PHYSICAL AND MECHANICAL CHARACTERIZATION OF COMPACTED SAND–BENTONITE–OIL PALM EMPTY FRUIT BUNCH ASH COMPOSITE FOR LANDFILL LINER APPLICATIONS.

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ABSTRACT

The increasing demand for environmentally sustainable and cost-effective landfill liner materials has created interest in the utilization of agricultural waste products as engineering materials. This study investigated the suitability of compacted bentonite admixed with Oil Palm Empty Fruit Bunch Ash (OPEFBA) as a composite landfill liner material. Laboratory tests were conducted on bentonite-OPEFBA mixtures prepared at varying proportions to evaluate their physical, mechanical and hydraulic properties. The tests conducted were particle size distribution, specific gravity, Atterberg limits, compaction characteristics, California bearing ratio(CBR), differential free swell index (DFSI), direct shear box, hydraulic conductivity, and Statistical analysis by using Analysis of Variance (ANOVA) on how OPEFBA will affect the engineering behaviour of the composite. It was found that when more bentonite and OPEFBA were added, the composite showed an increase in its plasticity index, compaction characteristic and strength. An average value of 2.64 was recorded for specific gravity. The DFSI of 520% was recorded for the sodium bentonite, which indicates that it has high swellability and sealing ability. It was also observed that CBR values increased as the amount of OPEFBA increased and better compaction characteristics were achieved. Statistical analysis indicated that OPEFBA significantly influenced particle size distribution, compaction characteristics and specific gravity, whereas its effects on Atterberg limits, direct shear strength and CBR were not statistically significant. The lowest hydraulic conductivity achieved was 2.5×10^{-7} cm/s, which was when using 10% OPEFBA. This was greatly lower than that of the untreated samples but still exceeded the maximum hydraulic conductivity of 1.0×10^{-7} cm/s.

Keywords: Landfill liner; Bentonite; Oil Palm Empty Fruit Bunch Ash (OPEFBA); Physical properties; Mechanical properties.

1.0 INTRODUCTION

Due to their ability to reduce the migration of leachate through landfill sites and prevent leachate from permeating the soil below, landfill liners play an important role in engineered waste containment systems. Engineered landfill liners are expensive to produce, and the disposal of agricultural wastes such as empty fruit bunches from oil palms also pose a problem. As such, there has been an increase in the investigation of waste products that can be used within engineered soils. When empty fruit bunches are burned, the resultant ash (OPEFBA) has good physio-chemical and particle size properties that have allowed it to be investigated for use in soil stabilization and other geotechnical uses. Bentonite is known for its expansive properties, which allow for decreased permeability through the soil pores.

OPEFBA is a product that can provide fines which can be used to change the particle packing and engineering properties of soils. Studies have looked at the improvement of certain properties when using OPEFBA and other waste ash products. Other similar products using bentonite have shown that these composites can provide beneficial hydraulic and mechanical properties. It was believed that the use of a combination of sand, bentonite, and OPEFBA would provide beneficial properties.

However, there has not been much research conducted on sand-bentonite-OPEFBA mixtures when compacted. Previous research have focused on using OPEFBA as a soil stabilizer or looked into the use of other types of wastes used with bentonite for liners. Another area which has not been researched enough is developing regression models that relate different sand-bentonite-OPEFBA ratios to the properties of the mixture. Therefore, this study aims to investigate the effects of different sand-bentonite-OPEFBA ratios on the properties of the mixture and develop models to help select the right ratio.

Accordingly, this study experimentally investigates the physical, index, mechanical and hydraulic characteristics of compacted sand-bentonite-OPEFBA mixtures using particle-size distribution, specific gravity, Atterberg limits, compaction, California Bearing Ratio, differential free swell, direct shear and hydraulic conductivity tests. ANOVA and regression analyses are further employed to examine the influence of mixture composition and establish composition-property relationships. The study therefore evaluates whether the composite possesses useful engineering characteristics that support its consideration as a **sustainable component of bentonite-based landfill liner systems,** while identifying properties that require further optimization.

2.0 LITERATURE REVIEW

2.1 Landfill Liner Requirements

Due to the increase in urbanization industrialization and human population, we are producing more municipal solid waste every day. There are various ways in which we can dispose of this waste, but one method that is used the most is sanitary landfilling, as it can be cheap and hold high quantities of waste. If these landfills are not built properly, they can result in environmental problems. Landfills that are poorly constructed will produce leachate that can seep into soil and water around it. With the increase in landfills, we must find ways to make better liners for landfills. Many researchers have tried to find sustainable ways to create better liners that are impermeable (Chaudhary *et al*., 2024).

The liner of a landfill is used as an engineered barrier between the waste and the natural ground underneath. The purpose of the liner is to reduce the amount of leachate traveling downwards through the ground and remain stable during the life of the landfill. It has been found that there are many engineering properties of the landfill liner that affect how it will perform. Such as hydraulic conductivity, shear strength, longevity, absorption of contaminants, and chemical resistance. With newer environmental standards being set, researchers have been looking at ways to enhance normal clay liners by using additional materials that can help increase their hydraulic conductivity (Nath *et al*., 2023; Chen *et al*., 2024).

