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UTILIZATION OF BLACK COTTON SOIL STABILIZED WITH BRICK DUST-LIME FOR PAVEMENT ROAD CONSTRUCTION: AN EXPERIMENTAL AND NUMERICAL APPROACH

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Abstract. Black cotton soil is highly susceptible to volume change due to moisture fluctuations. This leads to the deformation of structures built on such soil. Therefore, the aim of this study is to improve the soil-bearing capacity and deformation analysis of black cotton soil. The laboratory tests were done according to the American Association State of highway and Transport Official (AASHTO) and the American Society for Testing and Materials (ASTM). These tests were natural moisture content, grain size distribution, X-ray diffraction test, Atterberg limit test, modified compaction, California bearing ratio, and triaxial test. Soil sample was stabilized with a ratio of 0%, 4%, 8%, 12%, and 16% of brick dust and 0%, 1%, 3%, 5%, and 7% of lime, respectively. The result of the laboratory test at the optimum percentage of 12% brick dust and 5% lime shows that the liquid limit improved from 93.2% to 67.5%, plastic limit

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improved from 48.71%, to 58.2%. The optimum moisture content improved from 26.76 to18.5% and Maximum dry density improved from 1.42 g/cm^3 to 1.58 g/cm^3. The California bearing ratio improved from 1.29%, to 13.6%. The deformation analysis result shows that at optimum percentage of stabilizing agent, the deformation reduced from 2.087 mm to 0.973 mm. Therefore, brick dust-lime soil stabilization shows the promising improvement of weak subgrade soil.

Keywords: black cotton soil, Brick dust, FEM, Lime, soil stabilization.

Introduction

Black cotton soil is a porous soil that is not a good material to use when building roads. The key characteristics of this soil type are high swelling-shrinkage capacity, weak bearing capacity, and high levels of plastic clay. The expansive property of the soil is mostly caused by the clay mineral montmorillonite (Altmeyer, 1955). The expansive soils are also known as swelling soils or soils of black cotton. The black cotton soil is highly strong when dry but entirely weakens when wet (Yilmaz, 2004). Nature's soil deposits are exceedingly irregular, resulting in an endless number of conceivable combinations that might alter the soil strength and the steps required to use it for a certain purpose. Therefore, in the specific instance of BCS, there are numerous construction-related obstacles (Murray, 2007). These soils had considerable strength in the summer and quickly declined in the winter. Expanding and contracting expansive soil results in a deferential settlement, which severely damages the foundations of buildings, roadways, and retaining walls (Enkhtur & Dalai, 2011). Black cotton soil is composed of a variety of substances, including humus, iron oxide, and chemicals like calcium carbonate and iron oxide, as well as minerals and compounds like montmorillonite and kaolinite (Barasa et al., 2015). When a structure is built on weak or expansive soil, a major difficulty for civil engineering arises since this soil can contract and expand when moist. These soils more frequently harm buildings, foundations, or other light-weight structures like pipelines, pavements at airports, and highways. The harm is even greater than the damage caused by other natural dangers, such as earthquakes, hurricanes, and floods (Adey, 2017). Due to changes in soil characteristics, infrastructure like pavement and foundations suffer extensive damage. Therefore, to enhance the geotechnical engineering features of this expansive soil and to combat irritating environmental factors like dust, calcined termite hill clay powder and a stiffener like lime or cement are used. It is often recognised via laboratory and visual identification (Guyo et al., 2019).

Black cotton soil presents a challenge to civil engineers in terms of construction technology. This soil is difficult for any building construction on it overall. With the rapid advancement of soil improvement, construction methods, and social necessities, various structures are being built (Russell et al., 2007). Black cotton soil is found in numerous places, including Australia, Canada, Ghana, Mongolia, Egypt, the United States, and others (Ismaiel, 2013). The most difficult soil in the world is black cotton soil. The expansive black cotton soil exhibits high volume changes, a property for expansion, and low bearing capacity when wet. These soils have a high concentration of clay and are prone to swelling when wet and contracting when dry. Therefore, it is necessary to enhance this soil characteristics as a result of this flaw. It is impossible to avoid it or find a suitable replacement because it covers such a large area in the north-eastern region of Nigeria, where this soil is prevalent (Kavish & Mehta, 2014).

The highlands and lowlands of Ethiopia are typical places where expansive soils are found. Problems with ground heave and settlement are brought on by the volumetric changes that these soils experience when wet and dry. Inadequate attention to this attribute results in significant construction flaws (Damtew M. et al., 2023). For expansive soils, because of changes in moisture conditions, there could be a significant volume change problem at different seasons (Adamu et al., 2023).

Municipal solid waste ash is produced as a by-product of a waste-to-energy (WTE) power plant. The waste-to-energy power plant produces waste ash as the by-product of bottom ash, which poses a major threat to the environment, society, and economy. Expansive soil stabilization with municipal solid waste fly ash used in the construction industry, such as road construction, would solve the pavement performance problem and reduce municipal solid waste ash volume at the WTE power plant, thereby protecting the environment from waste ash disposal (Melese, 2023).

Pure lime stone undergoes metamorphic rock modification to create marble. Marble colour and look are determined by its purity; it is white if the limestone is made entirely of calcite (Barnat-Hunek et al., 2018). Marble is used in building and decorating because it is strong, has a noble appearance, and is therefore in high demand. Marbles are crystalline rocks that are mostly made of the minerals calcite, dolomite, or serpentine. The main mineral impurities in marble are quartz, muscovite, tremolite, actinolite, microline, garnet, osterite, and biotite, whereas the main chemical impurities are SiO_2, limonite, Fe_2O_3, manganese, $3H_2O$, and FeS_2. Phosphate, leads, zinc, alkalis, magnesia, and sulfides are the principal impurities that might alter the qualities of final cement when present in raw lime stone. Marble dust has very small, non-plastic, nearly well-grated particles that are created during the cutting and grinding of marble (Deepdarshan, 2020). Traditional soil stabilization methods include drawbacks such as high costs and/or environmental concerns. The alternate solution is to amend the soil with marble dust. The soil stabilized by marble dust can be used to build foundations, pavement constructions, and canal lining (Adamu et al., 2022).

