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# Influence of Geopolymer on Soil Mechanical Strength in Landfill Soil Liner Application

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## ABSTRACT

Landfill soil liner is an essential component, designed as a barrier between waste and groundwater for the environment. Improper soil compaction results in leachate infiltration into the environment. Compression of soil is vital to enhance the soil strength, improve bearing capacity, and soil stiffness of chemically modified soils or in-situ (natural). This paper aims to investigate the effect of the water content in geopolymer affecting the soil mechanical strength of compacted residual soil constructed according to existing standards. The soil was mixed with 5, 10, 15, and 20% of geopolymer by weight. The test carried out was divided into physical properties and compaction of residual soil, mix with geopolymer. Mixture samples were tested using a standard proctor and samples were compact at dry, wet, and optimum moisture content ranging from -2 and +2 of the optimum moisture content. The result shows that the addition of geopolymer as an additive has significant positive results on maximum dry density due to alteration in geopolymerization. The increases in geopolymer content are associated with a decrease in water content, leading to a significant increase in soil mechanical strength thus giving positive soil strength.

Keywords: *Geopolymer; soil liner; soil compaction; maximum dry density*

## INTRODUCTION

Malaysia is one of the world's largest palm oil producers and exporters until the year 2008 and the production is still increasing up to this day. According to Tan [1], the total palm oil product export was 21,7630929 tons with a value of RM 65,215.2 million in 2023. Without the utilization of this waste, palm oil boiler ash will be of disposal to the environment and contaminate the soil properties.

In landfill soil liner, the compacted soil liner is essential with the requirement of hydraulic conductivity, $k$ less $1 \times 10^{-9}$ m/s. The traditional material of landfill soil liner has studied the use of bentonite or lime to enhance the properties of soil liner. However, the consideration of alternative materials in utilizing industrial waste that provides an environmentally friendly source and is cost-effective has given a chance for geopolymerization studies as alternative additives in landfill soil liner. Palm oil boiler ash is an excellent potential alternative material in soil stabilization and sustaining the environment.

Geopolymerization has been well-known as a developing field of research that utilizes solid waste and by-products. Geopolymers were invented by the French scientist Joseph Davidovids around 1970-1972, which is derived from the fact that aluminosilicate raw materials can be used with chemical activators to produce new binders [2]. Geopolymerization is a reaction process that chemically integrates minerals involving silica-aluminate sources. Alumina and silica atoms act as precursor sources that are readily dissolved and synthesized by alkaline activation, which lends to geopolymerization. Any material that contains mostly silicon (Si) and aluminum (Al) in amorphous form is a possible source material for the manufacturing of geopolymer [3]. Geopolymers possess excellent adhesion to solid particles and a low shrinkage potential [4]. In soil enhancement, geopolymer can be effectively used due to its high resistance to acids [5].

A compaction test is conducted to achieve a soil layer of improved engineering properties. Compaction's purpose is to place soils in a denser state, decreasing further settlement, increasing shear strength, and decreasing permeability. It is possible to control the dry density and moisture content so that the soils exhibit the most desired properties, such as consolidation and permeability [6]. The compaction values of soils are considered good if 95% of the possible density of the soil through compaction efforts is attained during field compaction [7]. The literature revealed that an MDD value of >1.71 Mg/m$^3$ is recommended for soils to be used as landfill barriers, while Taha and Kabir [8] suggested MDD >1.6 Mg/m$^3$.

In this research, a study was conducted to investigate soil-geopolymer boiler ash-based additives that have been chosen to enhance the properties of soil. By applying the geopolymer green technology in the soil, the liner system can fulfill the requirement in designing a soil liner system and achieve the objective of becoming environmentally sustainable.

## EXPERIMENTAL DETAILS

The test determines the effect of different geopolymer percentages in improving soil mechanical strength properties on landfill soil liner application. The compaction characteristics of varying ratios of geopolymer in soil mixtures were examined and discussed. The experimental tests include the basic physical properties test and compaction characteristics according to BS1377: Part 4: 1990 Standard Test Method [9]. The tests aim to determine the maximum compaction strength of soil at different moisture content conditions (wet, optimum, and dry).

### *Materials and Methods*

The soil was collected at Tanjung Langsat, Johor. The geopolymer was produced by mixing palm oil boiler ash, with an alkaline solution of sodium hydroxide (NaOH), and sodium silicate ($Na_2SiO_3$). The primary materials used to produce geopolymer paste were boiler ash, NaOH, and $Na_2SiO_3$. Palm oil boiler ash as shown in Figure 1 was obtained from Palm Mill Teluk Sengat Kota Tinggi, Johor, Malaysia.