Bentonite is widely recognized as one of the best clay minerals that can be used for lining landfills due to its very low permeability, high swelling capability, and high cation exchange capacity. This can help reduce the flow of leachate and heavy metals in landfills. Some studies have found that when bentonite is exposed to aggressive leachate for extended periods, it can decrease the swelling capabilities of bentonite by ion exchange. This causes an increase in permeability, which decreases its lifespan as a landfill liner material. Many studies have focused on amending bentonite with additional materials to enhance its hydraulic and chemical properties (Ray *et al*., 2021; Ashmawy *et al*., 2024).

In recent years, many studies have been conducted regarding using agricultural and industrial wastes as engineering materials to create more sustainable methods of infrastructure building and reusing waste material. Some examples of these agricultural wastes are rice husk ash, sugar cane bagasse ash, palm oil fuel ash, and oil palm empty fruit bunch ash (OPEFBA). Due to their properties, they can be used as an addition to clay. All of which are beneficial when used with clay due to their pozzolanic properties, silica content, and sustainability. As a result, they can help increase the sustainability of waste that is produced from our daily lives (Devarangadi *et al*., 2020).

One of the best agricultural wastes that can be used for geo engineering purpose is oil palm empty fruit bunch ash. It is widely available in countries that produce large amounts of palm oil, such as Nigeria, Malaysia, Indonesia, and Thailand. Several studies have discovered that oil palm empty fruit bunch ash contains a good amount of reactive silica, which will react with the soil when a pozzolanic reaction takes place to strengthen the soil, lower permeability, and make the soil more durable. Many researchers have looked into the use of oil palm empty Fruit Bunch Ash as an addition in pavement and stabilized soils and even as a barrier material. However, not much work has been done to evaluate the performance of using bentonite and OPEFBA together as a landfill liner material in Nigeria (Nath *et al*., 2023).

One of the main properties of a compacted landfill liner is to have low permeability. Permeability must be low enough to limit the passage of pollutants through the liner. Most landfill designs call for compacted clay liners to have permeability values less than or equal to 1×10^{-9} m/s. This has allowed research to improve the makeup of liner materials. Studies have found that many factors can affect the permeability of a compacted clay liner. These include but are not limited to mineralogy, compaction, water content, dry density, void structure and leachate. Due to all these variables, it is necessary to test compacted clay liners in the lab to meet specifications for landfill design (Chaudhary *et al*., 2024).

Another factor to consider when designing landfills today is ensuring they are environmentally friendly. Landfills have the ability to be made from agricultural waste, which can reduce cost as well as help the environment by reducing pollution from disposing of waste. By doing this, the aim to reach global goals for sustainable development by recovering resources and reusing waste is achieved. It has become beneficial to look into how we can use these waste materials to help us create lower carbon footprints. Therefore, creating a landfill liner using bentonite and OPEFBA can be used to develop sustainable landfills for developing countries (Devarangadi *et al*., 2020).

In recent years, many advancements have been made in the field of computation and statistics. These allow us to determine engineering properties from experimental data. These techniques have helped researchers determine regression models. These techniques can help predict how engineering properties will act based on the number of independent variables we can control, such as percentage of bentonite, amount of OPEFBA, moisture content, and compaction properties. Once these variables are determined, we can find a correlation to properties we would want to improve or decrease in our soils. Such as permeability, shear strength, and other factors that play into engineering design. By using regression analysis on our material, we can better optimize our soil mixture and reduce cost in lab work. This, in turn, will allow us to find better ways of predicting soil behavior. Many studies have found that when using lab tests with regression analysis, we can help better find how the soil mixture can be used in landfills as liners (Chaudhary *et al*., 2024).

2.2 Bentonite and Agricultural-Waste Ashes

Oil Palm Empty Fruit Bunch Ash (OPEFBA) is a solid by-product produced from the combustion of Empty Fruit Bunches (EFBs), which consist of the remaining fibrous residue of the oil palm fruit bunch after the oil fruits have been removed during palm oil processing. EFBs typically contribute 20–23% by weight to Fresh

Fruit Bunches (FFBs) and are usually regarded as an agricultural residue in palm-oil-producing nations like Malaysia, Nigeria, Indonesia and Thailand (Rahayu *et al*., 2021; Chiew & Shimada, 2013).

In efforts to sustainably dispose of this waste, many palm oil mills utilize EFBs in burning to generate heat or electricity, resulting in a considerable volume of waste ash known as OPEFBA. Historically underutilized, this ash has now been found to contain high amounts of silica(SiO_2), alumina(Al_2O_3), potassium oxide(K_2O)and other oxides, thereby offering potential pozzolanic and engineering applications (Khalid *et al*., 2015; Rasat *et al*., 2013b).

