

Research Article

The Effectiveness of Heated Black Cotton Soil as a Low Calcium Pozzolanic Aluminosilicate Precursor in Lime-activated Stabilization of Black Cotton Soil for Use in Flood Prone Areas

¹Charles K. Kabubo, ²Sylvester O. Abuodha and ³Zachary A. Gariy

¹Sustainable Materials Research and Technology Centre, Jomo Kenyatta University of Agriculture and Technology (JKUAT), P.O. Box 62000-00200,

²Department of Civil and Construction Engineering, University of Nairobi, P.O. Box 30197, GPO, Nairobi, Kenya

³Department of Civil and Construction and Environmental Engineering (JKUAT), Kenya

Abstract: The aim of this study was to investigate the effectiveness of heated black cotton soil as a precursor in lime-activated stabilization of black cotton soil in-place for use in flood-prone areas. Most methods used to improve expansive soils include the use of lime or lime-activated materials, cut to spoil followed by replacement and thermal treatment. Most lime treatment methods yield a material that cannot withstand high moisture levels and long flooding periods. Cut to spoil results in high costs and negative environmental consequences. Lime activated Ground Granulated Blast Furnace Slag (GGBS) has been found to be effective in flood conditions, but it has to be locally available. In this study, Unconfined Compressive Strength (UCS) tests were done on 50 mm diameter by 100 mm long stabilized soil specimens using various mixes of heated black cotton soil and lime which established an optimal mix of 14% heated black cotton soil at 400°C and 6% lime as the binders with 80% neat black cotton soil. Investigations of properties of this mix subjected to moist curing periods of 7, 14, 28, and 90 days followed by soaking them in water for 4 and 10 days after each curing period to simulate flash and severe flooding respectively were done. The durability reduction indices for each flooding scenario were computed. The mix yielded a strong durable product able to withstand flooding conditions. The heated black cotton soil at 400°C is, therefore, an effective low calcium aluminosilicate precursor with lime as the alkali activator.

Keywords: Expansive soils, flooding conditions, lime-activated materials, low calcium aluminosilicate precursor, strength reduction index, unconfined compression strength

INTRODUCTION

The presence of expansive soils greatly affects the construction activities in many parts of South-Western United States, South America, Canada, Africa, Australia, Europe, India, China and Middle East (Chen, 1975). Black cotton soil, an expansive clay occupies about 3% of the world area, about 340 million hectares (Bhavsar and Patel, 2014).

Various methods that have been employed to improve expansive clays include mechanical compaction, surcharge loading, pre-wetting, lime stabilization, cement stabilization, fly ash stabilization, chemical stabilization and organic compounds treatment (Nelson and Miller, 1992). Other methods include cut to spoil followed by importing good material for replacement (Mokhtari and Deghani, 2012;

Kalantari, 2012; Ministry of Transport and Communications (MOTC), 1987) and thermal treatment (Li *et al.*, 2014; Wang *et al.*, 2008; Terzaghi *et al.*, 1996; Bell, 1993; O'Flaherty, 1974).

Cut to spoil followed by replacement with good materials and lime stabilization are among the more frequently used methods of dealing with black cotton soils (Mokhtari and Deghani, 2012; Kalantari, 2012; Yang and Zheng, 2006; MOTC, 1987). But excavating and importing good material for replacement has huge cost implications due to increase in carbon footage resulting from burning fossil fuel or cost due to damage to the environment resulting in increase in greenhouse gases, responsible for global warming (Prusinki and Bhattacharja, 1999; Yang and Zheng, 2006). Furthermore, good replacement materials put pressure on agricultural land since they are located in arable land

Corresponding Author: Charles K. Kabubo, Sustainable Materials Research and Technology Centre, Jomo Kenyatta University of Agriculture and Technology (JKUAT), P.O. Box 62000-00200, Nairobi, Kenya

This work is licensed under a Creative Commons Attribution 4.0 International License (URL: <http://creativecommons.org/licenses/by/4.0/>).

which has led to legislation and imposition of levies in some countries for their excavation and transportation making them more and more expensive.

A number of industrial based bi-products and agricultural waste materials have been recently developed as stabilizers and the current emphasis is to amend these aluminosilicates with alkali activators such as lime in one-part geopolymer reactions to enhance their pozzolanic and cementitious properties (Luukkonen *et al.*, 2018; Sharma and Sivapullaiah, 2016). The precursors that have been used include Ground Granulated Blast furnace Slag (GGBS), fly ash, silica fume, bagasse ash and rice husk ash with lime as the alkali activator (Kavak and Bilgen, 2016; Obuzor *et al.*, 2012; Obuzor *et al.*, 2011; Dang *et al.*, 2016b; Wubshet and Tabese, 2014; Satyanarayana *et al.*, 2016; Karatai *et al.*, 2016). Only lime-activated GGBS has been found to be effective in withstanding flooding conditions (Obuzor *et al.*, 2012). GGBS is not available in Kenya.

Thermal stabilization by heating or freezing has been used (Li *et al.*, 2014; Wang *et al.*, 2008; Bell, 1993; O'Flaherty, 1974), but it's a very expensive process. In-place improvement methods can result in natural resource conservation, reduction in energy usage, reduction in carbon dioxide emission and increased cost efficiency (Lee and Karunaratne, 2007; Phanikumar *et al.*, 2008).

In Kenya, black cotton soil covers large areas and the solution has been to remove and replace them with suitable material. Structures and roads constructed in areas where black cotton soil is not removed crack extensively as the moisture levels change, with failures experienced depending on how extensive black cotton soil is. Thus, obtaining an effective local method of improving black cotton soil in-place will reduce the negative effects of black cotton soil and optimize on cost of construction. This study considers use of heated black cotton soil as a pozzolanic low calcium aluminosilicate precursor with lime as an alkali activator in a one-part geopolymer reaction in treatment of expansive black cotton soils in-place, to withstand flooding and high moisture conditions. According to Provis (2018), effectiveness of use of geopolymers is dependent on local availability of binders.

