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CURING EFFECTS OF LIGNIN AND TERRAZYME AS STABILIZERS IN PROBLEMATIC SOIL

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Graphical abstract

Abstract

A primary concern of lignin and terrazyme as soil stabilizers is the optimization of curing time, as there is considerable uncertainty in determining the ideal duration for different soil types and environmental conditions. There is limited understanding of the chemical interaction mechanisms between these stabilizers during the curing process, particularly when used in combination. The main aim of this study is to evaluate the effect of the number of curing days and the percentages of stabilizers. The laboratory tests, including compaction, Unconfined Compressive Strength (UCS), and California Bearing Ratio (CBR), were done for untreated and treated soils. According to the Unified Soil Classification System (USCS), both laterite and kaolin are high-plasticity clays. The moisture-density relationship from compaction shows insignificant changes after adding the stabilizers for all soils. From the UCS test results, laterite with 5% of terrazyme (LT5%) showed the highest improvement with 926 kPa at day 21. The highest CBR values came from LT5% samples, at 19.13% under unsoaked conditions and 16.27% for soaked conditions. Curing has been demonstrated to strongly influence the properties and performance of chemically stabilized soils. As additional analysis, two-factor analysis of variance (ANOVA) with replication was employed to investigate potential interactions between the number of curing days and the percentages of stabilizers. The interaction effects between terrazyme and laterite with p-value of 3.78E-08, indicates that their combined proportion and curing duration may determine terrazyme's effectiveness.

Keywords: Lignin, terrazyme, curing, soil stabilizer, problematic soils

Abstrak

Kebimbangan utama lignin dan terrazim sebagai penstabil tanah ialah masa pengawetan yang optimum, kerana terdapat ketidakpastian yang besar dalam menentukan tempoh yang ideal untuk jenis tanah dan keadaan persekitaran yang berbeza. Terdapat pemahaman yang terhad tentang mekanisme interaksi kimia antara penstabil ini semasa proses pengawetan, terutamanya apabila digunakan dalam kombinasi. Matlamat utama kajian ini adalah untuk menilai kesan bilangan hari pengawetan dan peratusan penstabil. Ujian makmal, termasuk pemadatan, Kekuatan

Mampatan Tidak Terkurung (UCS), dan Nisbah Galas California (CBR), telah dilakukan untuk tanah yang tidak dirawat dan dirawat. Menurut Sistem Klasifikasi Tanah Bersepadu (USCS), kedua-dua laterit dan kaolin adalah tanah liat berkeplastikan tinggi. Hubungan ketumpatan lembapan daripada pemadatan menunjukkan perubahan yang tidak ketara selepas menambah penstabil untuk semua tanah. Daripada keputusan ujian UCS, laterit dengan 5% terrazim (LT5%) menunjukkan peningkatan tertinggi dengan 926 kPa pada hari ke-21. Nilai CBR tertinggi datang daripada sampel LT5%, pada 19.13% dalam keadaan tidak direndam dan 16.27% untuk keadaan direndam. Pengawetan telah menunjukkan sifat dan prestasi tanah yang distabilkan dipengaruhi secara kimia. Sebagai analisis tambahan, analisis dua faktor varians (ANOVA) dengan replikasi digunakan untuk menyiasat potensi interaksi antara bilangan hari pengawetan dan peratusan penstabil. Kesan interaksi antara terrazim dan laterit dengan nilai p 3.78E-08, menunjukkan bahawa gabungan perkadaran dan tempoh pengawetan mereka boleh menentukan keberkesanan terrazim.

Kata kunci: Lignin, terrazim, pengawetan, penstabil tanah, tanah bermasalah

1.0 INTRODUCTION

Problematic soils such as clays and heavily weathered residual soils pose challenges in construction due to poor engineering qualities like excessive compressibility, strength loss, and susceptibility to shrink-swell processes [1]. Various soil stabilization methods, including fly ash, cement, and lime, are employed based on factors like particle size distribution, soil type, water content, fines content, organic matter, and swelling potential [2]. However, overuse of conventional stabilizers like fly ash, cement, and lime can have adverse environmental impacts [3][4].

