCC) to address two parallel problems. The first was the risk associated with slope stability of hillslopes and embankments where clayey and loamy soils are encountered, and the second was that of the abundance of a series of materials currently viewed as primarily waste, but with untapped potential as a cementitious stabilizer. Some of the examples of cementitious stabilizers mentioned in this paper are lime, cement, coal-combustion fly ash, kiln dust, potassium and ammonium compounds, silicates, polymers, organic fibers, and the main topic of their study – Lime Cake precipitated calcium carbonate (PCC).

The PCC Lime Cake discussed in their study is a product produced similar to that of our sponsor's FIBP, from a sugar manufacturing process. This material consists of approximately 60 to 85% calcium carbonate, 10 to 15 % organic matter, and less than 1%

nitrogen, phosphorus, and potassium. This material has significantly higher organic matter content than the FIBP supplied by our sponsor, but also lower levels of trace fertilizer chemicals.

Langroudi et al. (2019) state that, in Europe, it has already become common practice to utilize lime spoils to remediate distressed hillslopes. When calcium-enriched electrolytes are introduced to the clayey soil, a pozzolanic reaction is triggered, and the water formerly surrounding clay particles is converted to calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels. This replacement reduces swelling capacity and increases bearing capacity and stiffness.

Langroudi et al. (2019) prepared a blend of natural firm sandy, clayey silt, kaolinite clay, and PCC Lime Cake. The blend demonstrated a decrease in the liquid limit from the natural soil, which is directly associated with swelling capacity. An increase was noted in the maximum dry density of the blend compared to the original soil as well. When the soil and the blend were viewed with electron micrographs, the closest particle packing was observed with the PCC Lime Cake blend due to the diminished swelling potential of the clay particles.

When analyzing the samples, shear strength was highest under unsaturated conditions. Where calcite cementation occurred, yield stress and brittleness increased, generating a strain-hardening plastic behavior in unsaturated samples. This brittle behavior is worth further investigating in applications where the soils will not be properly confined.

Sharma et al. (2012) studied a waste material different from ours to address a similar problem. They discussed the issues presented in building pavement structures on expansive, clayey subgrades, and how treating the subgrade soil with fly ash and lime can combat undesirable engineering properties. Commercially available lime is commonly used to treat expansive, clayey subgrade soils beneath pavement structures. However, this treatment can be very cost-prohibitive due to the quantities needed. When lime is introduced to clay, the pozzolanic reaction discussed above occurs, displacing water between the clay particles and replacing it with the C-S-H and C-A-H gels, reducing the thickness of the double diffuse layer surrounding each clay particle. The pozzolanic reaction in the subgrade helps prevent shrink and swell potential and high moisture susceptibility, responsible for early distress in pavements.

At the time of the study by Sharma et al. (2012), fly ash's capabilities were being studied aggressively, and fly ash was an under-utilized waste material with enormous potential, which justifies our attempt to follow in line with some of the successful fly ash pursuits. Sharma et al. (2012) recognized that fly ash alone would not provide a sufficient pozzolanic reaction with the clay soil, so they chose to supplement a portion of the commercially available lime with fly ash. Although this measure may sound small, when quantities are applied to a significant transportation project that may contain miles of pavement, the savings—from the use of recycled materials instead of commercially available lime—could be significant.

The properties chosen to evaluate the effect of fly ash in their study were as free swell index, plasticity, compaction characteristics, unconfined compressive strength, California bearing ratio, and Atterberg limits. The clayey soil used in their study was a native soft lean clay with expansive characteristics. The tested blends varied from soil with 0% fly ash to 25% fly ash and 0% to 10% lime.

Comparing test results for the properties evaluated by Sharma et al. (2012), it was determined that the most effective blend had approximately 20% fly ash and 8.5% lime. The lime content was a minimum value required to bring the blend to the target pH. Additional fly ash past 20% did not appear to have any positive effects on the engineering properties. However, this almost 1 to 2 ratio of lime to fly ash imposes a considerable cost compared to a waste requiring no or much less lime.

Both academic approaches offer valuable insight into what we may expect throughout our research. Langroudi et al. (2019) provide information about how combining a precipitated calcium carbonate with a clay-based soil improves bearing capacity, and stiffness, as well as maximizes particle packing. It points out a reduction in liquid limit and plasticity index and correlates these to a likely reduction in swell potential, but this needs to be verified. Sharma et al. (2012) do perform free-swell tests to verify this property in the blends evaluated. It would, however, be valuable to also compare blends in this study based on properties such as hydraulic conductivity since the ultimate goal is to improve pavement subgrade.

Materials and Methods

This paper hypothesizes that combining two problematic materials—the FIBP provided by our sponsor and local expansive clay soil—can create an engineered product with at least one of the following improvements: acceptable swelling potential for engineering applications, acceptable bearing capacity for engineering applications, and the ability to immobilize potential leachates.

Materials

As discussed briefly, the FIBP studied in this paper is a fine-grained silt-size, flour-like waste material that can cause a pozzolanic reaction when combined with clay and water. The FIBP material used in this study is slightly heterogeneous within one or across varying sponsor sites. Table 2.1 presents average test data for 2018, 2019, and 2020 for a variety of chemical and environmental properties. A rating is provided for reference.

Table 2.1 FIBP environmental testing provided by the sponsor

FIBP TEST DATA		
Parameter (units)	**Value**	**Rating**
pH	8.4	High
Salts (mmhos/cm)	6.6	Moderate to Very High
Chlorides (ppm)	116.7	High to Very High
Sodium (meq/100g)	0.2	Very Low
CEC (meq/100g)	23.0	High
Excess Lime (%)	19.4	Very High
Organic Matter (%)	4.6	Very High
Organic N (lb/acre)	60.0	Moderate
Ammonium- N (ppm)	48.1	Moderate to Very High
Nitrate- N (ppm)	317.7	Very High
Phosphorous (ppm)	152.0	Very High
Potassium (ppm)	338.3	High to Very High
Calcium (meq/100g)	12.3	High to Very High
Magnesium (meq/100g)	9.4	Very High
Sulfate- S (ppm)	798.7	Very High
Zinc (ppm)	2.9	High
Iron (ppm)	58.2	Very High
Manganese (ppm)	6.1	High to Moderate
Copper (ppm)	1.8	High
Boron (ppm)	2.0	High to Very High

Expansive clayey soils in construction applications create many hurdles for design and construction teams to overcome. They typically provide low bearing capacity, low permeability, and high swelling potential, and they are difficult to compact. Clays play a role in many geotechnical engineering failures—from the differential settlement of foundations to pavements riddled with cracks and potholes.

The clay selected for this study is a local Fat Clay soil from Marsing, Idaho with a high swelling potential, which is considered unsuitable soil for most engineering applications. If the characteristics of this material can be improved using FIBP, it is proven that there is undoubted potential for this FIBP in soil stabilization.

Methods

As the laboratory testing schedule was prepared, specific tests were considered. Those included sieve analysis (ASTM 2017c), hydrometers (ASTM 2018), Atterberg limits (ASTM 2017b), moisture-density curves (ASTM 2012), unconfined compression tests (ASTM 2016a), swell tests (ASTM 2021), direct shear tests (ASTM 2017a), and permeability (ASTM 2016b). One goal of this study is to utilize as much FIBP as possible, so five blends were created, working up from 0% FIBP to 60% FIBP mixed with clay to analyze the impact FIBP has on engineering properties. As the starting point, a 30% FIBP blend was selected to perform all of the tests and evaluations.

As the work on these mixes started, the difficulty in using some of these tests and obtaining accurate results was realized. Sieve analysis was performed, but with such high percentages passing the #200 sieve, a hydrometer test proved crucial to be added to the testing schedule. The Atterberg limits were less problematic. Developing moisture-density compaction curves using a standard proctor was also problematic due to the high degree of fine-grained material and their high moisture retention. Due to the fine nature of the materials, this test experienced an excessive loss of fines. A Harvard Mini Compaction Apparatus—a device designed specifically for determining moisture-density curves on soils finer than the #10 sieve— was then used instead. This device worked better on the prepared blends. Other tests are ongoing and not completed, but the small amount completed thus far fits the expectations and shows promise.

Results and Discussion

Preliminary laboratory test results are shown in Table 2.2 below. Both materials are very fine-grained, so no significant change in the percent passing the #200 sieve is observed. Significantly, replacing 30% of the Fat Clay brings the mix into the nonplastic range. While none of the materials have particularly high densities, the blend has a slightly higher maximum dry density than the FIBP or the clay, which is an improvement to the reduction of DDL of clay, allowing it to play the role of a nonexpansive filler. The optimum moisture content of the blend seems to fall at a midpoint between the two base materials, which comes as no surprise. The moisture-density curves for these materials are shown below in Figure 2.1.