MATERIALS AND METHODS

Materials: The target soil for investigation in this research was naturally occurring black cotton soil (NBC), an expansive clay. The aim of the study was to investigate the effectiveness of using lime-activated low calcium pozzolanic heated black cotton soil as a local in-place method of treating NBC to be used as a fill

material for roads in high moisture conditions and areas subject to flooding, where suitable replacement fill material is not available. Wang *et al.* (2008) found that the highest temperature that heated expansive clay should be heated to lose swelling characteristics was, 600°C. Thus, in this research, mixes of Heated Black (HBC) soil only in temperature range 200-700°C and hydrated lime were used to stabilize the neat black cotton soil. Hydrated lime was preferred to quicklime because the latter is exothermic, extremely dangerous and capable of causing severe caustic burns (Mehta *et al.*, 2014; O'Flaherty, 2002).

The NBC used as the expansive soil in this research was obtained from Mwhoko area of Kiambu County, about 25 km North East of Nairobi City in Kenya located 500 mm below ground. Basic soil tests to establish that the soil was expansive, were conducted in the Civil engineering laboratories of Jomo Kenyatta University of Science and Technology (Kenya) and at the Ministry of Transport, Infrastructure, Housing and Urban Design Materials Testing and Research Department (MTIHU DMTRD) laboratories in Nairobi, Kenya. The California Bearing Ratio (CBR), CBR swell, Unconfined Compressive Strength (UCS), specific gravity for the NBC soil determined in accordance with British Standards BS 1377 (1990), were 1%, 4.95%, 44.1 kN/m² and 2.47 respectively. The liquid limit, plastic limit, plasticity index and linear shrinkage for the neat NBC soil were 65, 35, 30, 15 and 74%, respectively whereas compaction (proctor test T99) results revealed that the maximum dry density was 1272 kg/m³ at optimum moisture of 29.5% and air void content of 11%. The NBC was thus weak, had a high swell potential (O'Neil and Poormoayed, 1980) and was an expansive clay (Bhavsar and Patel, 2014).

X-ray diffraction (XRD) tests were done at the soils laboratories of the International Centre for Research in Agroforestry (ICRAF), Nairobi, for the NBC and HBC to obtain their mineralogy using a benchtop Bruker D2 Phaser diffractometer connected to a computer which had a software linked to International Center for Diffraction Data (ICDD), from which the mineralogy was inferred from the spectra obtained for each sample, based on Bragg's Law. The results revealed that for each of the minerals, there were mainly 3 broad peaks for 2θ between 5° and 69° representing first, second and third order reflections corresponding to n values of 1, 2 and 3 from Bragg's Law. The number of minerals varied from 5 to 7. The clay minerals and their percentages are shown in Table 1.

The swelling potential in Albite is mobilized if other factors influencing swelling such as presence of water and montmorillonite are fulfilled (Skippervik, 2014). In the soil under study, the presence

Table 1: Clay minerals composition as a percentage of all the minerals for HBC

Reference Mineral	Soil sample type (HBC in °C)							
	NBC	HBC at 200	HBC at 300	HBC at 400	HBC at 500	HBC at 600	HBC at 700	HBC at 800
Albite	26.2	31.2	30.1	31.4	28.3	35.3	26.3	25.5
Microcline	38.5	30.2	31.7	34.3	33.9	39.1	36.6	30.8
Kaolinite	1.7	-	-	2.5	3.2	2.5	-	2.0
Montomo-rillonite	3.3	5.8	7.1	4.8	-	-	-	-
Muscovite	2.7	-	-	4.2	4.2	5.1	5.0	5.6
Calcite	5.8	5.3	4.5	-	5.8	-	-	9.5
Imogolite	-	3.3	4.0	-	-	-	2.5	-

Table 2: Chemical properties for HBC

Reference	Neat soil	Heat soil at temperatures stated in °C					
		200	300	400	500	600	700
SO ₃ (%) × 10 ⁻²	6.6	0.30	0.66	3.9	1.7	2.8	8.1
SO ₄ (%) × 10 ⁻²	7.92	0.36	0.72	4.68	2.04	3.36	9.72
Cl (%)	0.01	0.044	0.043	0.011	0.032	0.011	0.034
pH	7.42	7.19	7.2	7.35	7.23	7.17	7.0
LOI (%)	12.8	11.8	10.2	10.1	9.2	7.22	6.45

SO₃ - Sulphate (III) Oxide; SO₄ - Sulphates (IV) Oxide; Cl - Chloride Content; LOI - Loss on Ignition

Table 3: Mix proportions for stabilization (in percentages)

Neat material (NBC)	Heated soil (HBC)	Lime
80	20	0
80	18	2
80	16	4
80	14	6
80	12	8

of montomorillonite and water mobilized the swell potential due to the significant presence of the albite. The chemical tests done which included oxide content indicated that the calcium levels as CaO were low (less than 3%) for NBC and HBC and that they were pozzolanic agreeing with Greaves (1996) and Sherwood (1993) that clay minerals are natural pozzolans. However, pozzolanic action can only be manifested in the presence of water and calcium hydroxide.

The sulphates, chlorides, pH and loss on ignition determined in the MTIHUDEMTRD laboratories were as shown in Table 2.

The highest sulphate content as SO₄ was 0.097% for HBC at 700°C. High levels of SO₄ in clays cause the SO₄ to react with CaO for lime stabilized soils, to form ettringite [Ca₆Al₂(OH)₁₂(SO₄)₃.27H₂O] or thaumasite [CaSiO₃.CaCO₃.CaSO₄.14.5H₂O] which results in expansion and heave of the stabilized soil, causing distress in the structures built on the soil, which may lead to failure (Kavak and Bilgen, 2016; Beetham *et al.*, 2015; Bell, 2007; Mitchell and Soga, 2005; Rajasekaran and Rao, 2005). SO₄ level in lime stabilized clays should therefore not exceed 0.25% (Beetham *et al.*, 2015). Thus, the NBC and HBC at all temperatures could be used in lime stabilization without any risk of formation of ettringite or thaumasite.