Lignin, a paper industry by-product, has shown promise in stabilizing soil, increasing California Bearing Ratio (CBR) values, and enhancing soil cohesion and stiffness without affecting asphalt mixtures [5], [6], [7], [8], [9], [10]. Enzymes like terrazyme, derived from fruit and vegetable extracts, act as organic catalysts, improving soil stabilization by dissolving clay lattice, preventing water absorption, and increasing soil strength [11], [12], [13].

Research on lignin and terrazyme for soil stabilization lacks comparative information across different soil types. Studies [12], [13] have evaluated the impact of lignin and terrazyme on maximum dry density (MDD) and strength properties of laterite with high clay, kaolin, and peat soils. Understanding the mechanical behaviour of soils is essential for constructing dependable and resilient infrastructure in the field of geotechnical engineering. The dry density and strength of soils are crucial parameters used in any construction. Besides, the chemical interaction mechanisms between these stabilizers during curing remain poorly understood, especially in combined applications, limiting the ability to predict and optimize their performance. The laboratory tests results were compared between 2% and 5% of lignin and terrazyme when added into laterite with high clay, manufactured kaolin and peat soil. The physical characterization and the chemical composition of soil samples were analysed.

In addition, the behaviour of the treated soil was observed at curing day of 0, 7, 15, 21, and 30. Moisture effects on cured UCS samples were also recorded. To date, no statistical analysis has been conducted to determine the interaction between curing duration and stabilizer percentage. The purpose of this study is to evaluate the effect of the number of curing days and the percentages of stabilizers. The significance of this study centers on several crucial aspects that contribute to both theoretical understanding and practical applications in soil stabilization. The investigation of soil behavior across multiple curing periods provides essential insights into evolution of soil stabilization, enabling engineers to make informed decisions about construction scheduling and load application timing.

2.0 METHODOLOGY

Three soil samples used were laterite soil, kaolin and peat. The laterite soil is a local residual red-brownish soil, while the peat is black colour organic soils. The soils were obtained from field sites via excavation. The laterite soil was sourced from Bukit Banang (1.8140541°N,102.9199953°E) and the peat from Kampung Parit Nipah (1.869801°N, 103.129933°E), both located in the Batu Pahat district of Johor, Malaysia. The kaolin was an industrial product. The kaolin was used to represent clay soil which is a problematic soil. Both lignin and terrazyme were obtained commercially in liquid form and been used as stabilizer in this study. The percent composition of elemental constituents for both stabilizers is delineated in Table 1. Lignin and terrazyme were each added at percentages of 2% and 5% of the dry weight of the soil as given in Table 2.

Table 1 Chemical composition of lignin and terrazyme

Element	Composition (%)	
	Lignin	Terrazyme
Ca	0.027	1.317
CH_2	99.000	-
K	0.014	0.479
Mn	0.001	-
Na	0.264	0.260
P	0.041	0.094
S	0.670	0.055
Al	-	0.019
Cl	-	2.642
Cu	-	0.005
Fe	-	0.004
H2O	-	95.10

Table 2 Soil-stabilizer used in this study

Soil type	Stabilizer	Notation
Laterite	Untreated	LU
	2% of lignin	LL2%
	5% of lignin	LL5%
	2% of terrazyme	LT2%
	5% of terrazyme	LT5%
Kaolin	Untreated	KU
	2% of lignin	KL2%
	5% of lignin	KL5%
	2% of terrazyme	KT2%
	5% of terrazyme	KT5%
Peat	Untreated	PU
	2% of lignin	PL2%
	5% of lignin	PL5%
	2% of terrazyme	PT2%
	5% of terrazyme	PT5%

Physical and Chemical Properties of the Soil

The physical properties including particle size distribution, Atterberg limit test and specific gravity, loss on ignition and pH value of the soil samples were determined following standard test methods British Standard [14], [15], [16]. Chemical analysis of the samples was conducted using an X-Ray Fluorescence (XRF) spectrometer called PANalytical Axios Max. This instrument uses high-energy X-rays to identify and quantify soil sample elements based on emitted fluorescence X-rays' wavelengths and intensities.