Due to the growing demand for construction materials, bottom ash has been utilised in various beneficial applications, particularly in civil engineering infrastructures such as road base layers, sub-base layers, road subgrades, and parking lots, because of the high demand for construction materials (Abe & Wakatsuki, 2014)). Bottom ash can be used successfully for subgrade and embankment to produce mixtures for sub-base and base course as gravel substitutes (Russell et al., 2007). Bottom ash, fly ash, and other materials are also used in construction as soil stabilizers due to their lower specific gravity, higher shear strength, and pozzolanic properties. The use of these ashes as stabilizing materials reduces both the disposal problem and the cost of stabilization (Hussein, 2021). Lime reduces plasticity, improves workability, and increases strength in medium, moderately fine, and fine-grained soils (Habtamu, 2015). Gain in strength is mostly caused by chemical interactions between lime and soil particles. These two-phase chemical processes have both short-term and long-term advantages. The initial changes in soil texture and characteristics brought on by cat-ion exchange constitute the first stage of the chemical reaction. The diffused water layer surrounding the clay particles shrinks as a result of an exchange between the free calcium of the lime and the adsorbed cat-ions of the clay mineral (Abhishek et al., 2016). The clay becomes more silt- or sand-like due to the clay ability to flocculate or aggregate when the dispersed water layer is reduced, allowing the clay particles to come into closer contact with one another. Overall, the lime stabilization process flocculation and agglomeration phase produce soil that is easier to mix, deal with, and ultimately compact (Eden, 2017). The lime-soil mixture undergoes pozzolanic reactions in the second stage of the chemical reaction, which eventually leads to increased strength. The pH of a clay soil increases when lime is added to it. The silica and alumina in clay become soluble and are liberated from the clay mineral when the pH hits 12.4. The calcium from the lime then reacts with the silica and alumina that have been released to create cemented material, which strengthens gradually over several years. The pozzolanic reaction will continue as long as there is enough calcium from the lime to combine with the soluble silica and alumina and as long as the pH is high enough to sustain the alumina and silica solubility. Strength gain also largely depends on the amount of silica and alumina available from the clay itself; thus, it has been found that lime stabilization is more effective for montmorillonitic soils than for kaolinite soils (Syed et al., 2021).

A finite element method-based numerical program for two-dimensional analysis is called Plaxis 2D. It is particularly beneficial for analysing soil deformations and groundwater movement as well as for building geotechnical structures. The finite element method (FEM) has established a strong position in geotechnical analysis and design (Yuan et al., 2021). The finite element method is more suited for scenarios with complicated geometries and soil-structure interactions, nevertheless. The finite element method does, however, have significant limitations, particularly when it comes to large deformations and material movement. In these circumstances, the recently developed Material Point Method (MPM) is considerably more appropriate to cope with the consequences of significant deformations. The type of analysis needed and the geometry being modelled play a big role in determining which finite elements should be utilised for two-dimensional situations (Damtew et al., 2023). For geotechnical issues, the primary requirement is that the element types should be applicable to all potential geometric circumstances, such as those involving constructions with curved boundaries or curved material interfaces (Hailemariam et al., 2023).

Brick dust is the by-product of a demolished house, and the waste is an element of environmental pollution that can contaminate the air, which can inhibit quality of life and ecosystems. From this perspective, the enormous amount of brick dust strewing cities in Ethiopia is one of the major areas of apprehension. This study enhances consumption of brick dust, in reducing the massive increase in amount of deposit in the cities. Hence, the use of brick dust tends to reduce construction material cost, thereby reducing greenhouse emissions enacted by brick dust and improving the strength of weak road payment subgrade. Therefore, this study aims at performing the deformation analysis of black cotton soil stabilized with brick dust and lime for subgrade using the finite element method.

1. Materials and methods

1.1. Characterisation of the materials used

Expansive soil samples were collected using the non-probability sampling technique, known as the purposive sampling technique. The primary method was the identification of an expansive soil site based on the previous investigation of the engineering properties of soils in Jimma Town. The experimental activities considered in this study analysed three different materials, which included black cotton expansive soil, brick dust and lime. The black cotton soil is considered for unsuitable pavement subgrade construction. Thus, this material is unlikely used it for purpose without improvement. Brick dust and lime are used as stabilising agents by employing various proportions of the mix. These two materials are mixed together with black cotton soil with a varying mix ratio, and their effect is investigated.

Brick dust, a lavish material that is dumped, not only occupies the land but also affects the environment in which we live and poses a hazard to the environment. The waste is generated in brick kilns, masonry construction sites, and during construction. We reused this waste for soil stabilization. Black cotton soil, brick dust, and lime were used. Burning limestone in a kiln produces lime. The parent substance and the manufacturing procedure both affect the quality of the resulting lime (Russell et al., 2007). Lime is an economic way of soil stabilization, used mainly in black cotton soils, which are highly unstable (Kavish & Mehta, 2014). Lime reacts with clay minerals in the soil; this causes chemical reaction or Pozzolanic reaction, which results in the formation of cementitious material. These cementitious materials bind the soil particles together, increasing its strength and reducing its susceptibility to volume change. For this study, lime was bought from a local market. Deformation analysis was performed for stabilized and unstabilized soil. The materials for this laboratory test were prepared using various percentages of brick dust and lime (Walker & Pavía, 2011).

1.1.1. Laboratory test program

Table 1 shows standard procedures for a laboratory test. A laboratory test program was carried out to determine the engineering parameters of untreated and treated expansive soil, as well as the chemical characteristics stabilizing agents. Wet sieve analysis, hydrometer analysis, Atterberg limit, moisture content, modified Proctor compaction, the California bearing ratio, a triaxial compression test, and an X-ray diffraction (XRD) test were performed in the laboratory. Then, soil sample was mixed with brick dust-lime at the specified amount, i.e., brick dust and lime at 0%, 4%, 8%, 12%, 16%, and 0%, 1%, 3%, 5%, and 7% proportions by weight respectively of soil dry weight. Finally, the mixture of the samples was subjected Atterberg limit, linear shrinkage limit, modified Proctor compaction, CBR, and triaxial compression tests. A laboratory test program for determining the engineering parameters of untreated and treated expansive soil is provided in Table 1.

