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THE EFFECT OF WATER PH ON UNCONFINED COMPRESSIVE STRENGTH OF LIME-TREATED CLAY SOIL FOR LINER MATERIALS IN WASTE CONTAINMENT FACILITIES

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Abstract
Clay soil obtained from the Gwagwalada area of Abuja in the Northern part of Nigeria was obtained and used for this study to determine the suitability of water pH on soil strength for waste containment facilities such as landfills and surface impoundments. Water pH influences the strength and durability of soils employed in these facilities and the potential for chemical reactions that can damage containment barriers. An unconfined compressive strength test was conducted using British Standard Light (BSL) and British Standard Heavy (BSH) compaction at varying water pH (i.e., Acidic, Neutral, and Alkaline water) to see the effect it can have on the life span of the clay as a liner material. High-quality liner materials must meet the minimum unconfined compressive strength requirement of 200 kN/m^2. According to the test outcomes, when the amount of lime in the soil increased, especially at 4% content, the maximum dry density (MDD) increased to 1.81, 1.78, and 1.71 Mg/m^3, and the optimum moisture content (OMC) decreased to 15.0,14.0, 16.0% for BSL compaction similar trend to BSH. The MDD is 1.93,1.83, 1.90 Mg/m^3, and OMC is 13.2, 14.0, and 12.4% for BSH compaction for acidic, alkaline, and neutral water, respectively. The unconfined compressive strength (UCS) decreases as moulding water increases. The UCS values meet the 200 kN/m^2 minimum requirement for soils compacted with acidic and neutral pH water for all compaction efforts. When treated with neutral water, the recommendation of 4% lime addition compacted at BSH for liner material construction at -2%, 0, +2% OMC. It is also recommended that alkaline water is unsuitable for constructing liners because it reduces the strength of treated soil.

1.0 INTRODUCTION
Due to its huge capacity, ease of use, efficiency, affordability, and simplified method, engineered landfills have emerged as the most typical technique for disposing of municipal solid waste (MSW) worldwide [1]. Under engineered landfill sites, liners prevent leachates and their toxic components from flowing downward, reducing pollution in nearby water bodies or underlying aquifers. Because of their sufficient compressive strength, balanced swelling potentials, and low hydraulic conductivity, compacted clays are frequently used as ideal materials for building landfill liners [2]. The materials chosen for landfill barriers should follow standard design guidelines. Prior to application, testing should be conducted to ascertain the materials' geotechnical properties and compliance with the design process [3]. Under waste collection sites, the soil utilised to build barriers like this should be geotechnically stable,

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appropriate for building foundations, and not prone to subsidence. If the locally available soil does not fulfill the minimal requirements to produce building liner materials, it must be improved [2], [4].

Numerous chemical stabilisation methods are commonly used to improve natural soil's engineering characteristics when combined with appropriate implementation techniques (compaction, soil-mixing, soil-chemical-mixing, etc.) [4]. Organic or inorganic binders, such as fly ash, lime, slags, alkaline activators, cement kiln dust, etc., can stabilise chemicals [5], [6]. Quicklime or hydrated lime, derived from lime, is a widely employed chemical additive for conventional stabilisation due to its cost-effectiveness and efficacy [3], [6]. Besides being adaptable and affordable, lime is a readily available compound [7], [8]. The field of geotechnical engineering practice and research has advanced significantly due to the body of knowledge that has been gathered on the stabilisation of clays using lime. It was demonstrated to be crucial in several applications utilising eco-friendly methods. Another economical approach is the reusability of lime-treated soil [6]. According to several studies, lime reduces clay's permeability and provides resistance against chemical assault by organic solutions—two essential components of waste containment systems [8], [9], [10].

One significant factor influencing the performance of such lime-stabilised clays is the pH level of the water with which they come into contact. This study explores the complex link between the UCS of lime-modified clay soils and water pH to determine how different pH levels affect the material's structural integrity. Understanding these dynamics is essential to improving waste containment system design and performance, leading to more robust and sustainable environmental management techniques.