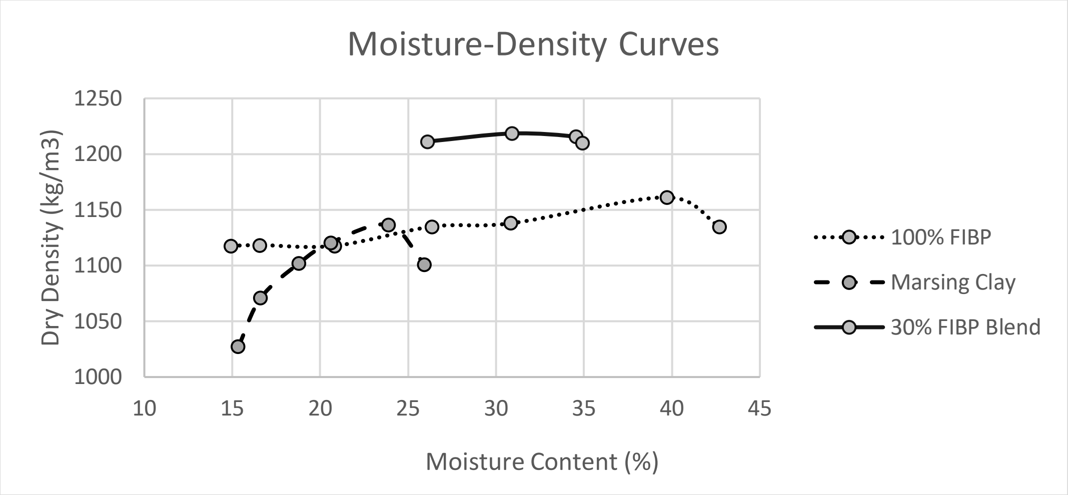


Figure 2.1 Moisture Density Curves

Table 2.2 Preliminary Testing Results

Property	FIBP	Marsing Clay	Blend
Percent Passing #200 (%)	93.1	95.0	93.2
Liquid Limit	NV	111	NV
Plasticity Index	NP	52	NP
Maximum Dry Density (kg/m^3)	1161.2	1136.5	1218.5
Optimum Moisture Content (%)	39.8	24.2	30.9

Conclusions

The ultimate three-fold goal of this work is to evaluate whether the swelling capacity can be reduced simultaneously with an increase in the bearing capacity and immobilization of any leachates within an expansive clay soil.

These preliminary results show that the Atterberg limits are improved. The liquid limit and plasticity index are directly related to the swelling potential of soil, but a swell test is necessary for verification. The first tested blend showed that the blends became nonplastic, leading to belief in the assumption that the FIBP can reduce the swelling capacity.

The results show that the maximum dry density is increased and the optimum water content for compaction is decreased during compaction tests. Despite the increase in the maximum dry density, a higher increase in the maximum dry density is still desired. All these conclusions suggest that this waste may be of value to the construction industry.

However, the maximum dry density is a predictor of the strength of compacted soil, but ultimately, it will be the unconfined compression test results that can determine how the strength of the soil is impacted by the presence of FIBP.

A significant amount of work is still needed to test and validate the hypothesis of this paper. For example, the ongoing permeability tests will evaluate how capable these blends are to immobilize any leachates.

In moving forward, the most promising blend will be selected, and any additional laboratory testing will be determined. A cost-benefit analysis to ensure that the transportation and potential regulatory costs of using this material will not negatively impact its reusability will also be performed.

CHAPTER THREE: USING FOOD INDUSTRY BYPRODUCT TO STABILIZE AN EXPANSIVE CLAY

Manuscript 2:

Abstract

Lime stabilization has proven to be a valuable method in improving the properties of expansive clays where ground improvement methods are necessary over a large area. Hydrous and quick lime products are also utilized in various types of food processing operations to remove impurities from agricultural products. During purification, waste is produced consisting of precipitated calcium carbonate, organic debris, and trace amounts of soil and agricultural contaminants. This food-processing waste contains commercially available unspent lime products, which are viable for construction applications.

This waste is typically stockpiled on land adjacent to food processing facilities due to its large volume and chemical composition. This paper studies the potential to use the waste material in construction applications where the organic content by weight is measured at lower than 5%. Using a series of geotechnical and environmental laboratory testing procedures, engineering properties (e.g., swell potential, permeability, and strength properties) of various blends of this waste and expansive clay are measured. Preliminary testing on blends with an expansive clay suggests decreased swelling potential, increased density, and potential leachate immobilization.

Introduction

The coauthors' research team was introduced to a sponsor facility located at multiple sites in Idaho (henceforth referred to as the 'sponsor') that wishes to remain anonymous. A nondisclosure agreement is in place to protect their anonymity. The materials, discussed in this paper, generated on their sites, will generally be referred to as FIBP (Food-industry Byproducts), not identifying the specific food products being processed, and the sponsor.

The sponsor operates as an agricultural processing facility throughout Idaho and produces the key material of this study, subsequently referred to as Food Industry Byproduct (FIBP). Similar FIBP materials are produced in many food purification processes and typically involve converting calcium carbonate to hydrated lime to be mixed with the juice from impure plant material. When mixed with the juice, the hydrated lime withdraws impurities from the juice. The resulting materials are a purified plant juice and the FIBP—a precipitated calcium carbonate mixed with trace quantities of soil, organics, fertilizers, pesticides, herbicides, and heavy metals. This waste is generally white to gray, very fine-grained, and of a high moisture-retention capacity and high alkalinity.

The sponsor has historically had difficulty attempting to utilize the FIBP due to the ever-changing nature of the FIBP with varying soil conditions and agricultural practices. Similar types of facilities throughout the United States can sell their FIBP back to local farmers to fertilize their fields. However, due to the relatively high pH encountered in the native soils in arid regions, such as those in Idaho, this is not an option for the facilities located in Idaho. The sponsor has shared data indicating that approximately 100,000 tons of FIBP are produced annually at their facilities throughout Idaho. The current practice is stockpiling the material on-site, which places a heavy economic burden on the facilities and leads to substantial negative environmental and societal impacts. The price of land, combined with equipment and personnel to maintain stockpiles and mitigate dust hazards makes storage a costly endeavor. The potential for leachates and countless unknown factors presents environmental risks. The need for dust mitigation, odor control, and the presence of unsightly stockpiles also presents societal challenges for which the sponsor is responsible. It is apparent that finding a way to *dispose* of the FIBP is necessary; however, finding a way to *repurpose* the FIBP is preferred, and finding a way to *profit* from the FIBP is desired.

Literature Review

There are parallels to be drawn between the FIBP material examined in this paper and several prior studies on ash from coal combustion and other similar waste materials. This suggests that many successful applications (e.g., geo-structural, soil remediation, ground improvement, and agricultural practices) with coal-combustion ash should be evaluated with FIBP. This paper has focused primarily on ground improvement applications by mixing the FIBP with expansive clay soils encountered within pavement subgrades. In comparing the FIBP with coal-combustion fly ash, the similarities include their alkalinity, impurity content, and cementitious properties due to the presence of unspent lime (Kolias 2005). Their associated transportation costs and unsustainable land use have also presented comparable problems for society.

There are three literature and studies sections presented in this paper; each included for a specific intention. Background studies performed by the sponsor and their subcontractors at a nonacademic level are explained first. These are examples of the material performing in engineering applications, albeit a deeper understanding of the FIBP is desired. At an academic level, two papers found in the literature are presented next. The first of these two papers focuses on a similar FIBP material but explores different applications and parameters. This study provides insight into expected conditions from the FIBP under study. The second paper goes through a process similar to the process utilized in this paper, but on different waste materials.

Trials by Sponsor

Due to the abundance of material and the cost associated with its storage, it has been in the interest of the sponsor to experiment with utilizing this material on their private property for small-scale construction activities. During travel to the sponsor's multiple sites, two projects were introduced to the research team to exemplify the potential of utilizing the FIBP in construction applications. The two projects utilized the same blend of on-site materials. Both projects have been considered successful and were able to utilize a large quantity of FIBP waste. While these projects demonstrate that the FIBP may have construction applications as fill materials, this material should be studied without fly ash and more to ensure that it can be used safely and that its engineering potential can be fully realized.

The first of the sponsor's projects consisted of creating an 18-foot-high embankment for a settling pond to be used for the retention of wastewater from an on-site process. The embankment is lined with a High-Density Polyethylene (HDPE) liner to prevent leaching wastewater into the fill materials and native ground surface below. Constructed in 2015, the sponsor considers this achievement significant. The second sponsor's project was a 2020 rehabilitation of a problematic gravel road on one of their sites. In lieu of placing an aggregate base for the road, a blend of native silt, fly ash, and FIBP, similar to the first project, was placed in an 8-inch lift, followed by a 4-inch gravel profile. Figure 3.1(a) presents the blend that was placed instead of the aggregate base, and Figure 3.1(b) presents the finished gravel road.

