The Effect of Heat on the Properties of Expansive Clay Soil

Charles K. Kabubo[1]; Sixtus K. Mwea[2], Sylvester O. Abuodha[3], Zachary A. Gariy[4]

[1]Senior Lecturer, Sustainable Materials Research and Technology Centre, Jomo Kenyatta Univ. of Agriculture and Technology (JKUAT), P.O Box 62000-00200 Nairobi, Kenya

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

[3]Senior Lecturer, Department of Civil and Construction Engineering, University of Nairobi, P.O Box 30197 Nairobi, Kenya

[4]Associate Professor, Department of Civil Engineering, Construction and Environmental Engineering (JKUAT)

Abstract: ***The cost of cut to spoil of expansive soils during construction of infrastructure projects such as roads, airports, and housing estates has continued to increase due to high cost of excavation and haulage and the increasing scarcity of spoil areas due to development. Further, suitable borrow materials continue to deplete, with their locations getting further and further from the location where they would be required. The environmental consequences of cut to spoil and borrow to fill continue to soar. This has led into continuous research into suitable ways of improving and using expansive clays. Most research methods currently concentrate on attempting to stabilize these soils. The need to eliminate cut to spoil of expansive clays followed by borrowing suitable material for fill led to this research - improving the performance of expansive clays by subjecting it to high temperatures in a closed kiln to eliminate emission of greenhouse gases. This paper reports the effect of heating the expansive clay for 2 hours at a temperature of 600^{0}C. The properties of the neat material were investigated which included compaction, the California Bearing Ratio (CBR), grading, atterberg limits, linear shrinkage, free swell, chemical composition and loss on ignition (LOI). The same properties were investigated for the heated expansive clay. The heating increased the maximum dry density (MDD), the CBR, altered the particle size distribution, reduced the plasticity index, the free swell and linear shrinkage hence reduction in plasticity. The properties of the expansive soil were therefore improved. It was concluded that subjecting the soil to 600^{0}C makes it suitable as a fill material.***

Keywords: expansive clay, heated soil, CBR, MDD, plasticity, free swell, linear shrinkage

1. Introduction

The cost of cut to spoil of expansive soils during construction of infrastructural projects such as roads, airports, and housing estates has continued to increase due to high cost of excavation and haulage and the increasing scarcity of spoil areas due to development. Further, suitable borrow materials continue to deplete, with their locations getting further and further from the location where they would be required. Yang and Zheng (2006) as cited in Obuzor et al. (2012) give the classical option for road construction in flood plains with troublesome materials which has always been to excavate and import good material for replacement. According to Prusinski and Bhattacharja (1999) and Yang and Zheng (2006) as cited in Obuzor et al. (2012) excavation and importing 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. The environmental consequences of cut to spoil and borrow to fill continue to soar. There is thus need to continually research into methods of improving expansive clays in place. Most research methods currently concentrate on attempting to stabilize this soil; according Obuzor et al. (2012) lime stabilization has been used for many years to improve soil properties. This research looked into the effect of heating the expansive clays to 600^{0}Cand to determine if it would be suitable for use as fill material as an alternative to either lime stabilization or replacement with suitable material.

West (1995) as cited in Barasa et al. (2015) defines expansive soils as soils consisting of clays which shrink and swell with the primary clay being Smectite. Expansive soils are highly problematic because of their tendency to heave during wet seasons when they absorb water and shrink during dry seasons when water evaporates from them (Mishra et al., 2008 as cited in Barasa et al., 2015; Muthukumar and Phanikumar, 2015). Expansive soils are characterized by excessive compression, collapse, low shear strength, low bearing capacity, and high swell potential (Rao and Thyagara, 2007 as cited in Karatai et al., 2016). In drier seasons they can form deep cracks and expand dramatically when wet affecting their strength performance as a construction material (Tripathy et al. 2002 as cited by Karatai et al. 2016). There is therefore need for improvement of these soils. Doing so without need for excavating to spoil and importing suitable material would give tremendous advantages and convert the expansive soil which is a ***waste into riches*** thus contributing to ***sustainable development goals***.