2.0 METHODOLOGY

2.1 Materials

2.1.1 Soil sample

Clay soils extracted in a borrow pit along Gwagwalada Road, Abuja, in the northern part of Nigeria, were used as the soil specimen for this study. The borrow pit's coordinates are 8.950833°N and 7.076737°E. A disturbed soil sample was retrieved from a depth of one meter below the natural earth's surface to minimise the impact of organic material.

2.1.2 Lime

Many types and qualities of lime have been successfully used as soil-stabilising agents for many years. However, the most widely used and best-performing limes in soil stabilisation are the quicklime (CaO) and hydrated ($Ca(OH)_2$) lime. While both quick and hydrated limes can provide calcium ions (Ca^{2+}) in sufficient amounts, the primary ingredient necessary for stabilising clay soil, they differ slightly in the reaction mode in the presence of water. The lime utilised for the research was hydrated ($Ca(OH)_2$) sourced from the Gwagwalada market in Gwagwalada, Abuja.

2.1.3 pH water

The water pH was obtained at varying pH values of 4.0, 7.0, and 9. Sulphuric acid (H_2SO_4) with deionised water was mixed to obtain a pH value of 4.0. The neutral water was obtained using distilled water samples, which have a pH of 7.0, while the alkaline water was obtained by mixing sodium hydroxide (NaOH) and deionised water to get a pH value of 9.0.

2.1.4 Sample preparation

A sample of the soil of known mass was prepared by mixing it thoroughly with 0, 2, 4, 6 and 8% lime content; the mixture was mixed with water at different pH values corresponding to acidic-, neutral-, and alkaline water. These mixtures were compacted at BSL and BSH to determine their optimum moisture content and maximum dry density value. Samples were compacted at different moulding water content, i.e. at the wet side and dry side of optimum moisture, to determine their unconfined compressive strength values.

2.2 Methods

2.2.1 Atterberg limits

The water content at which the soil changes from one state to another is known as the consistency limit or Atterberg's limit. These limits are expressed as per cent water content. The Atterberg limit test involves ascertaining the liquid limits, plastic limits, and plasticity index for the untreated soil samples BS EN 1997-2 [11].

2.2.2 Compaction test

In compliance with BS EN 1997-2 [11], the test was conducted on modified and natural soil (that is, at different water pH levels), utilising both the British Standard Light and Heavy energy.

At each stage, three kilograms of soil and five per cent water were added to the mixture to compact the natural soil. The specimen was compacted inside a mould measuring 1,000 cm^3, using a 2.5 kg rammer falling from 300 mm height (i.e., British Standard Light, BSL energy) and a 4.5 kg rammer falling from

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a height of 450 mm (i.e., British Standard Heavy, BSH energy), in three separate layers, with each layer receiving 27 blows from the rammer.

The soil is weighed after the collar has been removed, and the soil in the mould is levelled to the top of the mould. Two representative samples were retrieved from the compacted sample for moisture content determination. The specimen was broken out of the mould, and five per cent more water was added. The process was repeated until at least five distinct sets of samples were obtained, and samples related to the moisture content were gathered. The compacted soil's bulk density in mg/m^3 was subsequently determined using:

$$\rho = \frac{m2-m1}{1000} \quad (1)$$

Where, ρ is bulk density; m_2 is mass of dry soil; m_1 is mass of wet soil.

The dry density was obtained from the equation below:

$$\rho d = 100\rho/(100 + w) \quad (2)$$

Where, W is the moisture content of each compacted layer; ρd is dry density; ρ is bulk density.

The maximum dry density (MDD), determined to be the highest point on the resulting curves, could be calculated by plotting the dry densities, obtained using Equation 2, against the associated moisture contents. Employing the dry density versus moisture content graph, one can determine the associated moisture content values at MDD and optimum moisture content (OMC).

