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Enhancing Properties of Expansive Soils Using Cotton Stalk Ash

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Abstract

Expansive soils, rich in montmorillonite clays, undergo significant volume changes with moisture fluctuations, causing issues like settlement, heaving, and low strength. Conventional stabilization methods are often costly, prompting the need for affordable, eco-friendly alternatives. This study investigates cotton stalk ash (CSA) as a potential stabilizer for expansive soils. CSA's effectiveness was assessed through tests on soil properties, including index properties, shear strength, and free swelling, alongside an analysis of its chemical composition. The natural soil is classified as A-7-5 and CH according to AASHTO M145 and ASTM D2487, respectively. The results indicated that increasing CSA content significantly improved the soil's characteristics. Additionally, the curing period notably influenced the unconfined compressive strength of the treated soil. The chemical analysis of CSA revealed that the combined percentage of major elements (SiO_2, Al_2O_3, CaO, and Fe_2O_3) exceeded 70%. These elements can react with CaO in the presence of moisture to form stable compounds. Overall, the findings suggest that CSA is an effective stabilizer for expansive soils and can help mitigate environmental pollution caused by its indiscriminate disposal.

Keywords: Cotton Stalk Ash, Curing Time, Expansive Soils, Soil Stabilization

1. Introduction

Expansive soils are characterized by very low load-bearing capacity and significant swelling and shrinkage behavior. A key challenge with expansive soils is that their deformation is much greater than elastic deformation and cannot be accurately predicted using classical elastic or plastic theories (Nelson and Miller, 1993). The movement of these soils is typically uneven, leading to considerable damage to structures and pavements built on them. It is important to note that not all clay soils are expansive, and degree of expansion varies depending on the type of clay minerals present in the soil mass (Chen, 1988). The average annual cost of damage to structures caused by expansive soils is estimated at 400 million pounds in the UK and 15 billion dollars in the USA (Jones and Jefferson, 2012).

Expansive soils, including black cotton and other clayey soils, are prevalent across various regions of Ethiopia. They are commonly found in central, western, north-western, south-western, and parts of southern & eastern Ethiopia, often covering extensive areas. These soils typically occur in flat or gently sloping landscapes, such as highland plateaus, lowland floodplains, and valley floors. Known for its detrimental geotechnical characteristics, expansive soils pose significant challenges and costly risks, particularly in the construction sector (Morin and Parry, 1971; ERA, 2002; Yitagesu, 2012). Many roads constructed on expansive soils in Ethiopia face severe issues such as rutting and cracking. Due to seasonal climate changes, expansive soils undergo swelling and shrinkage, resulting in vertical and horizontal movements of the soil mass and the structures built on top. These movements cause pavement failures manifested as settlement, deep depressions, cracking, and uneven surfaces. Expansive subgrade soils, when wet, tend to heave into the upper layers of the pavement, especially when the sub-base material is coarse and has many voids. Roads built over such subgrade soils often develop surface undulations due to the loss of subgrade strength as it softens during rainy seasons. Excavating and replacing problematic soils can significantly increase project costs and time, as it involves removing the problematic soil, sourcing and transporting suitable materials, and compacting them to required specifications. Additionally, sourcing such materials often requires excavation from borrow areas, contributing significantly to environmental degradation.

Soil stabilization agents can improve soil properties by enhancing moisture retention, increasing particle cohesion, and acting as cementing and waterproofing agents. For the construction of highway embankments, earth dams, building foundations, and other geotechnical structures on clay soils, it is essential to increase their strength. In recent years, the use of unconventional waste materials as sustainable alternatives for soil improvement has gained significant attention. Examples include polyethylene terephthalate, plastic waste, glass powder, coal gasification slag, red mud, carbide slag, zeolite, sawdust, stone dust, waste marble dust, sugarcane bagasse ash, fly ash, onion peel ash, water hyacinth stem ash, groundnut shell ash, coffee husk ash and rice husk ash (Beju and Mandal, 2018; Ma et al., 2020; ShahriarKian et al., 2021; Salehi et al., 2021; Karthikeyan and Selvarani, 2021; Rezaei-Hosseinabadi et al., 2022; Li et al., 2023; Wei et al., 2024; Ke et al., 2024; Fang et al., 2024). Utilizing these by-products for soil stabilization offers an environmentally friendly solution to waste disposal

