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Assessment of lime stabilization of black cotton soil for roads construction projects

Abstract

The design foundation (i.e., pavements) on black cotton soil has always been a difficult task for the engineers as the structure resting on black cotton soil cracks without any warning. This research evaluates the effect of lime (anhydrous sodium sulphate) on engineering properties of black cotton soil which are considered highly problematic to civil engineering works. Black cotton soil brings about significant geotechnical and structural engineering challenges to property and infrastructure development around the world. The objective of the study is to investigate the use of lime-stabilized black cotton soil as subbase material in flexible pavements. Black cotton soil procured from the local area in Gaborone, Botswana, tested for suitability as subbase material, turned out to be unsuitable as it resulted in very less CBR value (4.8%). The black cotton soil-lime mix was checked for consistency limits, compaction, CBR for different proportions of lime (i.e., 0, 5, 10 and 15%). It was observed that the plasticity index of the soil shows a substantial decrease upon addition of the lime whereas CBR values show a marked increase with unsoaked CBR. The addition of 5%, 10% and 15% of lime produced some desirable soil properties. It can be concluded lime could be one of the best alternative stabilizer materials for highly expansive clayey.

Keywords: black cotton soil, lime, CBR, swelling, shrinkage, optimum moisture content, maximum dry density

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Introduction

Black cotton soil (BCS) is an expansive fine-grained soil which is considered problematic because of its characteristics. BCS contain high montmorillonite clay mineral content. It is considered as a problematic soil since it challenges the engineers during construction. BCS shows large volume changes because of fluctuations in moisture content. When water or moisture is exposed to this soil, the soil either shrinks or swell. Shrinking is whereby the soil increases in its volume whereas swelling is whereby the volume of the soil increases. Excessive swelling of black cotton soil leads to a process called heaving and shrinking of the soil leads to a process known as subsidence.[1,2]

Black clays or black cottons are known to be potentially expansive soils which are “black” or “greyish black” or in their eroded phase “greyish white” heavy loam or clay (usually 50 %), with predominant clay mineral of the smectite group, rich in alkali earth elements and the horizons sometimes contain calcium carbonate or magnesium oxide concentrations. Black cotton soils are susceptible to detrimental volumetric changes with moisture.[3] The black soils are formed when volcanic rocks and some sediments are weathered under humid, alkaline conditions. Because of poor drainage, these soils are rich in soluble bases and silica. The parent materials of expansive soils could also be classified into two groups. The first group comprises basic igneous rocks. Here pyroxene mineral of the parent rocks decomposes to form montmorillonite which is the predominant mineral of expansive soil and other secondary minerals. The second group comprises sedimentary rocks that contain montmorillonite.[3]

South Africa, Morocco, Mexico, Israel, Spain, Turkey, Iran, India, the United Kingdom, Ethiopia, Ghana, Australia, the United States, and Argentina are among the countries that have reported ES damages. The cost of expansive soils repairing construction damage in South Africa is projected to be R100 million per year. ES damages are estimated to be about £400 million each year in the United Kingdom. According to the American Society of Civil Engineers, ES causes damage to almost a quarter of all houses. ES damages result in a greater annual financial loss than hurricanes, floods, tornadoes, and earthquakes combined.[4]

According to Buruga et al.,[5] black cotton soil belongs to the smectite group, and incorporates montmorillonite, a highly expansive and the most troublesome clay mineral in construction. Montmorillonites incorporate a central octahedral sheet sandwiched among twofold tetrahedral sheets and it forms a three-layer element. Weak bonds between the elements leads to swelling and they can be broken down when water is absorbed.

As stated by Metry & Polli,[6] the chemical composition of BCS changes depending on components such as parent rock, generic characteristics of soil (transported or residual), degree of weathering, etc. However, BCS are generally rich in silica, lime, iron, magnesia and alumina. It also contains titanium oxide in small concentrations, which is liable for the black color of the soil. The organic matter components of black cotton soils are low.

