ENGINEERING PROPERTIES OF TROPICAL CLAY AND BENTONITE MODIFIED WITH SAWDUST

Isaac I. Akinwumi *(corresponding author)*
Covenant University,
Department of Civil Engineering
Ota, Nigeria
E-mail: isaac.akinwumi@covenantuniversity.edu.ng

University of the West of England,
Department of Architecture and the Built Environment
Bristol, United Kingdom
E-mail: isaac.akinwumi@uwe.ac.uk

Oluwapelumi O. Ojuri
Federal University of Technology Akure,
Department of Civil and Environmental Engineering
Nigeria
E-mail: ooojuri@futa.edu.ng

Adebanji S. Ogbiye
Covenant University,
Department of Civil Engineering
Ota, Nigeria
E-mail: ade.ogbiye@covenantuniversity.edu.ng

Colin A. Booth
University of the West of England,
Department of Architecture and the Built Environment
Bristol, United Kingdom
E-mail: colin.booth@uwe.ac.uk

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Abstract

Construction engineers typically avoid the use of expansive soils as construction materials because they are usually difficult to work on and can cause structural failure. This research work investigates how the application of sawdust to tropical clay and bentonite influences their geotechnical properties in order to determine their suitability for use as landfill-liner materials for the effective containment of toxic substances from landfills. X-ray diffractometry, X-ray fluorescence spectroscopy and scanning electron microscopy were used to determine the mineralogical composition, oxide composition and microstructure, respectively, of the clay and the bentonite. A series of laboratory tests were conducted to determine the specific gravity, Atterberg limits, compaction, unconfined compressive strength and permeability characteristics of the clay and the bentonite for varying proportions of sawdust application. Generally, increasing the percentage of sawdust caused a reduction in its specific gravity, maximum dry unit weight and unconfined compressive strength, while it caused an increase in the optimum moisture content and permeability of the modified clay and bentonite. The clay and bentonite both have a sufficiently low permeability that satisfies the hydraulic conductivity requirement for use as clay liners. Eight percent sawdust application to a clay having similar properties as that in this study is recommended as an economic way of modifying it – with the potential of improving its adsorbent property – for use in landfill-liner systems in order to prevent the toxic substances leaching from the landfills, thereby protecting the environment and public health.

1 INTRODUCTION

Globally, expansive soils have been identified as a cause of failure for many structures and the infrastructures built on them [1]. According to the Wyoming Office of Homeland Security [2], damage to infrastructure in the United States (US) caused by expansive soils is more than twice the sum of the damage that resulted from floods, earthquakes, tornadoes and hurricanes. The annual damage to structures (such as buildings, roads, bridges and pipelines) in the US alone is estimated at $2.3 billion [2].

Due to moisture-content changes, expansive soils swell or shrink [3] and, consequently, make the structures built on them unstable and susceptible to damage [4, 5]. Aside from being characterized by a large volume change, they also usually have a high moisture-holding capacity, low bearing capacity, low strength and low permeability [6]. Cracks develop when these soils are subjected to repeated dry-wet cycles [7]. Clay minerals, especially the smectite group, are responsible for the expansive nature of this category of soils. Many constructors and geotechnical engineers try to avoid the use of expansive soils as construction materials or constructing on them. However, the depletion of suitable natural soils and land areas has made it sometimes unavoidable.

The stabilization or modification of expansive soils in order to make them suitable for construction purposes has attracted the attention of many researchers in recent decades. Some of the stabilizers or modifiers that have been investigated include: lime [8], fly ash [9], steel slag [10], coconut fibres [11], marble dust [12], polypropylene fibre [13], blast-furnace slag [14] and bio-enzymes [15]. However, some of these stabilizers are expensive, not locally available in some places and do not suit some engineering applications.

Clays are commonly used to contain the wastes that are disposed in landfills, because of their hydraulic property [16]. They are normally used for lining the base, sides and engineered capping of a landfill [17]. Clay liners function to prevent the migration of leachates from landfills and to prevent groundwater from gaining access to these landfills [17]. The lining and capping can be provided using either natural or artificial materials, or a combination of these.

In this study a series of laboratory experiments was used to investigate the effect of modifying a tropical clay and bentonite using sawdust on their geotechnical properties in order to determine their suitability for use as landfill-liner materials. Bulut and Tez [18] found that sawdust is a good adsorbent for heavy metals. Therefore, its use along with clays in a landfill-liner system has the potential to provide a better retention of toxic substances (such as lead and cadmium) by landfills in order to protect public health via the prevention or minimization of groundwater pollution. Sawdust, a waste from wood processing, has the potential to provide a cheap and locally available choice of material for modifying the clay for use as a landfill-lining system by introducing an organic substance that can provide a better retention of the toxic leachates from landfills. In this way, protecting public health and the environment, while minimizing the environmental nuisance associated with the improper disposal of sawdust.