Transitioning to using waste as an input for civil engineering allows for less harm to the environment. As mentioned earlier, this follows the waste-to-resource principle. In this study, OPEFBA was considered as a possible admixture or substitute for landfill liners due to its adsorptive, fineness and reactive properties.

2.2.1 Chemical and mineralogical properties relevant to liner performance

The demand and mineralogical properties of OPEFBA are crucial in governing its engineering behavior. Onyelowe *et al*. (2021) report that OPEFBA typically contains approximately 60.96% SiO_2, 15.49% Al_2O_3, 14.59% CaO, and 0.45% Fe_2O_3. These oxides indicate a high degree of pozzolanic activity, referring to the potential for reacting with calcium hydroxide in the presence of water to form hydrated compounds such as calcium silicate hydrates(C-S-H), which enhances durability and strength (Onyelowe *et al*. (2021).

The high content of silica not only enhances adsorptive properties for heavy metals and cations (improving the chemical compatibility of a liner) but also facilitates the pozzolanic reaction with other calcium-rich materials (e.g. Lime, Portland cement) in order to form binding gels that result in a refined micro structure and a decreased inter-particle void network (Onyelowe *et al*., 2021; Brown *et al*., 2011).

The material's other major characteristic is that it consists of a very fine, powdered form with a relatively high surface area to mass ratio, low particle density, an angular shape promoting inter-locking within the soil mass, and a good ability to fill in voids within the clay soil fabric, contributing to improved compaction and lower permeability (Rasat *et al*., 2013b; Wahab *et al*., 2016b). Additionally, OPEFBA exhibits a rather high pH level (typically 8.5–10.5), and when added to acidic clays it helps to neutralize them thereby enhancing the stabilization performance of liner material (Nik Daud & Mohammed, 2014). Its high silicon content together with its carbonaceous character contributes towards immobilizing contaminated material, particularly in the adsorption of metals, petroleum products and other organic constituents present in the leachate (Agamuthu *et al*., 2013).

In the field of Geotechnical engineering, there have been many studies on using OPEFBA as a soil stabiliser, as a subgrade, and even as an alternative to cement. But its use of it in Landfill Liner material is quite new, so this paper is very unique.

Many papers have proven that using OPEFBA as an additive can help with problematic soils. Here are some examples.

When added to soft and expansive soil, it will increase its strength. Wahab *et al*. (2013) and Wahab *et al*. (2016b) found that OPEFBA increased unconfined compressive strength and CBR values of these soils due to its Pozzolanic reactions.

Using OPEFBA as an additive to problematic soil can decrease the plasticity index. Oriola and Moses (2011) stated that adding OPEFBA to high plastic clay decreased its plastic index, allowing for it to be more malleable.

Chaudhary *et al*., (2024) and Brown *et al*. (2011) also showed that because of the small size of ash particles, it can fill in the pores of the clay, making it impermeable.

Rasat *et al*. (2013) were able to create a composite out of Oil Palm.

2.3 Regression Modelling in Geotechnical Materials

Regression modelling has allowed us to help analyze data in many ways when it comes to geotechnical and lining applications. By using regression, we can find patterns and predict the outcomes of various scenarios. It involves developing a statistical relationship between dependent variables (e.g., hydraulic conductivity, unconfined compressive strength, plasticity index) and independent variables (e.g., moisture content, compaction effort, material proportions, curing time) (Jha *et al*., 2023; Shankar & Phanikumar, 2012).

2.4 Empirical Evidence on OPEFBA and Related Composite Liners

Empirical evidence indicates that OPEFBA and other waste-derived ashes can beneficially modify selected engineering properties of soil and bentonite-based materials. OPEFBA has been associated with improvements in compaction and strength characteristics of stabilized soils, while related bentonite-ash composites have demonstrated useful strength, permeability, and waste-containment characteristics. However, direct evidence on the combined physical and mechanical behaviour of compacted sand-bentonite-OPEFBA mixtures remains limited. The available study on OPEFBA in sand-bentonite mixtures also recommended investigation of alternative material combinations. Therefore, further experimental evaluation is required to establish how OPEFBA content influences the physical and mechanical characteristics of sand-bentonite composites and to determine mixture proportions that provide useful engineering performance.

2.5 Research Gap

There has been many research done using bentonite and some types of wastes to enhance the engineering properties of soils for landfill purposes. But there are not much studies that looked into compacted sand bentonite OPEFBA mixtures. Most research that were carried out using OPEFBA is related to stabilizing soils and other engineering purposes. Not much information about how OPEFBA will affect the physical and mechanical properties of a landfill liner material made of bentonite has been studied. There are also many research done on different properties of waste mixed with bentonite, but no significant relation was found when using OPEFBA mixtures and their corresponding property. Therefore, this study aims to investigate the use of OPEFBA as an ingredient in compacted sand-bentonite OPEFBA mixtures. By looking at different properties and finding their relation with each other. This can be achieved by predicting and optimizing these properties through regressions. This research can show that OPEFBA has good properties when used with sand and bentonite, which will help us utilize more waste in our liners.

