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EFFECT OF SOAKING ON THE UNCONFINED COMPRESSIVE STRENGTH LOSS OF METAKAOLIN STABILIZED LATERITIC SOIL

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ABSTRACT

Metakaolin (MK) holds promise for enhancing lateritic soil strength. The natural lateritic soil is initially classified as A4 fine silty material. MK, obtained through calcination at 700°C, is added to the soil in varying proportions (10% to 60% by dry soil weight). Unconfined compressive strength (UCS) tests are conducted under different conditions: samples conditioned for 7 days with 7 days of subsequent soaking, and unconditioned samples with a 14-day curing period. UCS exhibits improvement with rising MK content, peaking at 29.5%. Beyond this point, UCS starts to decline. For unconditioned samples, UCS increases from 224.93 kPa (10% MK) to 340 kPa (29.5% MK), and for conditioned samples, it ranges from 169.46 kPa to 270 kPa. The presence of MK results in an average 23% variation in UCS between unconditioned and conditioned samples. Regarding durability, the optimal MK content for the MK-lateritic soil combination lies within 20% to 35%, where the loss in strength remains at or below 20%. A Linear Regression Analysis establishes a predictive model for UCS at 14 days), with an R2 value of 0.926.

Keywords: Metakaolin, lateritic soil, soil stabilization, unconfined compressive strength, durability, mechanical properties, calcination, soil classification, Linear Regression Analysis.

1. INTRODUCTION

Soils are indispensable foundational materials in construction, serving as the bedrock upon which structures rest. Their ability to bear loads and exhibit requisite engineering properties, such as strength and minimal settlement, is paramount for the stability and durability of constructions like buildings and roads (Vincy and Muttharam, 2009). Lateritic soil, characterized by its cost-effectiveness, is a popular choice in road construction and other civil engineering projects.

However, some lateritic soils are inherently expansive, posing significant challenges when employed as foundational materials for superstructures. Traditional solutions involve costly soil replacement to eliminate these undesirable properties, exacerbating the economic and environmental burdens of construction projects. Contemporary practices seek to transform and strengthen existing weak soil materials, often through the incorporation of additives like lime, cement, calcium chloride, rice husk, or fly ash. While effective, these additives can be expensive and may not be economically feasible on a large scale.

In light of these challenges, this study explores an alternative approach by investigating the potential of metakaolin (MK) in soil stabilization processes. Metakaolin, a calcined clay produced from the heating of kaolin clay, has gained attention in recent years. The dwindling availability of fly ash in regions like the UK, as the coal-fired power industry declines, has spurred interest in alternative pozzolanic materials such as metakaolin (Jamal et al., 2018). Moreover, metakaolin has found extensive use in the construction industry, where it has been employed to replace cement in various capacities (Poon et al., 2006). Notably, its high initial reactivity in blended cement pastes surpasses that of both silica fume and fly ash, leading to accelerated compressive strength development.

Given its pozzolanic nature, this study aims to assess the potential of metakaolin in enhancing the properties of lateritic soil, with a specific focus on its impact on durability. By doing so, this research contributes to both the understanding of metakaolin-lateritic soil interactions and sustainable soil stabilization practices. Through this investigation, we aim to address the challenges posed by expansive soils, reduce reliance on traditional soil replacement, and mitigate the environmental impacts of construction while ensuring the longevity of structures.

1.1 Metakaolin

Metakaolin, derived from the thermal activation of kaolin clay, has emerged as a promising soil stabilization material. This research focuses exclusively on the utilization of metakaolin as a soil stabilizer, delving into its properties, advantages, and potential applications.

Soil stabilization holds paramount importance in civil engineering due to its direct influence on structural integrity, load-bearing capacity, and long-term durability. Inadequate soil conditions characterized by low shear strength and high compressibility can lead to structural failures and significant maintenance costs. Thus, the exploration of innovative soil stabilization methods becomes imperative.

Metakaolin, often recognized as $Al_2O_3 \cdot 2SiO_2$, is produced through the calcination of kaolin clay (Eq. 1). This process renders the clay highly reactive and capable of forming secondary calcium silicate hydrate (C-S-H) and other hydrates (Eq. 2) when mixed with soil. These reactions result in enhanced cohesion, improved load-bearing capacity, and increased durability of the stabilized soil.

Calcination process (Eq. 1):

Kaolin Clay → Metakaolin + CO_2

Formation of calcium silicate hydrate (Eq. 2):

$$SiO_2+2CaO+6H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O$$

Metakaolin presents several advantages as a soil stabilizer. Firstly, it significantly reduces the environmental footprint compared to traditional stabilizers like Portland cement. The production of metakaolin requires lower temperatures, resulting in reduced energy consumption and fewer associated carbon dioxide (CO_2) emissions. This makes metakaolin a sustainable choice for environmentally conscious engineering projects.