According to Chen,[7] the following are ways of identifying black cotton soil, usually have a color of black or grey, wide or deep shrinkage cracks, high dry strength and low wet strength, Stickiness and low traffic ability when wet, cut surfaces have a shiny appearance, the appearance of cracks in nearby structures. Arid and semiarid areas are particular trouble spots because of large variations in rainfall and temperature.

Black cotton soil has proved itself as a source of harm to the property and economical loss. Expansion and contraction of black cotton soil causes various issues to the civil engineers not only during construction but also throughout the life of structures. Uneven contraction and swelling decreases the serviceability of the structures. It causes the rise of hairline cracks, differential settlements, and sometimes even serious cracks, which may lead to the collapse of structures, railway lines and roadways. Decrease in the availability of suitable soil for construction has forced analysts to look for an appropriate strategy to improve the performance of locally available problematic soil. During the last four decades, lots of research have been conducted on black cotton soil to reduce its expansion and contraction, and to save a lot of resources.[8]

Mixing chemicals like lime and cement into these soils to change their physicochemical behaviour is a frequently utilized method in the United States and around the world. However, because of the greenhouse gases produced in the production of these compounds, as well as the detrimental effects on plant development caused by elevated pH levels in the soils following treatment, this creates environmental issues. When soil erosion is a concern and plant development is required to buffer soils from erosion, increased pH values become a severe problem.[9]

Soil stabilization is done when the available soil for construction is not suitable for the intended purpose. In a wide sense, stabilization is a method including compaction, pre-consolidation, drainage, etc. in various stages. The method may incorporate the mixing of soils to achieve a desired gradation or the blending of suitable additives which may lead to changes in the original soil gradation, texture or plasticity characteristics, or act as a cementation material of the soil. Soil stabilization is used to decrease the permeability and compressibility of the soil mass in soil structures, to decrease the swelling in case of expansive soils and to extend its shear strength.[10]

According to Bamigboye et al.,[11] chemical stabilization of these soils is a potential option for ensuring construction safety while also saving money by lowering repair and rehabilitation expenses. The most widely utilized stabilizing chemicals for treating expansive soils are cement and lime. Cement and lime treatments, on the other hand, tend to make soils brittle, which is disadvantageous in some dynamic loading scenarios, such as traffic loads on pavement systems.

Chemical stabilizers were recognized as important because of their potential to bring about desired changes in the soil's mineralogical structure, allowing for better agglomeration of soil particles and lowering the soil's attraction for water.[12]

As stated by Fondjo et al.,[4] the goal of chemical soil stabilization is to improve soil stability by increasing grain size particles, lowering plasticity index, reducing swelling-shrinking potential, and cementing. The use of lime to improve the engineering behaviour of expansive clayey soils is a well-established technique. In general, fine-grained treated materials show decreased plasticity, improved workability, and reduced volume fluctuations. Finally, the wetting-drying cycle is not typically thought of as a standardized stabilization technique. However, in a given construction project, the technique could be employed to lower the swelling potential of ES. By modifying the drying-wetting cycle on stabilized soil material, wetting-drying cycles are also used to test the durability of chemical additives used in soil stabilization in order to better understand the time-dependent performance of such chemicals under field settings.[4]

The main objective of the study is to stabilize black cotton soil by treating it with lime (anhydrous sodium sulphate). Also, evaluate the physical behaviour and strength characteristics of BCS and determine the effectiveness of adding lime to stabilizing black cotton soil.

Materials and methods

The study area is Gaborone, capital city of Botswana and it is situated between Kgale hill and Oodi hill near the junction of Notwane and Segoditshane River in the south-eastern corner of Botswana. As shown in Figure 1, the soil sample which was used for this research was black cotton soil and it was collected from Ramotswa. A picture of anhydrous sodium sulphate presents in Figure 2.

Figure 1 Black cotton soil .

