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BLAKEY, Samuel J and LAYCOCK, Elizabeth <http://orcid.org/0000-0003-3758-6829>

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A LABORATORY STUDY OF THE USE OF LIME STABILISATION ON CONTAMINATED AND UNCONTAMINATED CLAYS

Samuel J. Blakey[1] **and Elizabeth Laycock**[2]

Samuel J. Blakey studied BSc (Hons) Geography at Sheffield Hallam University and graduated in 2018 with a first class degree. He now works as a graduate engineer at VHE Construction. Professor Elizabeth Laycock is a lecturer and researcher at Sheffield Hallam University and supervised the dissertation.

This study presents the results of experimental research carried out to investigate the effects of lime treatment on naturally deposited kaolinite clay, containing quartz, and a contaminated clay, containing calcium sulfide and heavy metals, known as galligu. The efficacy of lime stabilisation may be evaluated using unconfined compressive strength (UCS) tests which were carried out for different lime contents (0%, 5% and 10% of the sample mass) and various curing times (7, 28 and 90 days). Chemical and mineralogical changes of the two clays were established using X-Ray diffraction (XRD) and X-Ray fluorescence (XRF) in order to establish their effect on the geotechnical properties of the stabilised materials. Lime stabilised clay demonstrated improved geotechnical characteristics including a drop in moisture content (the ratio of the mass of water to the mass of solids in soil), increase in bulk density (the weight of the soil in a given volume, in this case $1m^3$) and decrease in air voids (pockets of air between aggregate particles in the soil). However the net geotechnical improvements in the natural clay were demonstrably less than the galligu, principally in terms of strength. Galligu as recovered has a high moisture content and the alkaline conditions were able to supply sufficient moisture and the optimum chemical environment for effective cation

[1] sam_blakeyxd@hotmail.co.uk

[2] E.A.laycock@shu.ac.uk

exchanges and pozzolanic reactions. For the natural clay the lime addition caused an increase in the optimum moisture needed for effective compaction, which was higher than the natural moisture content of the clay.

Keywords: contaminated land; lime stabilisation; clay; galligu; calcium sulfate

INTRODUCTION

The stabilisation of soils is an important topic due to the high quantity of low quality soils in the UK (Dexter, 2004). Clay is of particular importance, especially in the north, as it dominates the strata type (British Geological Survey, 2018). Clay minerals exhibit characteristics of affinity for water and the resulting plasticity (ability to be deformed under load) is increased (Bowles, 1989). Therefore on UK earthworks sites clay is often found to be unfit in the natural state for construction purposes due to this high plasticity reducing its strength when used as a fill material.

Quicklime is a popular solution to the high plasticity of clay due to its moisture reduction capabilities. The stabilisation of low quality soils is a more economical and environmentally friendly option to the so called 'dig and dump off site' strategy (Bromage, 2006). By solving the problem on site it avoids the high costs (both direct and indirect) associated with landfill disposal (Hodson, 2010).

Although a number of studies have investigated the effects of lime stabilisation on clay (Beetham et al, 2013; Beetham, 2015; Bell, 1996; Harichane et al, 2012; Louafi et al, 2015; Modarres and Nousady, 2015; Wang et al, 2013; Yam-Nam, 2006), little to no research has examined the effects of lime stabilisation on galligu. This work focuses on remediation of Sighthill Park in Glasgow, with high volumes of galligu which would not have been possible without in-situ remediation.

Galligu is a contaminated by-product of the Leblanc process which was used to convert rock salt into sodium carbonate (Moore et al, 2003). Galligu can have similar characteristics to clay as the by-product material is bound with clay particles, and retaining a high moisture content. This material was disposed of by surface dumping throughout the 19th century. Chemical analysis shows galligu is high in calcium, as well as potassium, magnesium, arsenic, barium, chromium, lead, copper and zinc (Scientific Analysis Laboratories Ltd., 2016).

The purpose of this study is threefold: to evaluate the use of lime in geotechnically improving soils, to establish the effects and processes of lime on the differing soils, and to compare the usefulness of contaminated soils with more conventionally used soils in the field of land development.

LITERATURE REVIEW

Clay Mineralogy and Identification Methods

Clay mineralogy heavily influences the soil's strength in its natural state as well as post stabilisation. Different soil chemistry and mineralogy result in changes to the nature of the reactions between the lime and soil (Beetham et al, 2013). To investigate clay mineralogy, X-Ray diffraction (XRD) and X-Ray fluorescence (XRF) can be useful tools. They identify mineral and chemical compounds through their unique patterns and wavelengths, which act as fingerprints for identification (Sheffield Hallam University, 2018a).