Table 1. Laboratory test name and standard procedure used

No	Name of test conducted	Standard testing Used	
		ASTM	BS/IS
1	Moisture Content	ASTM D 2216	
3	Wet Sieve Analysis	ASTM D422	
4	Hydrometer Analysis	ASTM D422	
6	Atterberg Limit	ASTM D4318	
8	Proctor Compaction test	ASTM D1557	
9	California Bearing Ratio (CBR)	ASTM D1883	
10	Triaxial Compression Test	ASTM D2850	

1.1.2. X- ray diffraction test

To identify the phases of various sorts of samples, X-ray diffraction (XRD) has been a well-liked technique. The current method uses principal component analysis to provide a qualitative understanding of the minerals contained in the sample soil. The qualitative and quantitative investigation of soil mineralogy frequently employs X-ray diffraction (XRD). There is a need for computational methods that can help define the soil attributes of black cotton soil since the time and effort necessary for traditional methods of soil XRD data analysis are currently prohibitive for such huge data sets. A mineral study using X-ray diffraction (XRD) was performed to see what minerals were in the BC soil.

1.2. Deformation analysis model

Deformation analysis was performed using Plaxis 2D and soil parameters from laboratory tests. To analyse deformation on stabilization black cotton soil, Plaxis2D was both drained and un-drained condition options with its material property.

1.2.1. Mohr Coulomb model

The Mohr Coulomb model is the mathematical model that is used to describe the behavior of materials under stress, particularly in geotechnical engineering. It is a nonlinear model that takes into account the material strength and frictional properties. The model assumes that a material will fail when the shear stress exceeds the maximum shear strength of the material. The maximum shear strength is defined by the angle of internal friction, which is the angle between normal stress and shear stress at which the materials begin to fail. The Mohr Coulomb model is often used to analyse soil stability and slope stability, as well as to design foundations, road subgrade, and retaining walls.

1.2.2. Linear elastic model

A linear elastic model is a mathematical model that is used to describe the behavior of materials under stress. Let us assume that the material will deform elastically, i.e., it will return to its original state once the stress is removed. This model is often used in engineering to predict how it will behave under different conditions, such as when subjected to pressure or tension.

1.3. Geometric model

The geometric model is an important aspect of plaxis2D soil model. It refers to the representation of the physical structure and soil layer in digital format. The geometric model includes information about the shape, size, and location of the structure, as well as the properties and thickness of the soil. The accuracy and completeness of the geometric model are crucial for obtaining accurate results from the plaxis2D soil model. Engineers must ensure that the model reflects the actual physical conditions of the site, including any variation in soil properties or layer thickness.

In addition, the geometric model must be able to capture the complex behaviour of soil structures under different loading conditions. This requires careful consideration of factors such as soil deformation, consolidation, and shear strength. Overall, the geometric model is a critical component of the plaxis2D soil model, as it provides the basis for analysing the behaviour of soil structures and designing safe and stable subgrade construction. For this study, two-lane highways were used to set the model, with one-lane width of 3.6 m considered.

1.3.1. Boundary condition

The boundary condition in a plaxis2D soil model refers to the constraint applied to the model to simulate the real world condition. This constraint can be either displacement or force boundary conditions. The displacement boundary condition specifies the movement of deformation of the model boundaries. Force boundary conditions specify the force acting on the models boundary. The boundary condition is essential in determining the stability of the soil and embankment under various loads. The final stage in setting up the global system of equations is the application of the boundary condition. These are the load and displacement condition that fully define the boundary value problem being analysed.

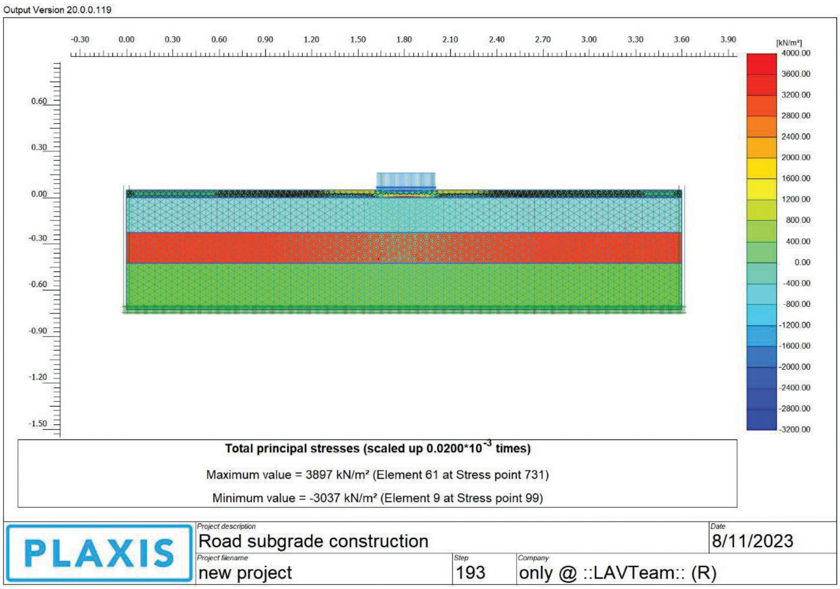

Figure 1. Deformation mesh under the applied boundary conditions

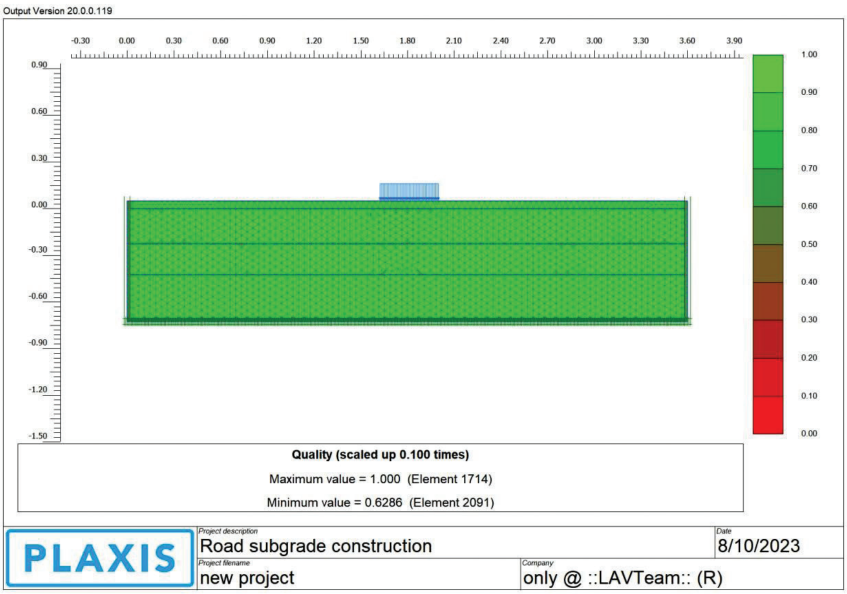

Figure 2. Meshing of finite element model

A boundary condition fixed both in horizontal and vertical directions was used at the bottom boundary as shown in Figure 1. The automated boundary condition defines that the displacement on the surface is free in all directions and that the bottom of the model is fixed in all directions ($ux = uz = 0$), as are the displacements. The x direction of the software is fixed along the x direction, and the displacements are random. Its displacements at the boundary are fixed in the x and z directions.