2.2.3 Unconfined compressive strength

The soil sample was subjected to UCS tests using the BSL and BSH energy levels in accordance with BS EN 1997-2 [11]. In a 1,000 cm^3 mould, soil samples that were natural and modified (samples containing lime admixture) were compacted at different water pH levels and moisture contents in relation to OMC (i.e., OMC-2, OMC, OMC+2, and OMC+4 to simulate field conditions in waste containment application). After removing the samples from the mould, the cylinder's top was appropriately trimmed to create a cylinder that measured 38 mm in diameter and 76 mm in height. After being cured for 48 hours (2 days), the samples from the compaction mould were crushed using the machine. With Equation 3, the UCS was obtained.

$$\text{UCS } (\delta) = \text{PCr}\frac{(100\text{-}\ \varepsilon\%)\ \text{x}\ 10^3}{100\text{Ao}} \quad (3)$$

Where, ε is Strain sustained sequent to failure = x/L_0; x is Strain dial reading in mm; L_0 is Initial length of the tested sample (m); A_0 is Initial cross-sectional area of tested sample (m^2); P is Load Proven Ring reading sequent to failure (kN); Cr is Compressive Stress Factor; δ is Compressive stress at strain ε (kN/m^2).

3.0 RESULTS AND DISCUSSION

3.1 Characterisation Tests

3.1.1 Mineralogy of soil sample

The mineralogy of the soil sample and lime was carried out using XRD. Figure 1 shows the peaks and mineral composition of the soil sample, indicating the different minerals present in the soil sample and kaolinite clay being the most abundant in the soil sample.

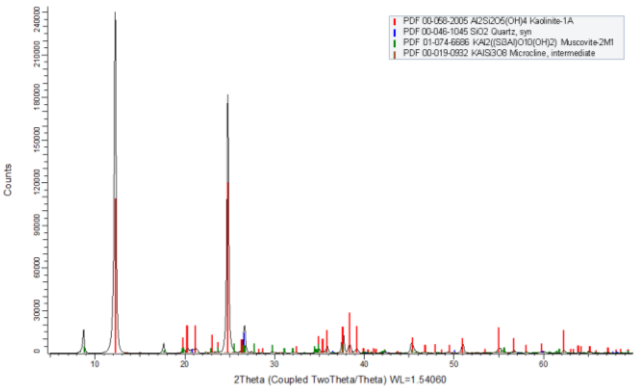

Figure 1: Mineralogical composition of the clay minerals

Table 1 shows the chemical oxide composition of the soil sample and lime. From Table 1, the principal chemical oxides observed for the clay sample include SiO_2, Fe_2O_3, Al_2O_3, CaO and Ti_2O. According to ASTM C618 [12], if the total sum of SiO_2, Al_2O_3 and Fe_2O_3 is above 50% of the total mass, then the matter can be considered a pozzolanic material. The clay sample can possess pozzolanic material since the summation is 70.82%. Meanwhile, the oxide composition of lime concentration shows that it contains 53.10% CaO, indicating that it possesses good cementitious properties, such as cement. Notably, the presence of the pozzolanic minerals (i.e., SiO_2, Fe_2O_3, and Al_2O_3) in the clay soil, along with the calcium oxide in the lime, would play an essential role in forming the cementitious matrix.

Table 1: Oxide composition of clay soil and lime

Oxide composition (%)	Clay	Lime
SiO_2	39.2	16.18
Al_2O_3	4.96	3.09
MgO	0.95	3.67
K_2O	1.03	-
CaO	3.86	53.1
Ti_2O	5.82	-
BaO	0.4	-
SrO	0.38	-
V_2O_5	0.15	-
Fe_2O_3	26.66	1.24

MnO	0.57	-
CuO	0.099	-
Cr_2O_3	0.02	-
Na_2O	1.17	-
ZnO	0.03	-
Loss on Ignition (LOI)	14.7	23.39

3.1.2 Atterberg limits of clay soil sample

In compliance with BS EN 1997-2 [11], the natural moisture content (NMC), liquid limit (LL), plastic limit (PL), plasticity index test (PI), and linear shrinkage (LS) tests obtained give a realistic range for the soil samples tested, especially clay soils to be used as liners, as shown in Table 2. The range of values obtained followed trends specified in [13] for clay liner soil samples.

Table 2: Atterberg limits test for soil sample

Sample	LL (%)	PL (%)	PI (%)	LS (%)	NMC (%)
Clay	48.0	31.1	16.9	13.6	11.3

3.2 Compaction Characterisation Test

3.2.1 Variation of lime content for MDD

Figures 2 and 3 illustrate the impact of the amount of lime content on the maximum dry density (MDD) of the clay soil sample at different water pH values, i.e., acidic, neutral, and alkaline for British Standard Heavy (BSH) and British Standard Light (BSL) compaction.