Roger, Glendinning and Dixon (1996) describe the quicklime reaction simplistically as:

$$\text{Calcium oxide} + \text{water} \rightarrow \text{Calcium hydroxide} + \text{heat}$$

$$CaO + H_2O \rightarrow Ca(OH)_2 + \text{heat.}$$

Beetham (2015) found that when the lime that is added is greater than the initial consumption of lime (ICL) value, the clay-soil pore water becomes 12.4pH. This high alkaline environment causes calcium, from the added lime, to react with the clay minerals, aluminosilicates, forming cementitious compounds binding the clay particles together. The clay mineralogy influences the rate at which pozzolanic reactions result in increased strength; expansive clay minerals, such as montmorillonite, provide the greatest rate of reactivity enabling maximum efficiency of the pozzolanic reactions. The SEM analysis identified calcium aluminate silicate hydrates (C-A-S-H) as the chemical component for the pozzolanic reaction in the samples a finding supported by XRD results.

Clay particles are almost always hydrated, surrounded by layers of water molecules called adsorbed water (Bowles, 1989). The edges of the clay minerals in the adsorbed layer have net negative charges, leading to attempts to balance the charges by cation attraction, thus assisting the soil-lime reaction through cation exchanges.

Table 1: Indicative literature on clay mineralogy and laboratory determination of mineralogical contents before and after lime stabilisation.

Author (Date)	Focus of work	Summary results	Summary findings
Nayak and Singh (2007)	XRD and XRF used in study aiming to characterise clay samples using a range of instruments	alumina and silica oxide were present in the clays in major quantities, while other minerals such as magnesium and calcium were present in trace amounts.	Characterisation of the XRD patterns indicated the presence of quartz, kaolinite, hematite, illite, and tridymite as the major phases.
Modarres and Nousady's (2015)	XRD study on the lime stabilisation of clay samples containing quartz, montmorillonite and kaolinite	in stabilised specimens clay minerals had a lower peak XRD intensity	Attributed to the occurrence of the pozzolanic reaction. Removal of calcium hydroxide and creation of calcite
Beetham's (2015)	XRD and scanning electron microscope (SEM) to identify the chemical composition of the pozzolanic reactions	The triaxial shear strength and California Bearing Ratio (CBR) tests saw strength improvements with increased curing time.	attributed to the cation exchanges in the short term and pozzolanic reactions in the longer term, but also to the heat generated in the exothermic reaction between the quicklime and soil moisture in the immediate short term.

Bell (1993) states that a decrease in strength with excessive lime addition is because lime itself has neither sufficient friction nor cohesion. The optimum lime content is estimated to range between 4.5-8% for soils, with a higher percentage needed for soils with higher clay fractions. Additionally Bell (1993) noted that soil-lime mixtures compacted at moisture contents above the optimum moisture content attain higher strength, after brief curing periods, than samples compacted at moisture contents below the optimum moisture content. This is because the lime is more uniformly diffused and occurs in a more homogenous curing environment at or above the optimum moisture content.

The literature review identified one case where galligu had been stabilised, reported by (Bromage, 2006). In this the top 350mm layer of a 4m deep galligu strata was stabilised and compacted to prevent surface water infiltration and decrease mobility of the galligu contaminants and various heavy metals including arsenic, zinc and lead.

Methods that have been used throughout the different studies on clay stabilisation and are useful to replicate include measuring an average UCS reading from at least 3 separate samples for each group, to improve the scientific validity of the data. Also increasing the lime dosage up to no more than 10%, with 0% lime acting as the control group, as it has been found that the UCS will reduce after reaching a maximum value. This value is expected to be reached after a lime dosage of between 6-10% and it is of no interest studying the samples after they have reached this value. A summary of the different studies into the stabilisation of clay can be seen in Table 2.

The variables selected for the laboratory study were lime content, curing period duration and material type. The dependent variables include the UCS as the primary focus, and air voids, bulk and dry densities and moisture content as secondary variables.

Table 2: A summary of the lime stabilisation studies

Author/s and Date	Lime Content Conditions (%)	Curing Period Conditions (Days)	Findings
Beetham (2015)	8.5	8, 32, 194	Strength increased with lime & curing time
Bell (1996)	2, 4, 6, 8, 10	1, 3, 7, 14, 28	Strength increased with lime (up to 4-6% then decreased to 10%) & curing time
Harichane et al (2012)	0, 4, 8, 10	1, 7, 28, 90	Strength increased with lime & curing time
Louafi et al (2015)	0, 2, 4, 6, 8	1, 7, 14, 21, 28	Physical and mechanical properties of soil improved with lime & curing time
Modarres and Nousady (2015)	3, 6, 9	7, 28, 60, 180	Stabilised samples contained high amounts of calcite
Wang et al (2013)	0, 3, 6	28, 90	Strength increased with lime (up to 3% then decreased to 6%) & curing time
Yam-Nam (2006)	0, 2, 5, 10, 15	0, 7, 28	Strength increased with lime & curing time

Samples of both clay and galligu for the laboratory study were sourced from the same site: Sighthill Park in Glasgow, which at the time was an active remediation site. The material for the laboratory testing was sampled by trained VHE geo-environmental engineers using standard sampling procedures, to ensure the samples were as representative of the material as possible.