Standard Proctor Compaction Test

The procedure outlined in [17] was followed for Proctor compaction testing on laterite and kaolin soils. This involved oven-drying the soils and gradually moistening high-moisture peat soil. Stabilizers like lignin and terrazyme were mixed into soils at specific concentrations using a putty knife and high-speed rotary mixer. Stabilized soils were wet-cured for over 24 hours before compaction. Peat soil underwent gradual air-drying to prevent permanent drying effects. Compaction testing adjusted soil moisture levels to reach optimal conditions for each soil type.

UCS Test

Soil samples prepared for unconfined compressive strength (UCS) testing underwent compaction using described techniques. Steel tubes were inserted into the soil and covered with plastic and aluminium foil. Samples were cured for 0-30 days in a controlled environment. UCS was measured after each curing period using a Loadtrac II apparatus to assess the stabilizing treatment's impact on strength and durability.

CBR Test

The CBR test determines the strength and bearing capacity of compacted soils, especially for road construction applications. Following the standards outlined in [17], the test employs molds to contain specimens compacted using modified Proctor techniques. A piston penetrates the specimen at a rate of 1.27 mm/min, measuring the forces required to achieve depths of 2.54 mm and 5.08 mm. Immersion of soaked samples in water for an extended period determines the worst-case load-bearing capability of the material. Adequate sample preparation techniques for molding and compaction are essential to ensure the test's accuracy and reproducibility.

Sample Curing Method

Air curing was employed to accelerate and control the curing of stabilized soil samples at 30°C ± 2°C for 7-30 days [18]. According to [19] in-situ soil temperatures generally range from 25°C to 32°C near the surface, with less variation at greater depths. Samples were sealed in plastic bags with plastic and aluminium foil to regulate humidity and prevent overheating (not exceeding 49°C). By adjusting the temperature and humidity during curing, the strength development, durability and overall performance of stabilized soils can be enhanced. The focus herein was to accelerate curing and conditioning through moisture regulation. As such, the influences of temperature, time and moisture content will be examined. The sample undergo curing process will be tested for UCS test.

3.0 RESULTS AND DISCUSSION

Physical and Chemical Composition of the Soil Samples

The physical characteristics and chemical composition of the soils are provided in Table 3 and

Table 4. According to the classification by the American Association of State Highway and Transportation Officials (AASHTO), soils with high plasticity clay (CH) and peat are categorized as Pt, designated as A-7 and A-8. This classification is referenced in the research. High plasticity clays, including laterite, kaolin, and peat (Pt), are among the soils studied. The predominant chemical compositions identified are silica dioxide and ferric oxide, indicating the prevalence of clay particles. Silicon dioxide is commonly found in rocks and soil, primarily in the form of quartz.

Table 3 Basic properties of the soils

Properties	Laterite	Kaolin	Peat
Gravel (%)	6.69	-	-
Sand (%)	32.51	-	-
Fine content (%)	60.80	100.00	-
D10 (mm)	0.0019	0.0014	-
D30 (mm)	0.008	0.0040	-
D60 (mm)	0.1	0.0086	-
Cu	52.63	6.14	-
Cc	0.337	1.33	-
Liquid Limit, LL (%)	54.00	71.00	162.50
Plastic Limit,PL (%)	23.10	37.43	-
Plastic Index, PI (%)	30.90	33.57	-
Gs	2.79	2.5	1.51
USCS	CH	CH	Pt
ASSHTO	A-7-6	A-7-5	A-8
pH	5.95	5.54	3.76
Loss on ignition, LOI (%)	21.83	14.22	92.70

Table 4 Chemical composition of laterite, kaolin and peat

Element	Composition, %		
	Laterite	Kaolin	Peat
CO_2	0.10	0.10	0.10
Fe_2O_3	7.29	1.60	29.80
SiO_2	51.60	53.50	29.60
Al_2O_3	38.90	41.20	11.00
CaO	0.32		9.35
SO_3	0.31		6.10
PbO			4.74
ZnO			3.37
K_2O	0.31	2.26	1.47
Cl			0.92
CuO			0.87
TiO_2	0.98	0.61	0.86
P_2O_5			0.69
MgO		0.29	0.67
Br			0.28
SrO			0.13
Total	99.81	99.56	99.95