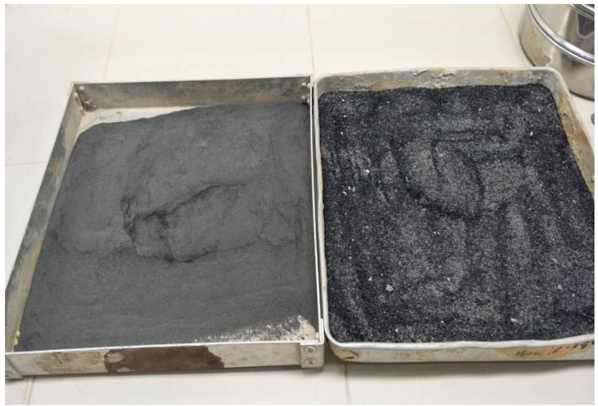

Figure 1. The boiler ash after sieve (left), the original boiler ash at the palm mill

Figure 2 shows NaOH, and $Na_2SiO_3$ as alkaline activators which were purchased from Bio-Am Industries Sdn. Bhd., Johor Bahru. The NaOH is consistently used to 5 M (molar) concentration in pellet form for all samples. The NaOH pellets were added to water to obtain the alkali solution and then mixed with the solution of $Na_2SiO_3$ at a ratio of 1:2 [10]. The paste of soil-geopolymer was prepared as shown in Figure 3 according to the experimental ratio.

Figure 2. The alkaline solution

Figure 3. The mixture of soil-geopolymer

***Physical Properties test***

All physical properties were tested according to British Standard (BS 1377: Part 2: 1990) as guidance. All experiments were repeated at least three (3) times. The basic properties tests conducted include Potential Hydrogen (pH), Plastic Index (PL), Liquid Limit (LL), Plasticity Index (PI), and Linear Shrinkage (LS) according to BS 1377: Part 2:1990.

Figure 4 shows the preparation of the soil-geopolymer mixture on the liquid limit test. The size and distribution of solid particles within the soil are the key factors that influence how silt or clay reacts to its moisture content and thus influence the Atterberg Limits [11]. The smaller the particle size, the better the soil's moisture retention [12].


Figure 4. The preparation of soil-geopolymer mixture on liquid limit test

In this study, the British standard (BS 1377: Part 3: 1990: 9) method was used to determine the pH of soils. Three (3) samples of each mixture specimen consisting of 30 g each of 63 µm by sieved specimens were added with 75 mL of distilled water and stirred for 10 min (Figure 5).

The soil linear shrinkage test in Figure 6 is the point at which the soil becomes solid from a semi-solid state. At this moisture content, the volume of the soil mass ceases to change with further drying of the material [13].

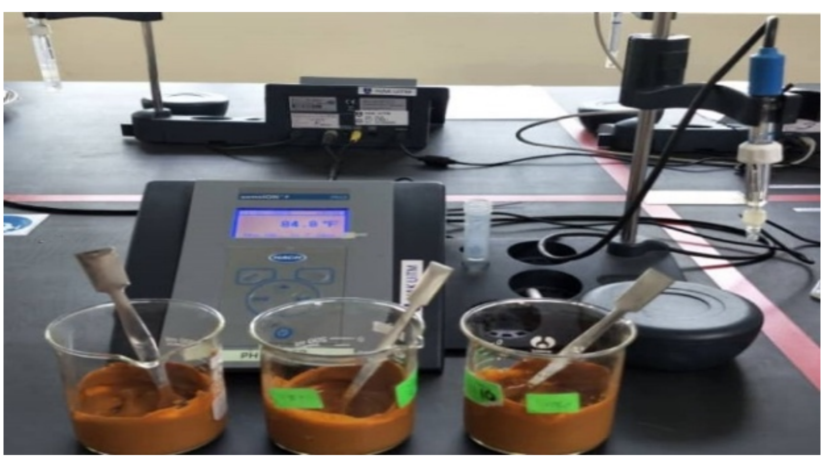

Figure 5. The pH test of soil-geopolymer mixture

Figure 6. The Shrinkage test of soil-geopolymer mixture

***Standard Proctor Test***

According to BS1377: Part 4, 1990, the maximum dry density (MDD) and optimum moisture content (OMC) values for all percentages are obtained from the compaction test using the standard proctor method. Before the compaction test, the samples were oven-baked between 60 ºC and 70 ºC for about 1 to 1.5 h to protect the soil mixture's mineral content and fabric structure as shown in Figure 7.

Figure 7. The preparation of soil-geopolymer mixture for compaction test

Five samples containing different percentages of geopolymer (0, 5, 10, 15, and 20%) were prepared based on the soil-geopolymer preparation described above. The soil-geopolymer sample was compacted dynamically with a 2.5 kg steel hammer, falling freely from 300 m height with 27 blows corresponding to each of the three layers [14,15]. The compaction tests were repeated by adding distilled water until the sample weight dropped due to the removal of excess water. The excess soil was removed using a scraper. The sample was removed from the compaction mold using an extruder and then weighed.