PROCEEDURE

Laboratory Testing

Sample Preparation:
Galligu and clay as received were passed through a 20mm sieve, in accordance with BS1377-7-1990 to ensure that the largest particle diameter did not exceed the one-fifth of the diameter of the compaction mould. A trial of the method outlined below was carried out to ensure that the procedure was robust and allowed the creation of replicate samples. The sample conditions summary for the cube moulds can be seen in Table 3. Quick lime percentages were added representative of the sample weights and then mixed into the samples by method of a laboratory mixer to obtain thoroughly mixed, homogeneous samples. The 0% lime conditions acted as the control group for both materials. Fifty-four 100x100mm cube moulds were compacted by method of a 4.5kg hand rammer, displayed in Figure 1, with a fall of 450mm in 5 layers with 27 blows, in accordance with BS1377-4-1990. Following the methodology outlined in BS1377-4-1990, moisture content of the soil prior to compaction was determined using gravimetric losses after drying at 100-105ºC for 24 hours.

Figure 1: photograph showing the 4.5kg hand rammer. (Credit: S. Williams)

UCS Sample Quantity				
Material	**Lime (% of Sample Mass)**	**Curing Period (Days)**		
		7	28	90
Clay	0	3	3	3
	5	3	3	3
	10	3	3	3 (2)
Galligu	0	3	3	3
	5	3	3	3
	10	3	3	3

Table 3: UCS Sample Conditions Summary Samples made (shown in brackets where number tested different)

Cured (conditions):

Mass and dimensions of the specimens was recorded just before UCS testing to ensure no residual moisture with resultant effect on strength.

The dry and bulk densities were established, as well as estimation of the volume of voids.

The UCS measurements were the product of an average of 3 readings from each condition.

As the only British Standard for the UCS test set out the methodology for tests with cylindrical specimens, a German standard was adopted for the deformation rate. The German institute for standardisation (DIN 18137-2:2011-04) states the deformation rate standard for the UCS test is 1% of the initial specimen height per minute. This equates to 1mm per minute for the 100x100mm test samples.

Table 3 shows that one clay +10% lime sample from the 90 days cured condition was lost due to the crumbling of the specimen rendering it untestable.

Chemical/Mineralogy Analysis

X-Ray diffraction (XRD) and X-Ray fluorescence (XRF) were utilised to analyse the mineralogy and chemical composition of the natural clay as well as clay and galligu stabilised with 10% lime. This was to establish what minerals and chemical components are present and are therefore playing a role in the soil-lime reaction and strengthening of the samples. A chemical report undertaken on VHE's behalf by Scientific Analysis Laboratories Ltd. (2016) testing 14 pure galligu samples was analysed with the same aim for the unstabilised galligu.

Statistical Analysis

Strength is the most important variable when considering soils for earthworks purposes and was used as the principle dependent variable in statistical tests. A between-variable univariate ANOVA was conducted to test the significance of the main effects, as well as the interactions between the means of the 3 independent variables. Bonferroni post-hoc tests were conducted where the ANOVA results were found to be significant.

RESULTS

XRF Characterisation

Table 4: Chemical Composition of XRF Samples

Analyte	Compound formula	Natural Clay	Clay +10% Lime	Galligu +10% Lime
			Concentration (%)	
Si	**SiO_2**	55.88	56.77	6.31
Al	**Al_2O_3**	25.47	14.88	5.37
Ca	**CaO**	7.58	21.02	77.08
Fe	**Fe_2O_3**	4.59	3.51	0.67
Mg	**MgO**	2.42	0.64	1.29
K	**K_2O**	2.42	1.99	-
Na	**Na_2O**	0.86	0.351	0.84
Ti	**TiO_2**	0.39	0.308	0.09
S	**SO_3**	0.16	0.10	8.12
P	**P_2O_5**	0.14	0.28	0.12
Mn	**MnO**	0.09	0.16	-
Cl	**Cl**	-	-	0.08
Sr	**SrO**	-	-	0.04

Silicon dioxide and alumina and calcium oxide were found in both the natural clay and clay +10% lime samples, as seen in Table 4. Calcium oxide was more prominent in the clay +10% lime sample, whereas more alumina oxide was detected in the natural clay sample. Calcium oxide was found in the galligu +10%

lime sample in high concentrations, alongside sulfur trioxide, silicon dioxide, alumina oxide.