2 MATERIALS AND METHODS

2.1 Materials

The clay soil used was collected, as a large mass clog of clay, from a borrow pit behind Covenant University,

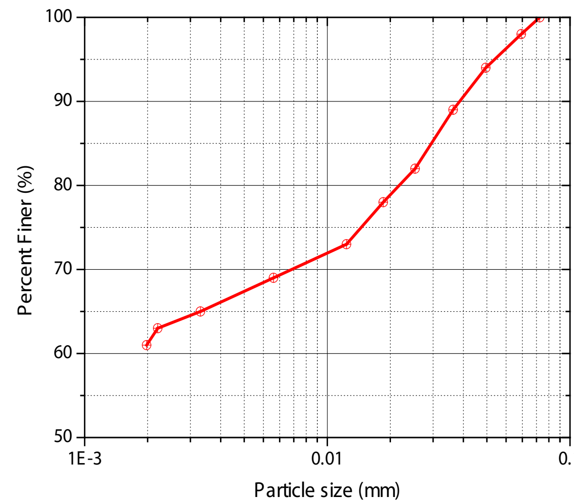

Figure 1. Particle size distribution of the clay.

Ota, Nigeria. It was then air-dried in the laboratory and pulverized, with all its particles passing through a sieve with 75-μm openings (Fig. 1). The bentonite used was procured from the market in powdered form. Before use, it was oven-dried for 3 hours to ensure that there is no moisture within it. All its particles were found to be clay-size. Sawdust of *Combretodendron Macrocarpum* was obtained from a wood sawmill at Ota, Ogun State, Nigeria and used to modify the clay and bentonite samples. This species of sawdust was so selected because it is reportedly found throughout tropical West Africa [19, 20] and can consequently be cheaply sourced. The sawdust was washed with distilled (de-ionized) water to remove the dust and soluble impurities, and then dried at room temperature. Only the fraction passing through 425-μm sieve openings was used in order to meet the requirement for the liquid and plastic limits tests. This procedure for preparing the sawdust is in accordance with that used by Bulut and Tez [18] and Gupta and Babu [21]. The sawdust was applied to the samples in the following proportions: 0, 2, 4, 6 and 8%, by dry weight of the clay or bentonite. The maximum percentage of sawdust used to modify the clay and bentonite was selected such that the permeability of the modified materials satisfies the permeability requirement ($\leq 1 \times 10^{-7}$ cm/s), which is the most generally acceptable criterion that materials to be used as landfill liners should satisfy [17].

Representative samples of the clay and bentonite were collected randomly from the thoroughly mixed bentonite and pulverised soil samples, in order to ensure homogeneity of the sample for the chemical and mineralogical composition and microstructural analysis. The microstructures of the clay and bentonite were obtained using a scanning electron microscope (SEM), while their chemical and mineralogical compositions were determined using an X-ray fluorescence spectrometer and an X-ray diffractometer, respectively.

2.2. Methods

Geotechnical characterization tests were performed in accordance with British Standard Institution (BSI) procedures. The natural or in-situ moisture content of the clay soil was determined using a laboratory oven-drying method [22] (Clause 3.2). The particle size distribution of the soil was determined by carrying out sieve and hydrometer analyses. The sieve analysis was conducted on the clay soil using the wet-sieving method [22] (Clause 9.2). The hydrometer analysis was conducted on the fine-grained fraction of the soil in accordance with BSI [22] (Clause 9.5). The plasticity of the clay and bentonite were determined from laboratory tests for the determination of the liquid and plastic limits. The liquid limit of the samples was determined using the Casagrande apparatus method, in accordance with BSI [22] (Clause 4.5). The procedure for the determination of the plastic limits of the samples was in accordance with BSI [20] (Clause 5.3), while the plasticity indices were derived in accordance with BSI [22] (Clause 5.4). The specific gravities of the samples were determined using the pycnometer method, in accordance with the procedures outlined by BSI [22] (Clause 8.3). The compaction characteristics of the samples were determined using the procedures outlined in BSI [23] (Clause 3.3). The procedure followed for the determination of the unconfined compressive strength was that for the load-frame method and is in accordance with the procedure outlined in BSI [24] (Clause 7.2). A falling-head permeameter was used to determine the permeability of the clay and bentonite in accordance with Head [25]. The geotechnical properties were determined (at least) in triplicate in order to ensure the scientific robustness of the results, which are presented as the mean and standard deviation.