1.3.2. Model discretization

Figure 2 shows the meshing of the finite element model. It is the process of dividing the soil into smaller, finite elements or nodes. This is done to simplify the analysis of complex soil structures and obtain more accurate results. The soil structure is divided into small elements, and each element has specific properties such as stiffness, density, and permeability. The elements are connected to each other at their nodes, and boundary conditions are applied to these nodes. Discretization involves determining the size and shape of the elements based on the complexity of the soil structure and the desired level of accuracy. The 8-node continuum three-dimensional brick element (C3D8R) with reduced-order numerical integration is modelled. In finite element analysis, the 8-node continuum three-dimensional brick element is a reduced-integration linear element. In this type of model, each node has three degrees of freedom. With the use of a smaller mesh, the accuracy of finite element method increases and model complexity increases. Thus, in this model the mesh was designed with an estimated global mesh size of 100 mm for all layers.

1.3.3. Loading condition

In addition to discretization, the plaxis soil model also considers the loading condition of the soil structure. This includes the magnitude, and direction of external loads such as gravity, wind, and seismic force, as well as the internal loads caused by soil deformation and settlements. The loading condition is essential in determining the response of the soil structure under different conditions. The wheel contact area is computed under a standard single axle load of 80 kN, and contact pressure of 480 Kpa by using a single seat of wheel with a rectangular contact area of 0.5227 L2. From wheel load 40 kN and contact pressure 480 Kpa, contact area dimension of 350 mm in length and 240 mm were determined. The way is to get the equivalent contact area dimension from wheel load and contact pressure. The traffic load was used to simulate the moving load. The applied load was specified as pressure to simulate the pavement model. When the FEM was modelled, the wheel pressure of vehicle had a uniform distribution load on contact area of the vehicle wheel as shown in Figure 3.

1.3.4. Fixity

The fixity of a structure affects its response to external load and soil deformation. The specification of boundary conditions is used to control the displacement of the pavement structure. In this model, the two sides are roller supports, so the finite element model is not allowed to move horizontally but is allowed to move vertically. The bottom of the finite element model has fixed support and is not allowed to move either horizontally or vertically. Asphalt surfaces are permitted for vertical displacement.

1.4. Properties of materials and sections

The properties of materials and sections are important information to analyse the pavement deformation using the 2D finite element methods. The material property, such as elastic modulus, is obtained

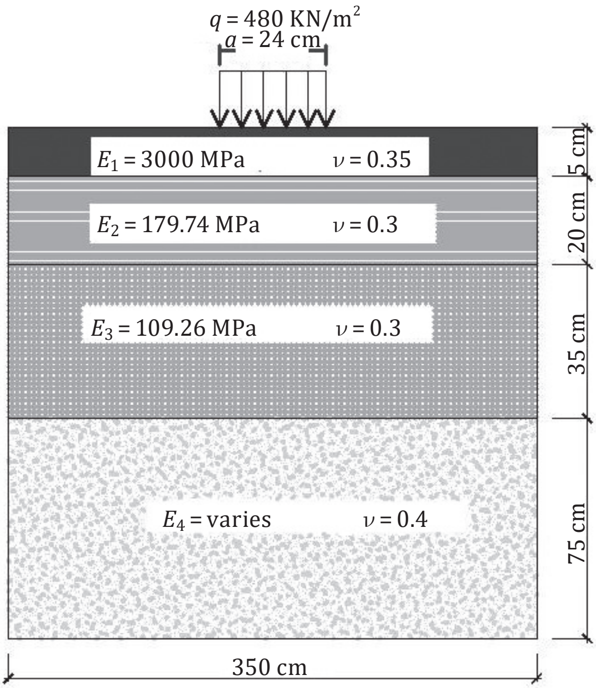

Figure 3. Wheel Load applied on pavement and section properties

through laboratory tests or correlation. The elastic modulus was obtained by correlating it with *CBR* values by the Georgia Department of Transportation (DOT) for some fine-grained subgrade soils, as follows:

$$Mr = 3116 \cdot (CBR)^{0.4779707}$$

where *CBR* is expressed in percent and resilient modulus is expressed in psi, where 1 psi equals 6.9 MPa. The *CBR* values of the granular road base and granular sub-base were taken from the manual specifications of the Ethiopian Road Administration (ERA); however, the *CBR* values for the subgrade were obtained from laboratory tests. The pavement layer thickness was taken from the selected design chart. The design chart was selected based on subgrade strength. In this study, the subgrade strength of stabilized expansive soil at the optimum percentage of brick dust-lime was S3. Depending on this subgrade strength, S3, the stabilized expansive soil was used only for design charts B and C1 because other design charts required additional selected fill or capping layers. However, when comparing design charts B and C1 from an economic point of view, design chart C1 is uneconomical because the thickness of the asphalt concrete surface was 100 mm, whereas the thickness of asphalt concrete surface in chart D was 50 mm. Therefore, in this finite element analysis, design chart D with the maximum traffic volume T6 of this design chart was used. The properties of materials and sections of the selected design chart are shown in Tables 2 and 3.