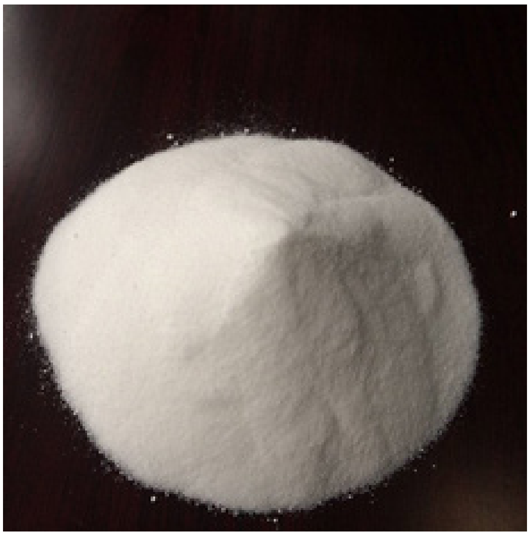

Figure 2 A picture of anhydrous sodium sulphate.

Preparation of test samples

The soil sample was air-dried and crushed in the laboratory, the sample was then transferred into an oven to remove hygroscopic moisture before starting the experiments. Compaction test, Atterberg limits and California bearing ratio (CBR) tests were then conducted in the laboratory for both treated and untreated soil samples by using THM1 and BS 1377 standard testing methods.

Lime was an additive or chemical treatment, percentages were varied on the control sample to observe the changes in comparison with untreated black cotton soil. 5%, 10% and 15% of lime were mixed with the soil to see its effects on the soil.

Test procedures

Compaction test: This test is aimed at determining the relationship between moisture content and dry density of soil. To evaluate these compaction characteristics, the untreated and treated soil samples were compacted in accordance with TMH1 standard. To determine the MDD and OMC, an adequate quantity of the air-dried sample is sieved, and the aggregate retained on the 19.0 mm sieve is crushed to pass through the sieve and added to the portion that passed the

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sieve. The material is then mixed. When mixing different moisture contents are used because the soil sample is divided in four basins, so each basin has its own amount of water. After mixing the sample, dry mould is weighed and assembled on the base plate with the spacer plate. Two 150mm round filter paper are placed on the spacer plate to prevent the material from sticking to the plate. The collar is then fitted to the mould. The material is then compacted. Firstly, the material is transferred to the mould into layers. It is tampered 55 times. Two more layers of the material is tampered in the same manner and each layer should be slightly more than 25 mm but not more than 30mm thick. Finally, the mass of the mould is taken (Figure 3).

Figure 3 A picture of tamping rod and mould with a base plate.

Same procedure was followed when lime was added to the soil. Here the only difference is that the soil was now treated with lime, the lime was varied on different soil samples. The aim here was to see the effect of lime when introduced to the black cotton soil.

Calculations

$$d = \frac{a-b}{b-c} \times 100$$

d- Moisture content expressed as a percentage of the dry soil

a- Mass of container and wet material (g)

c- Mass of container only (g)

$$D = \frac{\boldsymbol{W}}{\boldsymbol{d}+100} \times \frac{100}{\boldsymbol{V}} \times 1000$$

D- Dry density (kg/m^3)

W- Mass of wet material (g)

V- Volume of mould (ml)

After the calculations, the moisture content is plotted graphically against the respective dry densities. The peak of the curve indicates the optimum moisture content and the maximum density of the material.

CBR test: CBR is a measure of the strength of the subgrade of the materials used in construction of the road or pavement. The penetration test is used to evaluate the subgrade strength of pavements therefore the results analysed after the test are used to determine the thickness of the roads. The test was done for treated and untreated soil samples according to TMH1 standard. For CBR test, the optimum moisture content obtained from the compaction test was used as water added to the soil sample. However, that is why compaction test was done before CBR test. Firstly, soil sample that is oven dried is mixed with water (optimum moisture content). The required amount of water is measured out and added slowly by means of the spray-can. The material is mixed continuously as the water is added. The moist material is then covered with a damp sack to prevent evaporation and it is allowed to stand for about an hour to allow the moisture to distribute evenly throughout the material.