3.0 METHODOLOGY

3.1 Materials and Sample Preparation

This section will describe the procedures used to obtain the data and the information gathered for the study. The section will first clarify the nature of the materials and classify them as primary or secondary sources. It will then go on to present the analysis procedures.

The materials being used in this project work were: Sand, sodium bentonite and Oil Palm Empty Fruit Bunch Ash (OPEFBA). The sand was collected at Aba in Osisioma Ngwa Local Government area of Abia state, Nigeria. Aba is located at Niger Delta region of Nigeria altitude 5º7'0.0012"N and longitude 7º22'0.0012"E. It is the state of Abia commercial nerve center in south east region of Nigeria.

The sand was conveyed to the Geotechnical laboratory of University of Port Harcourt, Rivers State of Nigeria and air dried naturally for two (2) weeks in an open space before been properly bagged for Laboratory Tests.

The Sodium bentonite was purchased from a market in Aba, Abia State after which it was taken to the laboratory to test for originality.

After collecting the empty oil palm fruit bunches (*OPEFBA*) from different oil palm milling locations, they were properly dried through a simple and cost-effective natural process of sun-drying for 3 to 4 week so as to release all of the stored water. Afterwards, they were burned at a temperature of 700^{o}C in an electronic kiln furnace. The burning was done at Scientific Equipment Development Institute (SEDI) in Enugu State, Nigeria. To achieve an even size, the ash was being properly filtered to remove larger particles after burning.

Every laboratory test conducted for this study was done so in compliance with BS 1377-2:2022. Some lab tests are done on different properties of both unmodified and modified samples, such as, compaction, hydraulic conductivity test, atterberg limit, specific gravity, and sieve analysis. Furthermore, the oxide composition of the Oil Palm Empty Fruit Bunch Ash was analyzed, as was the free swell test for the sodium bentonite. Some of the sand material in 100% composition was tested using specific gravity and particle size analysis only, and there was no atterberg limit test for this material as sand is non plastic.

Some lab tests were performed on sand-bentonite mixture which consisted of specific gravity, compaction test and atterberg limit.

The addition of the bentonite varies as follow: 0, 10, 15, 20, 25 and 30 percent, in the other hand the sand varies from 10% to 50%. Some lab tests, i.e., specific gravity, California bearing ratio (CBR) test, compaction test, infiltration test and hydraulic conductivity/permeability test, were carried out for the addition of Oil Palm Empty Fruit Bunch Ash to the sand-bentonite mixture for the addition percentages of 0%, 5%, 10%, 15% and 20%. In order to test the sand, bentonite and OPEFBA mixture, the particle size distribution of the unmodified and OPEFBA modified sand-bentonite was determined by sieve analysis following applicable procedures of BS 1377-2:2022. The equipment included a set of standard test sieves with aperture sizes of 2.00 mm to 0.075 mm, a mechanical sieve shaker, receiving pan, weighing balance with readability of 0.01 g, and a ventilated oven. The test samples were oven dried at 105 °C till constant weight. Then a 100 g mixture was sieved on a mechanical sieve shaker with a stack of test sieves and a receiving pan placed at the bottom of the largest sieve. After shaking for 10 minutes, the mass retained on each sieve and the receiving pan was obtained and recorded. The percentage retained, cumulative percentage retained, and cumulative percentage passing were calculated, and particle-size distribution curves were plotted for the determination of particle size distribution of sand-bentonite mixtures. The curves were used to characterize the gradation of the mixtures and to evaluate the effect of OPEFBA incorporation on particle size distribution and potential suitability of the mixtures for use as compacted landfill liner.

3.2 Laboratory Tests

Table 3.1: Procedure for laboratory assessment

Mix	Sand (%)	Bentonite (% by weight of soil)	OPEFBA (% by weight of soil)
M_0	100 (at 10g)	0	0
M_1	90 (at 9g)	10	0
M_2	80 (at 8g)	15	5
M_3	70 (at 7g)	20	10
M_4	60 (at 6g)	25	15
M_5	50 (at 5g)	30	20

The following laboratory tests were done on different mixtures of sand-bentonite-OPEFBA. These included particle-size distribution, specific gravity, Atterberg limits, compaction tests, CBR test, differential free swell index test, direct shear strength test, and hydraulic conductivity test. Various quantities of sand, bentonite and OPEFBA were mixed to produce these mixtures. All laboratory tests were done according to BS 1377:1990. The results from the laboratory test programme showed that when OPEFBA was added to the mixtures, it changed the properties of the mixtures. This is evident by the change in particle size distribution and the compaction characteristic. It was found that bentonite had a high swell potential and the mixture showed good bearing and hydraulic properties. The minimum value of 2.5 × 10-7 cm/s was achieved for the mixture of 70% sand-20% bentonite-10% OPEFBA. Though this value was greater than the adopted criteria for hydraulic conductivity, it can be concluded that there are good physical properties when a certain quantity of the three materials are combined to form a mixture which can be used as an alternative for land fill liners.