3 RESULTS AND DISCUSSION

3.1. Chemical and mineralogical composition

The chemical properties of soils are important and can provide an insight to their behavior or reaction with other materials. Fig. 2 presents the oxide composition of the clay and bentonite samples. Fig. 2 shows that silica, alumina and iron (III) oxide are the predominant oxides of the clay and bentonite. Silica is the main constituent oxide – having more than 50% of the oxides. The clay was obtained from a white rock-like mass having small embedment, whose colours are: brown (7.5YR 4/4), yellow (10YR 8/8) and purple (10P 5/8), in accordance with the Munsell colour chart. Its brown and yellow colour is believed to be an indication of iron oxide. The bentonite is fine and has a grey coloration (2.5GY 8.5/2).

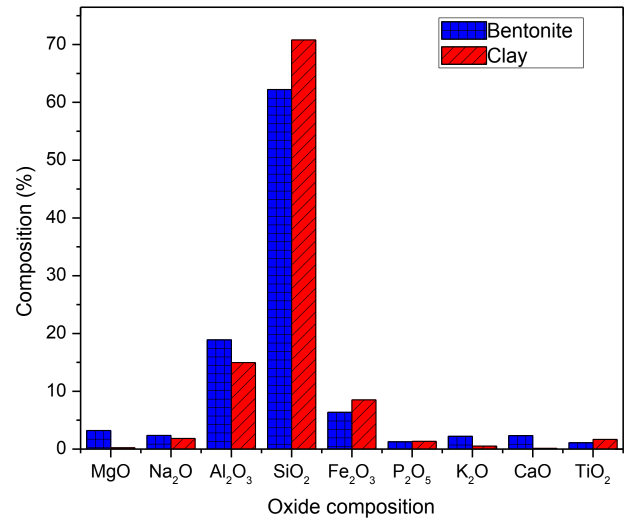

Figure 2. Oxides of the clay and bentonite.

The mineralogical compositions of the clay and the bentonite indicate that the clay is composed of kaolinite and quartz, while the bentonite is predominantly composed of montmorillonite. The white coloration of the clay results from the presence of kaolinite.

3.2. Modification of Clay and Bentonite with Sawdust

The geotechnical properties of the clay and bentonite are presented in Tables 1 and 2. According to the Unified Soil Classification System (USCS), the clay is classified as CH – clay of high plasticity. It has a natural moisture content of 10.1, a specific gravity of 2.64 and a plasticity index of 27%. The bentonite has an extremely high plasticity (plasticity index of 56.4%) and its specific gravity is 2.49. When the dry powdered bentonite comes in contact with water, it forms a gel-like slurry – making it difficult for water to flow through it.

The clay-size fraction of the clay makes up 61% of its particles (Fig. 1) and as such influences the overall engineering properties of the soil [26].

Table 1. Geotechnical properties of the natural clay.

Properties		Natural soil Mean (Standard deviation)
Classification	Unified Soil Classification System	CH - Clay
Physical	Colour	Pinkish White
	Specific Gravity	2.64 (0.052)
	Liquid Limit (%)	61.5 (0.398)
	Plastic Limit (%)	34.5 (0.657)
	Plasticity Index (%)	27.0 (0.768)
	Maximum Dry Unit weight (kN/m^3)	15.5 (0.208)
	Optimum Moisture Content (%)	19.7 (0.252)
	Coefficient of Permeability (cm/s)	0.189 x 10^{-7} (0.00339 x 10^{-7})
Strength	Unconfined Compressive Strength (kN/m²)	1148 (5.923)

Table 2. Geotechnical properties of the bentonite.

Properties		Bentonite Mean (Standard deviation)
Physical	Colour	Grey
	Specific Gravity	2.49 (0.072)
	Liquid Limit (%)	166.5 (1.354)
	Plastic Limit (%)	110.1 (1.099)
	Plasticity Index (%)	56.4 (1.230)
	Maximum Dry Unit weight (kN/m^3)	12.9 (0.000)
	Optimum Moisture Content (%)	21.1 (0.231)
	Coefficient of Permeability (cm/s)	0.058 x 10^{-7} (0.000968 x 10^{-7})
Strength	Unconfined Compressive Strength (kN/m²)	347.7 (2.082)

3.2.1. Specific Gravity

The variation of the specific gravities of the clay and bentonite with sawdust are shown in Fig. 3. The specific gravities of the clay and bentonite decreased with an increasing percentage of sawdust in the soil.