challenges. Locally available by-products, such as cotton stalk ash (CSA), can be used to improve the engineering properties of expansive soils. Cotton stalks are abundant in Ethiopia, particularly in the Metema cotton-growing region, which produces around 47,700 tons of cotton annually (Lançon and Worku, 2020). Attractive domestic prices and a growing textile and apparel industry further encourage cotton production (FAS Addis Ababa, 2019). Despite the increasing cotton production in Ethiopia, little attention has been paid to the potential use of CSA in treating expansive soils. The cotton plant including the cotton stalk is shown in Figure 1. The objective of this study is to investigate the effectiveness of CSA in enhancing the engineering properties of expansive soils for use as road bedding material. It involves a comprehensive analysis of the engineering characteristics of both expansive soil and CSA.



Figure 1 Cotton stalk plant in Metema Agricultural area

2. Materials and Methods

2.1 Materials

2,1.1 Soil

The soil sample used in this study was collected from a newly constructed road near the new Abay Bridge in Bahir Dar City. The soil was grayish-black in color and consisted of highly plastic clay. Disturbed samples were taken from three test pits, spaced 100 m apart, at a depth of 1.5 m below the natural ground level. To balance practicality with the need for reliable, consistent & engineering-relevant data, a uniform sampling depth of 1.5 m was established for all test pits. To prevent moisture loss, soil samples were stored in plastic bags and kept in a cool, dry place. The map showing the colour appearance of soil and locations of the soil sample collection sites are presented in Figure 2.



Figure 2 (a) Field observation colour appearance of soil (b) Location map of soil sample collection sites, Google earth image 2021

2.1.2 Cotton Stalk Ash

The cotton stalks (CS) were collected from the mechanized cotton farming area in Metema, Gondar (Northwest Ethiopia). The cotton stalks were burned in the open air, and the resulting cotton stalk ash (CSA) was collected, stored in a dry plastic bag, and tightly sealed to prevent exposure to atmospheric air.

2.2 Methods

The soil was treated with varying percentages of CSA based on the dry mass of the soil. To evaluate the engineering properties of the expansive soil treated with CSA, a series of laboratory tests were conducted, including specific gravity, particle size analysis, Atterberg limits (liquid limit, plastic limit, and shrinkage limit), free swell, compaction, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS). Additionally, a chemical composition test was performed on the CSA. All soil tests were carried out in the soil laboratory at Bahir Dar Institute of Technology, while the chemical composition test was conducted at the Ethiopian Geological Survey in Addis Ababa.

For preparing the soil-CSA compacted specimens, the optimum moisture content (OMC) and maximum dry density (MDD) were determined for different CSA contents. The soil, CSA, and water were first mixed on a large tray and then placed in a water-tight plastic bag for curing at room temperature. On the 7^{th} and 14^{th} day, the mixture was taken out and compacted using a modified compaction mould. The specific gravity of the soil and CSA was determined following ASTM D854. Soil samples were oven-dried at 105°C for 24 hours.

The free swell test was conducted as per (IS 2720) for both the natural and treated soils. Two oven-dried soil samples, passing through a 0.425 mm sieve, were prepared for both natural and treated conditions. One sample was placed in a graduated glass cylinder filled with distilled water, while the second sample was placed in another cylinder containing kerosene. Both samples were left undisturbed for 24 hours, and the volume changes were measured to determine the free swell index. The same procedure was repeated for the treated soil with varying percentages of CSA.

Wet sieve and hydrometer analyses were carried out to determine the grain size distribution of the soil samples according to ASTM D422. The Atterberg limit tests were conducted following ASTM D4318. The linear shrinkage test, which assesses the shrinkage characteristics of natural and treated soils, was performed as per IS 2718, using various CSA percentages and curing periods. The expansion potential of the soil was evaluated based on Altmeyer (1955). A modified Proctor test was conducted according to ASTM D1557 to simulate field conditions. The moist soil samples and CSA were air-dried, and boulders in the soil were pulverized using a rubber mallet and quartered to obtain representative samples. Each specimen was prepared with CSA contents ranging from 5% to 30% by weight of the soil sample.