Moisture-density Relationship of Soil at Different Percentage of Stabilizer

The change in compaction properties depends on the type and the total amount of the stabilizer. Figure 1 shows the dry density versus optimum moisture content (OMC) of the untreated and treated soil samples. The LT5% led to a slight 0.095% increase in MDD coupled with a 4.8% reduction in OMC. Similarly, LL5% increased MDD by a small 0.064% while reducing OMC by 3.8%. Research shows that adding LT5% and LL5% stabilizers decrease OMC and slightly increases the moisture-density relationship, aligning with improved soil particle interactions [20]. Rimbarngaye *et al*. [21] observed decreased MDD with 10% terrazyme, while Kong *et al*. [22] found no significant change with 3% and 6% lignin. Bara and Tiwary [23] noted increased moisture-density relationships due to compaction efficiency and soil parameter variations. Current stabilizers may not induce significant changes in dry density, as suggested by [24] and [25]. Further research is needed using higher enzyme concentrations, longer curing periods, and increased energy levels to fully comprehend potential improvements in moisture-density relationships.

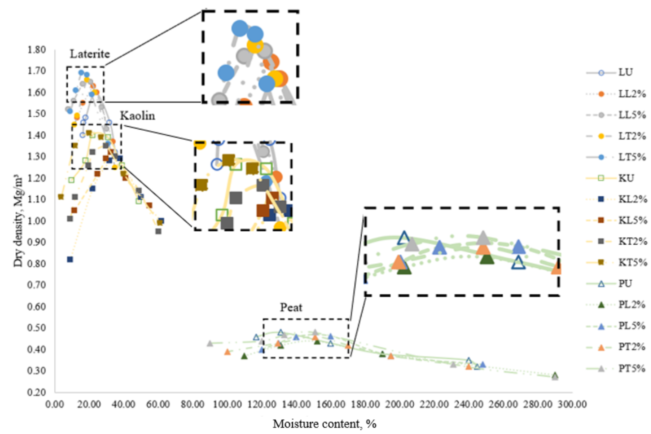

Figure 1 Moisture- density relationships for laterite, kaolin and peat

Stan and Ciobanu [26] stated that treated kaolin (87.67% clay) showed no significant changes in MDD and OMC when treated with lignin and terrazyme. Simmons [27] suggests that enzyme effectiveness could be compromised outside the optimal 12% to 30% concentration range for kaolin stabilization. Declines in MDD and OMC in lignin-treated samples may indicate soil flocculation due to moisture constraints. Enzyme activity in high-clay kaolin may require soils with a moderate fine concentration (18–30%) [28].

Addition of PL2% and PT2% led to a 8.71% and 4.56% decrease in MDD respectively, while PL5% caused a 2.45% drop compared to untreated samples. Incorporating 5% terrazyme into peat soil resulted in a 0.2% MDD reduction. However, neither stabilizer significantly impacted MDD across all soil samples. Nevertheless, OMC increased up to 16.2% for all treated sample with the highest increased is observed at PL2%. This suggests the stabilizer absorbs considerable moisture, modifying soil particle hydrophobicity and requiring more water to attain the desired MDD of the compacted soil.

Soil Strength of Control and Treated Samples

Figure 2 illustrates that after 30 days of curing, the strength of control samples of laterite and kaolin remains consistent. In contrast, peat shows increased strength at day 15, which peaks at day 21 before declining by day 30. Stabilizer-free control samples exhibit minimal strength changes. Peat's high organic matter content facilitates biotic interactions and matrix formation, enhancing strength initially. Reduced microbial activity and nutrient availability after 21 days lead to structural breakdown, resulting in decreased strength by day 30 [29].