Furthermore, metakaolin exhibits rapid pozzolanic reactivity (Eq. 3), meaning it can quickly react with calcium hydroxide (CH) present in the soil, forming additional C-S-H gel. This reaction enhances the soil's strength and reduces permeability, making it ideal for stabilizing weak or expansive soils.

Pozzolanic reaction (Eq. 3):

Metakaolin+ CH + H_2O→ Additional C−S−H Gel

In summary, this study endeavors to evaluate the effect of metakaolin on the durability of lateritic soil, offering insights into a potentially cost-effective and environmentally friendly approach to soil enhancement. Through comprehensive testing and analysis, we seek to provide valuable information for engineers, construction practitioners, and researchers looking to optimize soil stabilization techniques in the pursuit of sustainable and durable infrastructure.

2. METHODOLOGY

2.1 Materials

Metakaolin and Lateritic Soil Preparation: Metakaolin was derived from white clay through a process involving drying and calcination at 700°C. Afterward, the Metakaolin was ground into a fine powder and subjected to sieve analysis using Sieve No 200 (75μm) to determine particle size distribution. The oxide composition of the Metakaolin was also analyzed.

Lateritic Soil Source and Preparation: Lateritic soil was sourced from a burrow pit along the East West Road. Samples were collected from a depth of 1 meter below the ground surface and stored in nylon bags to maintain moisture content. The collected soil samples were divided into two portions, one left unmodified and the other modified using Metakaolin. Both portions underwent oven-drying and were subjected to sieve analysis (using a 4.75mm sieve) to remove undesirable particles.

Water Source: Clean portable water with a pH value of approximately 6.9 was used for experimental purposes.

2.2 Methods

This section outlines the methods employed in the study.

Materials Characterization:

1. Oxide composition of Lateritic soil and Metakaolin was determined.
2. Specific gravity was measured using the density bottle/pycnometer method.
3. Atterberg limits (liquid limit, plastic limit) were determined.
4. Plasticity index was calculated based on liquid and plastic limits.
5. Particle size distribution of lateritic soil was analyzed through the hydrometer test.
6. Standard Proctor compaction test was conducted to assess compaction properties.

Experimental Procedures:

1. Unconfined Compressive Strength (UCS) testing was performed using the Proctor mold specimen. The strain rate during shearing was maintained at 1% per minute.
2. Durability assessment involved measuring the loss in strength of stabilized samples after 7 days of curing and 7 days of soaking in water.

Equations:

1. Specific gravity was calculated using the formula: Gs = (m2 - m1) / [(m4 - m1) - (m3 - m2)]
2. Liquid limit was determined by the number of blows (25) at a specific moisture content.
3. Plastic limit was found by rolling soil into a thread until it crumbled (approximately 3mm in diameter).
4. Plasticity Index (PI) was calculated as PI = LL - PL, where PI is Plastic Index, LL is Liquid Limit, and PL is Plastic Limit.
5. Bulk density (ƿ) was determined using the formula: ƿ = (M2 - M1) / Volume of the mold.
6. Dry density (ƿ_d) was calculated as ƿ_d = ƿ / (1 + w), where ƿ_d is dry density, ƿ is bulk density, and w is moisture content.
7. Unconfined Compressive Strength (σ1) was calculated as σ1 = F / A, where F is force and A is the cross-sectional area of the sample.
8. The resistance to loss in strength and loss in strength were deduced using the provided equations.

3. DISCUSSION

3.1 Presentation and Analysis of Results

These results encompass a range of tests, including preliminary material assessments and the main experimental tests. To ensure a comprehensive analysis, we employed suitable statistical tools, aligning our focus with the objectives.

3.2 Material Characterization Test Results Presentation and Analysis

Oxide Composition Test Results of Metakaolin and Lateritic Soil Presentation and Analysis

The oxide composition of Metakaolin (MK) produced through calcination at 700°C is detailed in Table 3.1. This table also highlights the percentage variations between MK's oxide composition and that of Dangote Portland cement, as extracted from Wokoma's study in 2018.

MK exhibits pozzolanic characteristics and possesses significant binding potential. This is attributed to the presence of calcium oxide and a notably high silica oxide content of 80.24%, with a corresponding value of 4.67% for calcium oxide. It is worth noting that MK meets the minimum requirement set by BS EN 197-1 (2009) for a substance to be considered pozzolanic, with a minimum silica content of 25%. Furthermore, the total acidic oxides (Al2O3 + SiO2 + Fe2O3) constitute 91.34%, aligning with the requirements specified in ASTM C618 (2017) for a Class N pozzolan.