Pictures 3.1 (a) FIBP road base; (b) finished gravel surface upon project completion

Academic Literature Review

Langroudi et al. (2019) explored the use of a similar waste material to address a different set of problems. They studied precipitated calcium carbonates (PCC) from agricultural processes in abundance and are currently viewed as waste similar to the FIBP studied here, but to address as a likely candidate with untapped potential as a cementitious stabilizer. Examples mentioned in their paper include lime, cement, coal-combustion fly ash, kiln dust, potassium and ammonium compounds, silicates, polymers, organic fibers, and a waste similar to the primary topic of their study—Lime Cake precipitated calcium carbonate (PCC). Their study suggested there is a benefit in using this material to mitigate the risk associated with slope stability of hillslopes and embankments where clayey and loamy soils are encountered.

The PCC lime cake examined in their study is a product similar to that of the sponsor's FIBP. That material consisted of approximately 60 to 85% calcium carbonate, 10 to 15 % organic matter, and less than 1% nitrogen, phosphorus, and potassium. That material had significantly higher organic content than the FIBP supplied in this paper, but lower levels of trace fertilizer chemicals.

Langroudi et al. (2019) stated that, in Europe, it has become customary practice to utilize lime waste to remediate distressed hillslopes. When calcium-enriched electrolytes from the lime cake are introduced to clayey or loamy soils, a pozzolanic reaction occurs, and the water previously surrounding clay particles is transformed to calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels. This replacement increases bearing capacity and stiffness and reduces swelling capacity.

Langroudi et al. (2019) constructed a blend of natural firm sandy, clayey silt, kaolinite clay, and PCC Lime Cake. The blend exhibited a decrease in the liquid limit which is directly correlated with swelling capacity. An increase was observed in the maximum dry density of the blend. When the soil and the blend were viewed with scanning electron micrographs, the tightest particle packing was observed with the blend due to the reduced swelling potential of the clay.

Shear strength was observed to be highest under unsaturated conditions. Where calcite cementation occurred, samples became more brittle and yield stress increased, generating a strain-hardening plastic behavior in unsaturated samples. This brittle behavior is a property that should be further investigated in implementations where the blends will not be confined.

Sharma et al. (2012) studied a waste material unlike the FIBP in this study to address a similar obstacle. Issues were discussed surrounding building pavement structures on expansive, clayey subgrades. It was suggested that common problems faced could be remedied by treating the subgrade soil with a blend of coal combustion fly ash and commercially available lime to combat undesirable engineering properties. When lime is introduced to clay, the pozzolanic reaction discussed above occurs in the subgrade, helping to reduce swell potential and high moisture susceptibility, which is largely responsible for early distress in pavements.

During the time of the study by Sharma et al. (2012), fly ash’s potential was being researched vigorously, and fly ash's capabilities were not yet realized. At this time, fly ash was also a problematic waste material in need of a storage solution or use, which justifies following a similar path in evaluating a series of blends and engineering properties. Sharma et al. (2012) recognized that fly ash could not provide the necessary pozzolanic reaction with clay soil to reduce the double diffuse layer, so chose to supplement the blends with varying percentages of commercially available lime.

The laboratory tests performed to evaluate the effectiveness of fly ash in their study were the free swell index, plasticity, compaction characteristics, unconfined compressive strength, and California bearing ratio. The soil used was an expansive, soft lean clay. The tested blends varied from the soil with 0% to 10% lime and 0% to 25% fly ash.

In evaluating results obtained by Sharma et al. (2012), it was established that the highest-performing blend consisted of approximately 20% fly ash and 8.5% lime. It was determined that the lime content (8.5%) was a minimum value necessary to drive the blend to the target pH range. It was observed that additional fly ash surpassing 20% did not grant any improvements on the measured engineering properties. Although this blend proved successful, this ratio of lime to fly ash requires a sizeable cost compared to a blend requiring no or significantly less commercial lime.

The pair of the above-mentioned academic research perspectives offered a useful understanding of expectations throughout this research. Langroudi et al. (2019) demonstrated how blending a precipitated calcium carbonate with clayey soil increase bearing capacity and stiffness and maximizes particle packing. It also displayed a reduction in Atterberg limits, correlating these to a plausible reduction in swell potential; however, this requires verification. Sharma et al. (2012) went a step further to evaluate this engineering property and performed free-swell tests. Although this data is useful, it would be beneficial to compare the blends in this study based on their hydraulic conductivity as well.

Materials and Methods

The goal of this paper is to take two problematic materials—in this case, a local expansive natural clay and the FIBP provided by the sponsor—and create an engineered product with at least one of the following improvements: acceptable swelling potential for engineering applications, acceptable shear strength for engineering applications, and the ability to immobilize potential leachates from the FIBP.

Materials

As mentioned earlier, the FIBP utilized in this research is a fine-grained (silt-size) waste material that may cause a pozzolanic reaction when combined with clay and water. The FIBP material used in this study is slightly heterogeneous across varying sponsor sites. Table 3.1 presents average test data for 2018, 2019, and 2020 for a variety of chemical and environmental properties. A rating is provided for reference.

Table 3.1 FIBP test data provided by the sponsor

FIBP TEST DATA		
Parameter (units)	**Value**	**Rating**
pH	8.4	High
Salts (mmhos/cm)	6.6	Moderate to Very High
Chlorides (ppm)	116.7	High to Very High
Sodium (meq/100g)	0.2	Very Low
CEC (meq/100g)	23.0	High
Excess Lime (%)	19.4	Very High
Organic Matter (%)	4.6	Very High
Organic N (lb/acre)	60.0	Moderate
Ammonium- N (ppm)	48.1	Moderate to Very High
Nitrate- N (ppm)	317.7	Very High
Phosphorous (ppm)	152.0	Very High
Potassium (ppm)	338.3	High to Very High
Calcium (meq/100g)	12.3	High to Very High
Magnesium (meq/100g)	9.4	Very High
Sulfate- S (ppm)	798.7	Very High
Zinc (ppm)	2.9	High
Iron (ppm)	58.2	Very High
Manganese (ppm)	6.1	High to Moderate
Copper (ppm)	1.8	High
Boron (ppm)	2.0	High to Very High

The clay used in this paper is expansive. Clays, in general, play a role in numerous types of geotechnical engineering failures—from the differential settlement of foundations to pavements riddled with cracks and potholes. Expansive clayey soils are even more problematic, as they frequently create hurdles for design, construction, and infrastructure. They typically provide low bearing capacity, low permeability, high swelling potential, and low compactability.

The clay selected for this study is a local Fat Clay soil from Marsing, Idaho with a high swelling potential, which is considered unsuitable for most engineering applications. If the characteristics of this material can be improved by blending with the FIBP, it can be hypothesized that there is likely potential for this FIBP in the stabilization of Marsing clay, and the FIBP can be tested for the potential stabilization of a wider variety of expansive soils.

Methods

Specific laboratory tests to evaluate how the FIBP affects the Marsing clay were selected based on similar research studies as well as the information and resources available. Those included sieve analysis (ASTM 2017c), hydrometer (ASTM 2018), Atterberg limits (ASTM 2017b), compaction (ASTM 2012), unconfined compression (ASTM 2016a), swell potential (ASTM 2021), direct shear (ASTM 2017a), and permeability (ASTM 2016b) tests. In terms of ultimate sustainability, it is desired to utilize as much FIBP as possible in clay stabilization. Hence, the variations due to the FIBP fraction need to be studied. Thus, four blends were created, working up from 15% FIBP to 60% FIBP mixed with clay to analyze the impact of FIBP fraction on engineering properties. In addition to the four blends, the pure clay (i.e., 0% FIBP) and pure FIBP (100% FIBP) were tested in each category.

Each blend was hand-mixed with extreme care. As the work began on these blends, a few issues arose in using some of these test methods, proving to obtain accurate results difficult, resulting in modifications in testing procedures. Sieve analysis was performed, resulting in 100% passing the 0.425 mm (#40) sieve in all samples and 92.5 to 95.0% passing the 0.075 mm (#200). Then all samples underwent hydrometer tests. The sieve and hydrometer results were combined to create the broader grain-size distribution results. Developing compaction (moisture-density) curves using a standard proctor was also problematic due to the high degree of fine-grained material and their high moisture-retention capacity. Due to the fine nature of the materials, this test experienced an excessive loss of fines, rendering initial results inaccurate. Hence, a Harvard Mini Compaction Apparatus—a device designed specifically for determining compaction (moisture-density) curves on soils finer than the 2 mm (#10) sieve— was then used instead. This device provided results that were repeatable and consistent.

All blends were allowed to cure in a moisture-conditioned environment for at minimum one week before laboratory testing was performed to ensure the FIBP could begin to affect the clay. All remolded samples were prepared to the target maximum dry density and optimum moisture content and stored in a moisture-conditioned environment for seven days before testing.

Results and Discussion

Laboratory test results are shown in Tables 3.2 and 3.3 below. Figures 3.2 through 3.10 and the following sections investigate each of the measured properties. As mentioned, all blends were prepared to the target optimum compaction (i.e., maximum dry density and optimum moisture content). Table 3.2 shows these optimum compaction points (i.e., moisture content and maximum dry density) of samples of all blends with various FIBP fractions. These optimum compaction points were subsequently used to prepare blended samples at various FIBP fractions to evaluate other properties (i.e., plasticity, swell potential, and shear strength).