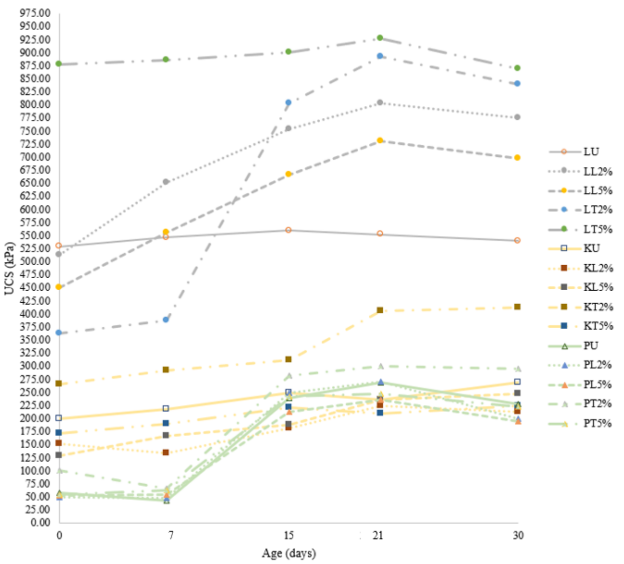

Figure 2 UCS value based on number of curing days

LT5% shows highest UCS values amongst the other. For LT2%, the UCS value rises sharply after day-15. Increased in terrazyme gives unbalance electric charge of the water molecule [30]. According to [30], the effect of the enzyme formulation in reducing the electric charge of the water molecule, there is sufficient negative charge to exert adequate pressure on the positively charged metal ions in the absorbed water film. So, when positive charged metal ions more than negative charge metal ions, the existing electrostatic potential barrier is broken. Thus, the film of absorbed water enveloping the particles is reduced.

Terrazyme reduces electrostatic potential barriers and clay particle swelling, potentially enhancing soil strength, although higher concentrations may diminish effectiveness [31], [32]. It significantly boosts soil strength by up to 12 times after 28 days by altering clay material properties [33]. Lignin addition at KL2% and KL5% concentrations minimally affect kaolin soil strength, consistent with previous findings [34]. In peat soils, all treatments show similar behavior except PT2% on day 0, indicating terrazyme's potential to generate cementitious materials and enhance strength. However, overall, both lignin and terrazyme are less effective in stabilizing peat due to its unconsolidated nature and lack of binding components.

Moisture Effects on Cured UCS Samples

In stabilized soil, moisture content is pivotal for compaction and hydration. Variations occur with stabilizer addition and curing, positive values indicating increase, negatives decrease as shown in Table 5. Notably, on day 21, LT2% shows a 9.61% decrease and LT5% no loss by day 15. This is attributed to early strength and cementation, aided by terrazyme's soil reactions promotion. Conversely, KU had a 13.69% loss by day 30 due to easier evaporation in untreated soil pores. Kaolin's plasticity makes it prone to shrinkage fractures from moisture loss, releasing more moisture via capillary action [35].

Peat soil, rich in organic matter, retains moisture but may hydrate slowly, impacting strength. Peat contains hydrophilic components and humic acids binding water. Lignin and terrazyme enhance moisture absorption by breaking down organic matter and exposing hydrophilic sites. High-moisture soils dilute water-soluble stabilizers, reducing their efficiency. Curing conditions significantly influence moisture loss and stabilization efficiency [36][37].

Unsoaked and Soaked CBR Test

Figure 3 presents trends in CBR values for soil samples treated with different substances. LT5% treated soils exhibited the highest CBR value of 19.13% under unsoaked conditions. Other treatments, LL2%, LT2%, LL5% also showed increased CBR values of 16.73%, 18.81%, 17.49% respectively. Terrazyme, in combination with silicates and iron oxides, forms cementitious gel products that enhance particle bonding, unlike lignin which lacks similar effects. Lignin-treated soil showed reduced benefits after soaking compared to untreated soil, indicating reduced mechanical effects. Kong *et al*. observed a significant increase in CBR values over time for 3% lignin-treated soil, suggesting improved stability with age [22].