For a comparative analysis between MK and cement, it is essential to acknowledge the considerable differences in their oxide compositions. The calcium oxide content, for instance, exhibits a substantial difference of 91.3% between MK and cement, with cement containing significantly higher calcium oxide. Conversely, MK showcases a greater percentage of silicon oxides, reflecting a 74.75% difference. These disparities in oxide composition could lead to varying outcomes when using MK and cement as soil modification materials, as the resulting properties are intricately linked to these compositions.

To affirm the lateritic nature of the soil used in this study, we present the oxide composition test results in Table 3.2. An essential metric for classifying lateritic soil is the silica-to-sesquioxide ratio, which we calculate as 1.42. This ratio falls within the range of 1.33 to 2.00, confirming the lateritic nature of the soil material (Akije, 2015). Akije (2015) defines a soil as lateritic if the silica-to-sesquioxide ratio falls within this specified range. Additionally, the soil exhibits minimal cementing properties, as indicated by the low calcium oxide value of 0.352.

Table 3. 1: Metakaolin oxide composition test results

S/No.	Property (Oxide)	Value (%) MK	Cement (Wokoma, 2018)	% Difference
1	CaO	4.67	53.69	91.3
2	Al_2O_3	3.54	4.96	28.63

3	Fe_2O_3	2.89	3.08	6.17
4	SiO_2	80.24	20.26	74.75
	$(Al_2O_3 + SiO_2 + Fe_2O_3)$	91.34		

Table 3. 2 Oxide Composition result of natural lateritic Soil

S/N	Property (Oxide)	Value (%)
1	CaO	0.352
2	SiO_2	40.80
3	Al_2O_3	24.30
4	Fe_2O_3	4.50
	$SiO2/(Al_2O_3+Fe_2O_3)$	1.42

3.3 Specific Gravity Analysis

Specific gravity measures substance density. Results in Table 3.3 and Table 3.4 show specific gravities of 2.66 for natural lateritic soil and 2.28 for MK. Fine-grained soils typically fall between 2.60-2.90, and the 2.66 value for lateritic soil confirms its fine-grained nature.

Table 3. 3 Specific Gravity Result of untreated lateritic soil

S/N	Test no Observations	1	2	3
1	Mass of density bottle alone(m_1)	27.65	27.55	27.50
2	Mass of density bottle + oven dry soil (m_2)	53.06	53.49	53.50
3	Mass of density bottle + oven dry soil + distilled water (m_3)	96.17	96.68	96.27
4	Mass of density bottle + distilled water (m_4)	80.36	80.36	80.17
5	m_3-m_2	43.11	43.19	42.77
6	m_4-m_1	52.71	52.81	52.67
7	$(m_4-m_1)-(m_3-m_2)$	9.60	9.62	9.9
8	m_2-m_1	25.41	25.94	26
9	Applying Equation (3.1), G_s	2.65	2.70	2.63

Table 3. 4 Specific Gravity Result of MK

S/N	Test no Observations	1	2	3
1	Mass of density bottle alone(m_1)	27.65	27.63	27.65
2	Mass of density bottle + dry MK (m_2)	43.24	43.28	43.35
3	Mass of density bottle + dry MK + distilled water (m_3)	89.94	90.29	90.99
4	Mass of density bottle + distilled water (m_4)	81.43	81.72	81.74
5	m_3-m_2	46.7	47.01	47.64
6	m_4-m_1	53.78	54.09	54.09
7	(m_4-m_1)-(m_3-m_2)	7.08	7.08	6.45
8	m_2-m_1	15.59	15.65	15.7
9	Applying Equation (3.1), G_s	2.202	2.210	2.434

Atterberg Limits for Natural Lateritic Soil

In this section, we present the Atterberg limits, including liquid limit, plastic limit, and plasticity index for the natural lateritic soil. Liquid limit is determined as the moisture content corresponding to 25 blows, resulting in a value of 20.4% (Figure 4.1). Plastic limit, signifying the boundary between plastic and semisolid states, is found to be 13.06%. The plasticity index, calculated using Equation (3.2), is 7.34%, indicating the presence of very fine expansive particles in the material.