Table 3.2 Laboratory Test Data

Sample	Passing 0.075 mm (%)	Compaction	
		Optimum Moisture (%)	Maximum Dry Density (kg/m3)
0% FIBP	95.0	24.2	1136.5
15% FIBP	93.3	29.6	1267.0
30% FIBP	93.2	30.9*	1218.5*
45% FIBP	92.5	24.7	1205.5
60% FIBP	92.5	17.0	1183.7
100% FIBP	93.1	39.8	1161.2

**Suspected outlier*

Table 3.3 shows various properties (e.g., plasticity, shear strength, swell potential) of blended samples prepared at the corresponding optimum moisture content and maximum dry density for each FIBP fraction.

Table 3.3 Plasticity, swell, and shear strength data of blends of various FIBP fractions**

Sample	Atterberg Limits		Swell Strain at 11.5 kPa (240 psf)	USCS Fines Classification	Measured Friction Angle	Unconfined Compressive Strength	Hydraulic Conductivity
	LL	PI			(deg)	(kg/m2)	(cm/s)
0% FIBP	111	52	17.3	Fat Clay (CH)	30.8	8177	3.4x10^{-6}
15% FIBP	88	33	9.3	Elastic Silt (MH)	29.6	10370	2.4x10^{-6}
30% FIBP	NV	NP	6	Silt (ML)	26.3	3058*	6.7x10^{-4*}
45% FIBP	NV	NP	1.5	Silt (ML)	30.8	4113	5.1x10^{-6}
60% FIBP	NV	NP	1.1	Silt (ML)	26.4	3881	6.3x10^{-5}
100% FIBP	NV	NP	0	Silt (ML)	32.8	6897	6.5x10^{-5}

** Suspected outlier*

***Blends of various FIBP fractions were prepared at corresponding optimum compaction*

Particle-size Distribution

Like clay, FIBP material is very fine-grained, i.e., about 92.5 to 95% passing the #200 sieve was observed. The clay is significantly more fine-grained than the FIBP when measured down to 0.0010 mm (see Figure 3.1). While it appears that more than 50% of the clay is finer than this size, a near-complete particle-size distribution curve was observed for the FIBP. Due to this high fine fraction in blends, the hydrometer test results more clearly evaluate whether proper mixing of each blend was achieved. The consistency of the spacing and shape of each curve suggests that the target blends were accurately calculated and mixed.

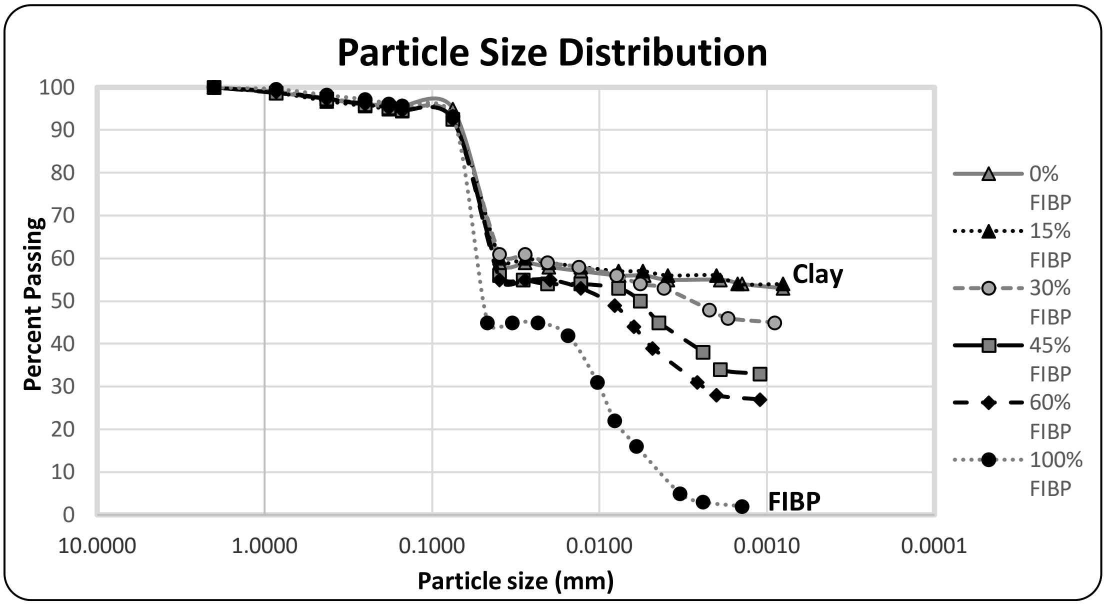


Figure 3.1 Hydrometer Analysis for all samples

Compaction

It is noteworthy that even though none of the two materials (i.e., clay and FIBP) have particularly high densities, all blends have a higher maximum dry density than the FIBP or the clay. This is an improvement to the blend properties making them more suitable for construction purposes. In addition, this may be due to the reduction of the double-diffuse layer thickness, which can consequently lead to a lower swell potential of clay, allowing it to play the role of a nonexpansive filler.

The compaction (moisture-density) curves were necessary not only to gain insight into material properties, but also because they produce the density values that are used when molding samples for other tests in this research, such as direct shear, unconfined compressive strength (UCS), permeability, and swell tests. Therefore, as mentioned, it was important to have reliable moisture-density values before moving forward in testing. The values obtained for all samples are presented in Figure 3.2.

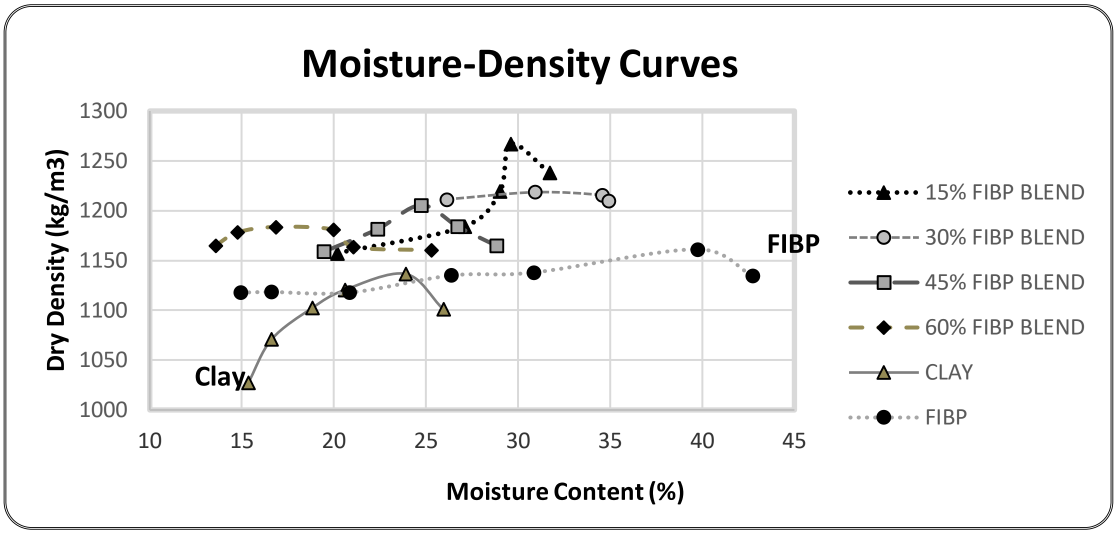


Figure 3.2 Combined Moisture-Density Results for all samples

The compaction curves, produced initially, did not raise any suspicion. In general, they follow trends that seem reasonable. However, after reviewing results from UCS and permeability testing, one sample stood out as a likely outlier. The 30%-FIBP blend tended to behave as a more loosely bound or porous material than expected. In contrast, when reviewing the DST and swell tests of the 30%-FIBP blend, which was also prepared using the same target optimum compaction point, the results seem to fall in line with expected trends (see Figures 3.3 and 3.4). This may be to the advantage that the

DST and swell test have over the UCS and permeability test, i.e., they are tests that are run under confining and normal loads. The initial loading of the samples may have provided the necessary compactive effort to bring the 30%-FIBP blend sample into its true maximum dry density range. It could be assumed that the true maximum dry density range for this blend may be around 1240 kg/m^2 while the optimum moisture content of the test sample is slightly lower.