The sawust used has a specific gravity of 1.16. Consequently, the specific gravities of the sawdust-treated clay and sawdust-treated bentonite did not deviate from the expectation that partial replacement of the clay (having a specific gravity of 2.64) or bentonite (having a specific gravity of 2.49) with sawdust would cause a reduction in the specific gravity of the modified samples. A study by Tran [27], on how the application of sawdust to an agricultural soil influences its corn yield, reported a reduction in the bulk density (which is related to the specific gravity) of the sawdust-modified soil with increasing sawdust application. This agrees with this study. The replacement of some of the clay and bentonite with sawdust might also have generated increased void spaces within the modified samples.

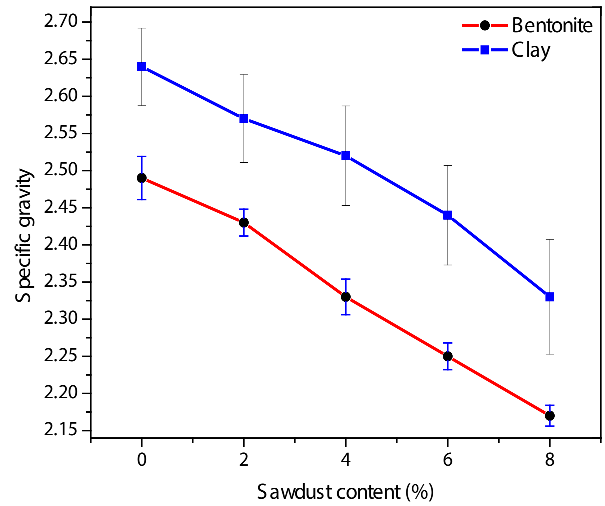

Figure 3. Variation of specific gravities of the clay and bentonite with sawdust.

3.2.2. Atterberg limits

The Atterberg limits of the clay varied with the proportion of sawdust added to it, as illustrated in Fig. 4. The liquid limit and plastic limit of the soil decreased with increasing sawdust content. The mean plasticity indices of the clay and that of its modification with 2% sawdust was comparatively the same, while a subsequent increase in the sawdust content resulted in a decrease in the plasticity index of the clay. The plasticity indices of soils give a measure of their plasticity [26]. Therefore, it can be said that the plasticity of the clay decreased with an increasing percentage of sawdust in the mixture.

When the clay minerals in the soils interact with water, a thin layer of water called the diffuse double layer gets bonded to their surfaces [26, 28, 29], which influences their plasticity. The application of sawdust to the clay makes the sawdust cling around its clay minerals and absorbs water from them – thereby reducing their moisture-holding capacity and their ability to freely interact with themselves and become aggregated. Consequently,

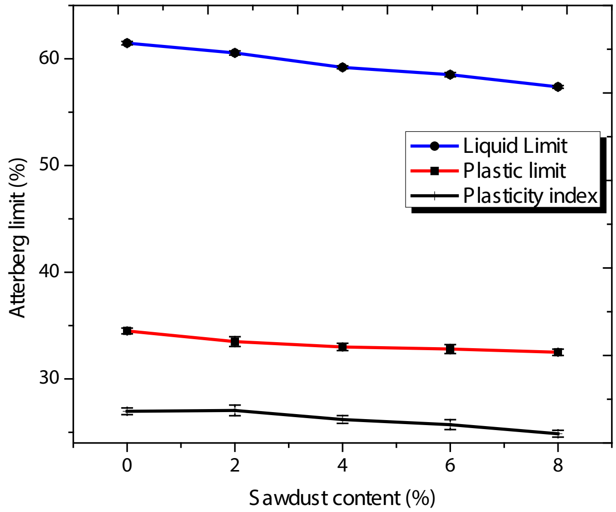

Figure 4. Variation of Atterberg limits of the clay with sawdust.

Though sawdust is non-plastic, it is not quite clear why its progressive addition increased the plasticity of the bentonite. Its interaction with bentonite might have transformed it from being non-plastic to behaving like a plastic, thereby increasing the range of water content for which the sawdust-treated bentonite exhibits plastic properties.

3.2.3. Compaction Characteristics

The compaction characteristics of a soil are described by its optimum moisture content (OMC) and maximum dry unit weight (MDUW). The variation of the OMC and MDUW of the clay with sawdust and bentonite with sawdust are graphically illustrated in Figs. 6 and 7.