XRD Characterisation

Table 5: Chemical Composition of XRD Samples

Compound Name	**Chemical Formula**	**Natural Clay**	**Clay +10% Lime**	**Galligu +10% Lime**
		Detection Score		
Quartz	SiO_2	75	71	-
Calcite	$Ca(CO_3)$	53	52	71
Calcium Hydroxide	$Ca(OH)_2$	-	41	50
Anorthite	$CaAl_2Si_2O_8$	9	4	-
Kaolinite	$Al_2Si_2O_5(OH)_4$	17	-	-
Allevardite	$K_1 Al_4 Si_8 O_20$	15	7	15
Cronstedtite	Fe_3FeSiO_4	-	10	-
Magnesium Sulfate	$MgSO_4$	-	-	6
Cordierite	$Mg_2Al_4Si_5O_{18}$	-	-	11
Calcium Sulfate	Ca_2SO_4	-	-	4

Table 5 displays the XRD analysis results. Calcium hydroxide was found in both the clay +10% lime and galligu +10% lime specimens in large quantities, but not in the natural clay. Quartz and calcite were present in the clay samples, with generally consistent levels between both the natural clay and clay +10% lime, reducing slightly in the stabilised sample. The kaolinite present in the natural clay sample was not found in the stabilised clay sample at all. The galligu +10% lime sample contained calcite too, in even higher quantities, among magnesium sulfate, cordierite and calcium sulfate.

Physical properties of compacted clays

Figure 2 shows the effect of lime on the moisture content in all of the curing period conditions across both materials. The negative correlation is clear, meaning lime has a universal effect on both galligu and clay; increased lime content results in decreased moisture content. The density of the clay follows a trend of reduction after lime application, whereas the galligu's density increases. These changes can be seen in Figures 3 and 4. A negative correlation between lime application and air voids can be seen in Figure 5. The effect across both materials increased lime content results in decreased air voids.

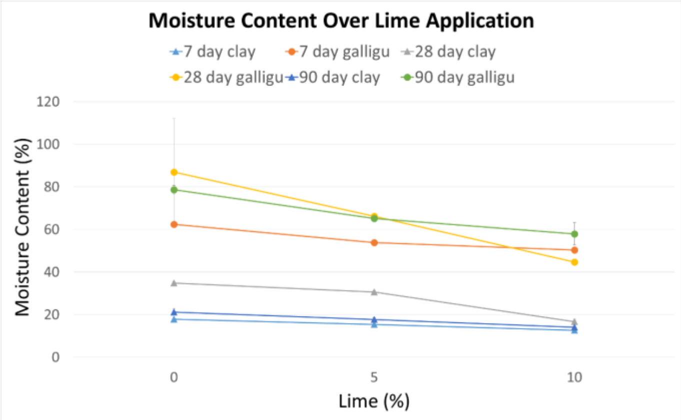

Figure 2: the effect of lime on the moisture content of the soils, across the different curing periods and material conditions.

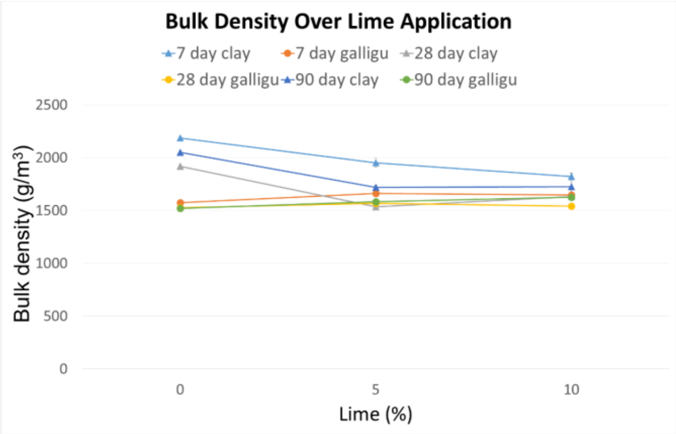

Figure 3: the effect of lime on the (apparent) bulk density of the soils, across the different curing periods and material conditions; measured at lab conditions.

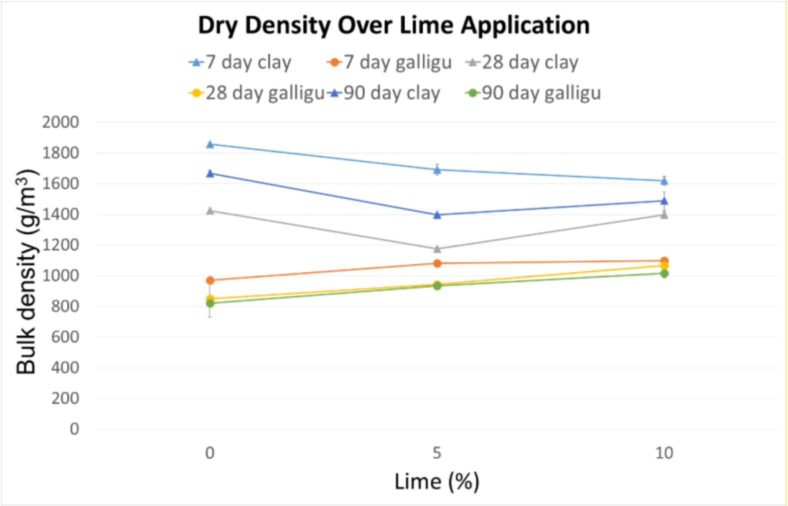

Figure 4: the effect of lime on the dry density of the soils, across the different curing periods and material conditions. (Measured after oven drying).