Although heating is a high energy consumer, it has been used to convert waste into useful products. Rashad (2013) in a review of heat conversion of kaolin into metakaolin concluded that production of metakaolin can be done by calcining waste paper sludge or kaolin in temperature range of between 700^{0}C and 800^{0}Cfor 1 to 12 hours of heating, with the best temperature range for paper sludge being 600-800^{0}C for 2-5hours. Merino et al. (2010) developed simple mathematical equations to predict weight loss and porosity as a function of the treatment temperature, for soils treated up to 900^{0}C. Various researchers have worked on improvement of expansive soils using heat. Wang et al. (2008) found that the swelling potentials of two expansive ***commercial clays***, Edgar Plastic Kaolin (EPK) and Western Bentonite (WB) diminish when heated to about 400^{0}C for EPK and 600^{0}Cfor WB, and concluded that heating can effectively stop expansive soils from swelling. Thermal treatment reduces the swelling capacity and compressibility of clay soils (Bell, 1993). It has been used to prevent shear failure in clay soils and to stabilize clay slopes (Beles, 1957 as cited in Bell, 1993) and to stabilize collapsible loess by increasing its strength appreciably (Litinov, 1960 as cited in Bell, 1993 and Terzaghi et al., 1996).

As a clay soil is heated, it losses adsorbed water and hardens and its strength increases. If heated to a high enough temperature, the crystalline structure of clay minerals undergoes irreversible changes and the soil will remain hard (Bell, 1993). Thus, as the temperature is increased to more than 100^{0}C, the adsorbed water is driven off and the strength is further increased. Soils containing large proportions of organic colloids and colloidal minerals begin to develop some water resistance at 200^{0}C to 400^{0}C as fine particles begin to aggregate into granules. When the soil is heated to temperature of 400^{0}C to 600^{0}C, some irreversible changes occur which make the soil non plastic and non-expansive. The clay clods are converted into aggregates. A significant reduction in the plasticity index of clay occurs at 400^{0}C. After it has been heated to 600^{0}C, the moisture absorption capacity is significantly reduced. The permeability initially increases on heating up to 600^{0}C or 700^{0}C. Above these temperatures, the permeability decreases slightly as fusion and verification set in (Bell, 1993). With further increase in temperature, there is some fusion and verification, and a brick like material is obtained which can be used as an artificial aggregate for mechanical stabilization.

In-situ methods that have been successfully used include driving exhaust gasses from burning oil, at temperatures of about 1000^{0}C, into holes in the ground. The soil must not be saturated because the latent heat of evaporation of water makes it too expensive (Bell, 1993). This type of treatment has been done for depths of up to 20m. A borehole of 0.15 to 0.20 m in diameter stabilizes a column of some ten times as wide and depths of up to 10 m can be stabilized in 10 days (Evstatiev, 1988 as cited by Bell, 1993). This treatment has competed economically with pile foundations for large structures (Terzaghi et al., 1996).

As an alternative to in-situ methods, electric heaters have been used. In one system compressed air was blown through an electric heater at the top of a borehole, achieving temperatures ranging from 500^{0}C to 1200^{0}C. In another, the heaters were inserted in the borehole, baking the soil around the borehole to form a column. Interlocking columns can form structural walls and mats. This system treats soils regardless of water content or gas permeability. However, power and fuel consumption are high (Bell, 1993).

The changes that occur in clay soils brought about by heating produces hard durable construction materials with the following properties (O'Flaherty, 1974) :

1) Reduced compressibility, both soaked and un-soaked, due to decreased water sensitivity
2) Increased permeability due to shrinkage of clays by desiccation and the formation of cracks
3) Decreased plasticity index and a reduction in attraction of water.

Experimental data on the effect of heat on most of the properties that contribute to a soil being expansive is lacking. Further, Wang et al. (2008) published data for swelling behavior for commercial expansive clays. The research presented explored the effect of heating to 600^{0}C of naturally occurring expansive clay.