The highest chloride level was 0.044% for HBC at 200°C; all the other levels were lower, for the NBC and HBC. The chloride level has no adverse effect because chlorides can be used to stabilize expansive clays, for levels of up-to 2% for sodium chloride. Where

chlorides are used with lime, 1-5% sodium chloride can improve expansive soil with lime in the range 2-8% regardless of the percentage of lime (Davoudi and Kabir, 2011). The pH of the soil indicated a low alkaline level for the NBC and HBC at the tested temperatures. High levels of pH are desirable in lime stabilization. In lime stabilization, sufficient excess lime is added to ensure that the stabilized mixture maintains a pH value of at least 12.4 which is necessary to ensure the long-term stability of the hydration products (O'Flaherty, 2002; Dang *et al.*, 2016a, 2016b). There was progressive decrease in LOI due to combustion of organic matter. These results indicate that the NBC and HBC can be used in lime reactions without adverse effects.

Hydrated Lime was obtained from Athi River Mining of Nairobi.

Stabilization: Air dried NBC soil was stabilized with varying mixes of HBC soil and lime. A hand mixing process was adopted to ensure a homogeneous mix for a maximum stabilizer content of 20%. The specimens made were cylindrical 50 mm in diameter and 100 mm in length at moisture contents of 24, 28, 32 and 36%, respectively enveloping the optimum moisture content of the neat material.

Compaction was done in three layers and the specimen extruded with a metal plunger from a cylindrical mould, after which they were wrapped with cling film to regulate moisture movement. The mix ratios were as tabulated in Table 3. For each mix ratio, 16 specimens were made for each temperature of 200, 300, 400, 500, 600 and 700°C a total of 400 specimens. UCS tests were done in accordance with ASTM D559/D559M-15 (2015): Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures. The method is used to determine the resistance of compacted soil-cement specimen to repeated wetting



Fig. 1: Specimens curing

and drying. This was done on each specimen after moist curing at room temperature for periods of 7, 14, 21, 28 days with samples wrapped in cling film to prevent rapid moisture loss.

From tests on these specimens, an optimum mix was obtained with the highest UCS value at an acceptable temperature of heated soil and lime content. Specimens were then made of the optimum mix which were subjected to various tests, making four specimens for each test.

There is a trend to use UCS as an alternative to CBR as the default test for strength for road works (Thomas, 2001) since UCS is better than CBR as a strength test because CBR being a penetration method is not good for soils taking tension as is the case in roads (Bandara *et al.*, 2017). Further, the CBR tests also use too much material (Thomas, 2001). Thus, the strength tests for the trial mixes and the optimum mix for the various curing regimes were done in terms of UCS, to British Standards BS 1377 (1990). However, since the 7-day cure 7-day soak CBR test is the standard test for stabilized materials, it was done for the optimum mix in this research to compare the results with strength requirements in Kenya which are still in terms of CBR (MOTC, 1986; MOTC, 1987). Compaction characteristics and CBR were done to British Standards BS 1377 (1990).

Long term curing and simulated flooding regimes:

UCS and physical properties comprising grading and Atterberg limits (British Standards BS 1377, 1990), free swell according to the method proposed by Holtz and Gibbs (1956) and XRD were tested after moist curing at room temperature for periods of 7, 14, 28, 56 and 90 days, with samples wrapped in cling film to prevent rapid moisture loss (Fig. 1) to investigate effect of long-term curing.

To simulate different flooding scenarios, UCS tests were done for specimens partially soaked in water for 4 and 10 days to simulate a normal flood and fully soaked/submerged for 4 and 10 days to simulate severe

flooding, after each of the moist curing periods (Obuzor *et al.*, 2011; Obuzor *et al.*, 2012). Hossain *et al.* (2006) considered a moist curing period of 84 days followed by immersion in water for 7 days. The simulation by Obuzor *et al.* (2011) and Obuzor *et al.* (2012) was adopted since it represents a more severe scenario. The partial soaking was achieved by immersing 10 mm of the specimen in water.

RESULTS AND DISCUSSION

Test results for trial mixes: The neat black cotton soil (NBC) was maintained at 80% for all mixes and thus the references were called out only in terms of the stabilizers' mixes, while the binder proportions were varied. Thus mix 16-4 means 16% HBC and 4% lime as stabilizers. Max values were obtained at 36% compaction moisture content, due to the high-water demand for lime hydration. Peak values were obtained from mixes of 16-4, 14-6 and 12-8 for all the temperatures. Plots were therefore done for these mixes for each temperature of HBC, as shown in Fig. 2.

The highest UCS values were established as 264.5, 398 and 333 kN/m² for mix 16-4, 14-6 and 12-8 with HBC at 400°C respectively and 458 kN/m² for mix 12-8 with HBC at 600°C. Relatively low UCS values were obtained for HBC at 200, 300°C, 500°C and 700 °C. This was very consistent for all the mix ratios. Though the highest strength was 458 kN/m² for mix 12-8 with HBC at 600°C, it was disregarded because of the high temperature of HBC and the fairly high lime content. Therefore, the optimal mix was selected as 14-6, with a strength of 398 kN/m² for a temperature of HBC at 400°C and lime content of 6%. Generally, strength increases with increase in lime content for lime-stabilized soils up-to a certain level, after which the strength decreases or remains constant with addition of lime (Bell, 1996; O'Flaherty, 2002). A maximum UCS value of 360 kN/m² was obtained at lime content of 6.2% with lime as the only stabilizer for 7 days soak and 7 days cure. The strength of the optimal mix was 12% greater than this and will therefore perform better as a fill material.

Properties of the optimal mix: These are compaction, CBR, UCS, grading, swelling characteristics and XRD.

Compaction test results: The compaction results for the optimal mix are illustrated in Fig. 3.

The Maximum Dry Density (MDD) was 1348 kg/m³ with an optimum moisture content of 30%, at about 7.5% air voids, compared to NBC values which were 1272 kg/m³, 29.5% and 11% respectively.