Table 2. Material properties of natural soil and stabilized subgrade materials

Sample	γ_{dry}, kN/m^3	γ_{wet}, kN/m^3	Cohesion, Kpa	Poisson ratio	ϕ, degree	Resilient modulus, Kpa
Natural soil	14.2	18	15.5	0.4	24.92	13 332.15
4% BD & 1% L	14.8	18.34	14.9	0.4	19.45	46 507.5
8% BD& 3 % L	14.27	17.4	14.5	0.4	27.36	65 129.75
12% BD & 3% L	13.81	16.36	11.4	0.4	29.25	93 692.55
16 % BD & 7% L	14.78	17.41	11.85	0.4	29.12	32 038.5

Table 3. Material properties of other pavement layers

Name	Materials	Layer thickness, cm	CBR values, %	Elastic modulus, MPa	Poisson ratio
Wearing surface	Asphalt concrete	5		3000	0.35
Road base	Granular road base, GB1	20	85	179.74	0.3
Road sub-base	Granular sub-base, GS	35	30	109.26	0.3
Sub-grade	Black cotton soil	75	1.29 (virgin black cotton)	varies	0.4

2. Result and discussion

2.1. Engineering properties of black cotton soil

Table 4 describes the natural expansive soil properties. The natural moisture content of soil is 40.0%. From this result, the soil sample is soft clay soil, according to Das BM (2019). The percentage of soil samples passing No. 200 sieve is 68.80%. This result indicated that the soil sample was fine-grained since the percentage of soil passing No. 200 sieve was greater than 35% of the total soil as per the AASHTO classification system. The liquid limits of soil samples are 93.3%, and the plasticity index is 44.49%. From these results, the soil has a very high swelling potential. The expansive soil sample of the study area was classified as A-7-5 and high clay (CH) soil using the AASHTO and USCS soil classification systems. This indicates that the soil samples have a high expansive index and high clay content, according to Prakash & Sridharan (2004). The modified Proctor compaction test was conducted to determine the optimum moisture content and maximum dry density of the natural expansive. The result of this test was 1.42 g/cc maximum dry density and 26.76% optimum moisture content. From the California bearing ratio test, the soaked CBR value of soil sample is 1.29%. As per the ERA manual's 2013 recommendation, the soil has a poor subgrade rating because the value of the soaked CBR is less than 3%. According to these findings, the natural expansive soil sample has a very poor

Table 4. Geotechnical property of black cotton soil

Parameter	Property	Values
Moisture content		Jimma town
		40.01
Grain size	Coarse, %	0.2
	Sand, %	7.35
	Silt, %	13.469
	Clay, %	68.801
Atterberg limit	Liquid limit, %	93.3
	Plastic limit, %	48.71
	Plastic index, %	44.49
Compaction test	MDD, g/cc	1.42
	OMC	26.76
CBR		1.29

subgrade rating, a high clay content, and a high plasticity index, making it difficult to work with as a subgrade material. Therefore, soil improvement is required to use these soils as subgrade material in road construction.

2.1.1. Chemical composition of black cotton soil

This chemical composition was determined by subjecting the soil to an XRD laboratory test machine to analyse the mineral that was found in black cotton soil. The soil sample used for this test passed the sieve size of 75 microns, and the sample powder was scanned from 10° to 75° (2 thetas) in one second at continuous scanning speed. The software used to determine the mineral found in the sample was Match!2. Table 5 represents the oxide composition of subgrade black cotton soil. Aluminium oxide ($Al2O_3$) is the second most common chemical composition in soil after silicon oxide (SiO_2), making up 78.12% and 9.19% of its weight, respectively. The least important compounds in the composition, however, are calcium oxide, ferric oxide, and potassium dioxide (KO_2). Thus, the silicon oxide, the dominant oxide in black cotton soil, has a significant impact on its inherent features.

Table 5. Chemical composition of black cotton soil

Chemicals	Chemical formula	Composition, %
Calcium oxide	CaO	1.03
Silicon dioxide	SiO_2	78.12
Magnesium oxide	MgO	2.13
Aluminium oxide	Al_2O_3	9.19
Ferric oxide	Fe_2O_3	4.03
Potassium dioxide	KO_2	4.1
Barium oxide	BaO	1.4

2.2. Chemical composition of lime

Both the chemical compositions of black cotton soil and lime are used to determine the reaction between the soil particles and the stabilizing agent. Table 6 represents the chemical composition of lime. Magnesium oxide (MgO), which makes up 0.74% of lime weight, calcium oxide (CaO), is a major constituent of lime, which makes up 73.22% of lime total chemical compositions. On the other hand, the least important compounds in the composition are calcium sulfate ($CaSO_4$) and ferric oxide (Fe_2O_3). Because calcium oxide is the main oxide, its characteristic features have a significant impact on the intrinsic properties of lime. This indicates that the reaction between black cotton soil and lime improves the geotechnical properties of this expansive soil (Adamu et al, 2022). The workability of clay soil would be greatly improved by addition of lime. Studies found that lime as a stabilizing agent greatly improves weak subgrade material, by reducing the plasticity index and improving the bearing capacity of weak soil. The reactions of lime to soil are still anonymous. Lime can stabilize soil trough (a) aggradations caused by flocculation of dispersed clay, (b) exchange of calcium ions for other adsorbed ions such as hydrogen, sodium or potassium, (c) pozzolanic reactions, which were thought to be the formation of calcium silicates by reaction of lime with free silica in the soil, (d) the gradual reaction of lime and CO_2 from the atmosphere and the soil to form calcium carbonate and thereby cementing the soil particle together (Walker & Pavía, 2011).

2.3. Sieve size analysis and soil classification

Figure 4 shows the distribution curves of the expansive soil sample grain size. A wet sieve was made after soaking the soil for 24 hours.

Table 6. Chemical composition of lime

Chemicals	Chemical formula	Composition, %
Calcium oxide	CaO	73.22
Phosphorous oxide	P_2O	0.08
Calcium sulphate	$CaSO_4$	0.12
Ferric oxide	Fe_2O_3	0.17
Magnesium oxide	MgO	0.74
Aluminium oxide	Al_2O_3	0.11

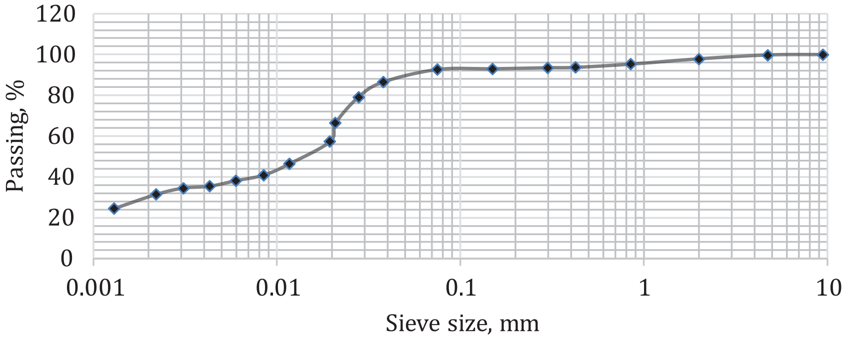

Figure 4. Grain size distribution curve of expansive soil

The grain size distribution required for soil categorization is provided through grain size analysis (ASTM D422-63). The results of this test are used to calculate the proportion of various grain sizes in the soil. These results showed that the soil samples contained more fine-grained material. Therefore, soil samples are fine-grained clay soil because the percentage of fine material passing sieve No. 200 is more than 35%, and clay percent is greater than silt percent as per the AASHTO soil classification system. In this study, the soil is classified under CH and A-7-5, which shows that the soil is inorganic, highly clayey, and highly expansive.