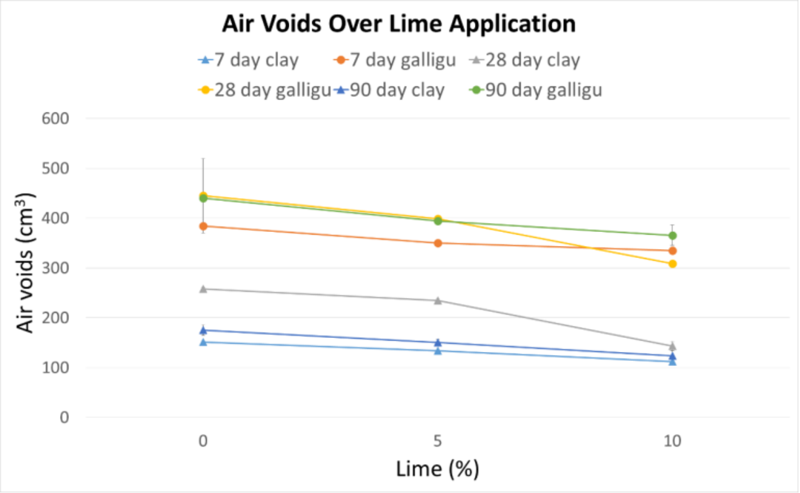

Figure 5: the effect of lime on the air void quantity in the soils, across the different curing periods and material conditions.

Soil Strength

The means and standard deviations of the primary data can be seen in Table 6.

Table 6a: Descriptive Statistics *Dependent Variable: Unconfined compressive strength of Galligu*

Galligu				
Lime Content (%)	**Curing Time (Days)**	**Mean (N/mm^2)**	**Std. Deviation**	**N**
0	7	0.0024	138.39	3
	28	0.0011	120.98	3
	90	0.0044	877.43	3
	Total	**0.0026**	**1502.2**	**9**
5	7	0.005	1055.07	3
	28	0.0024	246.47	3
	90	0.0081	1240.14	3
	Total	**0.0052**	**2592.44**	**9**
10	7	0.0037	249.36	3
	28	0.0056	1405.78	3
	90	0.0136	1444.43	3
	Total	**0.0076**	**4630.86**	**9**
Total	7	0.0037	1248.44	9
	28	0.0031	2108.94	9
	90	0.0087	4098.31	9
	Total	**0.0052**	**3688.52**	**27**

Table 6b: Descriptive Statistics *Dependent Variable: Unconfined compressive strength of natural clay*

Natural Clay				
Lime Content (%)	Curing Time (Days)	Mean (N/mm2)	Std. Deviation	N
0	7	0.0008	201.63	3
	28	0.0029	1095.31	3
	90	0.0044	2098.36	3
	Total	**0.0027**	**1951.07**	**9**
5	7	0.0038	848.2	3
	28	0.0014	276.91	3
	90	0.0006	373.9	3
	Total	**0.0019**	**1524.69**	**9**
10	7	0.0004	152.62	3
	28	0.0006	478.15	3
	90	0.0006	71.99	2
	Total	**0.0005**	**287.78**	**8**
Total	7	0.0017	1646.98	9
	28	0.0016	1168	9
	90	0.002	2281.38	8
	Total	**0.0018**	**1670.79**	**26**

A between-variable univariate ANOVA was conducted to test whether material strength significantly varied by: 1) material (clay, galligu) and 2) lime content (0%, 5% and 10%); and to test how: 3) material influences soil strength in varying levels of lime content; 4) curing time influences strength in varying levels of lime content for each material.

There was a significant main effect of material, $F(1, 35) = 191.45$, $p < .001$, such that galligu (Mean = 0.0052) was stronger than clay (Mean = 0.0018) overall, as seen in Figure 6.

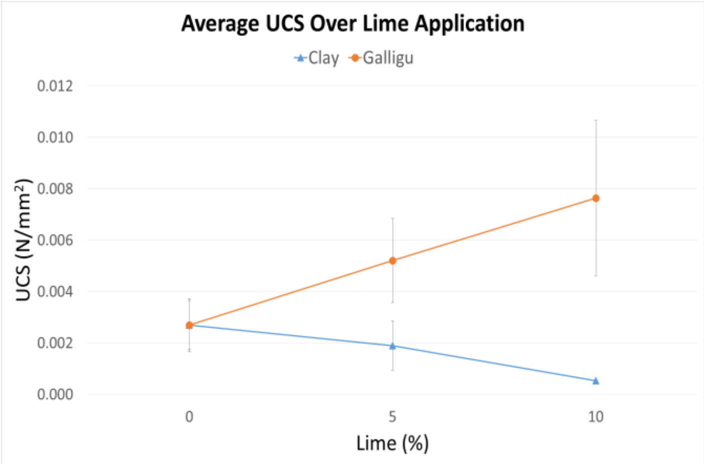

Figure 6: The average unconfined compressive strength of each material, across the different lime dosages.