The specific gravity was 2.58 which was an increase of 10% from the value for the neat material which was 2.47. Thus, the stabilizing improved the

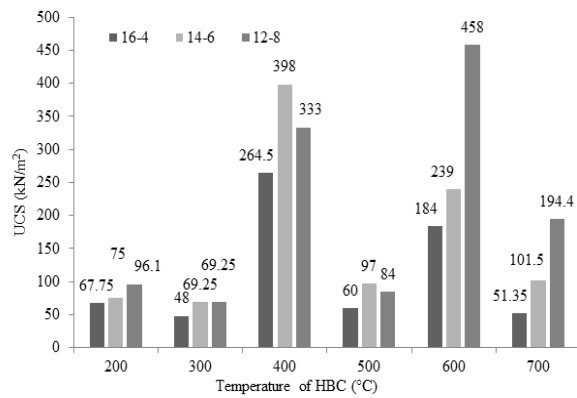


Fig. 2: UCS for selected trial mixes

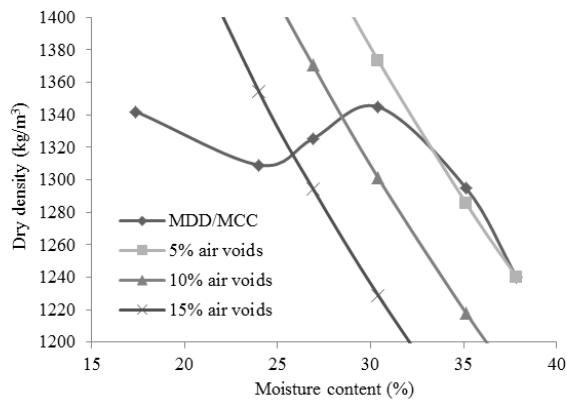


Fig. 3: Compaction test results for optimal mix

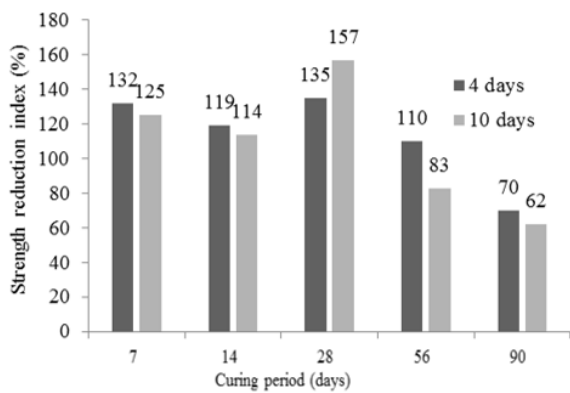


Fig. 4: SRI values for partial soaking

packing together of the soil particles. A highly permeable lime stabilized material can potentially lose strength through softening and removal of the pozzolanic products (McCallister and Petry, 1992; Le Runigo *et al.*, 2009). Compaction should therefore achieve a minimum air voids value throughout the fill (Sherwood, 1992). Ingress of water in a highly permeable material causes the calcium silicate hydrates (C-S-H) to de-constitute into Ca(OH)_2 and silicate when the water is of neutral pH and Ca^{2+} levels are low,

raising the pH and Ca^{2+} levels. CSH gel continues to de-constitute with the supply of more water (Taylor, 1990). In this study, the reduction of air voids by 32%, increase of specific gravity and MDD by 10% and 6% respectively gave a less permeable material, with a high durability suitable as fill material in high moisture conditions.

CBR results: The CBR increased from 1% for the NBC to 39.6% for the lime-HBC-NBC mixture, a percentage increase of 3860%, while the CBR swell reduced from 4.95 to 0.22%. The lime-HBC-NBC stabilized soil under test was class S6, with the CBR value exceeding the minimum required value of 30% for this class, with a negligible swell value. Thus, the stabilized material is suitable as a fill and subgrade material. The higher the subgrade strength, the more economical are the sub-base and base layers for any desired pavement structure (MOTC, 1987).

Effect of long-term curing and simulated flooding regimes on strength: The effect of long term curing and simulated flooding regimes was investigated by soaking the cured samples in water for specified periods and then taking the UCS value at the end of these periods. The durability of the stabilized soil was measured in-terms of the Strength Reduction Index (SRI) which is an empirical way of expressing the strength of a soaked material as a percentage of the same material in its un-soaked state. It is also called the durability index (Obuzor *et al.*, 2012; Hossain *et al.*, 2006; Thomas, 2001). The results for partial and full soaking regimes which simulate a normal and a prolonged flood are illustrated in Fig. 4 and 5 respectively for 4- and 10-days soaking periods. The 4- and 10-days soaking periods simulate the effect of a flash flood and a severe flood respectively.

As illustrated in Fig. 4, the 4 days partial-soak SRI values were above 100%, up-to 56 days of curing and then dropped to 70% at 90 days. This reflects a very high level of stability of the stabilized soil. The partial saturation ensured gradual availability of water for the hydration process, enhancing the curing process. The 10 days partial-soak SRI values were above 100%, up-to 28 days of curing and then dropped to 83% and 62% for 56 and 90 days curing respectively. They were generally below the values for the 4 days soak, except for the 28 days cure which was 22% higher. This represents a high level of stability up-to 28 days of curing, with a drop to 83% and 62% for 56 and 90 days respectively. The normal severe flood therefore has a more severe impact than the normal flash flood. Despite this the lowest strength recorded for a normal flood scenario was 75 kN/m^2 at 56 days curing, which is strength of a Kenyan red soil which has UCS values in the range 75-100 kN/m^2 and is used for fill and subgrades where it is available. It is worth noting that the strength recovered and became 139 kN/m^2 at 90 days. Most road construction projects have construction projects exceeding one year and therefore by the time

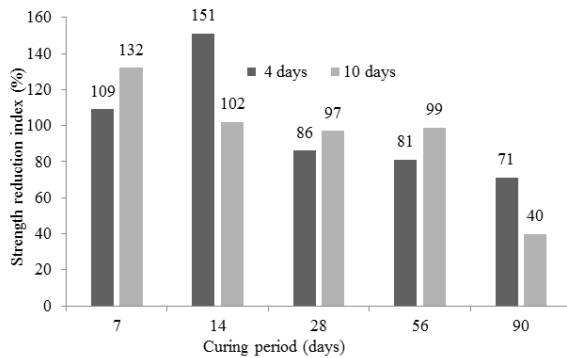


Fig. 5: SRI values for full soaking

the road is fully loaded, the strength of the fill and subgrade will have recovered even if the road were to experience flooding during the construction period.