Table 3. 5 Liquid Limit of natural Lateritic Soil

	Liquid Limit (%)		
Container No.	A	B	C
No. of Blows	31	25	11
Wet sample + Container (m_t+m_c)	208.00	213.00	207.00
Dry sample + Container (m_d+m_c)	182.00	184.00	178.00
Water (m_w= m_t- m_d)	26.00	29.00	29.00
Container, m_C	46.00	44.00	45.00
Dry soil, m_d	136.00	140.00	133.00
Moisture Content,w=(m_w/m_d)*100	19.12	20.71	21.80

Table 3. 6 Plastic Limit of natural Lateritic Soil

Container No.	A	B	C
Wet sample + Container (m_t+m_c)	70	71	69
Dry sample + Container (m_d+m_c)	67	68	66
Water (m_w= m_t- m_d)	3	3	3
Container, m_C	44	44	44
Dry soil, W_d	23	24	22
Moisture Content,w=(m_w/m_d)*100	13.04	12.50	13.64

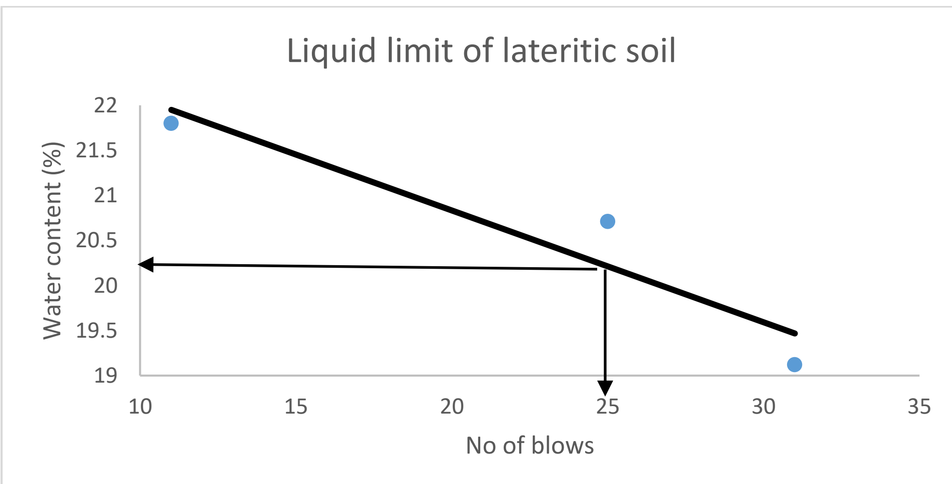

Figure 3.1: Liquid limit of natural lateritic soil

Hydrometer/Sedimentation test result of lateritic soil presentation and analysis

Table 3.7 presents the hydrometer test result of the natural lateritic soil which was used in producing the particle size distribution curve (Figure 3.2). The lateritic soil is basically composed of silty and very fine sand particles as depicted by Figure 3.2. The fine sand content of the soil constituent about 46% of the total soil mass, thereby representing the basic material of the lateritic soil. Silt content of the soil is about 6.2% with the medium coarse sand particles accounting for about 28% while coarse sand particles accounts for 19.8% of the total soil mass. This is an indication that the soil material is a silty- fine sand soil material.

Table 3.7: Hydrometer test result of natural lateritic soil

Sieve Sizes (mm)	Percentage Passing
2	95.1
1.18	84.9
0.6	50.6
0.3	18.3
0.212	10.3
0.15	4
0.063	1.7
0.0495	0.5