Figs. 6 and 7 show that the OMC increased, while the MDUW decreased, as the sawdust content in the treated samples increased. With increasing sawdust content, the plasticity of the clay decreases as its sawdust content increases. This makes the treated clay more workable. This finding reiterates the statement of Abd El Halim and El Baroudy [30] that sawdust can be used to reduce the plasticity of expansive soils.

The variation of the liquid and plastic limits and the plasticity index of the bentonite with sawdust is presented in Fig. 5. The liquid and plastic limits decreased, while the plasticity index of the bentonite surprisingly slightly increased as its sawdust content increased. This may, however, be due to the extremely high plasticity of the bentonite.

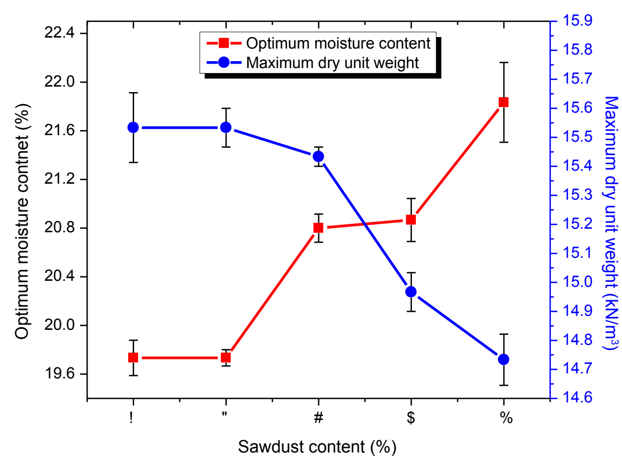

Figure 6. Variation of the compaction characteristics of the clay with sawdust.

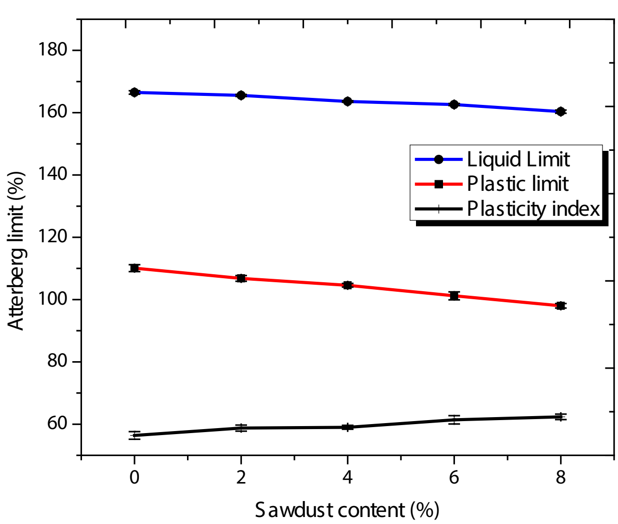

Figure 5. Variation of Atterberg limits of the bentonite with sawdust.

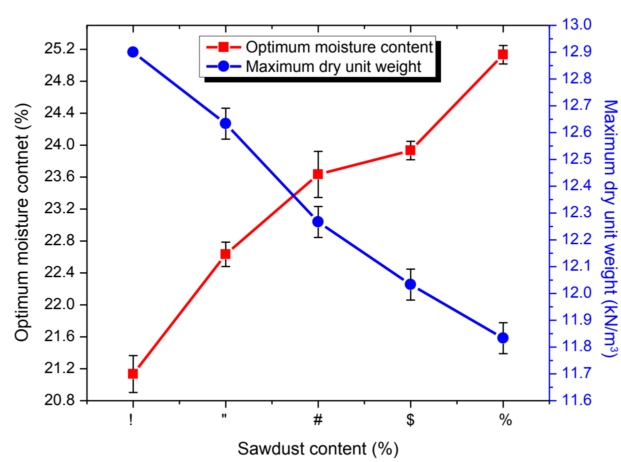

Figure 7. Variation of the compaction characteristics of the bentonite with sawdust.

treated samples required more water in order to attain the MDUW. This is because some of the water in the sawdust-modified samples gets absorbed by the sawdust. However, the MDUW achieved decreased with increasing sawdust content. This can be attributed to the lower specific gravity of the sawdust. The MDUW are lower and the OMC greater for the modified bentonite.

3.2.4. Strength Characteristics

The variation of the unconfined compressive strengths (UCS) of the clay and the bentonite are shown in Fig. 8. The UCS of a soil is a measure of the maximum load it can withstand per unit area, when its lateral confining pressure is zero. The UCS of the treated samples decreased with increasing sawdust content. The sawdust has a low density and compressive strength compared with that of the clay and bentonite. This explains why the UCS of the treated clay and bentonite decreases as their sawdust contents progressively increased.