Therefore, the stabilized soil is suitable for use as a fill and subgrade material for road construction for flash floods, without risk of collapsing. The best curing period for normal flooding is 28 days which increased the strength by 35% and 57% for the 10 days and 4 days partial soak respectively.

As illustrated in Fig. 5, the 4 days submerged samples had SRI values higher than 100% for 7- and 28-days curing, while SRI values decreased steadily from the 28, 56- and 90-days curing period. Except for the 14- and 90-days cure, the SRI values for the 4 days soak were lower than for the 10 days soak. The latter were basically 100% and over except for the 90 days cured sample which was 40%. The UCS for this latter scenario was 89 kN/m² which is a good strength for fills and subgrade. The lowest strength for full submergence was 73 kN/m² for 56 days cure and 4 days soak. However, there was good recovery and the 90 days cure, 4 days soak gave a strength of 158 kN/m².

The stabilizing thus produced a strong durable material, useful for fills in roads, buildings and other lightly loaded structures and also as a subgrade material for roads. The material withstood the worst simulated environment of severe prolonged flooding.

In both the normal and severe flooding regimes, there was a general trend of decrease in strength as the curing period increased as illustrated in Fig. 4 and 5. The drop-in strength at 56 days curing was a maximum of 19% which is considered not too significant, because the stabilized soil needed adequate moisture to satisfy the moisture demand for completion of the lime and lime-heated soil activated pozzolanic and hydration reactions. The greatest reduction was 40% for 90 days cured severe prolonged flooding scenario. According to Obuzor *et al.* (2012) in lime-activated Ground Granulated Blast furnace Slag (GGBS) stabilized soil, SRI values increase up-to 56 days, after which they start decreasing because the active period of moisture demand approaches its ultimate at 56 days when the hydration reaction nears completion. Further addition of

moisture causes water to enter into the void spaces, causing a deleterious effect of reduced strength. At this point, the free lime and pH are in short supply. In this study, the same trend is apparent. The active period for moisture demand was ultimate at period of 56 days when the strength stabilized and hydration apparently had reached completion. However, it may not be practical to allow for a long curing period on site. Wild *et al.* (1998) suggested a moist curing period of 28 days before the stabilized fill material gets saturated with water, which agrees very well with the results of this study where the maximum loss of strength was 14% for the 28 days cured 4 days soak severe flooding regime.

Generally, the pozzolanic products of lime stabilization are Calcium-Silicate-Hydrate (CSH), Calcium-Aluminate-Silicate-Hydrate (CASH) from hydration and pozzolanic reaction (Das, 2016; Dang *et al.*, 2016a), with CSH being the principal cementitious product resulting in enhanced strength of the stabilized material (Saravanan *et al.*, 2017; Kavak and Bigen, 2016; Obuzor *et al.*, 2012; Wild *et al.*, 1999; Sharma and Sivapullaiah, 2016). These products contribute to the flocculation process by bonding adjacent soil particles together into larger-sized aggregates which strengthen the soil as curing occurs. However, where free lime and Ca²⁺ and pH are in short supply especially when water enters the voids of stabilized soil particles, the CSH de-constitutes into Ca(OH)₂ and silicate (Taylor, 1990). Although this raises the pH and Ca²⁺, with the supply of more water the CSH gel will continue to de-constitute, explaining why the strength dropped for curing periods of 56 and 90 days in flooding scenarios. This is what happened to the lime-activated heated soil-black cotton mixture in this research. The pozzolanic properties of the heated soil had the same effect as the GGBS, although GGBS is a calcium rich alluminosilicate, compared to the HBC at 400°C which is a low calcium pozzolanic alluminosilicate. Therefore, the heated soil at 400°C is effective as a low calcium pozzolanic alluminosilicate precursor in stabilization of black cotton soils, which aided in formation of more CSH gel and change in micro-pore orientation, forming a strong durable material for use as a fill material for roads and ground floor slabs and also for use as a subgrade. Ideally the stabilized soil should be moist cured for 28 days before exposure to flooding. These 28 days period gave the higher SRI values for normal flooding, with hardly any change between the 28- and 56-days cure for the prolonged flooding.

Grading/particle size distribution: The grading test results are shown in Fig. 6, for moist curing periods of 7, 14, 28, 56 and 90 days respectively. Fine soils have at least 35% by mass finer than 0.06 mm while coarse soils have less than 35%

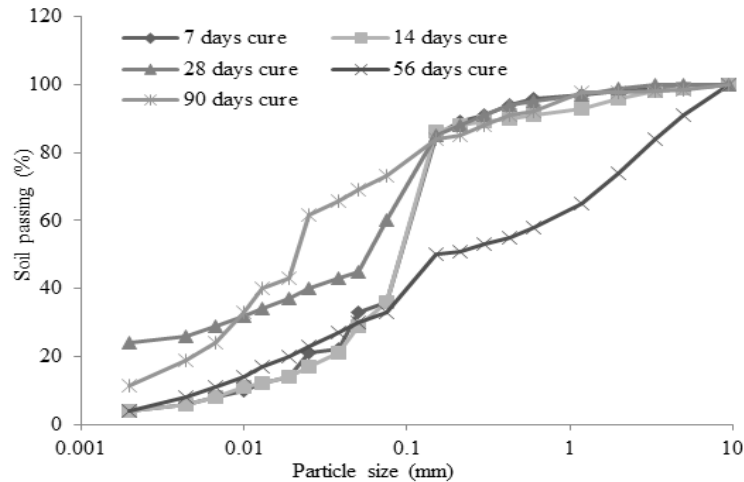


Fig. 6: Grading for various curing periods

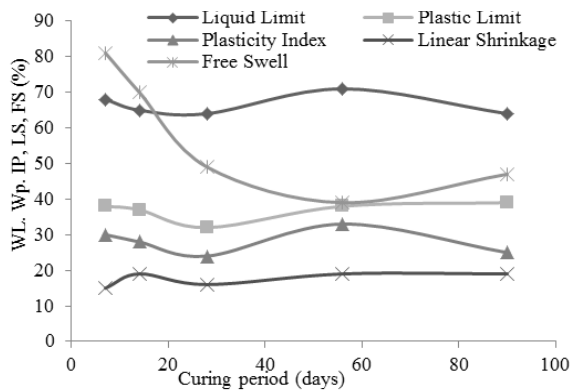


Fig. 7: Swelling characteristics

finer than 0.06 mm. The samples cured for 7, 28, 56 and 90 days were fine, whereas the samples cured for 14 days were coarse. The first process that occurs when hydrated lime is added to a clay is lime modification followed by stabilization. Modification is a rapid cation exchange process which forms cementitious products in a flocculation-agglomeration process, transforming the clay into a more silt-like or sand-like material which has improved plasticity, swelling, workability and stability resulting into a better fill material (O’Flaherty, 1974; O’Flaherty, 2002; Dang *et al.*, 2016a).