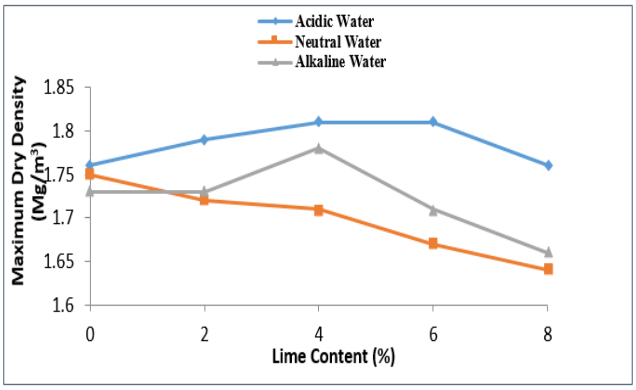

Figure 2: Variation of lime content at different water pH of MDD for BSL compaction effort

When the lime content was increased to 4% for BSL compaction, the MDD values rose to 1.81 and 1.78 mg/m^3. Then, a decrease was observed at 8% lime content of the MDD to 1.76 and 1.66 Mg/m^3 for acidic and alkaline water, respectively. Meanwhile, for neutral water, the MDD value reduces to 1.71 Mg/m^3 as the amount of lime in the water increases. This can be attributed to the low density of the lime, which makes up a significant portion of the soil sample matrix. Therefore, a decrease is evident. Compared to neutral water, the MDD values for acidic and alkaline waters are greater, indicating that the reaction between the lime, acidic and alkaline water raises the MDD value. This trend is similar to that described by [14]; the MDD values increased to their peaks before declining at higher admixture contents.

For samples compacted using BSH energy, the compaction (see Figure 3) indicates peak MDD values of 1.97 and 1.85 Mg/m^3 at 6% lime content using acidic and alkaline water. For neutral water, MDD was 1.92 Mg/m^3 at 8% lime content. Generally, there was a rising trend in MDD with increased lime content.

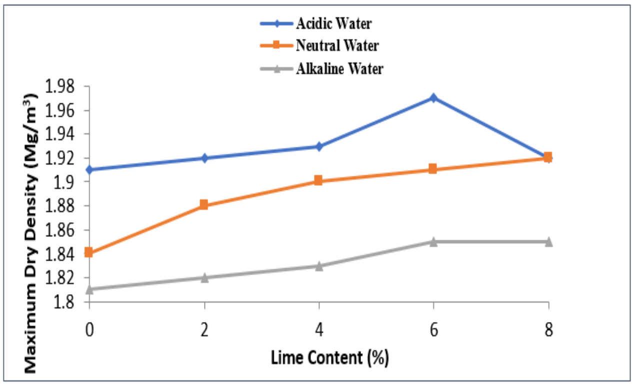

Figure 3: Variation of lime content at different water pH of MDD for BSH compaction effort

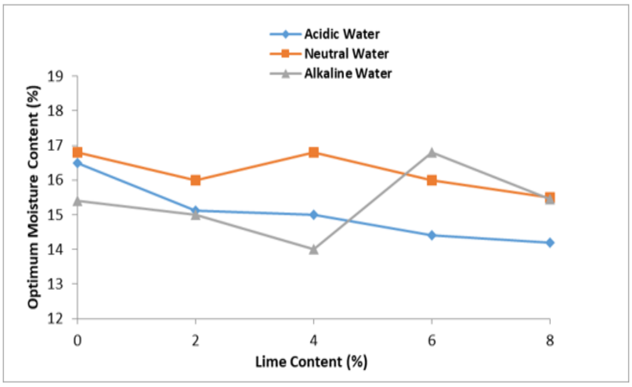

Figure 4: Variation of lime content at different water pH of OMC for BSL compaction effort