2.4. Effect of brick dust-lime on Atterberg limit test

The effect of *brick dust-lime* on Atterberg limits is shown in Figure 5. The effect of brick dust and lime on black cotton soil was determined. The Atterberg limit was improved after stabilizing black cotton soil with brick dust and lime for subgrade usage. The results of the liquid limit, plastic limit, and plasticity index decreased from 93.2% to 46.6%, 48.71% to 58.2% and 44.49% to 8.08%, respectively. This is related to cation exchange reactions that result in the flocculation and agglomeration of the soil particles, with a consequent reduction in the amount of clay-size materials, and, hence, the soil surface area to volume ratio was reduced, which certainly accounted for the reduction in plasticity. Therefore, the stabilization of expansive soil was used as subgrade material because it fulfilled the requirement for subgrade

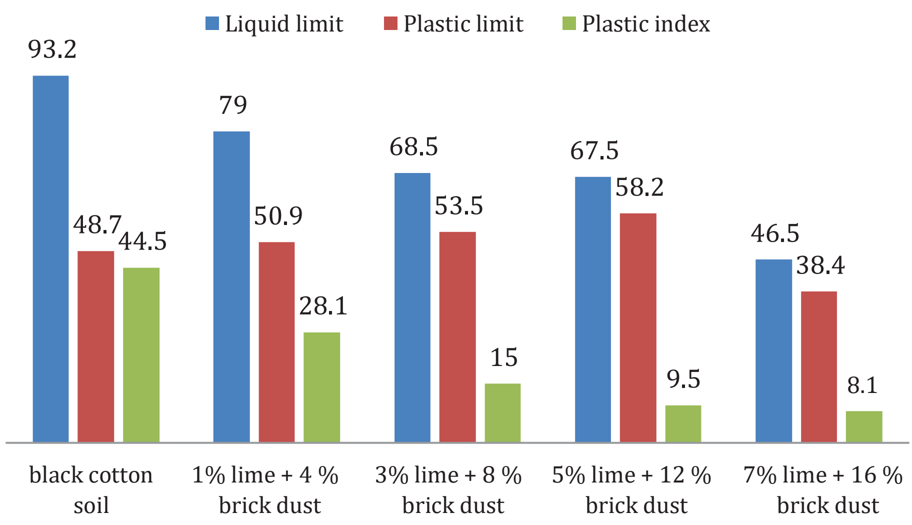

Figure 5. Effect of brick dust-lime on Atterberg limit results

material since the plasticity index of 8.08% was less than 30%, which was recommended by the Ethiopian Road Administration (ERA) manual.

2.5. Effect of brick dust-lime on the modified Proctor test

The objective of compaction is to bring the soil grains closer by applying an external effort and using some compaction equipment such as rollers. Water is added to the soil during compaction to act as a "lubricant," making the process more effective (Walker & Pavía, 2011). This laboratory test determines the relationship between soil moisture content and dry density for a given compaction effort. In this study, a modified Proctor test was done (ASTM D 1557).

The relationship between maximum dry density and optimum moisture content demonstrates that maximum dry density grew as stabilization proportion increased, while optimum moisture content declined, as shown in Figure 6. In stabilized subgrade black cotton soil, the use of stabilizer has the lowered optimum moisture content (OMC) and raised (the maximum dry density (MDD). Maximum dry density

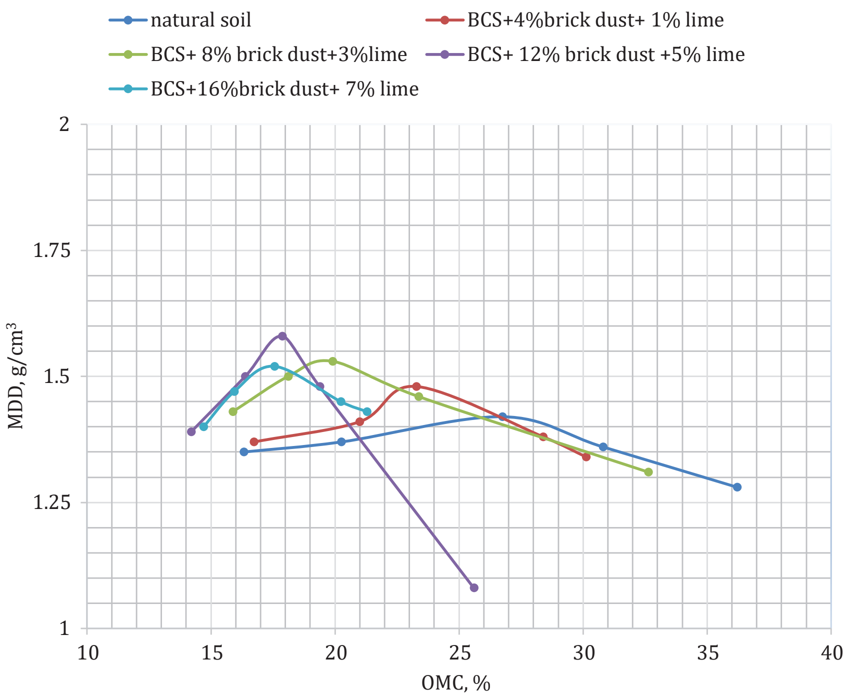

Figure 6. Effects of brick dust-lime on dry density-moisture content of expansive soil

increased from 1.42 g/cm^3 to 1.58 g/cm^3, whereas the optimum moisture content decreased from 26.76% to 17.8%. Decreasing the optimum moisture content, brick dust and lime act as stabilizers by reducing the plasticity and swelling characteristics of black cotton soil. Lime reacts with clay minerals between clay particles, causing flocculation and reducing soil plasticity. Flocculation results in changing the soil particles and reduces water absorption capacity, leading to a decrease in the optimum moisture content required for compaction. Increasing in maximum dry density, brick dust, and lime improves the compatibility of black cotton soil (Adamu et al., 2022; Walker & Pavía, 2011).