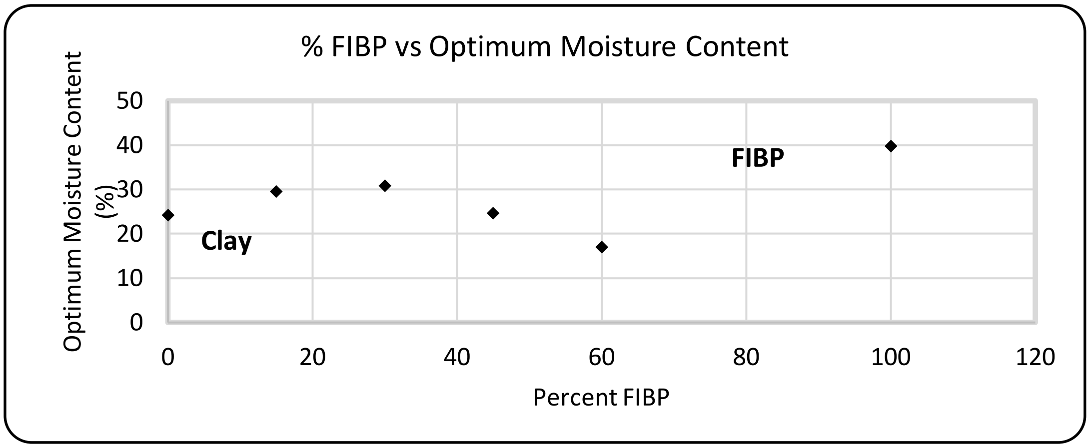


Figure 3.3 Optimum Moisture Trends

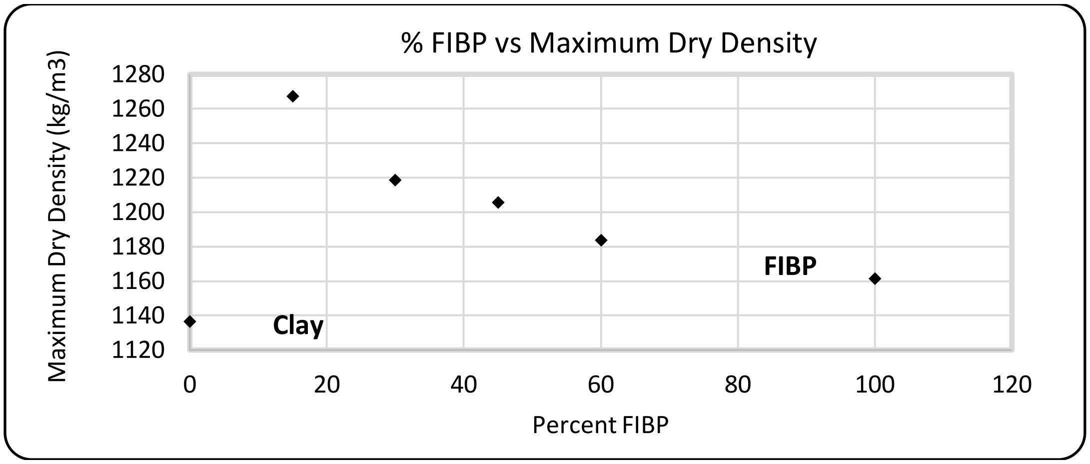


Figure 3.4 Maximum Dry Density Trends

After evaluating the compaction data, it seems it would be valuable to re-run the testing program on the 30% FIBP blend sample and add two data points (7.5% and 80% FIBP) to the compaction testing to confirm whether, or how far, the potential trendlines observed in Figures 3.3 and 3.4 continue in either direction.

Stress-strain Behavior and Shear Strength

Direct Shear Tests

Direct Shear Tests (DST) were performed on each sample to evaluate the stress-strain behavior of the materials. While this is a test that is ordinarily performed on more granular soil, it was a valuable test to gain more insight into the stress-strain behavior of samples. Triaxial testing of samples may provide more information but was not performed at this time. The confined samples were vertically loaded and laterally sheared. As seen in Figure 3.5, the samples behave close to perfectly plastic material with minimal work-hardening or -softening.

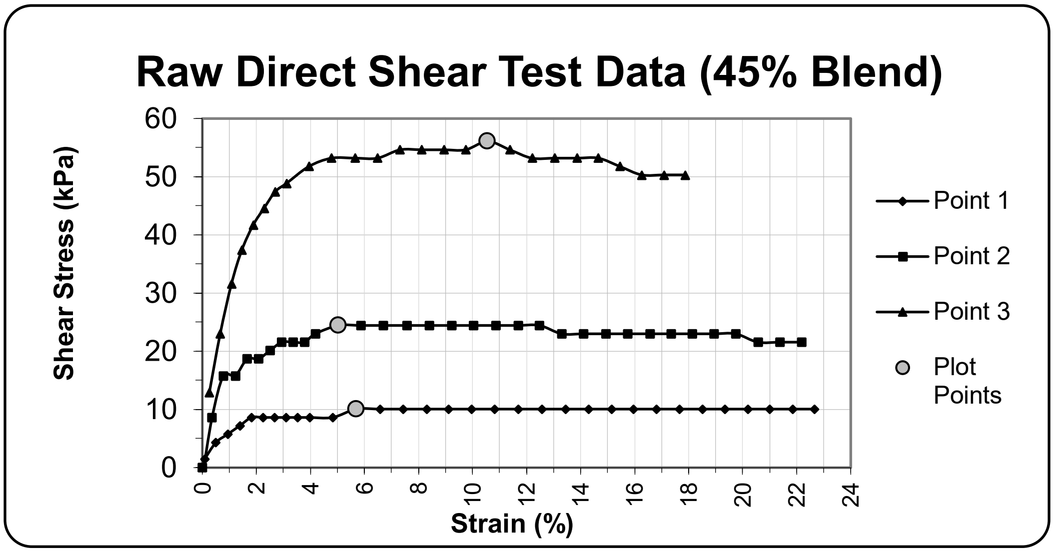


Figure 3.5 Direct shear test data to demonstrate how peak effective stress points are selected

The angle of internal friction (phi) was then determined by fitting a line through the peak values obtained during the DST and measuring the angle and y-intercept this line makes with the x-axis. There are a variety of factors that could impact the results, mostly due to human error in sample preparation and testing.

This test shows variations of the angle of internal friction and any potential cohesion as a function of the FIBP fraction. Surprisingly, the variation of cohesion and internal friction angles with FIBP fraction is negligible. The normally consolidated, remolded clay, 100% FIBP sample, and all four blends had cohesion intercepts of near-zero kPa. Figure 3.6 suggests that the results obtained from each DST did not show any significant impact by the FIBP fraction on cohesion and internal friction angle for the blends. Measured values for the internal friction angle range from 26.3 to 32.8º, with no clear trend following the percentage of FIBP added.

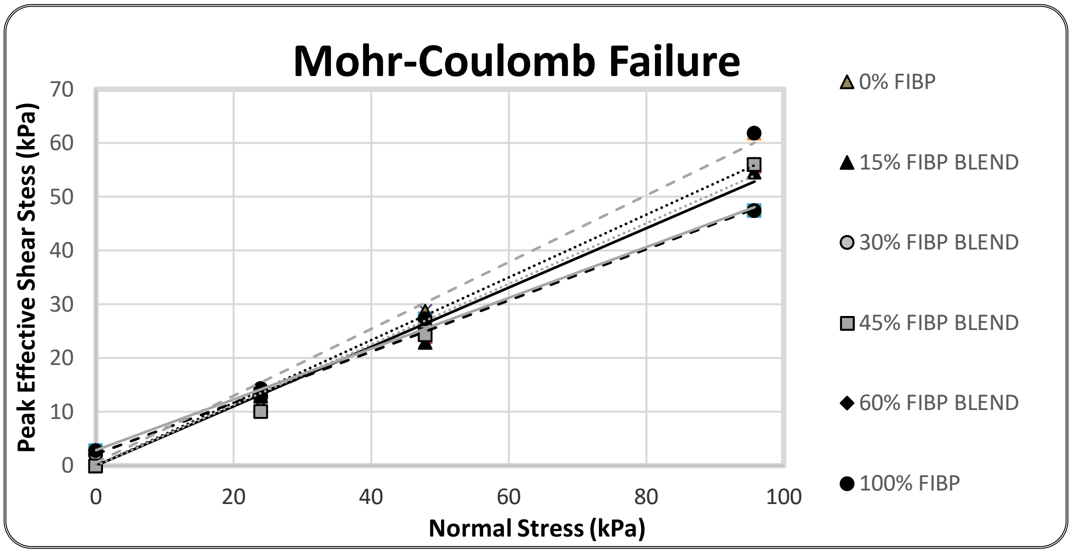


Figure 3.6 Mohr-Coulomb failure parameters observed for all blends

Unconfined Compressive Strength: Shear Strength

Unconfined compressive strength (UCS) testing provided insight into the strain-hardening and strain-softening behaviors exhibited as the FIBP fraction varied. While this behavior was not observed under confined conditions of the DST, the UCS test results shown in Figure 3.7 demonstrates how the brittle nature of the FIBP can control the properties of the blend under high loads with smaller confinement.