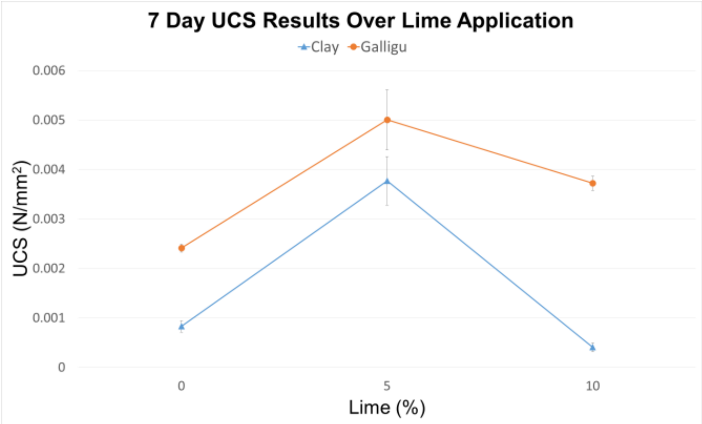

Figure 7: The effect of lime on the unconfined compressive strength of the soils, across the different material conditions after 7 days of curing.

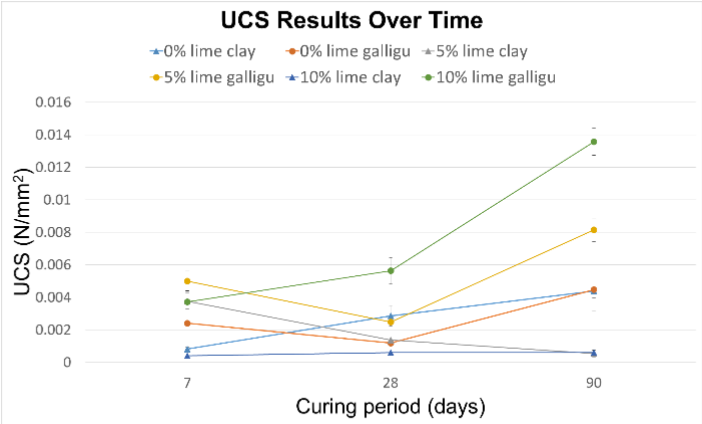

Figure 8: The effect of curing time on the unconfined compressive strength of the stabilised soils, across the different lime dosages and material conditions.

There was a significant main effect of lime content $F(2, 35) = 10.46$, $p < .001$, such that strength increased when lime content increased across material and curing time (0%: Mean = 0.0027; 5%: Mean = 0.0036; 10%: Mean = 0.0043).

In order to interpret this finding Bonferroni post-hoc tests were conducted. The factors found to have statistically significant effects are listed below.

Figure 6.	Significant two-way interaction between material and lime content across curing time, $F(2, 35) = 66.01$, $p < .001$. For Galligu, strength was highest at 10% lime content (Mean =0.0076) Natural clay was stronger at a lime content of 0% (Mean = 0.0027)
Figure 7:	significant increase in strength between lime content at 0% and at 5% ($p = .022$) non-significant difference in strength between lime content at 5% and 10% ($p = .065$)
Figure 8.	There was a significant three-way interaction between curing time, lime content and material, $F(4, 35) = 14.38$, $p < .001$. For galligu, curing time increases strength partially in lime contents of 5% Greater strength increase with time for galligu with 10% lime For clay curing time decreases strength in lime contents of 5% For clay with 10% lime content, strength increases at first before stabilising between 28 and 90 days

DISCUSSION

XRD Analysis

The cured galligu +10% lime contained greater quantities of calcite than either the natural clay or the clay and lime, suggesting that the gain in strength is related to the formation of calcite, and highlighting the potential for a higher strength to be found in the galligu (Modarres and Nousady, 2015). Calcium hydroxide was identified as the cementitious chemical component of the lime-soil reaction, although this could only be detected in the natural clay and galligu at 10% lime content. Calcium hydroxide content was greater in the galligu, and it is postulated that high pH of galligu, found in Scientific Analysis Laboratories Ltd.'s chemical report (2016) to be 10.58 as an average of 14 samples due to the high calcium content, aided the pozzolanic reactions between existing aluminosilicates after lime application, as proposed by Beetham (2015).