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2.6. Effect of brick dust and lime on the California bearing ratio test

The soil strength was determined using the Californian bearing ratio values at 2.54 mm penetration and 95% MDD. The most crucial factors used to assess the strength of the soil were the *CBR* values. When black cotton soil was stabilized with brick dust and lime, the *CBR* value improved and went from being very poor to fair for the subgrade road construction. *CBR* was raised from 1.29% to 13.6%. This improvement happened after soaking the soil sample for four days. The *CBR* value of expansive soil before stabilizing is 1.29%, however at 12% of brick

Table 7. The California bearing ratio value of stabilized expansive soil with brick dust-lime

Sample mixing ratio	CBR, %	Subgrade strength rate as per ERA manual
Black cotton soil, %	1.29	S1
BCS +4% of brick dust + 1% lime	4.5	S2
BCS +8% of brick dust +3% lime	7.85	S3
BCS +12 % of brick dust +5% lime	13.6	S3
BCS + 16 % of brick dust + 7% lime	3.1	S2

dust +5% lime, the *CBR* value of black cotton soil increased to 13.6%. Therefore, the *CBR* test result fulfilled Ethiopian Road Administration (ERA) standards after stabilization was performed which was greater than 3%.

2.7. Deformation of natural black cotton stabilized with brick dust-lime mixture

Table 8 shows improvement in deformation of black cotton soil when stabilized with brick dust and lime. The FEA results indicated that the deformation of the pavement structure decreased from 2.087 mm to 0.973 mm at optimum percentage of lime-brick dust. When applying constant tire pressure on stabilized black cotton soil, there was a decrease in deformation because improving the subgrade increased the strength of the subgrade soil. If the soil has a high amount of elastic modulus, it is stiffer and less deformable under stress. The combination of brick dust and lime helps improve the overall stability and load-bearing capacity of black cotton soil. It reduces its compressibility and increases its shear strength, making it more resistant to deformation and settlement. Thus, stabilizing black cotton soil with brick dust and lime decreases deformation settlement by improving the soil compaction, reducing volume change, and increasing its strength.

Table 8. Effects of brick dust-lime soil stabilization on deformation of pavement

Trials	Deformation, mm
Black cotton soil	2.087
Black cotton soil+4% brick dust + 1 % lime	1.846
Black cotton soil + 8% brick dust + 3% lime	1.456
Black cotton soil + 12% brick dust + 5% lime	0.973
Black cotton soil + 16 % brick dust + 7% lime	1.047

Conclusion

Construction of road subgrades can employ black cotton soil. It is crucial to consider that black cotton soil is extremely expansive, and variations in moisture content cause severe volume changes. Soil stabilization procedures should be followed in order to protect the road surface. To increase the strength of the soil and lessen its sensitivity to moisture-induced volume change, techniques like lime-brick dust stabilization can be applied. Brick dust-lime stabilization of soil can raise the ideal moisture level. This is because lime interacts with the soil clay minerals, making them more resilient to fluctuations in moisture content and more stable. The soil can store more water, as a result, without getting too mushy or unstable, which helps increase the project overall strength and stability. It is crucial to remember that the precise impact of lime on the ideal moisture content depends on the unique characteristics of the soil being utilized and the quantity of lime supplied. Based on the laboratory test results and numerical analysis results, the following conclusions were drawn:

- The results showed that the natural expansive soil samples from this study had A-7-5 as per the AASHTO and high clay (CH) as per the USCS classification system. Plasticity index was 44.49%, MDD was 1.42 g/cc, optimum moisture content (OMC) was 26.76, un-soaked CBR was 1.29%. Therefore, depending on these results, the soil samples were categorized as fine-grained soil with a high clay content, expansive potential, swelling potential, and poor subgrade strength.
- The soil sample liquid limit and plasticity index decreased from 93.2% to 46.5% and 48.71 to 38.42%, respectively, brick-dust percentage increased.
- The maximum dry density (MDD) increased from 1.42 g/cc to 1.48 g/cc, and the OMC decreased from 26.76% to 17.8% as the when the brick-dust percentage increased. But by further increasing the brick-dust beyond 12% brick dust +5% lime, both OMC and MDD decreased.
- The soaked CBR value increased from 1.29% to 13.6%, at the optimum percentage of brick-dust (12% of brick dust +5% limes). However, with an increase in percentage beyond this value, the soaked *CBR* decreased.
- The FEA results indicated that the deformation of the pavement structure decreased from 2.087 mm to 0.973 mm at optimum percentage of lime-brick dust.

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REFERENCES

Abhishek, D., Manish, N., & Rahul, M. (2016). Effect of fly ash geotechnical properties of soil. *IJETMR, 3*(5), 7–14. https://doi.org/10.29121/ijetmr.v3.i5.2016.62

Abe, S., & Wakatsuki, T. (2014). The influence of the mound-building termite (*Macrotermes bellicosus*) on soil clay mineralogy. *Tropics, 22*(4), 169–177. https://doi.org/10.3759/tropics.22.169

Adamu, B., Hailemariam, M., & Damtew, T. (2023). Suitability analysis of vertically installed scoria gravel drains for enhancing consolidation performance of clayey ground. *Results in Engineering*, *17*, Article 100975. https://doi.org/10.1016/j.rineng.2023.100975

Adamu, B., Yada, T., Damtew, T., Alemineh, S., & Teyba, W. (2022). Experimental study on potential suitability of natural lime and waste ceramic dust in modifying properties of highly plastic clay. *Heliyon*, *8*(10), Article e10993. https://doi.org/10.1016/j.heliyon.2022.e10993

Adey, G. (2017). Stabilization of expansive soil used as subgrade materialusing cement kiln dust [MSc. thesis, Addis Ababa University]. http://etd.aau.edu.et/handle/123456789/20916