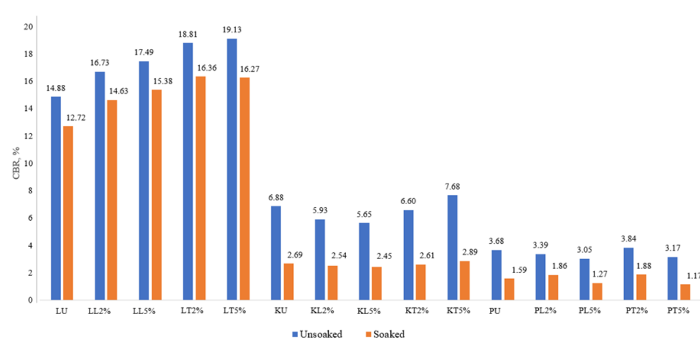

Figure 3 Overall CBR value for unsoaked and soaked condition

Table 5 Percentage of moisture loss after curing from day-0

Days	0	7	Percent change, %	15	Percent change, %	21	Percent change, %	30	Percent change, %
LU	17.45	17.64	+1.09	17.61	+0.89	16.16	-7.39	16.08	-7.85
LL2%	19.32	19.07	-1.29	19.01	-1.60	18.96	-1.86	18.18	-5.90
LL5%	17.93	17.16	-4.29	16.93	-5.58	17.39	-4.29	16.47	-8.14
LT2%	19.04	17.56	-7.77	17.23	-9.51	17.21	-9.61	17.40	-8.61
LT5%	16.86	16.48	-2.25	16.86	0.00	16.63	-1.36	16.47	-2.31
KU	27.46	27.64	+0.66	26.38	-3.93	25.45	-7.32	23.70	-13.69
KL2%	34.43	33.77	-1.92	33.45	-2.85	33.17	-3.66	31.91	-7.32
KL5%	29.08	26.65	-8.36	28.34	-2.54	28.14	-3.23	28.08	-3.44
KT2%	21.31	21.14	-0.80	21.25	-0.28	21.84	+2.49	19.82	-6.99
KT5%	20.77	20.86	0.43	20.63	-0.67	20.03	-3.56	19.56	-5.83
PU	135.97	133.40	-1.89	130.51	-4.02	130.30	-4.17	127.43	-6.28
PL2%	157.56	154.57	-1.90	150.05	-4.77	148.29	-5.88	147.15	-6.61
PL5%	155.55	153.76	-1.15	152.42	-2.01	148.56	-4.49	147.15	-5.40
PT2%	158.04	158.28	+0.15	155.47	-1.63	149.40	-5.47	146.47	-7.32
PT5%	157.66	153.42	-2.69	152.05	-3.56	149.51	-5.17	142.76	-9.45

The study found that while KL5% showed significant improvements, CBR values for KT2%, KL2%, and KL5% decreased. This suggests that grain size influences CBR performance, explaining why lignin and terrazyme additions to kaolin only marginally enhanced performance [38]. Peat samples' CBR values did not increase with stabilizers due to cohesive nature; effective chemical stabilization requires proper curing. CBR is crucial for measuring soil strength under controlled conditions.

Interaction of Soil - Stabilizers with number of curing days on UCS

A two-factor analysis of variance (ANOVA) with replication was employed to investigate potential interactions between the number of curing days and the percentages of stabilizers utilized as shown in Table 6. The columns represent the curing days, while the samples indicate the various percentages of stabilizers.