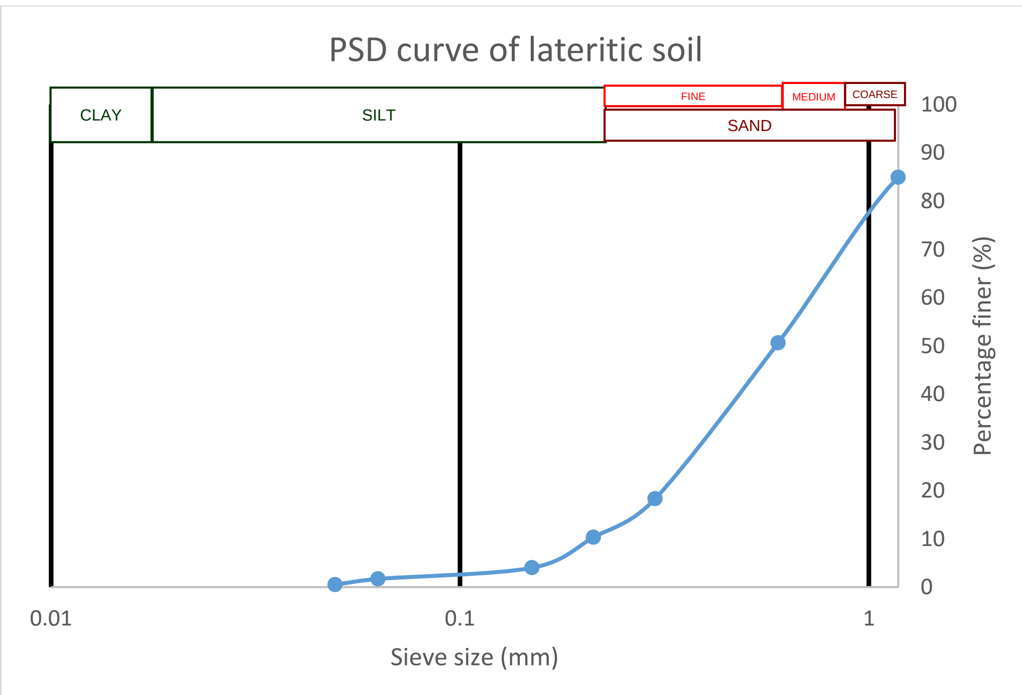

Figure 3. 1 Particle Size Distribution Curve of natural lateritic soil

Standard proctor compaction test result of natural lateritic presentation and analysis

Table 3.8 presents the summarized compaction test results of natural lateritic soil. Figure 3.3 presents a plot of the dry density against moisture content. The optimum moisture content (OMC) and maximum dry density (MDD) were obtained as 8% and 1.29g/cm^3 respectively.

Table 3. 7: Compaction test results of natural lateritic soil

Moisture content (%)	6.6	7.0	9.6	10.5
Dry density (g/cm^3)	1.26	1.28	1.26	1.22

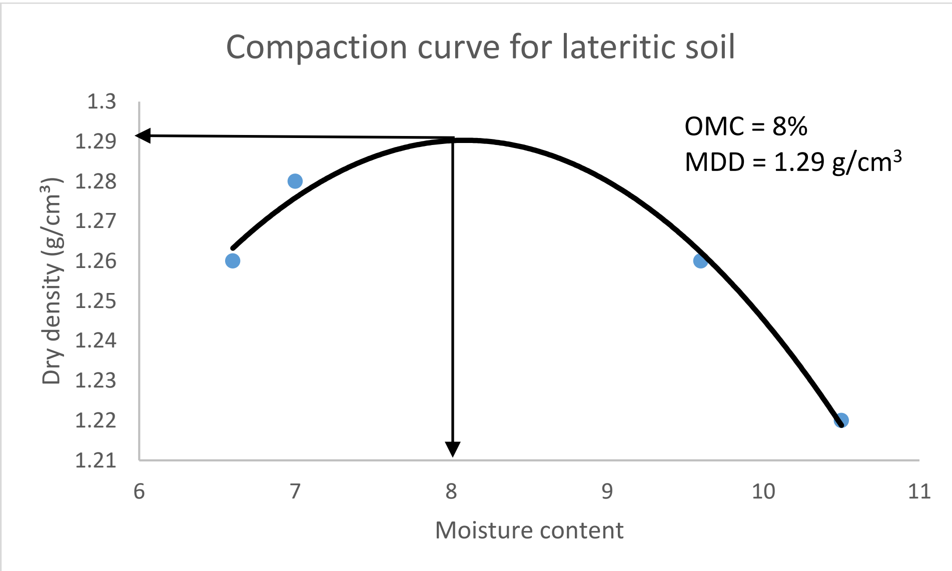

Figure 3. 2 Dry density Vs moisture content of natural lateritic soil

UCS Results and Durability Analysis for MK Stabilized Lateritic Soils

Table 3.9 presents the UCS of conditioned and unconditioned stabilized soil samples and durability results of MK stabilized lateritic soil in terms of loss in strength.

Table 3.8: Durability test result of MK Stabilized Lateritic Soil

N	**MK (%)**	**UCS in kPa (14 days curing)**	**UCS in kPa (7days curing & 7days soaking)**	**Res. to loss in strength (%)**	**Loss in strength (%)**
1	10	224.93	169.46	75.34	24.66
2	20	301.55	241.51	80.09	19.91
3	30	338.24	278.11	82.22	17.78
4	40	272.49	210.96	77.42	22.58

5	50	189.77	140.86	74.23	25.77
6	60	105.92	64.48	60.88	39.12

Effect of MK on Unconditioned and Conditioned MK-Lateritic Soil

We examine the impact of MK on unconditioned and conditioned MK-stabilized lateritic soil.