The combined silt and sand content obtained in the stabilized soil was above 50%, as a result of modification; the maximum clay content was 24% at 28 days cure, a reduction of 31% which gave a better fill material, with improved swelling characteristics due to reduced influence of the clay fraction. Silts, sands and gravels are normally non-plastic (Mitchel and Soga, 2005). The plasticity was established from Atterberg limits as discussed below, because grading is not a measure of plasticity.

Atterberg limits and free swell for varying curing periods: The swelling characteristics of the stabilized

soil are shown in Fig. 7. The liquid limit (W_L), the plastic limit (W_p), the plasticity index (I_p) and the Linear Shrinkage (LS) experienced very minor changes during the whole 90 days curing period, while the Free Swell (FS) decreased steadily.

In the curing periods of 7, 14, 28, 56 and 90 days respectively, the key index property of I_p dropped from 30 to 25%, while the W_L dropped from 68 to 64% from 7 days to 90 days of curing respectively. These results indicate that the swelling properties of the stabilized black cotton improved during long term curing.

The lime-HBC-NBC system behaviour is apparently very similar to behaviour of a lime stabilized expansive clay, which causes cation exchange by replacing the monovalent ions adsorbed on the clay surface with the divalent Ca^{2+} in the lime, reducing the diffuse double layer thereby causing attraction between the clay particles forming flocs with reduced swelling properties, during the modification stage.

According to O’Neil and Poormoayed (1980), suitable fill material for road construction should have a marginal swell potential, with W_L ranging between 50-60% and I_p between 25-35%. However, MOTC (1987) limits the I_p to a maximum of 20 for stabilized material, without a qualification on W_L . Based on these two requirements, the stabilized soil can be classified as being of marginal swell potential and thus suitable as fill material for road construction; the I_p is only nominally above 20% while the negligible value of CBR swell of 0.22% noted above affirms a non-swelling product. The linear shrinkage remained below 20% throughout the curing period, whereas the FS dropped to below 50% after 28 days curing. Lightly loaded structures such road pavements, residential buildings and canal linings suffer most damage when built on expansive soils (Chen, 1988). For free swell values below 50%, there is no appreciable volume change during wetting or drying even under light loads

Table 4: Variation of classification with curing period

Curing period (days)	Description	Symbol
7	Gravelly SILT of high plasticity	MHG
14	Very silty SAND of high plasticity	SMH
28	Gravelly SILT of high plasticity	MHG
56	Very clayey SAND of high plasticity	SCH
90	Sandy SILT of high plasticity	MHS

Table 5: Clay minerals as a percentage of all minerals

Mineral	Curing period (days)				
	7	14	28	56	90
Albite	24.9	21.2	21.7	18.6	23.9
Microcline	24.6	27.6	29.0	37.2	34.9
Montmorillonite	6.6	10.1	8.4	4.6	5.9
Calcite	16.0	15.4	11.5	15.1	14.8
Imogolite	5.1	5.9	0	3.4	3.3
Kaolinite	0	0	1.3	2.1	0

(Holtz and Gibbs, 1956). The formation of CSH, CAH and CASH during the curing process as noted earlier gave a strong and durable material (Dang *et al.*, 2016a; Das, 2016; O’Flaherty, 2002) suitable as a fill material for road construction and other light structures such as ground floor slabs.

Classification for varying curing periods: The classification was done as for the stabilized material based on the British System Classification System (British Standards BS 5930, 1990). The results are shown on Table 4, for the various curing periods.

The soil after stabilizing was either a silt or a sand of high plasticity. The modification process in stabilization transformed the clay into a more silt-like or sand-like material which improved plasticity, swelling, workability and stability resulting into a better fill material (O’Flaherty, 1974; O’Flaherty, 2002; Dang *et al.*, 2016a).

Although the stabilized soil is classified as of high plasticity it has a marginal swell potential, with negligible CBR swell and therefore suitable as fill material for road construction.

XRD Properties: The percentages of the clay minerals were as shown in Table 5 for the various curing periods.

There were three broad peaks for 2θ between 5 and 62° while the number of minerals varied from 5 to 7. The main clay minerals were albite and microcline, whose percentage sum by weight were 49.5, 48.8, 50.7, 55.8 and 58.8 for the samples cured at 7, 14, 28, 56 and 90 days respectively. The percentages for the NBC are shown in Table 1, which shows that the percentage of albite and microcline were 26.2 and 38.5 respectively, giving a total of 64.7%. The montmorillonite increased from 3.3% for the neat to 6.6, 10.1, 8.4, 4.6 and 5.9 % for the 7, 14, 28, 56 and 90 days curing respectively. The most significant increase was for the calcite, which increased from 5.8% for the neat soil to 16, 15.4, 19.5, 15.1 and 14.5% for 7, 14, 28, 56 and 90 days curing

respectively. Calcite is mainly calcium carbonate, which formed due to cementitious reactions (Solanki and Zaman, 2012). Despite the relative increase in the montmorillonite and the presence of albite, the soil remained non-swelling as indicated by the low CBR swell value of 0.22% accompanied with a high strength value as measured by CBR, which was 39.6% for the 7 days cure and 7 days soak indicating high strength stability.