Table 6 ANNOVA for soil samples and number of curing days

Source of Variation	SS	df	MS	F	P-value	F crit
Sample						
a)	46807.5	1	46807.5	19.95495	0.000236	4.351244
b)	414175.8	1	414175.8	130.5491	3.22E-10	4.351244
c)	1234.438	1	1234.438	0.755093	0.395177	4.351244
d)	134607	1	134607	306.4016	1.35E-13	4.351244
e)	1225.219	1	1225.219	3.197293	0.088922	4.351244
f)	13856.75	1	13856.75	17.62196	0.000443	4.351244
Columns						
a)	329122.3	4	82280.57	35.07781	8.91E-09	2.866081
b)	440627.9	4	110157	34.72171	9.73E-09	2.866081
c)	43310.36	4	10827.59	6.623124	0.001454	2.866081
d)	43626	4	10906.5	24.82611	1.63E-07	2.866081
e)	230610.2	4	57652.56	150.4483	1.27E-14	2.866081
f)	271817.2	4	67954.31	86.41912	2.5E-12	2.866081
Interaction						
a)	977.13	4	244.2825	0.104142	0.979741	2.866081
b)	375766.9	4	93941.73	29.61063	3.78E-08	2.866081
c)	3111.104	4	777.776	0.475758	0.753062	2.866081
d)	17045.54	4	4261.385	9.700051	0.000157	2.866081
e)	2676.194	4	669.0485	1.745928	0.179535	2.866081
f)	3885.437	4	971.3593	1.235301	0.327724	2.866081

Source of Variation	SS	df	MS	F	P-value	F crit
Within						
a)	46913.18	20	2345.659			
b)	63451.34	20	3172.567			
c)	32696.32	20	1634.816			
d)	8786.314	20	439.3157			
e)	7664.101	20	383.205			
f)	15726.68	20	786.3342			
Total						
a)	423820.1	29				
b)	1294022	29				
c)	80352.22	29				
d)	204064.9	29				
e)	242175.8	29				
f)	305286.1	29				

Note: a) LL2% & LL5%, b) LT2% & LT5%, c) KL2% & KL5%, d) KT2% & KT5%, e) PL2% & PL5%, and f) PT2% & PT5%

For laterite soil, both lignin percentages and curing days significantly impact the UCS, as indicated by F-values surpassing the critical threshold and p-values below 0.05. However, there's no interaction detected between these factors. This absence aligns with the understanding that each variable independently affects the dependent variable, as noted by [39]. Whilst, the interaction effects between terrazyme and laterite with p-value of 3.78E-08, indicates that their combined proportion and curing duration may determine terrazyme's effectiveness. Different mechanisms of action between these materials likely influence soil stabilization and UCS outcomes, explaining why interaction effects differ from those involving lignin and terrazyme.

The curing days do not interact with kaolin and lignin-treated soil, but curing duration significantly impacts UCS values. Lignin's effectiveness as a stabilizer may depend on soil compatibility. Strength remains consistent across lignin percentages, possibly due to experimental variability or design constraints. Further experiments under varied conditions could clarify lignin-kaolin behaviour. Terrazyme modifies surface characteristics of clay particles like kaolin, influencing UCS values by enhancing particle bonds and arrangement. This alteration optimizes soil properties through strengthened particle interactions.

In peat soil, the UCS value is solely affected by the curing duration. Neither lignin proportion nor their interactions significantly affect the outcome. Lignin molecules likely undergo oxidation and aging during curing, altering their chemical properties and potentially impacting binding and stabilization abilities in treated peat. There are no interactions between variables, but UCS values are notably affected by terrazyme percentages and curing duration. Organic-inorganic interactions in soils, driven by terrazyme, likely influence how terrazyme percentage and curing time interact. This coupling may have a stronger impact on terrazyme-mineral interactions in laterite and kaolin than in peat.

4.0 CONCLUSION

The inclusion of stabilizers showed minimal impact on the moisture-density relationship. UCS results indicated that LT5% exhibited the highest increase which is 926 kPa at day 21, while KT2% showed immediate strength enhancement. Stabilized peat soil strength was generally unremarkable, except for PT2%, which increased by 72%. Moisture levels varied during UCS curing, with the KU sample experiencing the most moisture loss. Lignin and terrazyme additions did not yield significant improvements. Curing duration significantly affected the qualities and performance of chemically stabilized soils. The interaction effects between terrazyme and laterite with p-value of 3.78E-08, indicates that their combined proportion and curing duration may determine terrazyme's effectiveness. Future recommendations include extending curing duration and exploring the use of additives in combination with other stabilizers like cement, lime, or fibres to address problematic soil behaviours across different textures.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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