2. Materials and Methods

The expansive soil used in this research was black cotton soil obtained from Mwihoko area of Kiambu County, about 25 km North East of Nairobi City in Kenya. The material used was located 300mm below ground to avoid vegetable matter. The tests conducted on both the air dried neat and heated samples were compaction (proctor test T99), California Bearing Ratio (CBR), particle size distribution, plasticity index, linear shrinkage, free swell, chemical composition and loss on ignition. Four tests were conducted for each test and the mean value taken. Thermal treatment at 600^{0}Cwas done for 2 hours in a Elsklo s.r.o closed electric kiln with a power rating of 108 kVA, to eliminate emission of greenhouse gases (figure 1). The tests were done after the soil had cooled to room temperature, thus allowing for any possible reversal of properties.

Figure 1: Esklo s.r.o heating kiln –Sample in position

Compaction

The proctor test (T99) which was carried out in accordance with BSS 1377 (Part 4) :1990, was done using a 2.5 kg rammer on a dried pulverized material passing a 5mm test sieve. A graph for dry density versus moisture content was done and the maximum dry density at the optimum moisture content determined.

Determination of CBR

This test was conducted according to BS1377 (Part 4) :1990 on samples compacted in a compression machine in 3 equal layers and soaked for 4 days. According to this standard, the CBR value gives the relationship between force and penetration when a cylindrical plunger of a standard cross-section is made to penetrate the soil at a given rate. The

Paper ID: 28121602 DOI: 10.21275/28121602

CBR then is defined as the ratio of the applied force to a standard force at certain values of penetration, expressed as a percentage. The CBR was taken as the average resistance to penetration of 2.5mmand 5.00mm of a standard cylindrical plunger of cross sectional area of 1935 mm^2 for the top and bottom of the specimen expressed as a percentage of 13.2 kN and 20 kN respectively which are the resistances of the plunger in crushed aggregate for the same penetrations.

Determination of Particle Size Distribution (Grading)

The tests were done in accordance with BS1377 (Part 2): 1990, and were wet sieving on a nest of British Standard (BS) sieves in descending order on an oven dried material passing a 20mm sieve, and sedimentation by hydrometer analysis on soil finer than 63 micronssieve to the clay size. This enabled a continuous particle size distribution curve to be plotted from the size of the coarsest particles down to the clay size. A plot on a semi-logarithmic chart was then done of the percentage of material passing each sieve against the sieve sizes to give the grading.

Determination of Atterberg Limits/Soil Plasticity

These included the liquid limit, the plastic limit, the plasticity index and the linear shrinkage. They were carried out in accordance with BS1377 (Part 2) :1990.

Liquid Limit. (LL)

This is the water content at which the soil changes from liquid state to the plastic state. It was carried out using the cone penetrometer method since it is easier to carry out and gives more reproducible results than the earlier Casagrande test, according to BS 1377 (Part 2) :1990. It was done on a sample passing the 425 microns BS test sieve, and was determined as the moisture content at cone penetration of 20mm from a plot of the moisture content against the cone penetration.

Plastic Limit (PL)

This is the lowest moisture content at which the soil is plastic. The test was carried out using the paste from the liquid limit test. A sample was dried partially on a glass rolling plate and rolled between the plate and the finger. The plastic limit was determined as the moisture content at which a 3mm diameter thread sheared longitudinally and transversely.

Plasticity Index (PI)

This was determined as the difference between the Liquid Limit and the Plastic Limit (PI = LL-PL).

Linear Shrinkage (LS)

It was done on a sample passing a 425 microns test sieve, having the moisture content of the liquid limit. The sample was placed in a brass linear shrinkage mould, air dried for 2 days until the soil shrunk from the walls of the mould, after which it was oven dried at 105^0C. The length of the oven-dry specimen (Ld) was measured and the linear shrinkage calculated as a percentage of the original length of the specimen (Lo) as follows:

$$\text{Percentage of linear shrinkage} = (1-\frac{Ld}{Lo})\ x100 \qquad (1)$$

Free Swell

The test was carried out in accordance with the method proposed by Holtz and Gibbs (1956) on an air dried material passing the 425 micronstest sieve. The material was slowly poured into a graduated cylinder, after which the cylinder were filled with distilled water. The soil was allowed to settle and the initial volume of the soil taken as Li. The mixture was allowed to stand for 24 hours, and the swelled volume taken as Lf. The free swell was computed as follows:

$$\text{Free swell} = \frac{Lf-Li}{Li} x\ 100 \qquad (2)$$

Loss on Ignition

This test was done in accordance with BS 1377 (Part 3): 1990, to determine the percentage by mass that is lost from a soil by ignition at a temperature of 1000^0Cin an electric furnace on a sample passing the 425 micronstest sieve. The sample was placed in a previously dried crucible and dried to 50^0C in an oven, and then ignited at 1000^0C for 8 hours in the furnace, after which it was allowed to cool in a desiccator. The mass of the crucible and oven-dry soil specimen was taken as m1, the mass of the crucible and specimen after ignition taken as m2, while the mass of the crucible was taken as mC.

The Loss on Ignition (LOI) was computed as the percentage loss in mass as shown:

$$\text{LOI } (\%) = \frac{m1-m2}{m1-mC} \times 100 \qquad (3)$$

Chemical composition/Oxide Content test (X-ray Fluorescence, XRF)

The X-ray diffraction test was done on samples ground to a fine powder to analyze the soil for oxide composition, using a Ray ny EDX-800HS energy dispersive X-ray spectrometer at the Materials Testing and Research Division of the Ministry of Transport and Infrastructure, Nairobi (figure 2).

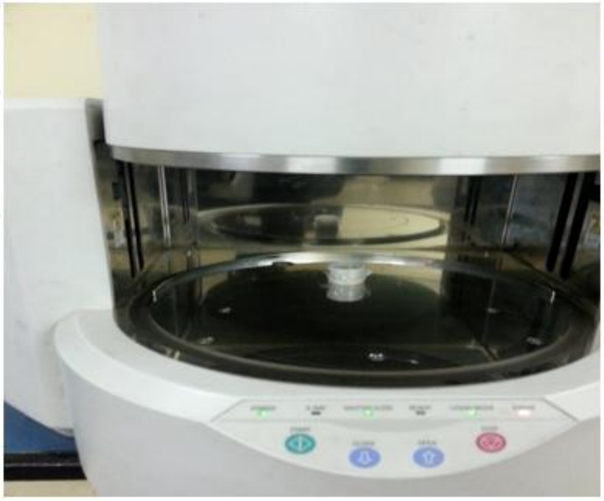

Figure 2.X-ray spectrometer - Specimen in position

3. Results and Discussion

Compaction Results

Figure 3 shows the compaction results for neat soil, giving the maximum dry density (MDD) as 1272 Kg/m^3 at an optimum moisture content (OMC) of 29.5%, whereas figure 5 shows the compaction results for neat soil, giving the

MDD of 1465 Kg/m^3 at an OMC of 29.0%. The heated soil has a higher MDD at about the same OMC as the neat soil, meaning that it will be stronger in service. This is probably due to formation of granules (Bell, 1993) which seem to bond better.

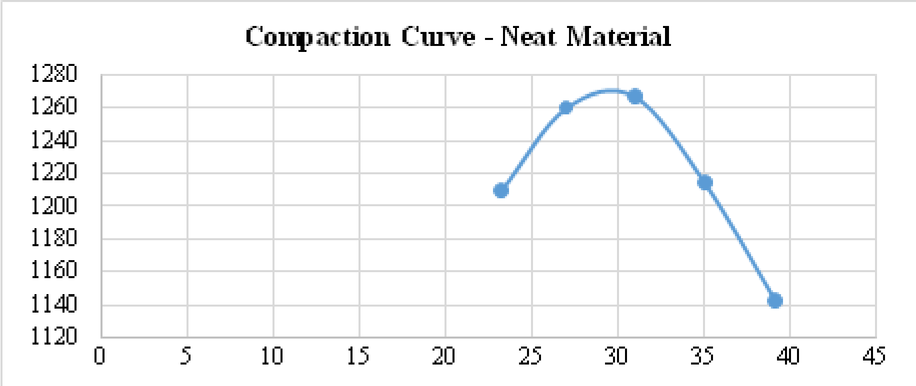

Figure 3: Graph of dry density (Kg/m^3) versus moisture content (%) (Neat black cotton soil)