Figure 8. The compaction test using Standard Proctor test

## RESULTS AND DISCUSSION

This study aimed to examine the maximum dry density of different percentages of soil-geopolymer boiler ash with water content at dry, optimum and wet conditions.

### *Physical Properties test*

Table 1 shows the physical properties measured in this study. The average shrinkage of the soil was 11.49% as it reduced to 10.54, 7.67, 7.11, and 7.23% when added with 5, 10, 15, and 20% geopolymer. According to Daniel and Wu [16], cracking is unlikely in soil liners that undergo less than 10% shrinkage upon drying. The shrinkage value decreases up to 15% of geopolymer, with an increase with increasing percentages of geopolymer. Ion exchange occurs within the soil-geopolymer mixture and may account for the decrease in shrinkage value [17]. Soil pH changes from acidic to alkaline from 6.49, 8.05, 9.51, 10.90, and 11.40 at 0, 5, 10, 15, and 20%. The addition of geopolymer-boiler ash-based turns soil to alkaline and makes it less soluble, and does not absorb or allow leachate infiltration.

The Atterberg test of soil-geopolymer mix gives an LL range of 39 to 48%, a PL range of 29 to 34%, and a PI range of 10 to 19%. According to the minimum requirement based on BS 1377, 1990 test specification, the plasticity index ranges between 10% and 65% ($10 \leq PI \leq 65\%$), and LL at $\leq 90\%$. The addition of geopolymer to soil satisfies the requirement for plasticity index and liquid limit in soil liner applications.

The soil classification of samples was identified using a Plasticity chart classification of soil (British Standard Institute BS 5930, 2015) as shown in Table 2. There were no changes in the soil classification of mixed soil. It can be seen that the laterite soil and laterite with the addition GeoPOBA were classified as silt of intermediate plasticity (MI), respectively.

Table 1. Physical properties soil-geopolymer boiler ash based

| Properties | 0% | 5% | 10% | 15% | 20% |
|---|---|---|---|---|---|
| pH | 6.49 | 8.05 | 9.51 | 10.90 | 11.40 |
| Liquid Limit, LL (%) | 48.00 | 45.00 | 39.00 | 40.00 | 44.00 |
| Plastic Limit, PL (%) | 29.00 | 32.00 | 24.00 | 28.00 | 34.00 |
| Plasticity Index, PI (%) | 19.00 | 13.00 | 15.00 | 12.00 | 10.00 |
| Linear Shrinkage, LS (%) | 11.49 | 10.54 | 7.67 | 7.11 | 7.23 |

Table 2. Summary results of Atterberg Limit test

| Sample | LL (%) | PL (%) | PI (%) | Classification (British Standard) |
|---|---|---|---|---|
| LS00 | 48.00 | 29.00 | 19.00 | Silt with Intermediate Plasticity (MI) |
| LS05 | 45.00 | 32.00 | 13.00 | Silt with Intermediate Plasticity (MI) |
| LS10 | 39.00 | 24.00 | 15.00 | Silt with Intermediate Plasticity (MI) |
| LS15 | 40.00 | 28.00 | 12.00 | Silt with Intermediate Plasticity (MI) |
| LS20 | 44.00 | 34.00 | 10.00 | Silt with Intermediate Plasticity (MI) |

***Compaction Characteristics***

One of the aims of this study is to determine the suitable percentage or optimum geopolymer content to produce the most effective soil mechanical strength. Compaction tests were conducted at different moisture content levels (wet, optimum, and dry) considering the climate change in wet and dry weather. All the soils studied showed maximum dry density within an acceptable range (> 1.71 $Mg/m^3$). Therefore, geopolymer boiler ash is suitable for landfill barrier materials [17].

Table 3 shows the compaction characteristics of soil geopolymer at different percentages. According to the result, 15% soil-geopolymer gives the highest MDD content at 2.19 $Mg/m^3$ with a reduction of OMC at 13.58%, indicating positive results for geopolymerization reactions.

Figure 9 shows the 15% soil geopolymer content produced significant positive results even in wet and dry conditions acceptable to soil liner requirements. Nik [18]. support this result, in their study on laterite soil and fly ash, geopolymer was mentioned, whereby geopolymer added to soil showed an increment in dry density due to an alkaline attack, which changed the soil mineral composition.

Adding 20% geopolymer to the soil decreased the MMD and increased the mixture's moisture content. The increase in OMC at 20% of geopolymer in Figure 9 was attributed to the increase in fine content. The mixtures indicate higher moisture content due to boiler ash's inclusion with a larger surface area that needed more water to react.