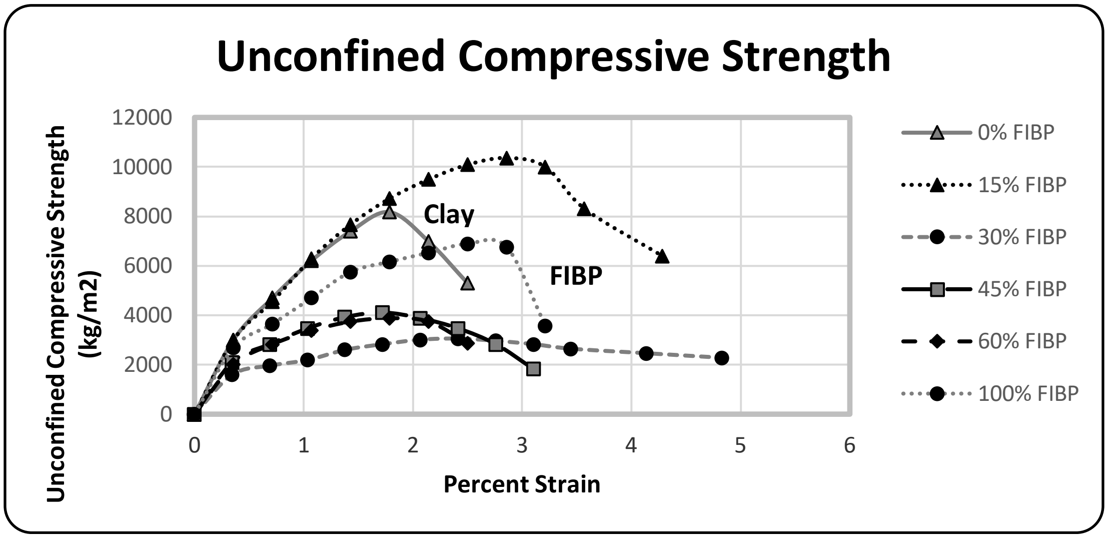


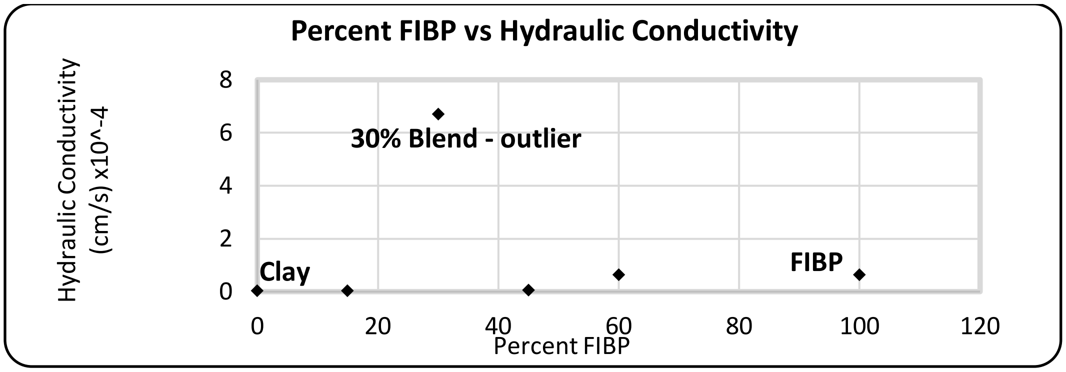
Figure 3.7 Unconfined compressive strength trends for all samples

The blends became more moisture sensitive with increased FIBP. Desiccation cracking was observed on the surface of the samples of the 45%, 60%, and 100% FIBP-fraction samples at the completion of their seven-day cure time. This suggests that these samples may have needed to be remolded at a higher-than-optimum moisture content. The 100% FIBP sample shows a very brittle nature since it manifests minimal residual strength at rupture. While the rupture point is much lower for the 45% and 60% blends, these two samples demonstrate a more slow, steady failure. All samples except for the 30%-FIBP blend show a work-softening behavior while the 30%-blend shows near-perfectly plastic behavior. It is noteworthy that this is the sample identified as a likely outlier due to improper compaction. The 15% FIBP blend shows the highest yield stress in this category, gaining plasticity from the clay and strength from blending with the FIBP. However, it seems that the clay blended with 15% FIBP is the only blend that has yield stress larger than the pure FIBP.

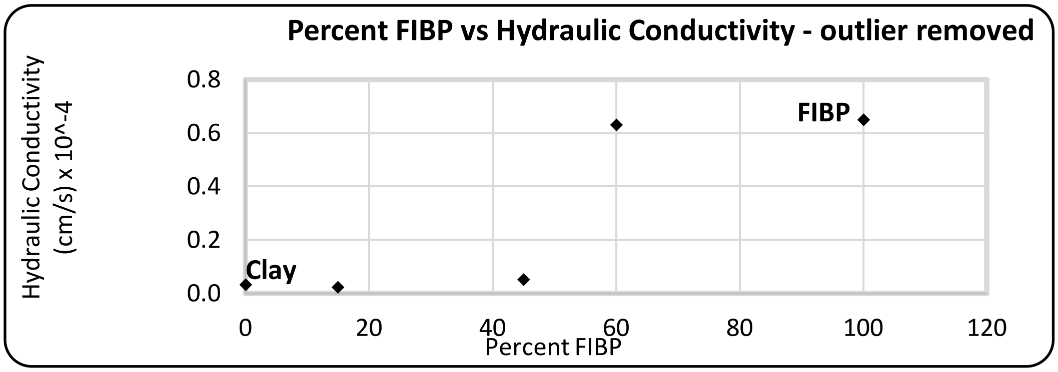
Even though, blending with the FIBP results in the desired targeted outcome (i.e., improving clay properties), it is suggested that in future research, the suite of testing should be performed at dry and wet of optimum conditions, to evaluate this conclusion.

Hydraulic Conductivity

Hydraulic conductivity was measured using a falling-head, flexible-wall permeability test. Raw data is presented in Figure 3.8(a), with the presumed outlier (30%-FIBP blend). Figure 3.8(b)shows the same data after removing the potential outliner (i.e., 30%-FIBP blend) and using a finer vertical scale. While the other samples measured in typical ranges for silts and clays, the 30%-FIBP blend achieved a hydraulic conductivity in the typical range of clayey sand, suggesting that there is significantly more pore space available for water to travel through this sample.



(a)



(b)

Figure 3.8 (a) Hydraulic conductivity trends; (b) hydraulic conductivity trends with outlier removed

When the 30%-FIBP blend datapoint is removed from Figure 3.8(a), the resulting Figure 3.8(b) shows an interesting pattern. It seems that the clay controls the hydraulic conductivity behavior of the blends in the 15%- and 45%-FIBP blends, while the 60%-FIBP blend behaves more like the pure FIBP sample. This shows that there is potential for using a larger fraction of FIBP for treatment than originally expected in comparison with other waste materials such as fly ash. It is noteworthy that all samples (apart from the potential outlier 30% FIBP blend) have low hydraulic conductivity rates within the same order of magnitude as clay, which is a valuable piece of information in terms of minimizing FIBP leachate by adding clay to the blend, which is one example that the clay reciprocates benefits to FIBP, referring to the point made in the hypothesis of this paper.

The primary concern in evaluating the permeability of the blends was to determine whether adding clay could further immobilize potential leachates from the FIBP, if necessary. It appears that depending on the needs of any specific project, a blend could be selected in an appropriate range. Below 45% FIBP fraction, all blends seem to take on the properties of the clay and have a very low hydraulic conductivity, improving the immobilization of leachates.

Plasticity and Swelling

The final property evaluated to determine the effectiveness of FIBP in improving the qualities of the Marsing Clay was the swell potential. A simulated pavement load of 11.5 kPa (240 psf) was applied to the samples before adding water. This load helps to indicate the swell strain (%) expected from each blend if it were to be placed beneath a roadway.

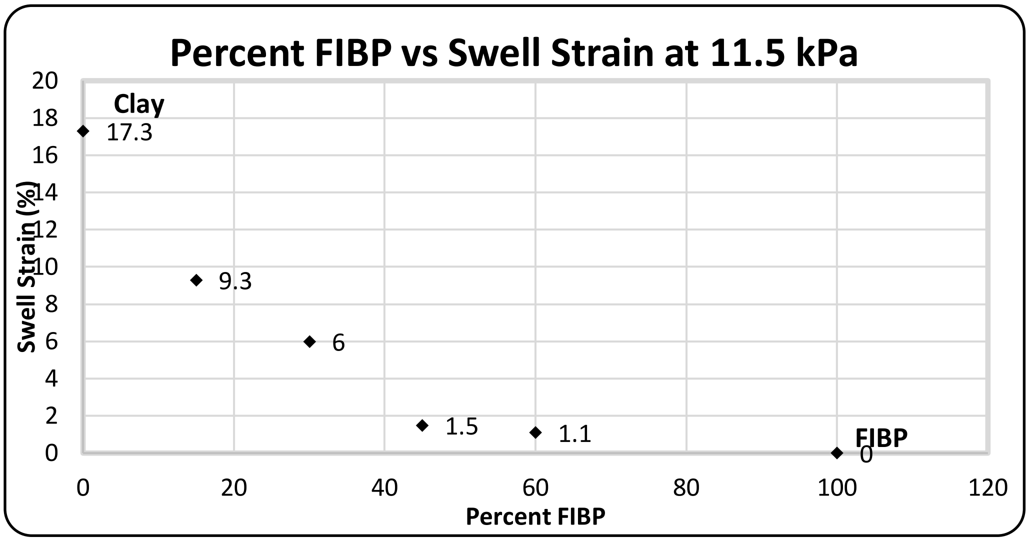


Figure 3.9 Swell Strain Trends

As expected, and seen in Figure 3.9, the pure clay sample was the worst-case swelling scenario, and the pure (100%) FIBP sample did not manifest any swelling. The blends followed a trend suggesting that replacing more clay with FIBP results in a decrease in the swell potential. For this specific (i.e., Marsing) clay, the only acceptable blends for engineering applications are likely the 45%- and 60%-FIBP blends. However, this might differ for other clay.