The volume of three clean dry moulds is determined and the moulds are then weighed. Two round 150mm round filter paper are then placed on the spacer plate and the collar is fitted to the mould. The material is then compacted. Here the compaction differs from the compaction test used to obtain MDD and OMC. The first mould is tempered by 55 blows in 5 layers and a sample of moisture content is taken from the mixing bath. The second mould is the assembled immediately and tampered full of material in the same way but only 25 blows of the 4.536kg tamper are applied to each layer. The moulded material is the weighed and another representative sample of moisture content is taken from the mixing bath. The third mould is also tampered full of material but in this case only three layers of the material are compacted and on each layer 55 blows of the 2.495kg tamper are applied. A sample of moisture content is also taken from the mixing bath.

The average of the two moisture content determinations taken after the compaction of the first and second moulds is taken as the moulding moisture content for all three moulds. After compaction of the material, perforated soaking base plates and filter papers are prepared. Each moulded material is the placed on the filter paper and the with the finished-off surface facing downwards and screwed down tightly onto the soaking plate. The moulded material is then soaked for 4 days. After 4 days soaking the moulded material is removed from water. The mould containing the material, still screwed down on the soaking plate, is placed in the press and the penetration piston is placed on the surface of the material through the centre of the annular weight. The depth gauge is fitted in such a manner that the depth of penetration of the piston into the material is measured. The depth gauge is the set to zero and the load is applied at a uniform rate of the penetration of 1,27mm per minute. Load readings are taken at every 0.635 mm of penetration. Same procedure is followed when working with treated soil, the only difference is that the soil is now mixed with lime (Figure 4).

Figure 4 CBR apparatus.

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Atterberg limits test: The water content at which the soil changes from one state to other state are known as consistency limits or Atterberg limit. The liquid limit, plastic limit, and shrinkage limit are three Atterberg limits that are useful in engineering. These limits are given in percentages of water content. The test was done using BS 1377.

Liquid limit is defined as the water content at which the behaviour of a clayed soil changes from plastic state to the liquid state. However, the transition from plastic to liquid behaviour is gradual over a range of water contents and the shear strength of the soil is not actually zero at the liquid limit. While plastic limit is defined as the water content where the thread breaks apart at a diameter of approximately 3mm. It is the moisture content at the boundary between the plastic and semi solid states of consistency. Shrinkage limit is defined as the maximum water content at which a reduction in water content will not cause a decrease in the volume of soil mass. Some steps were followed when conducting the Atterberg Limits.

1) The soil sample was passed through No. 40 sieve (425µm) pass and the Atterberg limits were determined in accordance with BS 1377 standard.
2) A cone penetrometer method was used to determine the liquid limit.
3) Take about 400g soil sample and place it on a glass plate. Mix the paste for at least 10 minutes using the two palette knives. Add more distilled water if necessary, so that the first cone penetrometer reading is about 15mm.
4) Push a small amount of the mixed soil into the cup with a palette knife, being careful not to trap air. If required, lightly tap the cup on a firm surface. To create a smooth, level surface, use the straightedge to strike off any excess soil.
5) Lower the penetration cone so that it just touches the soil's surface, with the cone fixed in the higher position. A tiny movement of the cup will just mark the soil surface when the cone is in the precise place. Lower the dial gauge until it makes contact with the cone shaft, then record the reading to the closest 0. Imm.
6) For a total of 5 seconds, let go of the cone. Lower the dial gauge to make contact with the cone shaft after locking it in place, and record the reading to the nearest 0.1 mm. The "cone penetration" is the difference between the two readings.
7) Carefully remove the cone and clean it. The process should be repeated with a little additional wet soil in the cup. The average of the two penetrations shall be reported if the difference between the first and second penetration values is less than 0.5mm. A third test must be performed if the second penetration differs from the first by more than O.5mm but less than Imm.
8) Record the average of the three penetrations if the overall range is less than I mm. If the overall range exceeds I mm, the soil in the cup must be removed, blended, and the test repeated until consistent results are obtained. Determine the moisture content of a moisture content sample of around 20g taken from the area penetrated by the cone.
9) The penetration test must be done at least three times more using the same sample of soil with additional water increments. The volume of water added must be such that the four test runs cover a range of penetration values of around 15mm to 25mm. Each time soil is removed from the cup for the addition of water, wash and dry the cup.