3.2.2 Variation of optimum moisture content

Figures 4 and 5 respectively, illustrate the impact of lime content on the OMC of the clay sample at different water pH values, i.e., acidic, neutral, and alkaline for BSL and BSH compaction. In neutral and acidic water, OMC typically decreases from 16.8% to 15.5% and 16.5% to 14.2% as the lime content increases from 0% to 8% for BSL. However, in alkaline water, it reduces to 14.0% at 4% lime content before an increase. For BSH compaction, OMC reduced as lime content increased for all water pH values, but only for neutral water that underwent lime treatment more significantly than 2%. The reason for the increase in neutral water beyond 2% is that the lime and neutral water underwent a chemical reaction that increased the amount of water needed for the hydration of the lime-clay soil (i.e., more water was required to dissociate Ca^{2+} with OH^- ions to supply more Ca^{2+} needed for the cation exchange reaction). This response was made possible by the increased pore space resulting from using BSH compaction energy.

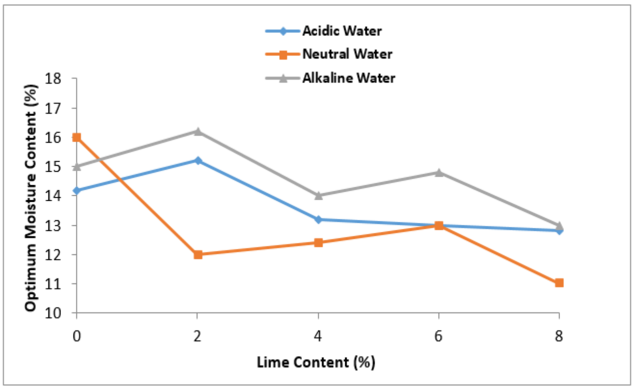

Figure 5: Variation of lime content at different water pH of OMC for BSH compaction effort

3.3 Unconfined Compressive Strength

Another essential consideration in constructing the liners in waste containment facilities is the durability of the compacted soil. For the construction of compacted clay liners, a minimum UCS of 200 kN/m^2 has been suggested [15].

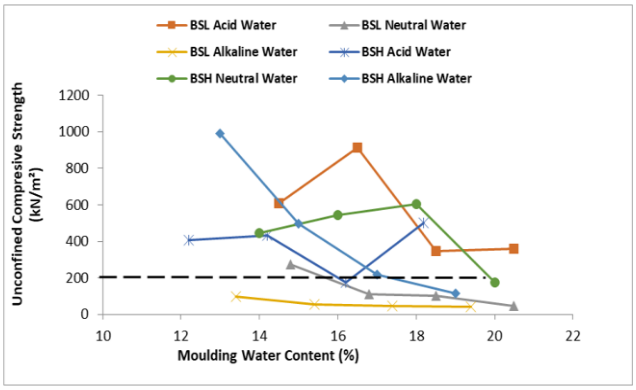

Figure 6: Variation of moulding water content at different water pH of UCS at compactive energy of 0% lime content

3.3.1 Effect of moulding water content

The UCS's variation with moulding water content for natural clay soil is displayed in Figure 6. The soil samples recorded an improved UCS as moulding water increased only for the natural soil compacted at BSH and for samples compacted at acidic water for both BSL and BSH. At the same time, the UCS value decreases with a rise in moulding water content for specimens compacted with alkaline water. The samples compacted using neutral and alkaline water at BSL do not meet the required minimum of 200 kN/m^2. The minimum necessary 200 kN/m^2 was satisfied by all soil samples prepared for the natural clay soil, with the moulding water content ranging from 14.1% to 20.8%, 12.1% to 18.1%, 14.0 to 20.0%, and 13.0% to 17.0% for BSL acid water, BSH acid water, BSH neutral water, and BSH alkaline water compactions, respectively.