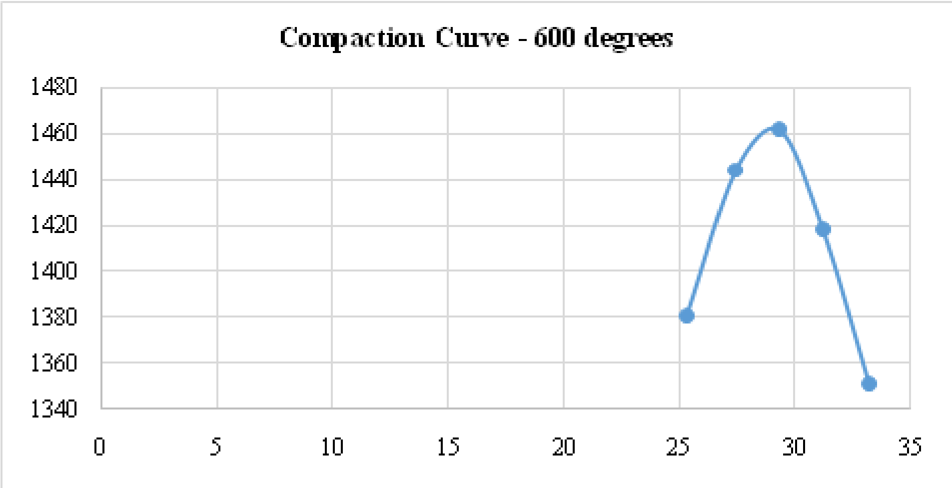

Figure 4: Graph of dry density (Kg/m^3) versus moisture content (%) (Heated soil to 600^{0}C)

Grading

Figure 5 shows the grading results for the neat material, showing that the material is predominantly clay (less than 0.002mm) at 37%, with a significant amount of silt (0.002-0.006mm) of one third (33%).

Figure 6 shows the grading results for the heated material, showing that the material is predominantly sand (0.006-2.0mm) at 45%, with a significant amount of gravel (greater than 2.00mm) of slightly more than one third (35%). The silt fraction (0.002-0.006mm) is 19%, while the clay fraction diminished. These results are consistent with those of Wang et al. (2008) who obtained a clay percentage of about 12% for commercial expansive WB at 600^{0}C, attributing it to destruction of the crystal structure of WB from de-hydroxylation as the temperature increased beyond 400^{0}C leading to formation of larger particles possibly due to electro-chemical bonds resulting in formation of larger particles. According Bell (1993), soil at temperatures of between 200 and 400^{0}Cbegins to aggregate into granules and when the soil is heated to temperature of 400^{0}C to 600^{0}C, some irreversible changes which make the soil non-plastic and non-expansive. Wang et al. (2008) also suggested that the formation of the larger particles is irreversible. Thus the black cotton under study experienced de-hydroxylation followed by an irreversible formation of larger particles/granules explaining the 80% combined sand and gravel fractions.