2.2.1 California Bearing Ratio

A three-point California Bearing Ratio (CBR) test was conducted according to AASHTO T193 to assess the strength of both natural and treated soil samples. Approximately 20 kg of air-dried soil, which passed through a 4.75 mm sieve, was mixed at the OMC in a large mixing pan. The sample was divided into three portions, each weighing about 6 kg, and compacted into five equal layers with 10, 30, and 65 blows per layer. Moisture content tests were carried out on the

samples before and after compaction. The compacted soil in the CBR mould was then soaked in water for four days with a 4.5 kg surcharge load applied. After soaking, the CBR mould was removed from the water tank and allowed to drain for 15 minutes before the CBR test was conducted. The tests were performed on both 7 days cured and uncured treated soil samples.

CBR tests were conducted at a strain rate of 1 mm per minute using a plunger force of 250 N, with force readings recorded at 0.5 mm intervals up to a maximum penetration of 7.5 mm. The CBR value was calculated for penetrations of 2.5 mm and 5.0 mm, with the higher value taken as the result. A graph was plotted for penetrations against dry densities, and the CBR value at 95% of MDD was selected as the design CBR value, which serves as an index measurement of soil strength. The CBR tests were conducted on compacted specimens at OMC using the modified compaction method. To determine the soaked and swell CBR values, the compacted soil samples in the CBR mould were soaked for 96 hours in a water bath. The swell of the soil was measured by placing a tripod with a dial indicator on top of the soaked CBR mould. The initial dial reading was taken immediately after soaking, and the final reading was recorded after four days to calculate the swell percentage of the initial sample length.

Three-point CBR tests with four days of soaking were performed to assess the subgrade soil condition under worst-case moisture conditions. The amount of water needed to achieve the desired moisture content, including an allowance for evaporation during mixing, was measured and prepared in a suitable container. Once the OMC was determined from the Proctor test, the water quantity required for mixing was calculated. For each test, the mould height and soil-CSA mixture were divided into five equal parts. Each layer was compacted with 10, 30, and 65 evenly distributed blows across the sample surface. The final surface level of the sample was prepared to be 5-10 mm above the top of the mould. The extension collar was then removed, and the compacted soil was trimmed with a straightedge, with any surface irregularities patched using small-sized material. A spacer disk was removed, and a coarse filter paper was placed on the perforated base plate. Finally, the compacted specimen was ready for curing.

2.2.2 Unconfined Compressive Strength

The unconfined compressive strength (UCS) test was conducted in accordance with ASTM D2166. The samples were prepared using a cylindrical metal mould with a diameter of 75 mm and a height of 150 mm, compacted at the OMC and MDD values determined from the modified Proctor compaction test. The mould was divided into three equal parts, and each layer of the specimen was tamped until it reached the desired volume. To ensure a uniform specimen, the top of each compacted layer was scratched before adding the next layer. After the final layer was compacted, the sample was carefully extruded from the mould and prepared for the curing process.

2.2.3 Swelling Potential

In this study, the swelling potential of the soil was determined by index properties of the soil using indirect methods developed by (Seed et al.,1962; Van Der Merwe, 1964; Carter and Stephen, 1991). Generally, soils with a clay content exceeding 30% and a Plasticity Index (PI) greater than 35% are considered to have a very high potential for shrinkage or swelling. Conversely, soils with clay content and PI between10% to 20% are

likely to experience at least slight swelling or shrinking due to environmental changes.

2.2.4 Mixing Schedule of CSA

The goal of a CSA mix design is to determine the optimal CSA content for stabilizing soil to meet required subgrade strength specifications. The required amount of CSA and water was calculated based on the MDD. The soil and CSA were thoroughly mixed by hand on a large tray. In the present study, a total of 36 tests were conducted.

2.2.5 Curing Temperature and Humidity

All soil samples were cured at room temperature (approximately 25°C). There are two primary methods of curing. In the first method, samples sealed in plastic bags are submerged in a water tank to maintain a curing environment with 100% relative humidity. In the second method, samples are sealed in plastic bags and stored at room temperature to prevent carbonation and moisture loss during the curing period. This study utilized the second method. In hot and dry climates, effective curing is essential, but preventing moisture loss is challenging. Constantly spraying the sample surface to keep it damp can stabilize moisture content in most of the sample, but this method risks leaching the stabilizer from the top layer.