CONCLUSION

- An optimal lime-activated stabilizer for black cotton soil with low calcium pozzolanic alluminosilicate heated black cotton soil heated at 400°C as the precursor was obtained, comprising 14% heated black cotton soil at 400°C and 6% lime. The stabilized black cotton is able to withstand harsh full soaking period of 10 days, representing a prolonged severe flood. Though the durability decreased with increasing curing period, the final product was acceptable as a fill and subgrade material at 90 days curing and 10 days soaking.
- The stabilized black cotton soil resulted into a very strong, non-swelling material with a very high soaked CBR of 39.6% and a CBR swell 0.22% giving a class S6 subgrade, suitable as a fill and subgrade material for roads and as a fill for ground floor slabs and other lightly loaded structures.
- The HBC at 400°C behaves in a similar manner to GGBS mixture in the stabilization process. GGBS is not available in Kenya since Kenya does not smelt iron ore. Thus, the HBC at 400°C is a suitable locally available low calcium aluminosilicate precursor for lime activation, in one-part geopolymer reactions whose effectiveness depends on local availability of binders (Provis, 2018).
- The use of the HBC at 400°C-lime mixture in-place will reduce negative environmental effects of dumpsites, reduce pressure on arable agricultural land as a source of fill material and reduce carbon dioxide emission in haulage of fill materials as well increase cost efficiency.

ACKNOWLEDGMENT

We acknowledge with gratitude the funding received from Jomo Kenyatta University of Agriculture and Technology (JKUAT). We are also thankful for the support given by the Sustainable Materials Research and Technology Centre (SMARTEC), the Department of Civil, Construction and Environmental Engineering both of (JKUAT), the Ministry of Transport, Infrastructure, Housing & Urban Design Materials Testing and Research Department (MTIHUDMTRD) laboratories in Nairobi and the soils laboratories of the

International Centre for Research in Agroforestry (ICRAF), Nairobi for availing their facilities for material testing.

REFERENCES

- ASTM D559/D559M-15, 2015. Standard Test Methods for Wetting and Drying Compacted Soil-cement Mixtures. ASTM International, West Conshohocken, PA.
- Bandara, W.W., W.K. Mampearachchi and K.H.S.M. Sampth, 2017. Cement stabilized soil as a road base material for use in Sri Lankan roads. *Engineer*, L(1): 21-29.
- Beetham, P., T. Dijkstra, N. Dixon, P. Fleming, R. Hutchison and J. Bateman, 2015. Lime stabilisation for earthworks: A UK perspective. *P. I. Civil Eng. Ground Improv.*, 168(2): 81-95.
- Bell, F.G., 1993. *Engineering Treatment of Soils*. E&FN Spon, London.
- Bell, F.G., 1996. Lime stabilization of clay minerals and soils. *Eng. Geol.*, 42(4): 223-237.
- Bell, F.G., 2007. *Engineering Geology*. 2nd Edn., Butterworth-Heinemann, Oxford, Burlington, MA.
- Bhavsar, S.N. and A.J. Patel, 2014. Analysis of swelling and shrinkage properties of expansive soil using brick dust as a stabilizer. *Int. J. Emerg. Technol. Adv. Eng.*, 4(2): 303-308.
- British Standards BS 1377, 1990. *Methods of Test for Soils for Civil Engineering Purposes*. HMSO, London.
- British Standards BS 5930, 1990. *Code of Practice for Site Investigations*. HMSO, London.
- Chen, F.H., 1975. *Foundations on Expansive Clays*. Elsevier, Amsterdam.
- Chen, F.H., 1988. *Foundations on Expansive Clays*. Elsevier, New York.
- Dang, L.I., H. Hassan, B. Fatahi, R. Jones and H. Khabbaz, 2016a. Enhancing the engineering properties of expansive soil using bagasse ash and hydrated lime. *Int. J. Geomate*, 11(25): 2447-2454.
- Dang, L.C., B. Fatahi and H. Khabbaz, 2016b. Behaviour of expansive soils stabilized with hydrated lime and bagasse fibres. *Procedia Eng.*, 143: 658-665.
- Das, B.M., 2016. *Principles of Foundation Engineering*. 8th Edn., Cengage Learning India Private Ltd., New Delhi.
- Davoudi, M.H. and E. Kabir, 2011. Interaction of lime and sodium chloride in a low plasticity fine grain soils. *J. Appl. Sci.*, 11: 330-335.
- Greaves, H.M., 1996. An introduction to lime stabilisation. *Proceeding of the Seminar Held at Loughborough University Civil and Building Engineering*, Thomas Telford Publishing, London, pp: 5-12.
- Holtz, W.G. and H.J. Gibbs, 1956. *Transactions of ASCE*, 121: 666-669.
- Hossain, K.M.A., M. Lachemi and S. Easa, 2006. Characteristics of volcanic ash and natural lime based stabilized clayey soils. *Can. J. Civil Eng.*, 33(11): 1455-1458.
- Kalantari, B., 2012. Foundations on expansive soils: A review. *Res. J. Appl. Sci. Eng. Technol.*, 4(18): 3231-3237.
- Karatai, T.R., J.W. Kaluli, C. Kabubo and G. Thiong'o, 2016. Soil stabilization using rice husk ash and natural lime as an alternative to cutting and filling in road construction. *J. Constr. Eng. Manage.*, 143(5): 04016127.
- Kavak, A. and G. Bilgen, 2016. Reuse of Ground Granulated Blast Furnace Slag (GGBFS) in lime stabilized embankment materials. *IACSIT Int. J. Eng. Technol.*, 8(1):11-14.
- Le Runigo, B., O. Cuisinier, Y.J. Cui, V. Ferber and D. Deneele, 2009. Impact of initial state on the fabric and permeability of a lime-treated silt under long-term leaching. *Can. Geotech. J.*, 46(11): 1243-1257.
- Lee, S.L. and G.P. Karunaratne, 2007. Treatment of soft ground by fibredrain and highenergy impact in highway embankment construction. *P. I. Civil Eng. Ground Improv.*, 11(4): 181-193.
- Li, J., X. Wu and L. Hou, 2014. Physical, mineralogical, and micromorphological properties of expansive soil treated at different temperature. *J. Nanomater.*, 2014: 1-7
- Luukkonen, T., Z. Abdollahnejad, J. Yliniemi, P. Kinnunen and M. Illikainen, 2018. One-part alkali-activated materials: A review. *Cement Concrete Res.*, 103: 21-34.
- McCallister, L.D. and T.M. Petry, 1992. Leach tests on lime-treated clays. *Geotech. Testing J.*, 15(2): 106-114.
- Mehta, K.S., R.J. Sonecha, P.D. Daxini, P.B. Ratanpara and S.K. Gaikwad, 2014. Analysis of engineering properties of black cotton soil & stabilization using lime. *Int. J. Eng. Res. Appl.*, 4(5): 25-32.
- Mokhtari, M. and M. Dehghani, 2012. Swell shrink behaviour of expansive soils, damage and control. *Elect. J. Geotech. Eng.*, 17: 2673-2682.
- MOTC, 1986. *Standard Specification for Road and Bridge Construction*. Roads Department, Ministry of Transport and Communication, Nairobi.
- MOTC, 1987. *Road Design Manual Part III*. Roads Department, Ministry of Transport and Communication, Nairobi.
- Mitchell, J.K. and K. Soga, 2005. *Fundamentals of Soil Behaviour*. 3rd Edn., John Willey and Sons, Inc., New Delhi.
- Nelson, J.D. and D.J. Miller, 1992. *Expansive Soils: Problems and Practice in Foundation and Pavement Engineering*. John Willey and Sons, Inc., New York.