Paper ID: 28121602
DOI: 10.21275/28121602

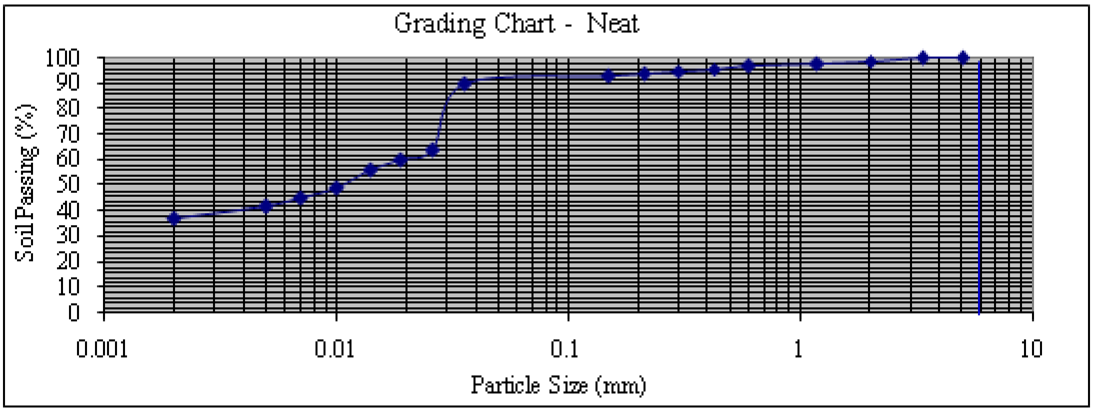

Figure 5: Grading curve for neat black cotton soil

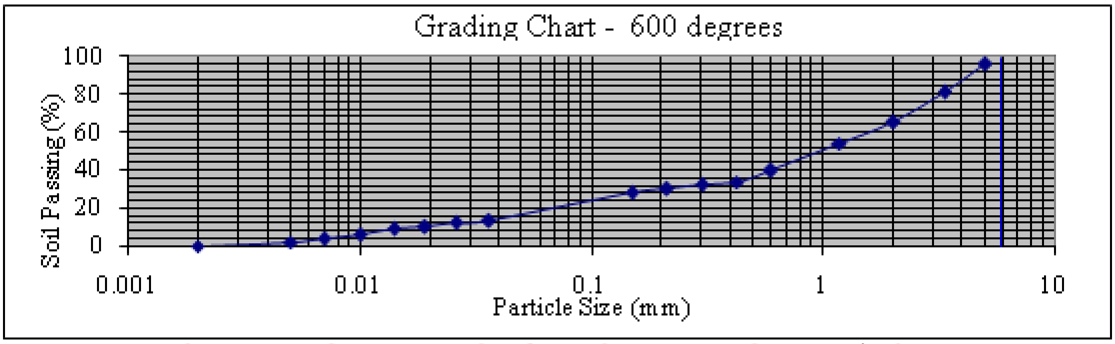

Figure 6: Grading curve for black cotton soil heated to 600^0C

Chemical Analysis of Neat and Heated Soil

Table 1 shows the oxide content as well as the Loss on Ignition of both the neat and the heated soil. The main oxides in both are Silicon, Aluminum and Iron. There was a reduction in Silicon, an increase in both Aluminum and Iron. These chemical changes are irreversible, if the heated soil were to be used as fill at normal temperatures. There was a reduction in LOI when the soil was subjected to a temperature of 600^0C, due to combustion of organic matter at the high temperature. This is also irreversible.

Table 1: Chemical Analysis of Neat and Heated Soil

Reference	Neat Black Cotton Soil	Black Cotton Heated to 600^0C
Silicon as SiO_2 % m/m	58.2	40.00
Aluminum as Al_20_3 % m/m	15.7	24.57
Iron as Fe_20_3% m/m	15.74	19.47
Potassium as K_20 % m/m	3.09	9.14
Manganese as MnO %/m/m	1.78	3.21
Calcium as CaO % m/m	2.96	2.05
Titanium as TiO_2 % m/m	1.67	0.98
Loss on Ignition LOI %	16.89	14.73

CBR, Atterberg Limits and Free Swell

As shown in table 2, heating increased the CBR from 1 to 3, reduced the plasticity index, the linear shrinkage, and the free swell from 30 to 21, 15 to 11 and 74 to 46 respectively. Due to combustion of organic matter, the potential to swell reduced, and the soil behaved like a cohesionless soil, which agrees with the findings of Wang et al. (2008). The increase in strength as shown by the increase in CBR, and the reduction in swelling and shrinkage are probably as a result of breaking of the montmorillonite structure, largely attributed to the expansive behaviour and low strengths of expansive clays (Mitchell and Soga, 2005). Thus the strength increased while the plasticity and free swell reduced giving the soil suitable properties for a fill material.