If the spraying is intermittent and the sample surface dries periodically, the curing will be ineffective. However, covering the sample surface with a 30 to 40 mm thick layer of sand and spraying it with water can create an effective curing system. This reduces the number of spraying cycles per day and the amount of water needed. After seven days, the sand should be brushed off, and the surface should be primed with a low-viscosity cutback bitumen. An alternative curing method involves a light spray of water followed by the application of a viscous cutback bitumen, such as MC-3000 (medium-curing cutback bitumen), or a slow-setting emulsion. These materials do not fully penetrate the stabilized layer and leave a continuous bitumen film that serves as a curing membrane. No traffic should be allowed on the membrane for seven days, after which excess bitumen can be absorbed by sanding the surface. A prime coat is not effective as a curing membrane because it penetrates too deeply and does not leave enough bitumen on the surface to form a continuous film (ERA, 2013).

2.2.6 Curing Time

In this study, the curing times of 7 and 14 days suggested by (Anupam et al., 2017; Patel and Shahu, 2017) were used. Two samples for each curing time were prepared to indicate reproducibility as well as to provide sufficient data for accurate interpolation of the results. After treatment of the clay soil with CSA of prescribed stabilizer contents, engineering properties of the stabilized soil were established.

3. Results and Discussion

The relevant engineering properties of the natural soil, CSA, and soil treated with varying percentages of CSA were evaluated. Curing periods of 7 and 14 days were applied for the Atterberg limits and UCS tests, while a 7-day curing period was used for the CBR tests.

3.1 Potential Swell

The free swell test results indicated that all soil samples fell into the category of expansive soils, with sample number two being relatively more expansive than the others. The free swell index values were found to be greater than 91%, classifying all samples as highly expansive soils, as per Sridharan and Prakash (2000). The free swell test results for all test pit soils are summarized in Table 1.

Table 1 Free swell test results of soil

Test Results	Sample number		
	1	2	3
Free Swell (%)	122.5	127.25	120
Free swell index (%)	122.5	127.25	120
Modified free swell index	2.235	2.27	2.2

According to the swelling potential classification chart proposed by Van Der Merwe (1964), the Plasticity Index (PI) and clay fraction values of these soils were determined to be 65.16% and 60.85%, respectively, classifying them as highly expansive soils. Based on the empirical method by Seed et al. (1962), these soils exhibit a very high swelling potential, exceeding 25%. The swelling potential of the soil was calculated to be 1.07, indicating it is "active to swell."

When classified using the plasticity chart, all test results are plotted above the "A-line," indicating that the soils are inorganic clays with high plasticity (CH). Such soils are prone to significant volumetric changes with variations in moisture content. The percentages of the soil's swelling potential, calculated using empirical methods based on different parameters, are provided in Table 2. All values exceed 25%, confirming that the soil has a very high potential for swelling.

Table 2 Swelling potential (SP) prediction of the soil using the empirical method

Reference	Description	Swelling potential (%)
Seed et al. (1962)	$2.16 \times 10^{-3} (PI)^{2.44}$	57.62
	$3.6 \times 10^{-5}(A)^{2.44} (C)^{3.44}$	58.32
Chen (1988)	$0.2558e^{0.0838(PI)}$	60.16

Note: Activity (Ac) = 1.07, Plastic Index (PI) = 65.16%, clay fraction (C) = 60.85%

3.2 Characteristics of Natural Soil and CSA

Three soil samples were collected from three test pits, and the most expansive soil among them was selected for stabilization. The free swell test was conducted to identify the highly expansive soil, and sample two was chosen as it exhibited the highest expansiveness. The soil had a fine particle percentage (<0.075 mm) of 97.39%, a liquid limit (LL) of 109.04%, and a plasticity index (PI) of 65.16%, classifying it as A-7-5 under AASHTO M145 and CH according to ASTM D2487. The test results indicated that this soil is highly expansive with significant volume change properties, as described by Chen (1988). For subgrade materials, the LL and PI values should not exceed 60% and 30%, respectively (Anupam et al., 2017). Soils with a swelling potential and clay content greater than 35% and 28%, respectively, have a high degree of expansiveness according to Anupam et al. (2017). The free swell index of 127.25% further confirmed that the soil is very expansive. Additionally, a linear shrinkage limit value above 8% suggests a high

swelling potential (Altmeyer, 1955), indicating that this soil does not meet the minimum requirements for subgrade materials.