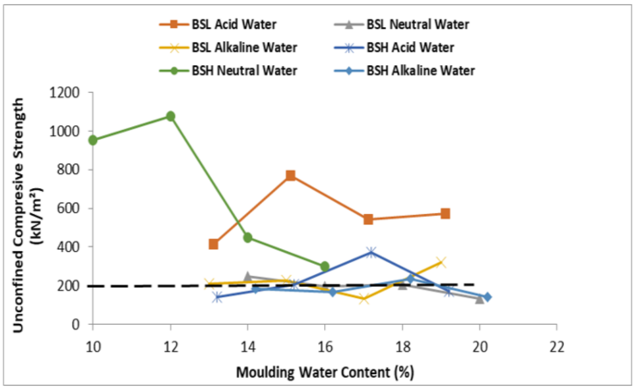

Figure 7: Variation of moulding water content at different water pH of UCS at compactive energy of 2% lime content

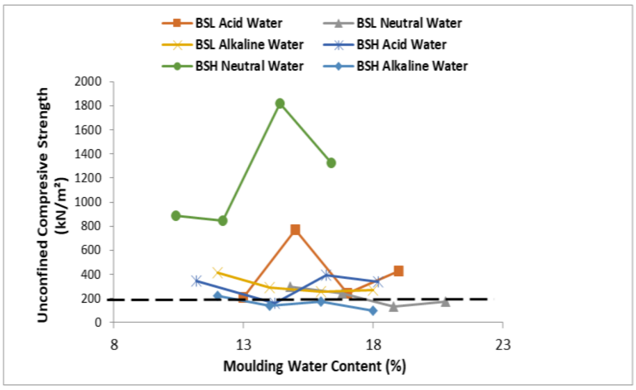

Figure 8: Variation of moulding water content at different water pH of UCS at compactive energy of 4% lime content

Figure 7 illustrates UCS for soil treated with 2% lime with the amount of moulding water content. Tested water pH samples show different UCS values for different moulding water content. UCS was 766.9 and 370.9 kN/m^2 for acidic water at 15.1 and 17.2 % moulding water content. In contrast, alkaline water UCS was 320.3 and 234.0 kN/m^2 at 19 and 18.2 % moulding water content for BSL and BSH, respectively. The samples that were compacted at BSL energy were the only ones that did not meet the minimum required strength of 200 kN/m^2. The highest UCS of 1078.6 kN/m^2 was observed at neutral pH water with 12% moulding water content compacted at BSH energy.

Figure 8 illustrates UCS values for soil treated with 4% lime change with moulding water content. The acidic water compacted with BSH effort showed an increase in UCS of 393.3 kN/m^2 at a moulding water content of 16.2% for the tested specimens. All compacted samples satisfied the minimum strength requirement of 200 kN/m^2 except those compacted with alkaline water for BSH compaction. The highest strength value was obtained at neutral water compacted at BSH energy.

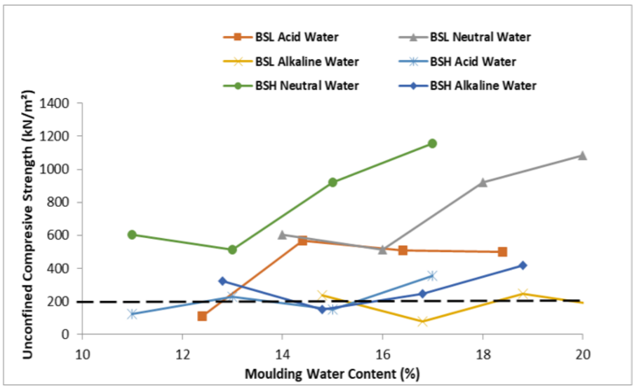

Figure 9: Variation of moulding water content with different water pH at compactive energy of 6% lime content

Figure 9 illustrates the UCS of different moulding water content in soil treated with 6% lime. Tested specimens' UCS increased as moulding water was added; this was observed in acidic and alkaline water compacted with BSH effort. Soil samples compacted met the 200 kN/m^2 minimum strength requirement, with the exception of samples that were compressed using alkaline water at BSL energy. Soil compacted with neutral water at BSH energy had the highest UCS value of 1155.1 kN/m^2 for a moulding water content of 17%.