Unconditioned UCS results are presented in Table 3.9 and visually represented in Figure 3.4. The UCS of MK-stabilized lateritic soil increases with MK content up to approximately 29.5%. Beyond this level, UCS starts to decrease. For unconditioned samples, UCS rises from 224.93kPa at 10% MK content to 340kPa at 29.5% MK content. For conditioned samples, the increase is from 169.46kPa to 270kPa.

The increased UCS is attributed to MK's higher surface area, which fills voids and stiffens the mixture. The hydration process between MK and lateritic soil also contributes to strength enhancement. However, reduced strength beyond the optimum MK content is due to differences in density or specific gravity between MK and lateritic soil, with lateritic soil being denser.

Figure 3.4 shows that conditioning reduced UCS in MK-lateritic soil, resulting in an average difference of 54.59kPa, equivalent to approximately 23%.

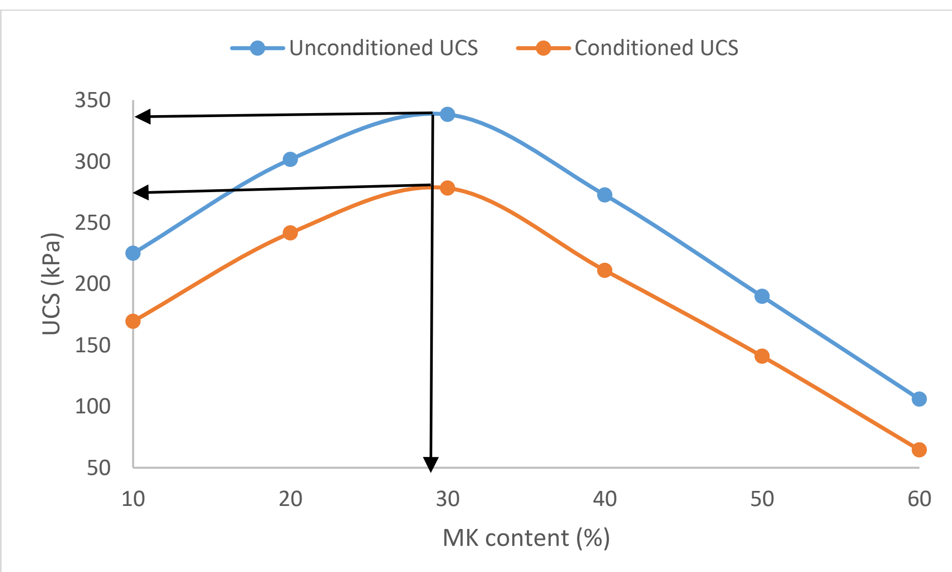

Figure 4. 3 UCS Vs MK content (Unconditioned and Conditioned MK-lateritic soil)

Analyzing the Effect of MK on the Durability of MK stabilized lateritic soil

In this analysis, the durability of the stabilized lateritic soil using MK is done in this section using the loss in strength term. Figure 3.5 presents the plot of loss in strength against MK content. It can be observed that loss in strength reduces from 24.66% at 10% MK content to 17.78% at 30% MK content. This shows that the optimum MK content lies very close to 30%. According to the standards and specifications, loss in strength value less than or equal to 20% is deemed satisfactory. From this, MK-lateritic soil combination is satisfactory when the MK content is between 20% and 35%. In this bracket, the loss in strength recorded for the MK-lateritic soil is 20% and below.