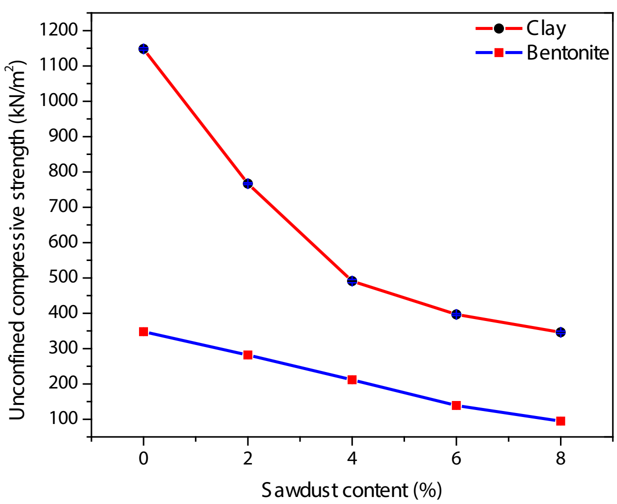

Figure 8. Variation of the UCS of the clay and bentonite with sawdust.

3.2.5. Permeability

The variation of the permeability of the treated clay and bentonite with their sawdust contents are presented in Fig. 9. The permeability of a soil gives a measure of the ease with which water flows through it. Fig. 9 shows that the higher the sawdust content, the easier it is for the water to flow through the sawdust-treated clay and sawdust-treated bentonite. This is attributed to the increasing pore space in the treated clay and bentonite as their sawdust content increases. The SEM morphology for the natural soil and for the soil admixed with varying percentages of sawdust (Fig. 10) show increasing

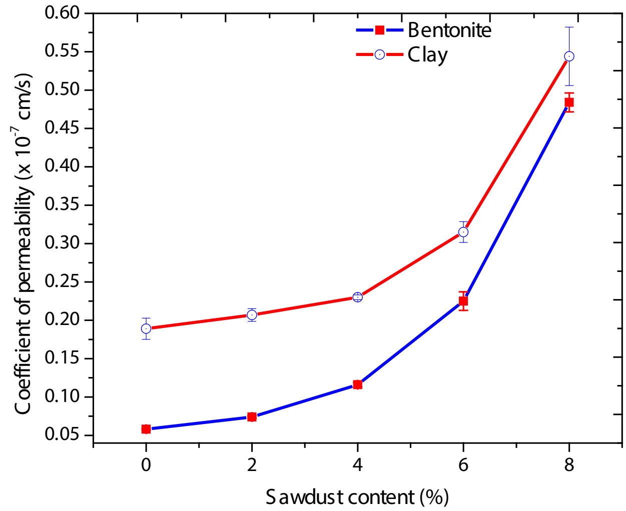

Figure 9. Variation of the permeability of the clay and bentonite with sawdust.

pore space as the percentage of the sawdust in the clay increases. The pore size of the bentonite also increased as its sawdust content increased (Fig. 11).

A typical clay liner material should have a hydraulic conductivity (permeability) less than or equal to 1 x 10^{-7} cm/s and a strength greater than 200 kN/m^2 [31, 32]. The coefficients of permeability of the clay and bentonite are less than 1 x 10^{-7} cm/s, which is generally specified as the hydraulic conductivity requirement that clays need to satisfy in order to be used as landfill-liner materials. The UCS of the clay and bentonite are greater than 200 kN/m^2, indicating that a layer of a lining system using this clay or bentonite can sufficiently support the load from landfilled wastes that may be imposed on it. Also, the modification of the clay with 8% or less sawdust and that of the bentonite with 4% or less sawdust satisfy these permeability and strength requirements. The National Rivers Authority (NRA) [33] stated that a soil to be used as a clay liner should have its liquid limit and plasticity index less than 90% and 65%, respectively, and clay content greater than 10%. The bentonite and its modification with sawdust have their liquid limits greater than 90%. Therefore, this makes the bentonite and its modification with sawdust unstable and unsuitable for use as a landfill liner.

4. CONCLUSIONS

The clay and bentonite samples contain silica, alumina and iron III oxide as their predominant oxides. The clay mineral in the clay is kaolinite, whereas that in the bentonite is montmorillonite, which is highly expansive.