The laboratory work showed replication in the results gained for natural clay in terms of a reducing moisture content with increasing lime corroborating work by several previous authors (Beetham, et al, 2013; Beetham, 2015; Bell, 1996; Harichane et al, 2012; Louafi et al, 2015; Modarres and Nousady, 2015; Wang et al, 2013; Yam-Nam, 2006). The natural clay has also been previously found to show a decrease in density after lime stabilisation in other studies (Beetham, 2015; Bell, 1996; Harichane et al, 2012; Louafi et al, 2015; Modarres and Nousady, 2015), again seen in this work. Air voids were observed to decrease in volume after the addition of lime to natural clay which correlates with the findings of previous studies (Beetham et al, 2013; Beetham, 2015; Louafi et al, 2015).

A significant increase in UCS strength 0 to 5% lime in clay was found by other researchers (Beetham, 2015; Bell, 1996; Harichane et al, 2012; Louafi et al, 2015; Modarres and Nousady, 2015; Wang et al, 2013; Yam-Nam, 2006) which was only replicated in the 7 day curing period condition.

Moisture Content

The explanation for the negative correlation of increased lime content resulting in decreased moisture content is the exothermic reaction between the lime and water, resulting in evaporation of the soil's moisture in the immediate short term (Beetham, 2015). Galligu had a higher moisture content than clay in all the curing period conditions, highlighting the material's lower quality in this geotechnical characteristic.

Soil Density

The improvement of the density of the galligu can be attributed to the rearrangement of the soil particles, creating a more solid structure. The greater moisture content improves the efficiency of the lime diffusion and provides sufficient water to precipitate pozzolanic hydrates. As the natural clay has a lower moisture content than the galligu, there is insufficient water to effectively complete the reaction of the lime in order to sufficiently bind the soil particles. As a result, the soil dries up and the density of the clay is reduced. Galligu generally had lower bulk and dry densities than those of clay, displaying the material's lower suitability than the clay for earthworks in this area.

Air voids

The reduction in air voids occurs due to the rearrangement of the soil particles after lime application, creating a more homogenous structured arrangement through the moisture reduction of the soils (Louafi et al, 2015). However, in the case of the clay, the reduction in air voids does not result in an increase in density as the soil is too dry to bind together, so although the voids are filled with soil particles, it does not mean the soil is compact or stable.

Galligu had a higher quantity of air voids than clay in all curing period conditions, highlighting the material's lower suitability for earthworks in this category.

Soil Strength

Galligu was found to be the stronger of the two materials in the laboratory study, as confirmed by the between-variable univariate ANOVA. This was an unexpected finding as the high moisture content, high quantity of air voids and the low density of galligu, was expected to reduce the strength potential of the material in comparison to clay. However, the high strength results can be explained as the higher moisture content in the galligu supplied the lime with adequate water for the cation exchanges in the short term, and for the pozzolanic reactions in the long term, to improve the soil strength (Louafi et al, 2015). In contrast, the clay did not have as much moisture to supply strengthening processes, so was dried out, and even in one case crumbled, thus reducing the strength.

Additionally, soil-lime mixtures compacted at moisture contents above the optimum moisture content attain higher strength after brief curing periods, than samples compacted at moisture contents below the optimum moisture content, such as the clay samples (Bell, 1993). This is due to the lime being diffused more uniformly in materials of a higher moisture content, and therefore the reaction is facilitated in a more homogenous curing environment. Furthermore, more water is needed for the dissociation of lime, accounting for the increase in optimum moisture content in the stabilised material (Harichane et al, 2012). The galligu contained sufficient moisture to reach this increased optimum moisture content; whereas the clay did not. The extent of the lack of moisture in the clay after stabilisation can be seen in Figure 9, displaying a natural clay sample and a clay +10% lime sample. The deformation of the natural clay sample highlights a lack of strength pre-stabilisation as well as post-stabilisation.

However, the secondary data analysis of the NDG readings of stabilised and unstabilised clay and galligu in the field determined clay was stronger than galligu. This was the expected outcome, but conflicts the findings of the primary research. This is likely due to the outside effects in the field, such as moisture input from rain through the infiltration of the soil, influencing the moisture content of the stabilised material and allowing the clay-lime reaction to reach its full potential in strengthening the soil.

It is also worth noting that, while still significant, the difference in strength between clay and galligu in the secondary field data was only 2.23% proctor compaction, whereas galligu was found to be almost 3 times as strong as clay on average in the laboratory. So even with the moisture infiltration in the field assisting the strengthening of the clay when stabilised, the galligu still attains high strength when compared to the clay, whereas in the laboratory, the galligu attains far greater strength than the clay.

Figure 9: photographs showing a clay +10% lime sample on the left, and a natural clay sample on the right.