Table 2: CBR, Atterberg Limits and Free Swell

Reference	CBR (%)	Atterberg Limits (%)				Free Swell
		LL	PL	PI	LS	
Neat Black Cotton Soil	1	65	35	30	15	74
Black Cotton Heated to 600^0C	3	47	26	21	11	46

4. Conclusion

The black cotton soil under study experienced irreversible chemical changes when subjected to heat at 600^0C since the tests were done on the soil after it cooled to room temperature which allowed for any possible reversal. This resulted in the following:

- The maximum dry density increased by 15%, reducing capacity for water ingress.
- The particle size distribution altered. The clay fraction diminished, and the soil became predominantly sand with a significant amount of gravel, and a reduction in the silt fraction.
- There was a reduction in silicon oxide by 31%, and an increase of aluminum and iron oxides by 56% and 4% respectively. These changes are irreversible.
- The strength increased as measured by the CBR which increased from 1 to 3.
- The plasticity and swelling characteristics reduced as measured by the Plasticity Index, Linear Shrinkage and the Free Swell which reduced by 30%, 27% and 38% respectively.

This made the soil stable and suitable as fill material and thus heating to 600^0C may be a better alternative to replacement with suitable material, and possibly comparable to stabilization.

5. Recommendations

It is recommended that long term field trials be done with the heated black cotton soil before use on a large scale, though there is great potential of use of the heated soil as a fill material. Further, cost comparisons need to be done between the cost of heating and the cost of cut to spoil, followed by replacement with suitable material. The latter must include the effect of 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 as noted in the introduction.

References

[1] Barasa, P.K., Too, J.K., and Mulei, S.M. (2015). *Stabilisation of Expansive Clay Using Lime and Sugarcane Baggasse Ash.* International Journal of Science and Research (IJSR). Vol. 4 (4).
[2] Bell, F.G. (1993). *Engineering Treatment of Soils*. pp 240-267. E&FN Spon, London.
[3] British Standards BS1377, 1990.*Methods of test for soils for civil engineering purposes*. HMSO, London, UK.
[4] Holtz, W. G. and Gibbs, H. J. (1956). *Transactions of ASCE*, 121, pp. 666-669.
[5] Karatai, T., Kaluli, J., Kabubo, C. and Thiongo, G. (2016). *Soil stabilization Using Rice Husk Ash and Natural Lime as Alternative to Cutting and Filling in Road Construction.* J. Constr. Eng. Manage., 10.1061/(ASCE) CO.1943-7862.0001235, 04016127.
[6] Merino, J., Pina, J., Errazu, A. F., Bucala, V. (2010). *Fundamental Study of Thermal Treatment of Soil.* Soil and Sediment Contamination: An international Journal
[7] Mitchell, J.K. and Soga K. (2005). *Fundamentals of Soil Behaviour*, 3rd Edition, pp. 74-75. John Willey and Sons, Inc. (New Delhi).
[8] Muthukumar, M. and Phanikumar, B.R. (2015). *Shrinkage Behaviour of GPA-Reinforced Expansive Clay Beds Subjected to Swell-Shrink Cycles*. Geotech. Geol. Eng., 33, pp. 475-485
[9] Obuzor, G.N., Kinuthia, J.M. and Robinson, R.B. (2012). *Soil Stabilisation with lime-activated-GCBS -A mitigation to flooding effects on road structural layers/embankments constructed on flood plains.* Engineering Geology, Vol.151, pp.112-119.
[10] O'Flaherty, C.A. (1974). *Highways 2nd Edition. Vol. 2 Highway Engineering*, pp. 221 – 267. Edward Arnold.
[11] Rashad, A.M. (2013). *Metakaolin as cementatious material: History, Scours, Production and Composition- A comprehensive overview*. Construction and Building Materials. Vol. 41, Elsevier, pp. 303-318.
[12] Terzaghi, Karl., Peck, Ralph B. and Mesri, Gholamreza, (1996). *Soil Mechanics in Engineering Practice*. 3rd Edition. John Wiley & Sons Inc., pp. 3 -17.
[13] Wang, M.C., Jao, O. and Ghazal, M.S. (2008). *Heating Effect of Swelling Behaviour of Expansive Soils.* Geomechanics and Geoengineering, pp. 121-127