The specific gravity of the soil was found to be 2.74, which is typical for inorganic clay soils. Grain size analysis showed that the soil consists of 1.3% gravel, 1.31% sand, 36.55% silt, and 60.85% clay by weight, with 97.36% passing through a 0.075 mm sieve. The grain size distribution curve for the soil and CSA is shown in Figure 3, and their engineering properties are listed in Table 3. The free swell value of CSA was determined to be 12.99%. Since this value is less than 50%, CSA can be used as a stabilizing agent for expansive soils. The Atterberg limits for CSA indicated low plasticity. The particle size analysis of CSA revealed that it consists of 1.74% gravel, 4.73% sand, 59.4% silt, and 34.12% clay by weight. Modified Proctor tests were conducted to determine the relationship between moisture content and dry density for the soils. The MDD and OMC of the soil were found to be 1.513 g/cm³ and 26.1%, respectively. The unconfined compressive strength (UCS) test result of the soil was obtained to be 133.98 kPa.

Table 3 Characteristics of natural soil and CSA samples

Property		**Values**	
		Soil	**CSA**
Natural moisture content (%)		32.8	1.4
Specific gravity (Gs)		2.74	2.28
Liquid limit (%)		109.04	26.1
Plastic limit (%)		43.88	NP
Plasticity index (%)		65.16	NP
Optimum moisture content (%)		26.1	--
Maximum dry density (g/cm^3)		1.513	--
Unconfined compressive strength (kPa)		133.98	--
Soaked CBR value (%)		0.98	--
CBR-swell (%)		10.62	--
Free swell index (%)		127.25	12.99
Group index, GI		20	--
Shrinkage limit (%)		12.04	2.21
Gravel (%)		1.3	1.74
Sand (%)		1.31	4.73
Silt (%)		36.55	59.4
Clay (%)		60.85	34.12
Fine particles (< 0.075 mm)		97.39	93.52
Classification	AASHTO M145	A-7-5	--
	ASTM D2487	CH	--

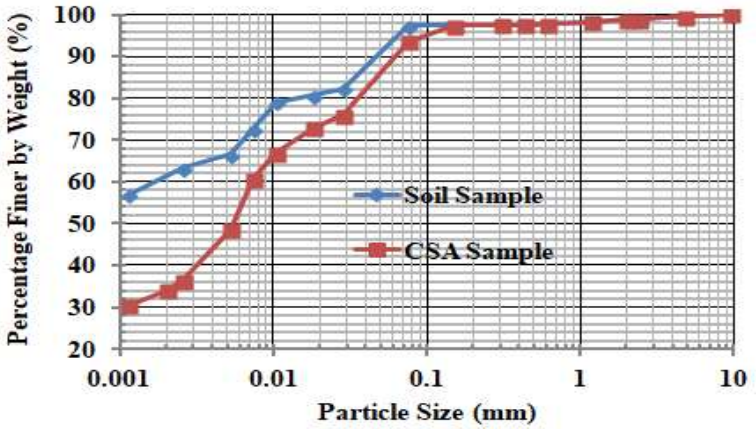


Figure 3 Grain size distribution curves of soil and CSA

3.2.1 Chemical Properties of CSA

The chemical composition test was determined using an X-ray fluorescence (XRF) test. The chemical composition test result of CSA is given in Table 4.

Table 4 Chemical composition test result of CSA

Chemical compound	Value (%)
Silicon Oxide, SiO_2	60.32
Calcium Oxide, CaO	19.44
Aluminum Oxide, Al_2O_3	11.1
Iron Oxide, Fe_2O_3	0.93
$SiO_2 + Al_2O_3 + Fe_2O_3$	72.35
Magnesium oxide, MgO	0.80
Sodium oxide, Na_2O	0.16
Potassium Oxide, K_2O	0.56
Manganese oxide, MnO	0.08
Phosphorus pentoxide, P_2O_5	0.29
Titanium Oxide, TiO_2	0.54
LOI	5.80

The main constituents found in CSA are silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) with a total amount of more than 72.35%. The calcium oxide (CaO) content is about 19.44%. It is thus classified as high-calcium CSA. As the summation of SiO_2, Al_2O_3, CaO, and Fe_2O_3 of CSA is greater than 70% of the total content it may be classified as silica volcanic ash. The XRF test result showed that the CSA may satisfy both the chemical properties of class N cement and class C fly ash stated in ASTM C618.