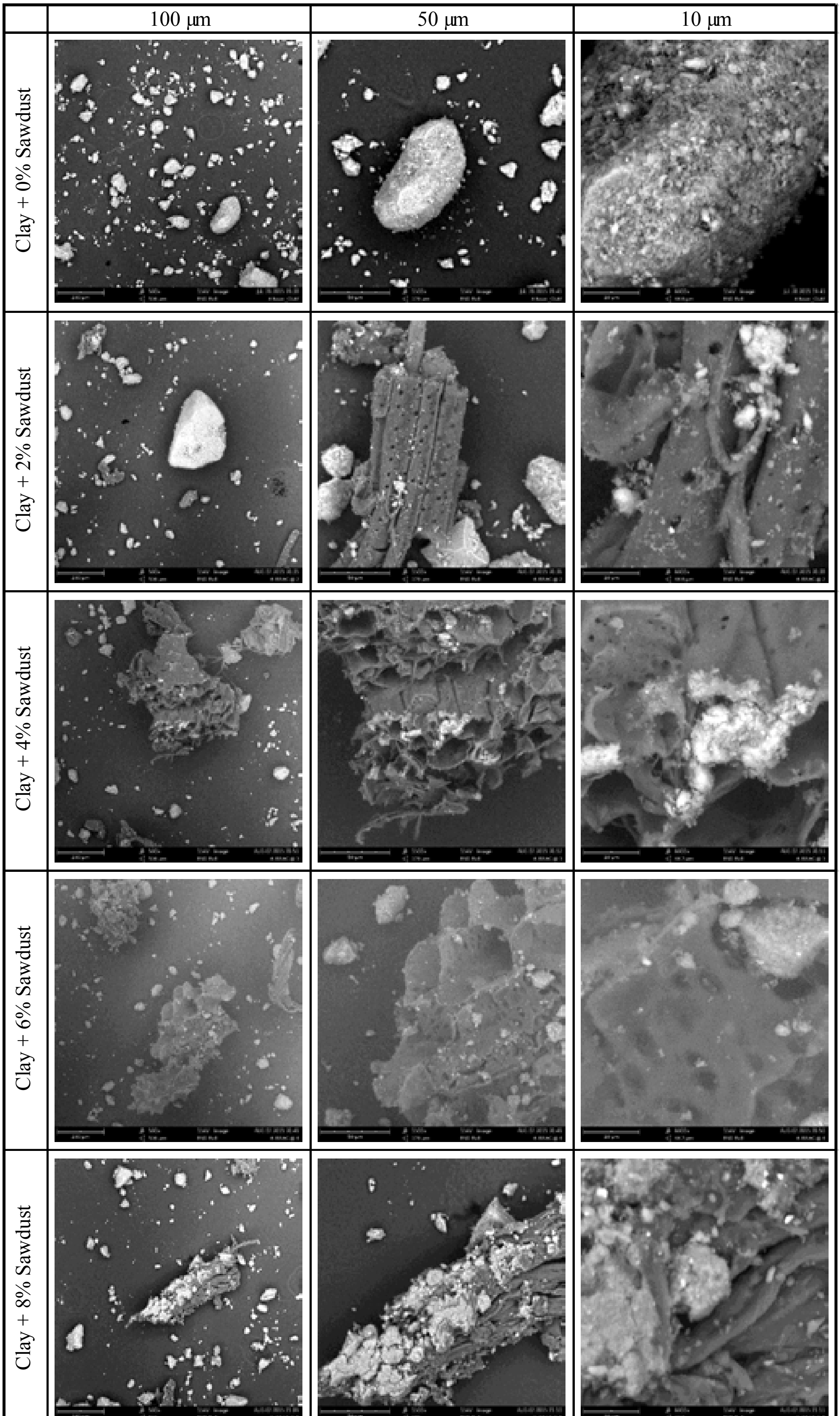

Figure 10. SEM micrograph of the clay with sawdust.