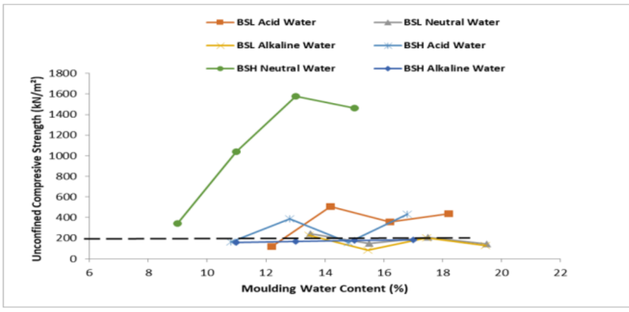

Figure 10: Variation of moulding water content at different water pH of UCS at 8% lime content

Figure 10 illustrates 8% lime-treated soil. The tested sample compacted with BSL and BSH met the 200 kN/m^2 minimum strength requirement, except for samples that were compressed using alkaline water at BSL energy. The highest UCS of 1576.7 kN/m^2 was obtained at neutral water compacted at BSH energy with the moulding water content of 13%.

Figures 6 – 10 shows that soil treated with lime increases significantly in UCS when soil samples are compacted at water slightly less than the OMC. This is explained by the fact that the soil-lime reaction needs a relatively high water content to sustain the chemical processes that are taking place. Additionally, the amount of water in the moulding impacts the strength gains of lime treatment; up to the OMC value, the UCS increases with increasing water content; after this point, the UCS declines. A similar observation was noted in [16].

3.3.2 Effect of lime content on UCS

The variation of UCS with lime content for specimens prepared at OMC-2, OMC, OMC+2 and OMC+4 treatments are shown in Figures 11-14. The general trend showed that UCS values decrease as the lime content and water pH increase. Peak UCS values of 600.00, 600.00, 400.00, 400.00, 997.00 and 1000.00 kN/m^2 were obtained at 0%, 6%, 4%, 0%, 2%, and 0% specimens prepared at -2% OMC and compacted with BSL acid, neutral, and alkaline waters and BSH acid, neutral, and alkaline waters energies respectively. Peak UCS values of 910.00, 550.00, 300.00, 450.00, 1100.00 and 500.00 kN/m^2 were obtained at 0%, 6%, 4%, 0%, 2%, and 0% for specimens prepared at 0% OMC and compacted with BSL acid water, neutral water, alkaline water and BSH acid water, neutral water, alkaline water compaction energies, respectively.

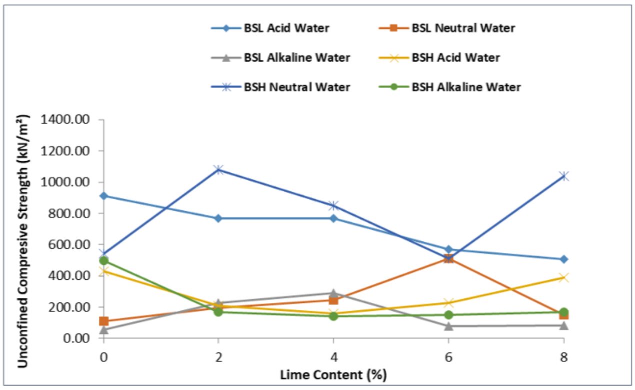

Figure 11: Variation of lime content at different water pH of UCS at compactive energy prepared at OMC

Peak UCS values of 590.00, 990.00, 300.00, 400.00, 1800.00 and 200.00 kN/m^2 were obtained at 2%, 6%, 4%, 4%, 4% and 2% for specimens prepared at +2% OMC and compacted with BSL acid water, neutral water, alkaline water and BSH acid water, neutral water, alkaline water energies, respectively. Peak

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UCS values of 590.00, 970.00, 290.00, 500.00, 1800.00 and 470.00 kN/m^2 were obtained at 2%, 6%, 4%, 0%, 8% and 6% for specimens prepared at +4% OMC and compacted with BSL acid water, neutral water, alkaline water and BSH acid water, neutral water, alkaline water energies, respectively.