Plasticity Index was calculated using the following formula: PI=LL-PL

Results and analysis

Compaction test results: results are plotted in Figure 5 and Table 1. The curves show that Optimum Moisture Content (OMC) increased with the increment of lime content whereas the Maximum Dry Density (MDD) also increased with an increase in lime content. An increase in the dry unit weight may be due to the higher specific gravity of lime, while an increase in the optimum moisture content may be as a result of water needed to be hydrated for lime. As shown in Table 1, by increasing lime from 0-10 or 15% optimum moisture content increased two times more (190%) the natural (untreated) soil sample had a maximum dry density of 1657 kg/m^3 and optimum moisture content of 11%, the additional of 10% lime increased the maximum dry density to 1748kg/m^3 that the increased was 89% and increased the optimum moisture content to 21%. As it is clear from Figure 5 and Table 1, additional more lime after 10% hadn't much increase in maximum dry density (6%) while optimum moisture content hadn't any increase then the optimum amount of lime reported 10% for this particular soil. Generally, the higher the maximum dry density, have a better soil for construction work.[13,14]

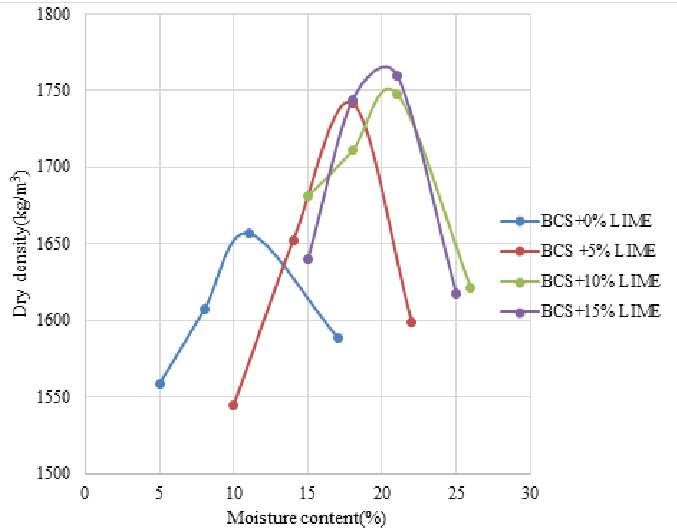

Figure 5 Relationship between dry density and optimum moisture content.

Table 1 Showing effects of Lime increment to the MDD and OMC of the soil

LIME (%)	MDD (kg/m3)	OMC (%)
0	1657	11
5	1744	18
10	1748	21
15	1760	21

CBR test results: The CBR of a soil is an indefinable symbol of its strength, which for a given soil, is dependent upon the conditions of the materials at the time of testing. This means that the soil needs to be tested in a condition that is critical to its design. At any given moisture content, the CBR of a soil will increase if its dry density is increased, i.e., if the air content of the soil is decreased.[15–17] Thus, a design dry density should be selected which corresponds to the minimum state of compaction expected in the field at the time of construction. The unsoaked CBR value for the clay soil was found to be 4.8%, which is a poor rated sub grade. Extra of 6% lime increased the unsoaked

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CBR value to 45%, while 4% lime reduced CBR to 25% which is rated a relatively poor sub grade (Figure 6). As it is clear in Figure 6, the graph it shows that the load increases as the content of lime is increased hence an increase in CBR value.

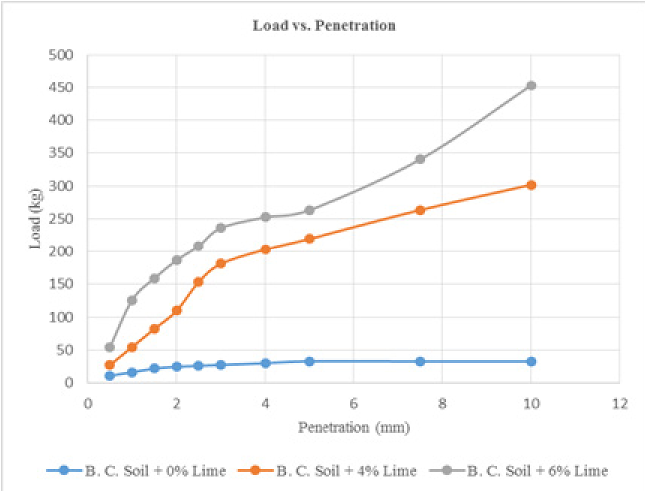

Figure 6 Relationship between load and penetration of soil.