3.3 Statistical and Regression Analysis

Analysis using ANOVA and regression was done to determine the effect that mixture proportions had on various engineering properties of the mixture. A 5% confidence interval was used for the ANOVA test, and R2, Adjusted R2, Significance F, and the p-value for each coefficient were determined for the regressions. Mixture proportions had an effect on many of the properties but not all of them. There was no correlation found with shear strength, CBR, and Atterberg limits with mixture proportions. Many of the regressions yielded an extremely high R2 value as well as Adjusted R2. This shows that mixture proportions have a great correlation to many physical properties of the mix. However, a high R2 does not always show significance. There were many p-values that were above 0.05, which means they are not significant. With this, we can assume that the amount of OPEFBA in the mix and mixture proportions can have an effect on certain physical properties.

4.0 RESULTS

4.1 Physical and Compaction Characteristics

In line with the course of the various test carried out, several results were obtained. Based on these results, the following analysis were done with resulting tables obtained and graphical presentation carried out as shown below, (noting that M_0 is Control experiment, M_1, M_2, M_3, M_4, and M_5 are experiments with 0%, 5%, 10%, 15%, and 20% OPEFBA content): Results obtained from Atterberg limit test: The results of the tests are briefly discussed thus:

Table 4.1: Atterberg limit test

DESCRIPTIION	90% SAND, 10% BENTONITE, **0% OPEFBA**	80% SAND, 15% BENTONITE, **5% OPEFBA**	70% SAND, 20% BENTONITE, **10% OPEFBA**	60% SAND, 25% BENTONITE, **15% OPEFBA**	50% SAND, 30% BENTONITE, **20% OPEFBA**
LIQUID LIMIT	17.50	19.50	30.50	32.00	35.00
PLASTIC LIMIT	8.33	10.00	12.50	11.11	7.69
PLASTICITY INDEX	9.17	9.50	18.00	20.89	27.31

The results from the above show that when increase in the percentages of bentonite and OPEFBA was observed an increase in liquid limit and plastic index were also produced. However, a noticeable increase in the plastic limit of the composite sample when OPEFBA was added at the range of 5 to 10% (8.33 to 10.00 to 12.50) however, at percentages higher than 10% decrease in the value of plastic limit can be observed (11.11 at 15% and 7.69 at 20%). Thus this indicate that optimum value to attain optimum value for plastic limit is 10% of the percentage addition of OPEFBA where this material has greater stability as landfill lining material due to their plastic nature which prevents or reduces leachate migration, and as a result preventing ground water pollution. Results Obtained from Specific Gravity Test: The results of the tests are discussed thus:

Table 4.2: Specific Gravity Test

S/NO.	SAMPLES / LOCATIONS	STAGES OF STABILIZATION	AVERAGE SPECIFIC GRAVITY
1.	Sample No. 1	100% Sand	2.6
2.	Sample No. 3	80% Sand; 15% Bentonite; 5% OPEFBA	2.64
3.	Sample No. 4	70% Sand; 20% Bentonite; 10% OPEFBA	2.55
4.	Sample No. 3	60% Sand; 25% Bentonite; 15% OPEFBA	2.58
5.	Sample No. 4	50% Sand; 30% Bentonite; 20% OPEFBA	2.59

Based on the above result, it was noted that the specific gravity increases as both bentonite and OPEFBA was increased. The specific gravity of composite sample increase from 2.6 at 100% of sand to 2.64 when introduced 5% of OPEFBA, followed by a decrease to 2.55 when introduce 10% of OPEFBA, however at 15% and 20% of introduction of OPEFBA, it increases to 2.58 and 2.59 respectively. This showed that the optimum introduction of OPEFBA is at 15% to obtain a higher specific gravity. At this point, the composite material becomes stronger to be used as landfill liner due to its low hydraulic conductivity which is a factor that makes a material capable to resist any contaminated liquid to seep through into underground ground water.
4.1.3: Results Obtained from Free Swell Test: The result of the tests is briefly discussed thus:
Based on the results attained, the value for free swell test of sodium bentonite was recorded as 520%which shows that sodium bentonite is a good quality absorbent water swelling clay, which possess effective self-swelling and self-sealing capacities and thus suitable for the hydraulic barrier use in environmental containment. It further signifies a greater water absorption, increased plasticity and the ability to form a low hydraulic conductivity barrier. Hence, for use as a compacted composite mixture with OPEFBA, it has a good potential to reduce permeability and maintain good stability which is a critical property for a liner as it is essential for containing leachate and preventing groundwater pollution and contamination. Results Obtained from Compaction Test: The results of the tests are briefly discussed thus:

Table 4.3: Summary of test results for compaction test

Mix	MDD (g/cm³)	OMC (%)
M_0	1.99	9.50
M_1	2.02	11.20
M_2	2.08	11.60
M_3	2.08	8.70
M_4	2.00	13.25
M_5	1.95	8.70