- Obuzor, G.N., J.M. Kinuthia and R.B. Robinson, 2011. Utilization of lime activated ground granulated blast furnace slag to reduce the deleterious effect of flooding on stabilized road structural materials: A laboratory simulation. *Eng. Geol.*, 122(3): 334-338.
- Obuzor, G.N., J.M. Kinuthia and R.B. Robinson, 2012. Soil stabilisation with lime-activated-GCBS-A mitigation to flooding effects on road structural layers/embankments constructed on floodplains. *Eng. Geol.*, 151: 112-119.
- O'Flaherty, C.A., 1974. *Highways, Highway Engineering*. 2nd Edn., Edward Arnold, London, Vol. 2.
- O'Flaherty, C.A., 2002. *Highways*. 4th Edn., Butterworth-Heinemann, Oxford.
- O'Neil, M.W. and N. Poormoayed, 1980. Methodology for foundations on expansive clays. *J. Geotech. Eng. Div.*, 106(12): 1345-1367.
- Phanikumar, B.R., A.S. Rao and K. Suresh, 2008. Field behaviour of granular pile-anchors in expansive soils. *P. I. Civil Eng. Ground Improv.*, 161(4): 199-206.
- Provis, J.L., 2018. Alkali-activated materials. *Cement Concrete Res.*, 114: 40-48.
- Prusinski, J.R. and S. Bhattacharja, 1999. Effectiveness of Portland Cement and Lime in Stabilizing Clay Soils. Transport Research Board, 1652, Portland Cement Association, Washington D.C.
- Rajasekaran, G. and S.N. Rao, 2005. Sulphate attack in lime-treated marine clay. *Marine Georesour. Geotechnol.*, 23: 93-116.
- Saravanan, R., T. Udhayakumar, S. Dinesh, C. Venkatasubramanian and D. Muthu, 2017. Effect of addition of GGBS and lime in soil stabilisation for stabilising local village roads in Thanjavur region. *IOP C. Ser. Earth Env.*, 80(1): 012060.
- Satyanarayana, P.V.V., S.K. Vijaya, R.G. Mohan and P.B.V. Jaya, 2016. A study on the engineering properties of expansive soil stabilised with fly ash and lime mixes. *Int. J. Emerg. Technol. Adv. Eng.*, 6(4): 54-58.
- Sharma, A.K. and P.V. Sivapullaiah, 2016. Ground granulated blast furnace slag amended fly ash as an expansive soil stabilizer. *Soils Found.*, 56(2): 205-212.
- Sherwood, P.T., 1992. Stabilized capping layers using either lime, or cement or lime and cement, Contractor Report 151. Transport and Road Research Laboratory, Berkshire.
- Sherwood, P.T., 1993. *Soil Stabilization with Cement and Lime*. HMSO, London.
- Skippervik, C.P., 2014. Study on the swelling potential of some selected rocks. M.Sc. Thesis, Submitted at the Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology.
- Solanki, P. and M. Zaman, 2012. Microstructural and Mineralogical Characterization of Clay Stabilized using Calcium-based Stabilizers. In: Kazmiruk, V. (Ed.), *Scanning Electron Microscopy*. Intechopen, London, pp: 771-798.
- Taylor, H.F.W., 1990. *Cement Chemistry*. Academic Press, New York.
- Terzaghi, K., R.B. Peck and G. Mesri, 1996. *Soil Mechanics in Engineering Practice*. 3rd Edn., John Wiley and Sons Inc., UK.
- Thomas, B., 2001. Stabilization of sulphide rich soil: Problems and solutions. Unpublished Ph.D. Thesis, University of Glamorgan, Wales.
- Wang, M.C., M. Jao and M.S. Ghazal, 2008. Heating effect on swelling behaviour of expansive soils. *Geomech. Geoen. Int. J.*, 3(2): 121-127.
- Wild, S., J.M. Kinuthia, G.I. Jones and D.D. Higgins, 1998. Effects of partial substitution of lime with ground granulated blast furnace slag (GGBS) on the strength properties of lime-stabilised sulphate-bearing clay soils. *Eng. Geol.*, 51(1): 37-53.
- Wild, S., J.M. Kinuthia, G.I. Jones and D.D. Higgins, 1999. Suppression of swelling associated with ettringite formation in lime stabilized sulphate bearing clay soils by partial substitution of lime with ground granulated blastfurnace slag (GGBS). *Eng. Geol.*, 51(4): 257-277.
- Wubshet, M. and S. Tadesse, 2014. Stabilization of expansive soil using bagasse ash and lime. *J. EEA*, 32: 21-26.
- Yang, H.P. and J.L. Zheng, 2006. The new engineering treatment techniques of expansive soils subgrade for Guangxi Nanning-Youyi Guan expressway. *Proceeding of the 4th International Conference on Unsaturated Soils*. ASCE Geo-Institute Arizona.