Figure 3.10 below shows all four FIBP blends and their measured hydraulic conductivity, UCS, and swell potential properties and ideal ranges. This will help to find sweet ranges for various applications where a combination of these three properties plays a decisive role.

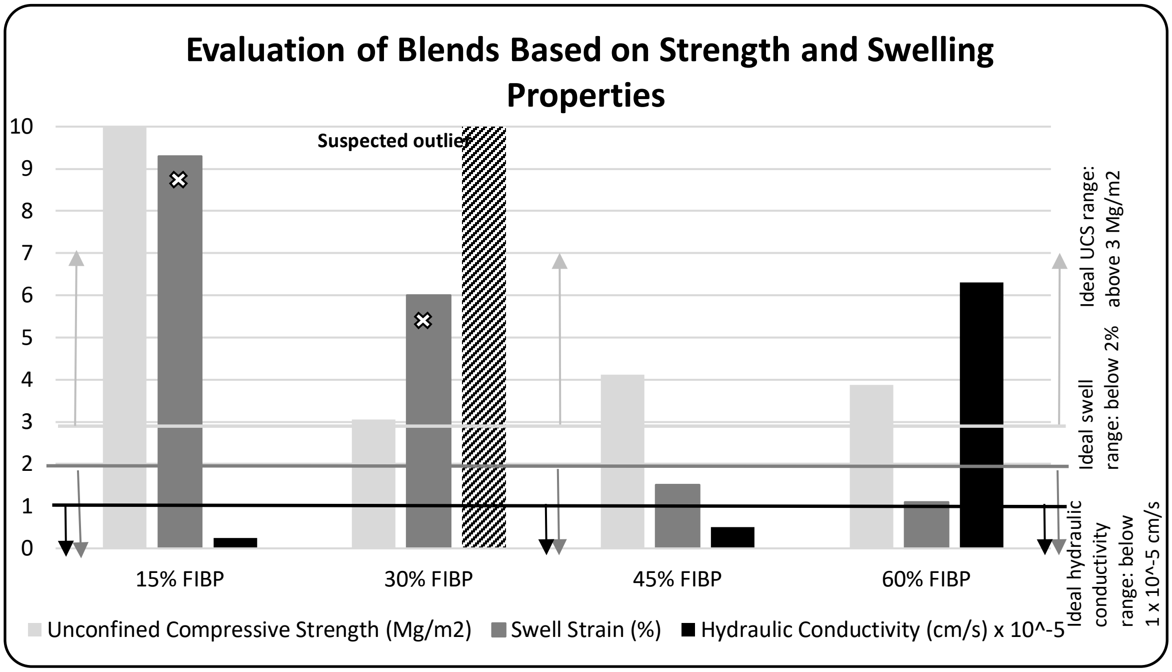


Figure 3.10 Final Evaluation of FIBP Blends based on critical engineering properties

As seen, Blends with 15%, 45%, and 60% FIBP are deemed acceptable in terms of their UCS category, but it would be ideal to create blends with higher strength values at 45% and 60% FIBP if it could be achieved by compaction at a different moisture content. The 45%- and 60%-FIBP blends were acceptable in the swell category, both at below 2% swell strain under load.

Conclusions

The ultimate three-fold goal of this work was to evaluate a mutual improvement in the properties of both clay and FIBP by mixing them. In other words, the goal was to evaluate whether the swelling potential of clay could be reduced by adding FIBP, while simultaneously adding clay would cause further immobilize any leachate out of the FIBP and cause an increase in the bearing capacity of the expansive clay.

The swelling properties of the clay soil are improved by adding FIBP. The bearing capacity of clay is also improved. However, as expected, this is at the price of reducing the bearing capacity of the FIBP, which highlights the need for research to evaluate the impact on granular fills' and embankments' bearing capacity, if mixed with FIBP. In the 15%-FIBP blend, an increase in strength is possible, but the blend is moisture sensitive, potentially impacting their strength properties. Combining these two materials results in low enough hydraulic conductivity to immobilize leachates, especially when the FIBP fraction is at 45% FIBP and below.

All blends seem acceptable in terms of their UCS category. Blends with a high FIBP fraction (45%- and 60 also reduce the clay swell potential to acceptable levels below 2% under a light pavement load.

Combining all properties, two blends appear to have properly improved the characteristics of the Marsing Clay. The 45% FIBP blend may be an even better option to ensure the immobilization of leachates due to its lower hydraulic conductivity, while the

60% FIBP blend may be better if leachates are less of a concern and the goal is to maximize the reuse of the FIBP material.

Ongoing and Future Research

To apply this work to other studies, there are several tasks to be completed. Our team is currently preparing scanning electron microscope (SEM) images of each sample to achieve a better understanding of how the FIBP and clay particles interact, and in terms of resulting clay structure—i.e., dispersed, aggregated, flocculated, deflocculated—helping to predict the impact on various properties. Chemical analysis on the leachate from the influent and effluent of the permeability tests are also being conducted to determine how the leachate may vary with FIBP fraction. All blends are deemed acceptable in terms of their UCS category, but it would be ideal to create blends with higher strength values at 45% and 60% FIBP if it could be achieved by compaction at a different moisture content.

These tests should be repeated on a wider variety of soil types and at a wider range of FIBP percentages. In future works, triaxial testing could substitute for DST where all materials are of fine-grained nature. UCS testing can be molded at a wider range of molding water contents to improve the quality of data obtained. Extra care should be practiced in determining all compaction criteria.

CHAPTER FOUR: CONCLUSION AND FUTURE WORKS

As stated in Chapter 3, the journal article, improvements in both the clay and FIBP were observed when the FIBP was blended with the expansive clay. The clearest and most notable improvement was seen in the reduction in the swell potential measured via the swell strain as the FIBP fraction increased. These results indicate that calcium carbonate in the FIBP can effectively reduce the swell potential by likely reduction in the thickness of the double diffuse layer of clay particles. Even at the lowest test FIBP fraction, the swell strain potential was reduced by nearly 50%. At the highest FIBP fractions, the swell strain was practically eliminated. If this material is tested to improve the properties of a wider variety of natural soils, its effectiveness in reducing swell potential can be generalized.

Another goal of this work was to maintain a low hydraulic conductivity in order to immobilize leachates from the FIBP. The blends maintained hydraulic conductivity trends lower than the FIBP and in line with typical clay values up to a FIBP fraction of approximately 45%. Higher fractions of FIBP produced hydraulic conductivity values in the range of pure FIBP, which is similar to typical silts. The hydraulic conductivity set of results was interesting in that it did not follow a particular trendline similar to that seen in other sets. It seemed that the hydraulic conductivity of blends was controlled by that of the dominant fraction (i.e., the material comprising more than 50% of the blend). In other words, the hydraulic conductivity of blends that have more than 50% clay is in the range of clay, and the hydraulic conductivity of blends with more than 50% FIBP is like that of the FIBP. The transition point appeared to occur around 50% FIBP fraction. A similar effect would likely take place if this property was tested on blends with other natural soils; however, it is interesting to measure where the transition point occurs.

More evaluations are necessary to determine if the FIBP can be effective in improving the strength properties of this clay soil. An increase in the density is observed with each of the blends, indicating closer particle packing; however, the density results did not always translate into higher strength properties in the corresponding blends. The blend with the lowest FIBP fraction obtained the highest maximum dry density and the highest unconfined compressive strength, but the trends did not correlate as well with other blends. Unconfined compressive strength testing needs further investigation on a wider range of molding water contents. By varying the molding water content, a better understanding of how strength varies with water and FIBP contents can be achieved. Further evaluating these blends with triaxial testing may provide more insight into the engineering properties of each blend.

Scanning electron microscope (SEM) imaging of each sample is ongoing and will confirm how closely particles are packed in each blend and whether the FIBP renders the packing of clay particles more dispersed, aggregated, flocculated, or deflocculated. These images may also be able to verify if the suspected outlier (30% FIBP blend) was molded below an approximate maximum dry density when compared to other images. Chemical analysis is ongoing on the influent and effluent collected from the falling-head permeability testing that may provide more information on the ability of each blend to immobilize leachates.