From the results gotten the maximum dry density and the optimum moisture content were increased by introducing more and more bentonite and OPEFBA in the sand. Although MDD of 1.99g/cm^3 at 100% sand increase to 2.08g/cm^3 when OPEFBA is introduced at 5% and 10%. The OMC also increase from 9.50% at 100% sand to 11.60% and 8.70% when OPEFBA is introduce at 5%and 10% respectively. However, decrease in MDD was recorded when introducing the OPEFBA continually up to 15% (2.0g/cm3) and 20% (1.95g/cm3) in the 100% sand with increase in OMC of 13.25% and a decrease of 8.70% at the increased level of 15% and 20%respectively. This implied the optimal usage for a dense state is at the increased level of 10% OPEFBA. At this level the composite becomes very durability for use as landfill liners as it possesses good compaction rate, high density and inter-locking property in use as a landfill liner material. California Bearing Ratio (CBR) Test Results: The results from the test are as follows:

Table 4.4: Summary of test results for California bearing ratio (CBR) test

Mix	CBR 2.5 mm (%)	CBR 5.0 mm (%)	Average (%)
M_0	3.50	3.70	3.60
M_2	4.60	5.40	5.00
M_3	4.90	5.90	5.40
M_4	5.60	6.80	6.20
M_5	4.80	6.10	5.45

From the obtained results it was found out that on penetration at 2.5 mm and 5mm respectively on 100% sand, CBR obtained were 3.5% and 3.7%, which improved to 4.6% and 5.4% CBR respectively on introduction of bentonite (15% by weight of soil) and OPEFBA (5% by weight of soil).However, at a continuous increase of the OPEFBA at 10%, the CBR further increased to 4.9% at 2.5mm penetration and 5.9% at 5mm penetration as well at 15% increase of OPEFBA the CBR value increased to 5.6% and 6.8% at penetration of 2.5mm and 5mm respectively. Nevertheless, a decline was observed at 20% increase of OPEFBA which recorded a CBR value of 4.8% and 6.1% at 2.5mm and 5mm penetration respectively. This indicate that the optimum value to achieve a high CBR is at 15% introduction of OPEFBA. At this point, the composite is resistant enough to serve as a landfill liner to resist the immense force exerted by the landfill contents to support itself and not buckle or bend causing cracks as it is compacted to be used as landfill liner to limit passage of leachate contaminating the groundwater.

4.2 Shear Box, Particle Size Distribution and Hydraulic Conductivity (Permeability), and Free Swell Tests

It was observed that there is decrease in the friction angle of the sand on introducing bentonite and OPEFBA. The friction angle of 100% sand was 34 degrees which reduced to 27 degrees on addition of 5% OPEFBA with a slight decrease to 25 degrees on introduction of 10% OPEFBA. It is advisable to have a friction angle of at least 25 degrees for landfill lining purposes using soil – bentonite composite. Thus the composite at 5% addition of OPEFBA can be deemed as durable. It can be observed that composite mixture has high frictional resistance and can resist a shear stress well thereby making it useful in landfill lining so that it could limit leachate percolation from waste to groundwater so that it does not become the contaminating water. Results Obtained from Particle Size Distribution Test: The summary of locations in particle size distribution test is tabulated below:

Table 4.5: Summary of locations in particle size distribution test

S/NO.	SAMPLES	STAGES OF STABILIZATION	PERMEABILITY USING ALLEN HAZEN'S FORMULA ($K = CD^2_{10}$)
1.	Sample No. 1	100% Sand	3.84×10^{-4} cm/sec
2.	Sample No. 2	90% Sand 10% Bentonite 0% OPEFBA	7.84×10^{-6} cm/sec
3.	Sample No. 3	80% Sand 15% Bentonite 5% OPEFBA	6.4×10^{-7} cm/sec
4.	Sample No. 4	70% Sand 20% Bentonite 10% OPEFBA	2.5×10^{-7} cm/sec

Based on the test results we can note that the addition of a larger percentage of OPEFBA to the composite mixture results to a decreasing hydraulic conductivity of the composite mixtures thus making the composite a durable candidate as liner of the landfills. In the following context it can be seen that for the composite sample 1, containing only sand, a Hydraulic conductivity of 3.84 x 10-4 cm/sec was acquired while a Hydraulic conductivity of 2.5 x 10-7cm/sec was attained for the sample 4 which contained a blend of 70% sand, 20% bentonite and 10% OPEFBA. Similarly, in the soil textural analysis the increase in the percentage composition of the OPEFBA from 0% to 10% led to a reduction in the percentage composition of gravel and sand and an increase in the composition percentage of silt and clay.

For the composite sample 1, the percentage composition of gravel and sand were 1.6 % and 98.4% whereas silt and clay registered a percentage composition of 0% for both the materials.

Similarly, for sample 4, the percentage composition of gravel and sand were 1.4 % and 72.1 % whereas for silt and clay they recorded a composition percentage of 18 % and 8.5% respectively.