According to Zainuddin [19], excessive moisture breaks the silica-alumina bond in geopolymers. The reaction happened because of the weakness of the geopolymer mortar bond. The structure of silica-alumina in geopolymerization was lost due to a larger surface area that needed more water to react to the soil. This result agrees with Noushini [20] study on soil behavior with sodium silicate-liquid stabilizer.

Table 3. Compaction results of geopolymer in soil

| Sample | Moisture Content, w (-2%, $w_{opt}$, +2%) | Moisture Content, OMC (%) | Maximum Dry Density, MDD ($Mg/m^3$) |
|---|---|---|---|
| 0% | At $w_{dry}$ | 12.07 | 1.81 |
| | At $w_{opt}$ | 14.07 | 1.80 |
| | At $w_{wet}$ | 16.07 | 1.60 |
| 5% | At $w_{dry}$ | 11.38 | 1.78 |
| | At $w_{opt}$ | 13.88 | 1.88 |
| | At $w_{wet}$ | 15.88 | 1.82 |
| 10% | At $w_{dry}$ | 11.70 | 1.80 |
| | At $w_{opt}$ | 13.70 | 1.90 |
| | At $w_{wet}$ | 15.70 | 1.88 |
| 15% | At $w_{dry}$ | 11.58 | 2.10 |
| | At $w_{opt}$ | 13.58 | 2.19 |
| | At $w_{wet}$ | 15.70 | 2.11 |
| 20% | At $w_{dry}$ | 14.38 | 1.69 |
| | At $w_{opt}$ | 16.38 | 1.71 |
| | At $w_{wet}$ | 18.38 | 1.80 |

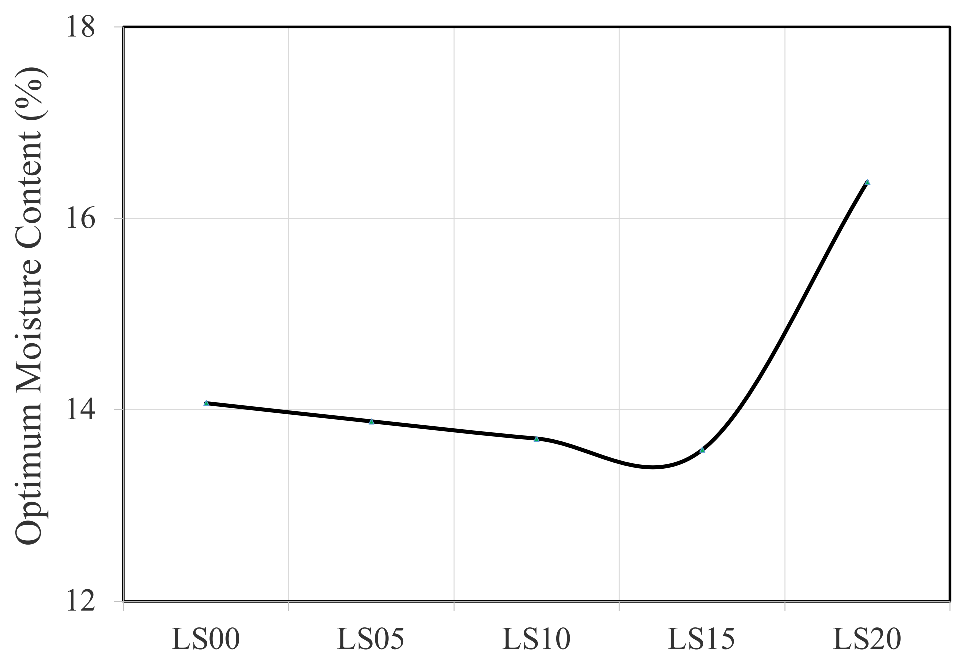


Figure 9: Comparison curve of value for soil-geopolymer mixture

In addition, on the overall result of physical properties and compaction test, Atterberg's result shows that the original soil gives the value based on landfill liner requirement however gives less maximum dry density and higher value in wet conditions during compaction. Therefore the addition of geopolymer gives soil higher strength and optimum moisture content comparing the original soil.

## CONCLUSIONS

This study shows that geopolymer boiler ash is suitable as an additive in providing good mechanical strength as landfill soil liner application. The 15% geopolymer content in the soil gives the best soil-geopolymer composition and the maximum geopolymer reaction as a mixed design. Adding a suitable ratio of geopolymer to soil leads to a higher MDD and lower OMC. Recycling boiler ash as binder material sustains the environment and economy for construction development. Using industrial waste as a by-product reduces waste in landfills, conserves acres of land, and reduces soil, groundwater, and air pollution. Boiler ash as source material to produce geopolymer can play a vital role in palm oil waste production's sustainability and environmental issues by introducing by-product material.

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## CONFLICT OF INTEREST

The authors agree that this research was conducted in the absence of any self-benefits, commercial, or financial conflicts and declare the absence of conflicting interests with the funders.

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