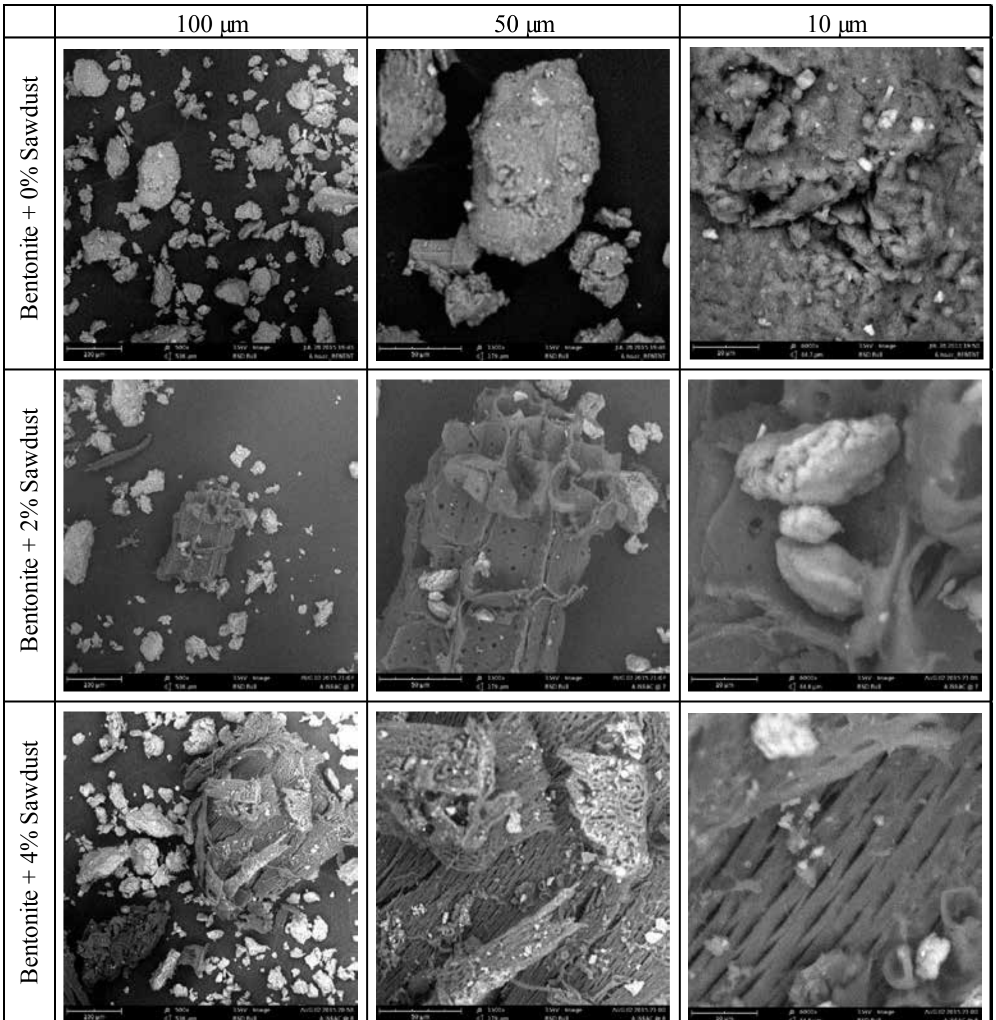

Figure 11. SEM micrograph of the bentonite with sawdust.

The clay is of high plasticity, while the bentonite has an extremely high plasticity.

The modification of the clay with an increasing percentage of sawdust caused a reduction in its specific gravity, plasticity, MDUW and UCS, while it caused an increase in its OMC and permeability. Consequently, improving the workability of the clay, but reducing its strength. The modification of the bentonite with the sawdust resulted in a reduction in its specific gravity, MDUW and UCS, while it increased its plasticity (slightly), OMC and permeability.

The clay and bentonite both have sufficiently low permeability to satisfy the hydraulic conductivity requirement for use as clay liners. The clay and sawdust-modified clay also satisfy the clay content, Atterberg limits and UCS requirements for use as landfill liners, whereas the bentonite and sawdust-modified bentonite did not satisfy the Atterberg limits and UCS requirements (for modification with more than 4% sawdust). An 8% sawdust application to a clay having similar properties as that of this study is recommended for modifying it for use in a landfill-liner system.

Following Bulut and Tez's [18] recommendation of sawdust as a low-cost adsorbent of heavy metals, the implication of these findings is that modification of a clay (having similar properties as that studied and suitable for use as a landfill liner) with sawdust has the potential of improving the removal of hazardous metals from landfills and protecting groundwater. Also, the use of sawdust –which is usually disposed improperly and thereby constitutes a nuisance to the environment and public health – gives assurance of the sustainable development of people and society.

The increase in the permeability of the clay and bentonite with increasing sawdust content indicate that when soil drainage is important to a construction project, sawdust can be used to improve the drainage capacity of clays of very high plasticity by the addition of an appropriate proportion that will not compromise the stability of the layer of earthworks. Sand may be added to the mixture of bentonite and sawdust using a proportion that ensures that the resulting lining system is stable, while the composite satisfies the permeability and strength requirements for use as a landfill liner.

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