Atterberg limits results: Figure 7 and Table 2 show the variation of liquid limit (LL) and PI of soils stabilized with different percentages of lime (i.e., 0, 5, 10, and 15%). Addition of stabilizer (lime) resulted in a decrease in LL and PI values. Previous studies also reported a decrease in LL and PI values of expansive soils due to chemical treatments.[18–20] The addition of stabilizers could have decreased the LL/PI values by reducing the diffuse double layer and inducing flocculation of clay particles.[15,17] Figure 7 show that soil stabilized with 15% of lime has the lowest LL/PI, whereas LL/PI values of untreated soil is the highest.

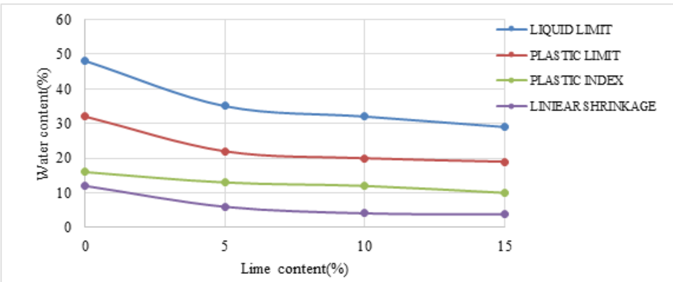

Figure 7 Atterberg limit results for black cotton soil and varying percentages of lime.

Table 2 Showing the effect of Lime increment to LL, PL and PI of soil

LIME (%)	LL (%)	PL (%)	PI (%)	LS (%)
0	48	32	16	12
5	35	22	13	6
10	32	20	12	4.1
15	29	19	10	3.8

Conclusion

Based on the test results obtained from the investigation of the selected soils treated with lime following conclusions were drawn:

1. The Atterberg limits test result shows that liquid limit and plastic limit natural soil samples are found to be 48% and 32 % respectively. The test results show that the soils of the study area have plasticity index of 16%. This tells us that the soil has high plasticity according to Chen,[13] however soils with high plasticity are likely to absorb more water, expand and shrink/swell causing damage to the foundation and engineering structures. Furthermore, the plastic limit decreased to 22%, 20% then 19% when lime was added. This is due to the non-plastic properties of lime. Similarly, the plasticity index decreased from 16% to 13% then 12% and finally 10% on the addition of lime. The liquid limit and plasticity index showed a reduction with increasing percentages of lime. This was a good observation since the aim to reduce the PI so that does not expand more and shrink.
2. The MDD increased with the addition of lime and whereas OMC also increased with the increase in the percentage of lime. The Optimum Moisture Content (OMC) for the untreated black cotton soil was found to be 11% and this increased to 18% when 5% lime was added. The OMC continued to increase when 10% and 15% lime was added to the soil. 21% of the OMC was obtained for these samples. Also, the MDD was found to be 1657kg/m^3 for untreated black cotton soil. The MDD increased when the increase in lime content. At 5% lime 1744kg/m^3 of dry density was obtained, at 10% 1748kg/m^3 and finally 15% showed an MDD of 1760kg/m^3.
3. The CBR value of black cotton soil mixed with 4% and 6% lime at 2.5 mm and 5mm penetration showed an increase.
4. It is recommended that further studies should be done on the anhydrous sodium sulphate to see if it can be a best chemical additive to improve the engineering properties of black cotton soil. Some tests such as UCS and specific gravity test need to be conducted to evaluate anhydrous sodium sulphate more.[21]

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Conflicts of interests

Author declares there are no conflicts of interests.

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