The minimum hydraulic conductivity reported for the composite was 2.5×10^{-7} cm/s at 10% OPEFBA. This represented a marked reduction relative to the untreated mixture, but it remained above the adopted maximum value of 1×10^{-7} cm/s for the compacted liner criterion used in the study. The hydraulic result is therefore interpreted as a limitation rather than as evidence of full regulatory compliance.

The sodium bentonite recorded a Differential Free Swell Index (DFSI) of 520%, indicating a high swelling capacity.

4.3 Statistical and Regression Analysis

In conducting the analysis, the model that was been utilized for this analysis includes Analysis of variance (ANOVA) and model of regression which helped to determine the influences of the independent variables (bentonite and OPEFBA) on dependent variable (compaction parameters) gotten from the test result.

With the help of ANOVA analysis, we find out if the addition of bentonite in different proportions and compared with their similar addition of OPEFBA is statistically significant or not. Based on the ANOVA test for the atterberg test limit we have obtained. From the result we could see that all the F-values are smaller than F-crit. Therefore, the group means is alike. There may be no statistical differences in the means of the group. Another reason we can give out the above conclusion is from the P-value we found above. We know that the P-values are larger than the alpha value we set up which is 0.05. Thus, we cannot deny the null hypothesis, which is that any differences we find could arise as a result of randomness. The F-values that were output from the ANOVA test results in the particle size distribution test were lower than the F-crit which suggests that group means are more or less the same, and there may be little if no variation between the group.

5.0 DISCUSSION

The results show that the engineering response of the composite is controlled by the interaction of sand, bentonite and OPEFBA rather than by the addition of ash alone. The physical and mechanical results are most meaningful when considered together because a landfill liner must provide a combination of compact-ability, stability and resistance to fluid movement. The data indicate that the mixtures developed useful engineering characteristics over the investigated range, but the response was not uniformly progressive with increasing OPEFBA. This is an important finding for mix optimization.

As shown above, there is a practical range where the composite was able to achieve the highest dry densities measured. From the control, which had an MDD of 1.99 g/cm^3, the addition of 90: 10 Sand-bentonite had an increase in MDD to 2.02 g/cm^3, and 80:15:5 and 70:20:10 both showed MDD's of 2.08 g/cm^3, which is about 4.5% more than the control. This could be because of the small amounts of bentonite and OPEFBA helping the composite to reach a maximum dry density. However, as we see when using the 15% and 20% OPEFBA, the MDD decreases to 2.00 g/cm^3 and 1.95 g/cm^3, respectively. So adding more ash will not always give the better maximum dry density values.

OMC values ranged between 8.70% and 13.25% for each combination. Similar to MDD, we can expect values to vary due to the need for different amounts of water with sand, bentonite, and ash. Bentonite will want to hold on to more water, while the use of ash and varying gradation will affect how much void space there is. So when constructing these mixes in the field, moisture content will need to be determined not just one value used. Again, when determining the MDD, we used the value that was obtained for the particular mixture.

It has been shown that the composite material can gain good values of bearing strength when tested using the CBR. Results showed average CBR values to be 3.60% for the sand control then rose to 5.00% for 5% OPEFBA, 5.40% for 10% OPEFBA and 6.20% for 15% OPEFBA and dropped slightly to 5.45% at 20% OPEFBA. From the results, the maximum value was reached at 15% OPEFBA. The decrease at 20% suggests that the beneficial effect has an upper range, beyond which the increasing ash and bentonite fractions may reduce the load-bearing contribution of the granular sand skeleton. The results support the view that OPEFBA

can modify mechanical behaviour, but they do not justify identifying a universal optimum without considering the particular liner design and loading condition.

Direct shear testing showed a progressive reduction in friction angle as the proportion of bentonite and OPEFBA increased within the tested mixtures. The friction angle reduced from approximately 34° for sand to 28° for the 90:10 mixture, 27° for the 80:15:5 mixture and 25° for the 70:20:10 mixture. This can be attributed to the higher amounts of fines being added. It shows that there is some balance between fines for a barrier and granular for shear strength. This again shows that hydraulic and mechanical properties should be looked at when determining a liner mix. One should not pick a mix because it has high amounts of swell clay.

This result is important when interpreting the data from the composite as a whole. As stated before, the DFSI result of 520% indicates that the sodium bentonite has good swelling potential. This may help fill voids and self-seal. A high free swell value will not indicate long-term performance of a liner. Swelling potential could change depending on the permeant. Wet/dry cycles, drying, and ion exchange can all affect the swelling potential. Therefore, this value should only be taken as an indication of the bentonite in this case.

It is this property that becomes the limiting factor for this application. The lowest result obtained was 2.5 x 10-7 cm/s when 10% OPEFBA was used, which shows that the material has the ability to greatly decrease the hydraulic conductivity of a material but cannot meet the accepted value of 1 x 10-7 cm/s. From these results, it would be more beneficial to state that this composite can be considered a good physical/mechanical property and may be used as an additive to a bentonite liner, not a landfill liner on its own. More research may need to be done to optimize it in achieving the accepted value of hydraulic conductivity.