Optimum Lime Percentage Dosage:

The optimum lime percentage dosage, out of the 0%, 5% and 10% conditions, for the best UCS results was found to be 10% for galligu. After lime stabilisation the galligu becomes stronger than the clay and continues to strengthen up to 10% lime application, meaning this percentage of lime suits the pozzolanic reactions the best in galligu. The pozzolanic reactions are able to reach higher strengths in galligu as more of the cementing agent, calcium hydroxide, was formed from cation exchanges at an earlier stage due to the higher moisture content in galligu, and can therefore be crystallised during the pozzolanic reactions to improve soil strength.

In clay the contrary is seen as the UCS decreases with lime application, meaning 0% is the optimum dosage for strength in clay. This is because the pozzolanic reactions are not able to crystallise the cementing agent and therefore improve the strength, as the soil had dried too much in the 5% and 10% conditions and could not bind together as well as in the galligu. The lower moisture content of the clay could not supply the lime with enough moisture for an optimum reaction at the earlier stage.

The UCS increase from 0% to 5% lime is due to the modification of the soil's characteristics by the lime through processes such as cation exchanges between silica and alumina, in the lime, and the water producing the gel cementing agent (Louafi et al, 2015). Between the 5% and 10% lime conditions the strength increase is less significant because, in some cases, the maximum UCS value had been reached (Balogun, 1984) as 10% samples were closer to the optimum moisture content than the 5% (Wang et al, 2013).

The secondary data analysis again found contradicting results; that unstabilised clay was stronger than stabilised clay, and that unstabilised galligu was stronger than stabilised galligu. However, this area of the secondary data research must not be considered with too much validity as only the inherently bad material was stabilised on site, because of high stabilisation material costs. In result the poor quality material which was stabilised had a much lower strength than the unstabilised material.

Effect of Curing Time on Strength Improvement:

The galligu strengthened with curing time as the pozzolanic reactions were able to reach their full potential and strengthen the soil over time. Whereas the pozzolanic reactions in the clay were not able to reach their full potential and the soil's moisture was dried up, meaning any strength improvements were not as significant as in the galligu. The visual difference between the two material types at the maximum curing time condition of 90 days can be seen in Figure 10 displaying a galligu +10% lime and a clay +10% lime sample, with the galligu sample clearly more structurally stable.

Figure 10: photograph displaying a galligu +10% lime sample on the left and a clay +10% lime sample on the right after a curing period of 90 days.

In some cases, as in the clay +5% lime, increased curing time resulted in a further decrease in the soil strength, as the longer the samples were left to cure, the drier the samples became, thus reducing the soil strength. Interestingly the natural samples continued to harden with curing time, due to the warm curing conditions under plastic bags allowing a slight strengthening of the material.

CONCLUSIONS

- Galligu had more air voids, a higher moisture content and lower bulk and dry densities than clay pre and post stabilisation.
- However, it must be concluded from the laboratory investigation that galligu is more suitable for earthworks than clay, due to the greater UCS results of galligu as strength is what is measured most commonly to validate earthworks sites.
- The effectiveness of lime in geotechnically improving the soils was varied. Galligu responded more effectively to lime stabilisation, increasing in density and strength, whereas the opposite effect was recorded in clay. Air voids and moisture content both reduced universally with lime application across both material types.
- The optimum lime percentage dosage was found to be 10% in galligu and 0% in clay. The high moisture content of the galligu increases the lime application threshold before the maximum UCS is reached, whereas the clay, in laboratory conditions, has a much lower lime application limit before the maximum UCS is reached.
- However, some constraint must be applied when generalising these findings as it is worth noting galligu is a variable material in terms of its geotechnical properties, dependent on what the contaminated material has binded with when dumped. In some cases the waste product has binded with different types of clay, wielding varying high moisture contents, in other cases it has fused with granular material, creating a solid mass. For the purposes of this study the former was used in the laboratory investigation, aiming to find a way to stabilise the worst of the material.
- Nevertheless, this study has identified the key processes occurring in both the clay and galligu when stabilised over a 90 day curing period. Galligu was found to be an effective earthworks material that can be utilised as a fill material on remediation sites once stabilised, or even in its natural state, offering an alternative to the dig and dump remediation method and its associated negative consequences.

RECOMMENDATIONS

There are several options to further this research:

- One would be to replicate a laboratory study with more targeted lime percentage dosage conditions between 2-12%, to identify with more accuracy the optimum percentage dosages. This research could include the addition of water after the mixing stage before compaction commences, in order to simulate water infiltration in the field.
- Another, and arguably more valid, method would be to undertake field research, similar to the secondary data collection method used in this study, but with a matched pairs design in which the same material is tested before and after stabilisation, instead of different qualities of material being tested and then compared.
- Different variations of clay and galligu could be tested in either of these experimental studies to investigate the difference in geotechnical properties, but also lime stabilisation processes, within the varying materials.
- The use of scanning electron microscope (SEM) analysis could also be incorporated in the research, as another method of analysing the soil mineralogy changes throughout lime stabilisation.

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