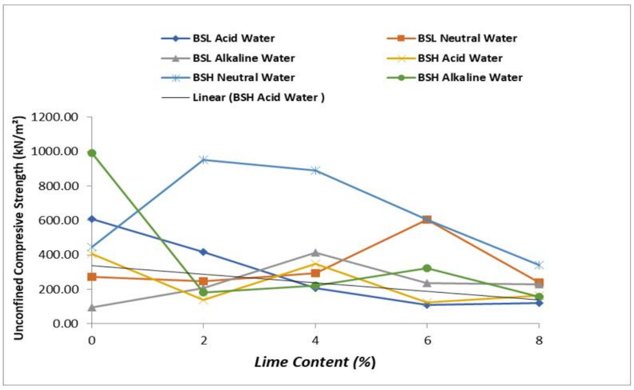

Figure 12: Variation of lime content at different water pH of UCS at compactive energy prepared at OMC -2

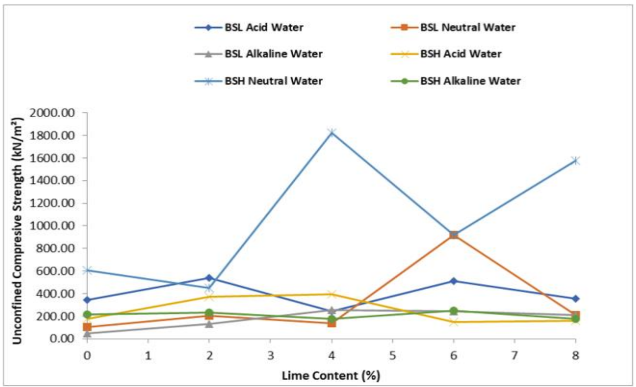

Figure 13: Variation of lime content at different water pH of UCS at compactive energy prepared at OMC +2

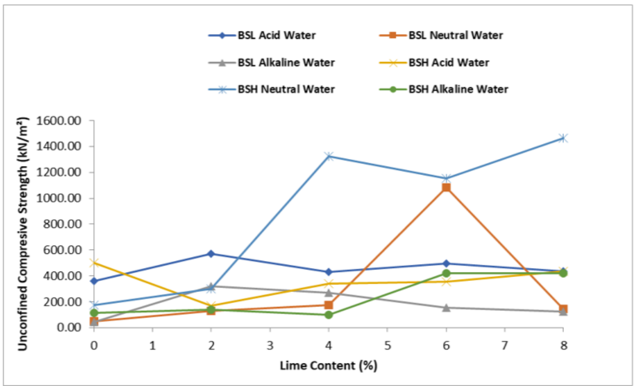

Figure 14: Variation of lime content at different water pH of UCS at compactive energy prepared at OMC +4

4.0 CONCLUSION

The importance of water pH on the unconfined compressive strength of lime-treated clay soil is an essential consideration in waste containment facility design and performance. Understanding the interactions between water pH and the soil strength of lime-treated clay soil can improve liner system design and construction. If the water pH is proactively managed, waste containment facilities can create sustainable and dependable containment solutions for hazardous wastes and pollutants.

The study focused on acidic, alkaline, and neutral pH water on compaction parameters, lime content variation, and the effect of different moulding water and lime content on the UCS of clay soil and the following conclusions were drawn:

An increase in lime content decreased the MDD of the lime-treated clay soil. This is due to lime content producing more flocculation in the soil structure. This occurred at BSL compaction energy of 4% lime content for acidic and alkaline water. For acidic water, BSH compaction energy, MDD rises with increasing lime content at 6% lime content.

However, the OMC reduces with an increase in lime content for both neutral water and acidic water but decreases for alkaline water at 4% lime content for BSL. Alkaline and acidic water decrease in OMC at 4% lime content, while neutral water decreases at 2% and increases after that for BSH. The increase observed can be attributed to additional water needed for pozzolanic reactions.

The UCS of untreated soil in acidic water reaches different strengths when compacted at -2, 0, +2 and +4% OMC but differs for neutral and alkaline waters. Reducing or adding the water content decreases the USC values and can be attributed to modification of clay soil structure, i.e. flocculation of soil particles when relatively dry and dispersion when wet. Also, the moulding water content affected the UCS of lime-treated soil. The variation observed in UCS for lime-treated soil can be attributed to cationic exchange, flocculation of soil particles and pozzolanic reactions. The strength improvement of clay soil can be based on cationic exchange, flocculation and dispersion of soil particles and pozzolanic reactions.

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