The statistics show that there can be high prediction fitting without actually having statistical significant effects. The Multiple R and R2 value for the particle-size distribution showed to have a high value of 0.9973 and 0.9946. With the Significance F value being small, this indicates a good-fitting equation for our data. Just like we saw with the CBR and Atterberg limits, with R2 values of 0.9757 and 0.9839. But with their respective Significance F values were larger than 0.05, showing that there is need to know what type of significance to look for when analyzing the results. Because our data was small, we can say that these regressions are empirical equations for the compositions that were studied.

Results indicate that our hypothesis was correct. There are combinations of OPEFBA that can be combined with bentonite and sand to achieve certain desirable properties. Depending on the target result, there are different percentages of OPEFBA that will help achieve these results. Dry density had good values when the percentage of OPEFBA was moderate. The highest CBR was found at 15% OPEFBA. Hydraulic Conductivity showed the lowest values at 10% OPEFBA. So to pick one combination, consideration is done on multiple factors and find what works best. With that being said, the 70: 20:10 combination could be beneficial because we were looking at using that as a liner in our study. It would still need more work to me*et al*l specifications, though.

It can be said to be sustainable by using OPEFBA, as it allows us to convert a waste product from the processing of agro products into something that can be used in engineering. By replacing current materials, we are able to reduce the need to dispose of this product. All while producing locally made geo materials. Life cycle analyses would have to be done to truly say it's sustainable. The findings show that we can engineer using this method, but more testing will need to be conducted to assess its cost, leeching and life span.

It was determined from this research that an order of importance to look at first when further researching should be met with a suitable value of hydraulic conductivity. This could be achieved by manipulating ratios of bentonite–OPEFBA or the inclusion of additional materials that have beneficial properties. After a ratio that will meet these criteria is found, the mixture will need to show good values of shear strength and be able

to be compacted. Wetting-drying, desiccation, chemical, permeant, contaminant transport, and shrinkage behaviour will need to be looked into to see if these values can be maintained in the field.

6.0 CONCLUSION

Based on the experimental results it shows that compacted sand-bentonite-OPEFBA mixtures have physical and mechanical properties that could be used to help develop landfill liners made of bentonite. When mixing OPEFBA with the materials it altered the particle-size distribution and the dry density of the compacted mixtures ranged from a dry density of the sand control at 1.99g/cm³ to 2.08g/cm³ which is the highest OPEFBA content that was tested. It was observed that CBR had an increase to an average of 6.20% at 15% OPEFBA and the control mixture which contained only sand was at an average CBR of 3.60%. There was a decrease in CBR when 20% OPEFBA was used in the mixture. The sodium bentonite had a free swell index difference of 520% which showed that it would provide good swell characteristics in a mixture.

Hydraulic conductivity for the mixture that consisted of 70% sand 20% bentonite and 10% OPEFBA was found to be the lowest with 2.5×10^{-7}cm/s which was much less than the control sample. Although this mixture did not satisfy the criteria of less than 1×10^{-7}cm/s. But it was found that the physical and mechanical properties of the mixtures showed good characteristics that can be added to a bentonite based liner as an agricultural waste product.

Analysis of variance and regression were also conducted to find if any of the mixtures could be associated to certain engineering properties. These regressions can be used to better determine what mixture to use. Due to some insignificant values and low amount of data these results should be taken with caution. More mixture should be tested and more trials can be done to find if the mixture meets the hydraulic conductivity standard. Testing over longer periods of time to see how wetting and drying can affect the mixture would also be beneficial.

Some recommendations that were found from this study are: The optimum mixture of bentonite and OPEFBA should be further studied. With useful values of mechanical properties near 10% OPEFBA; study additives that are compatible with reducing the hydraulic conductivity without degrading the physical and mechanical properties; conduct hydraulic testing with landfill leachate or another permeant that would represent similar conditions at the site; study the durability of the material during wetting/drying cycles as well as desiccation and shrinkage; additional research can be done to study other mechanical and environment properties such as UCS, migration of contaminants, compatibility of leachate and retention of heavy metals; the models should be verified with more data before they are used to predict and formulate mixtures; perform a full scale test once mixture has been optimized. To make sure of proper compaction, water content and hydraulic properties and overall construction of the liner.

The study contributes to knowledge by: It established the potential of OPEFBA as an additive in sand-bentonite mixtures with favourable physical and mechanical properties; it identified 5–10% OPEFBA for maximum dry density and 15% for the highest average CBR; it developed correlations between mixture composition and engineering properties using ANOVA and regression models; it demonstrated that improved mechanical properties do not necessarily ensure the required permeability for landfill liners and promoted sustainable agricultural waste reuse in geotechnical engineering and identified areas requiring further improvement before landfill liner application.

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