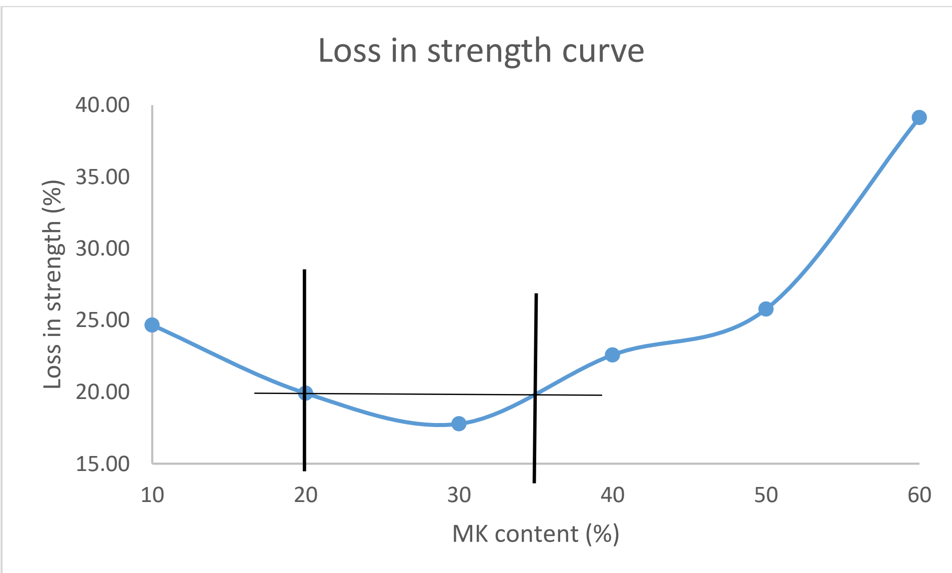

Figure 3.5: Loss in strength Vs MK content

3.2 Discussion of Research Findings

3.2.1 Materials' Characterization

Classification of Metakaolin

The metakaolin (MK) used in this study aligns with Class N pozzolan criteria as per ASTMC618 (2017). This classification is consistent with the work of Akinyele et al. (2017), who also identified 700°C as the optimum calcination temperature for MK. MK exhibits pozzolanic tendencies, supported by its high calcium oxide and silica oxide content (4.67% and 80.24%, respectively).

While MK shares some qualities with cement, there are notable differences in oxide composition, particularly in calcium oxide content.

Untreated Lateritic Soil Classification

The oxide composition of the sourced lateritic soil confirms its lateritic nature, with a silica-to-sesquioxide ratio of 1.42 (within the range of 1.33-2.00). Its low calcium oxide value (0.352) suggests limited natural cementing properties. Specific gravity analysis further confirms its suitability as lateritic soil, falling within the typical range (2.60-2.90). Atterberg limit analysis classifies the soil as an A4 soil, suitable for subgrade material in road construction. The particle size distribution reveals a silty-fines composition with fine sand and medium coarse sand particles.

Effect of MK on Unconditioned and Conditioned MK-Lateritic Soil

Analyzing the effect of MK on unconditioned and conditioned MK-lateritic soil, we observe that UCS increases with MK content up to 29.5%, beyond which it decreases. This increase can be attributed to MK's higher surface area and the hydration process between MK and lateritic soil. The reduction in strength beyond the optimum MK content is due to differences in densities between MK and lateritic soil. Conditioning results in reduced UCS, with an average difference of 54.59kPa, equivalent to approximately 23%.

Effect of MK on the Loss in Strength of MK-Lateritic Soil

In the durability assessment, we find that the loss in strength decreases from 24.66% at 10% MK content to 17.78% at 30% MK content, suggesting an optimum MK content close to 30%. A loss in strength value of 20% or below is deemed satisfactory. Therefore, the MK-lateritic soil combination is satisfactory when MK content ranges from 20% to 35%, with losses in strength meeting these criteria.

3.2.2 Regression Analysis Model

The regression analysis model for the dependent variable (UCS) in kPa for 14 days curing and independent variables (MK) in percentage was proven to have a good R square value.

$$y_i = \beta_0 + \beta_1 x_{i1} \ldots, \ i = 1, 2, \ldots, n \qquad (3.1)$$

where, y_i is the dependent variable unconfirmed compressive strength (UCS) in kPa, β_i is numerical constants and x_{i}` are the independent variable, metakaolin (MK) in percentage. In this model, regression analysis is applied to the metakaolin, MK (%) and unconfirmed compressive strength UCS (kPa) for 14 days curing. The resulting regression is as follows:

Table 3.9: Regression Analysis Model of Dependent Variable (UCS) and Independent Variables (MK)

For unconfined compressive strength:

	A	B	C	D	E	F	G	H	I
1	**SUMMARY OUTPUT**								
2									
3	***Regression Statistics***								
4	Multiple R	0.971053							
5	R Square	0.925535							
6	Adjusted R Square	0.896564							
7	Standard Error	0.52355							
8	Observations	6							
9									
10	**ANOVA**								
11		*df*	*SS*	*MS*	*F*	*gnificance F*			
12	Regression	1	14175.64142	14175.64	2.69516	0.175998			
13	Residual	4	21038.66131	5259.665					
14	Total	5	35214.30273						
15									
16		*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
17	Intercept	338.4307	67.51575088	5.012618	0.007424	150.9769	525.8844	150.9769	525.8844
18	MK	-2.84611	1.73364444	-1.64169	0.175998	-7.65948	1.967254	-7.65948	1.967254
19									
20	**UCS(@14 Days)= 338.4307 - 2.84611MK(%)**								

UCS(@14 Days)= 338.4307 - 2.84611MK(%) [$R^2 = 0.926$] (3.2)

The model for the unconfined compressive strength at 14 days and the R square value are shown in equation 4.2. The R square value is very satisfactory as it is close to unity.