Altmeyer, W. T. (1955). *Discussion of engineering properties of expansive clays*. ASCE. https://www.sciencegate.app/document/10.1061/taceat.0007284

Barasa, P. K., Jonah, T. K., & Mulei, S. M. (2015). Stabilization of expansive clay using lime and sugarcane bagasse ash. *International Journal of Science and Research (IJSR), 4*(4), 124–134. https://core.ac.uk/download/pdf/234680058.pdf

Barnat-Hunek, D., Góra, J., Suchorab, Z., & Łagód, G. (2018). Cement kiln dust. *Waste and Supplementary Cementitious Materials in Concrete,* 149–180. https://doi.org/10.1016/B978-0-08-102156-9.00005-5

Damtew, M., Dekebi, G., Yada, B., Alemineh, D., Tigist, M., & Mulatu, T. (2023). Interference effect of closely spaced foundation footing settlement variation. *Advances in Civil Engineering*, *2023*, Article 7464998. https://doi.org/10.1155/2023/7464998

Damtew, T., Meaza, K., & Adamu, B. (2022). Deformation analysis of cement modified soft clay soil using finite element method (FEM). *Heliyon*, *8*(6), Article e09613. https://doi.org/10.1016/j.heliyon.2022.e09613

Damtew, T. M. (2022). Improvement of engineering properties of expansive soil modified with scoria. *Jordan Journal of Civil Engineering*, *16*(2), Article 7716921. https://doi.org/10.1155/2022/7716921

Das, B. M. (2019). *Advanced soil mechanics* (5th ed.). London, CRC press. https://doi.org/10.1201/9781351215183

Deepdarshan, K. P., Buli, S., Kenea, D. F., Duresa, D. N., & Maru, D. A. (2020). Effect of fly-ash and geo-polymer in the stabilization of pavement foundation soil at Nekempt-Gudar road Ethiopia. *International Journal of Creative Research Toughts (IJCRT)*, *8*(5), 2414–2421. https://ijcrt.org/papers/IJCRT2005311.pdf

Eden, A. (2017). *Stabilization of expansive clay soils using quarry waste* [MSc. thesis, Addis Ababa University]. http://etd.aau.edu.et/bitstream/handle/123456789/21587/Eden%20Asres.pdf?sequence=1&isAllowed=y

Enkhtur, O. & Dalai, D. (2011). The distribution and characterization of expansive soils in Mongolia. *Proceedings of 2011 6th International Forum on Strategic Technology*, Harbin, China, 1327–1330. https://doi.org/10.1109/IFOST.2011.6021263

Chen, F. H. (1988). *Foundation on expansive soils.* New York, USA: Elseveier.

Guyo, K. T., Emer, T. Q., & Getachew, K. (2019). Calcined Termite Hill Clay Powder: As Partial Cement Replacement in Production of C-25 Grade Concrete. *American Journal of Civil Engineering and Architecture*, *7*(3), 128–134. https://doi.org/10.12691/ajcea-7-3-2

Habtamu, M. (2015). Critical assesment on the stabilization of expansive soils by different techniques [MSc. thesis, Addis Ababa University]. http://etd.aau.edu.et/handle/123456789/3560

Hailemariam, M. G., Damtew, T. M., & Adamu, B. (2023). Consolidation attributes and deformation response of soft reinforced with vertical scoria drains under road embankment. *Advances in Materials Science and Engineering*, *2023*, Article 2623062. https://doi.org/10.1155/2023/2623062

Hussein, M. (2021). Effect of Sand and Sand-Lime Piles on the Behavior of Expansive Clay Soil. *Advances in Civil Engineering*, 2021, 4927078. https://doi.org/10.1155/2021/4927078

Ismaiel, H. (2013). Cement kiln dust chemcial stabilization of expansive soil exposed at E1-Kawther Quarter, Sohag Region, Egypt. *International Journal of Geosciences*, *4*(10), 1416–1424. https://doi.org/10.4236/ijg.2013.410139

Kavish S. & Mehta. (2014). Analysis of Engineering Properties of Black Cotton Soil & Stabilization Using By Lime. *Engineering Research and Applications, 4*(5), 1–8.

Kumar, A., Walia, B. S., & Bajaj, A. (2007). Influence of fly ash, lime, and polyster fibres on compaction andstrength properties of expansive soil. *Journal of Materials in Civil Engineering*, *19*(3). https://doi.org/10.1061/(ASCE)0899-1561(2007)19:3(242)

Melese, D. T. (2023). Utilization of waste incineration bottom ash to enhance engineering properties of expansive subgrade soils. *Advances in Civil Engineering*, *2022*, Article 7716921. https://doi.org/10.1155/2022/7716921

Murray, H. H. (2007). Applied clay mineralogy occurrences, processing and application of kaolins, bentonites, palygorskitesepiolite, and common clays. In *Developments in Clay Science, 2,* 141–145. https://doi.org/10.1016/S1572-4352(06)02008-3

Russell, L. B., & Cerato, A. B. (2007). Stabilization of Oklahoma expansive soils using lime and class C fly ash. In *Problematic Soils and Rocks and In Situ Characterization*. https://doi.org/10.1061/40906(225)1

Syed, M., Guha Ray, A., & Garg, A. (2021). Performance Evaluation of Lime, Cement and Alkali-Activated Binder in Fiber-Reinforced Expansive Subgrade Soil: A Comparative Study. *Journal of Testing and Evaluation*, *50*(6), 20210054. https://doi.org/10.1520/jte20210054.

Walker, P., & Pavía S. (2011). Physical properties and reactivity of pozzolans, and their influence on the properties of lime-pozzolan pastes. *Materials and Structure, 44*(6), 1139–1150. https://doi.org/10.1617/s11527-010-9689-2

Yilmaz, I. (2004). Relationships between liquid limit, cation exchange capacity, and swelling potentials of clayey soils. *Eurasian Soil Science*, *37*(5), 506–512. https://hdl.handle.net/20.500.12418/11215

Yuan, W.-H., Wang, H.-C., Zhang, W., Dai, B.-B., Liu, K., & Wang, Y. (2021). Particle finite element method implementation for large deformation analysis using Abaqus. *Acta Geotechica*, *16*, 2449–2462. https://doi.org/10.1007/s11440-020-01124-2