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APPENDIX

Raw Data for Figures

Figure 2.1

100% FIBP

Moisture (%)	14.9	16.6	20.8	26.4	30.9	39.7	42.7
Dry Density (kg/m3)	1117.7	1118.4	1117.7	1135.0	1137.9	1161.2	1134.8

30% FIBP Blend

Moisture (%)	26.1	30.9	34.6	34.9
Dry Density (kg/m3)	1211.3	1218.5	1215.4	1209.9

0% FIBP

Moisture (%)	15.4	16.6	18.8	20.6	23.9	25.9
Dry Density (kg/m3)	1027.6	1070.9	1102.3	1120.6	1136.5	1101.1

Figure 3.1

100% FIBP		**60% FIBP Blend**		**45% FIBP Blend**	
Particle Size (mm)	**Percent Passing**	**Particle Size (mm)**	**Percent Passing**	**Particle Size (mm)**	**Percent Passing**
4.75	100	4.75	100	4.75	100
2	100	2	100	2	100
0.85	100	0.85	99	0.85	99
0.425	98	0.425	97	0.425	97
0.25	97	0.25	96	0.25	96
0.18	96	0.18	95	0.18	95
0.15	96	0.15	95	0.15	95
0.075	93	0.075	92	0.075	93
0.0466	45	0.0466	55	0.0466	56
0.033	45	0.033	55	0.033	55
0.0233	45	0.0233	55	0.0233	54
0.0154	42	0.0154	53	0.0154	54
0.0103	31	0.0103	49	0.0103	53
0.0081	22	0.0081	44	0.0081	50
0.006	16	0.006	39	0.006	45
0.0033	5	0.0033	31	0.0033	38
0.0024	3	0.0024	28	0.0024	34

0.0014	2	0.0014	27	0.0014	33

30% FIBP Blend		15% FIBP Blend		0% FIBP Blend	
Particle Size (mm)	**Percent Passing**	**Particle Size (mm)**	**Percent Passing**	**Particle Size (mm)**	**Percent Passing**
4.75	100	4.75	100	4.75	100
2	100	2	100	2	100
0.85	99	0.85	99	0.85	99
0.425	97	0.425	97	0.425	97
0.25	96	0.25	96	0.25	96
0.18	95	0.18	95	0.18	96
0.15	95	0.15	95	0.15	96
0.075	93	0.075	93	0.075	95
0.0466	61	0.0466	60	0.0466	59
0.033	61	0.033	60	0.033	59
0.0233	59	0.0233	59	0.0233	58
0.0154	58	0.0154	58	0.0154	57
0.0103	56	0.0103	57	0.0103	56
0.0081	54	0.0081	57	0.0081	56
0.006	53	0.006	56	0.006	55

0.0033	48	0.0033	56	0.0033	55
0.0024	46	0.0024	54	0.0024	54
0.0014	45	0.0014	54	0.0014	53

Figure 3.2

100% FIBP

Moisture (%)	14.9	16.6	20.8	26.4	30.9	39.7	42.7
Dry Density (kg/m3)	1117.7	1118.4	1117.7	1135.0	1137.9	1161.2	1134.8

60% FIBP Blend

Moisture (%)	13.6	14.8	16.8	20.0	21.1	25.3
Dry Density (kg/m3)	1165.1	1178.2	1183.7	1180.8	1163.6	1160.3

45% FIBP Blend

Moisture (%)	19.5	22.4	24.7	26.7	28.8
Dry Density (kg/m3)	1158.9	1181.5	1205.5	1184.0	1164.6

30% FIBP Blend

Moisture (%)	26.1	30.9	34.6	34.9
Dry Density (kg/m3)	1211.3	1218.5	1215.4	1209.9

15% FIBP Blend

Moisture (%)	20.2	27.1	29.0	29.6	31.7
Dry Density (kg/m3)	1157.4	1184.3	1219.1	1267.0	1238.2

0% FIBP

Moisture (%)	15.4	16.6	18.8	20.6	23.9	25.9
Dry Density (kg/m3)	1027.6	1070.9	1102.3	1120.6	1136.5	1101.1

Figure 3.3

% FIBP	Maximum Dry Density (kg/m3)
0	1136.5
15	1267.0
30	1218.5
45	1205.5
60	1183.7
100	1161.2

Figure 3.4

% FIBP	Optimum Moisture (%)
0	24.2
15	29.6
30	30.9
45	24.7
60	17.0
100	39.8

Figure 3.5

Point 1		Point 2		Point 3	
% Strain	Effective Shear Stress (kPa)	% Strain	Effective Shear Stress (kPa)	% Strain	Effective Shear Stress (kPa)
0.00	0	0.00	0		
0.00	0	0.00	0		
0.02	0	0.36	8.62621	0.00	0
0.08	1.4377	0.78	15.8147	0.00	0
0.50	4.3131	1.22	15.8147	0.02	0
0.94	5.75081	1.66	18.6901	0.04	0
1.38	7.18851	2.08	18.6901	0.26	270
1.82	8.62621	2.50	20.1278	0.66	480
2.24	8.62621	2.94	21.5655	1.08	661
2.66	8.62621	3.36	21.5655	1.46	781
3.10	8.62621	3.78	21.5655	1.88	871
3.52	8.62621	4.18	23.0032	2.28	931
3.96	8.62621	5.04	24.4409	2.70	991
4.82	8.62621	5.86	24.4409	3.12	1021
5.70	10.0639	6.70	24.4409	3.94	1081
6.58	10.0639	7.56	24.4409	4.78	1111
7.44	10.0639	8.40	24.4409	5.66	1111

8.30	10.0639	9.22	24.4409	6.48	1111
9.12	10.0639	10.04	24.4409	7.32	1141
9.96	10.0639	10.86	24.4409	8.12	1141
10.82	10.0639	11.68	24.4409	8.94	1141
11.68	10.0639	12.48	24.4409	9.74	1141
12.56	10.0639	13.30	23.0032	10.56	1171
13.44	10.0639	14.10	23.0032	11.38	1141
14.30	10.0639	14.94	23.0032	12.20	1111
15.14	10.0639	15.74	23.0032	13.04	1111
15.96	10.0639	16.56	23.0032	13.86	1111
16.80	10.0639	17.34	23.0032	14.66	1111
17.66	10.0639	18.14	23.0032	15.46	1081
18.50	10.0639	18.94	23.0032	16.26	1051
19.34	10.0639	19.74	23.0032	17.08	1051
20.18	10.0639	20.56	21.5655	17.86	1051
21.00	10.0639	21.38	21.5655		
21.84	10.0639	22.18	21.5655		
22.66	10.0639				
23.48	10.0639				
24.30	10.0639				
25.14	10.0639				
25.98	10.0639				
26.84	10.0639				

27.66	10.0639
28.48	10.0639
29.30	10.0639
30.12	10.0639
30.94	10.0639
31.74	10.0639

Figure 3.6

0% FIBP

Normal Stress (kPa)	**Peak Effective Stress (kPa)**
24	11.49
48	28.78
96	56.07

15% FIBP Blend

Normal Stress (kPa)	**Peak Effective Stress (kPa)**
24	12.93
48	22.98
96	54.63

30% FIBP Blend

Normal Stress (kPa)	Peak Effective Stress (kPa)
24	12.93
48	25.86
96	47.45

45% FIBP Blend

Normal Stress (kPa)	Peak Effective Stress (kPa)
24	10.05
48	24.42
96	56.07

60% FIBP Blend

Normal Stress (kPa)	Peak Effective Stress (kPa)
24	12.93
48	27.34
96	47.45

100% FIBP

Normal Stress (kPa)	Peak Effective Stress (kPa)
24	14.36
48	27.34
96	61.81

Figure 3.7

% FIBP	Unconfined Compressive Strength (kg/m2)
0	8177
15	10370
30	3058
45	4113
60	3881
100	6897

Figure 3.8

% FIBP	**Hydraulic Conductivity (cm/s) x10^-4**
0	0.034
15	0.024
30	6.700
45	0.051
60	0.630
100	0.650

Figure 3.9

% FIBP	**Hydraulic Conductivity (cm/s) x10^-4**
0	0.034
15	0.024
45	0.051
60	0.630
100	0.650

Figure 3.10

% FIBP	Swell
0	17.3
15	9.3
30	6
45	1.5
60	1.1
100	0

Figure 3.11

Sample	Unconfined Compressive Strength (Mg/m2)	Swell Strain (%)	Hydraulic Conductivity (cm/s) x 10^-5
0% FIBP	8.1770	17.3	0.340
15% FIBP	10.3700	9.3	0.240
30% FIBP	3.0580	6	67.000
45% FIBP	4.1130	1.5	0.510
60% FIBP	3.8810	1.1	6.300
100% FIBP	6.8970	0	6.500