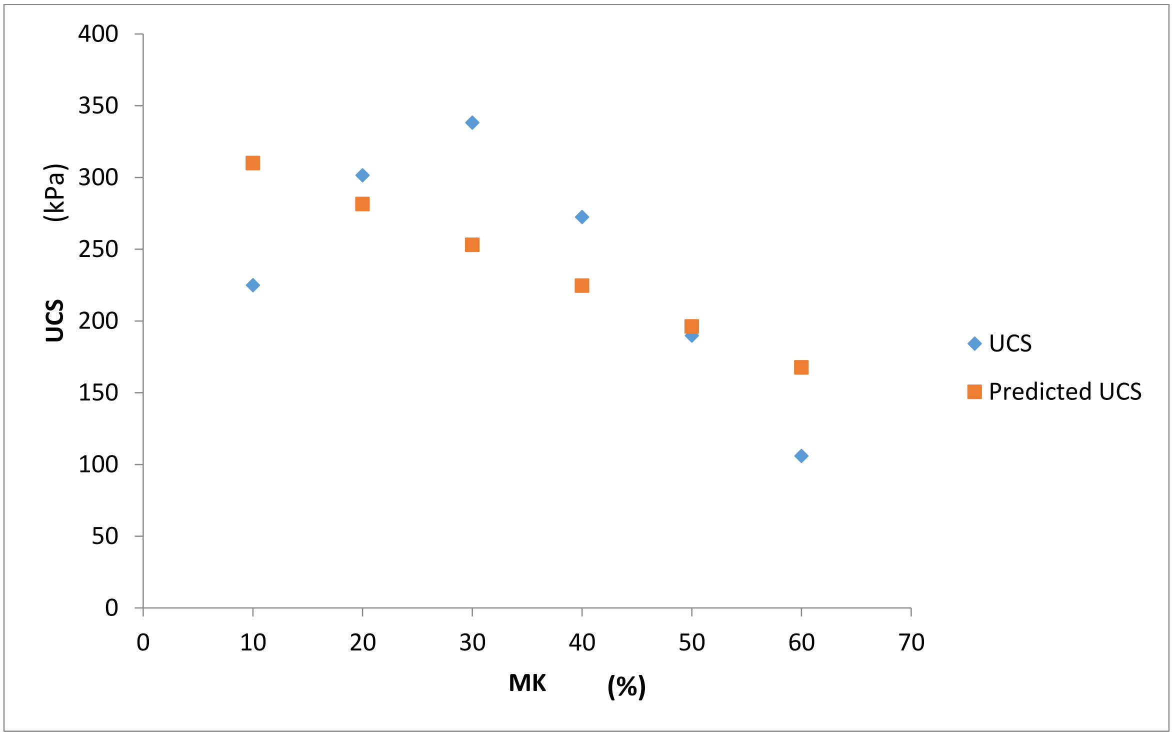

Figure 3.4: Unconfirmed Compressive Strength against Metakaolin (MK line fit Plot)

Figure 3.5 is a plot showing Unconfined Compressive Strength and the Predicted Unconfined Compressive Strength for different percentage of Metakaolin. Where UCS is the unconfined compressive strength in kPa, Predicted UCS is the predicted Unconfined Compressive Strength in kPa and MK is metakaolin in %.

4. CONCLUSION

Based on the research findings, "Effect of metakaolin on the durability of lateritic soil", it is therefore concluded:

According to the AASHTO method of classification, the lateritic soil is an A-4 fine - silty soil material which only just qualifies its usage as fair material to be used as a subgrade.

In investigating the effect of MK content on the conditioned and unconditioned stabilized samples, it can be observed that the UCS of MK stabilized lateritic soil increases as MK content increase to an optimum MK percentage of 29.5%. Beyond this MK percent content, the UCS was noticed to start decreasing. For the unconditioned samples, there is an increase in UCS from 224.93kPa at 10% MK content to 340kPa at 29.5% MK content whereas for the conditioned samples, the increase is from 169.46kPa to 270kPa.

Generally, an average difference in the UCS of unconditioned and conditioned samples of 54.59kPa was noticed due to MK presence in the stabilized lateritic soil, translating to percentage difference of 23%.

The loss in strength analysis for durability assessment, revealed that the MK-lateritic soil combination is satisfactory when the MK content is between 20% and 35%. In this bracket, the loss in strength recorded for the MK-lateritic soil is 20% and below.

The Linear Regression Analysis shows a linear regression model, for prediction the unconfined compressive strength at 14 days as UCS= 338.4307 - 2.84611MK(%), was proven to have a good fit with an R^2 value of 0.926.

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