3.2.2 CBR and CBR Swell of Soil

The CBR value of the natural soil was determined at a density of 95% of MDD and found to be 0.98%. If the CBR value found in the range of 0 to 3 is very poor subgrade soil whereas 3 to 7 is poor to fair subgrade soil utilized in pavement applications (Bowles, 1992). This indicated that the soil had a very low CBR value and did not satisfy the minimum requirements stipulated as subgrade and embankment materials. Hence, it can be concluded that this soil couldn't be used as subgrade and/or selected fill material for embankment construction unless its undesirable properties are rectified (Anupam, et al., 2017). The CBR swell value of the soil was 10.62%. This value does not satisfy the minimum permissible value of less than 2% (ERA, 2013).

3.3 Characteristics of CSA Treated Soil

In this study, the amount of CSA used to stabilize the expansive soil ranged from 5% to 30% by weight of the soil with a 5% increment. At lower ranges, the effect of CSA on the soil was not significant. The amount of stabilizing agent depends on the nature of the stabilizing agent and the properties of the soil to be stabilized.

3.3.1 Effect of CSA Content on Free Swell

The reduction in free swell (FS) and free swell index (FSI) are directly proportional to the quantity of CSA. The highest reduction in free swell and free swell index was attained when the soil was treated with 30% CSA which is an 85.82% reduction compared to untreated soil. The extent of variation of swelling potential varies from high to low (Sridharan and Prakash, 2000). The free swell test result for soil treated with CSA is reported in Table 5. The reaction between soil and CSA causes cementing the soil particles together and the cation exchange between expansive soil and CSA may happen to decrease the expansiveness of the soil.

Table 5 Free swell test result of treated soil

% of CSA	Free swell (%)	Free swell index (%)	Free swell ratio (FSR)
0	127.25	127.25	2.27
5	120.45	120.45	2.2
10	104.17	104.17	2
15	85.52	85.52	1.84
20	68.33	68.33	1.65
25	56.00	56.00	1.57
30	41.43	41.43	1.41

3.3.2 Effect of CSA Content on Atterberg Limit

The Atterberg limit value of treated soil, and cured for seven and fourteen days are summarized in Table 6. As can be seen in Table 6, 30% of CSA treated soil would be suitable for road subgrade material. Because of this, it changes the degree of expansion or the PI values from very high to low according to the USBR method (Ranjan and Rao, 2000) of soil classification.

Table 6 Atterberg limit of treated soil at 7 and 14 days of curing time

CSA (%)	Curing day	LL (%)	PL (%)	PI (%)
0	0	109.04	43.88	65.16
5	0	100.18	41.4	58.78
	7	97.63	41.72	55.91
	14	95.08	42.04	53.04
10	0	90.1	40.5	49.6
	7	86.7	40.11	46.59

CSA (%)	Curing day	LL (%)	PL (%)	PI (%)
	14	83.3	39.72	43.58
	0	78.9	39.2	39.7
15	7	75.84	38.83	37.01
	14	72.78	38.46	34.32
	0	69.71	37.4	32.31
20	7	65.28	36.6	28.68
	14	60.85	35.8	25.05
	0	58.4	34.5	23.9
25	7	55.3	34.1	21.2
	14	52.2	33.7	18.5
	0	49.6	32.4	17.2
30	7	47.9	31.7	16.2
	14	46.2	31	15.2

The LL and PI of the soil decrease with an increasing percentage of CSA. The LL, which is related to the thickness of the diffused double layer (Sridharan et al., 1997), reduces as more CSA is added. The most significant reduction in LL and PI, approximately 16.2%, is observed with the addition of 30% CSA. This decrease in LL is attributed to the increased water-holding capacity resulting from the flocculation and agglomeration of clay particles, which occurs due to the cation exchange when CSA is added (Sridharan, 1990). Additionally, the reduction in LL can be linked to the increased electrolytic concentration and cations in the soil (Sridharan and Satyamurty, 1996). A decrease in LL with the addition of CSA also indicates an increase in shear strength. The impact of CSA content and curing time on the free swell index (FRI) and Atterberg limit values is illustrated in Figure 4.

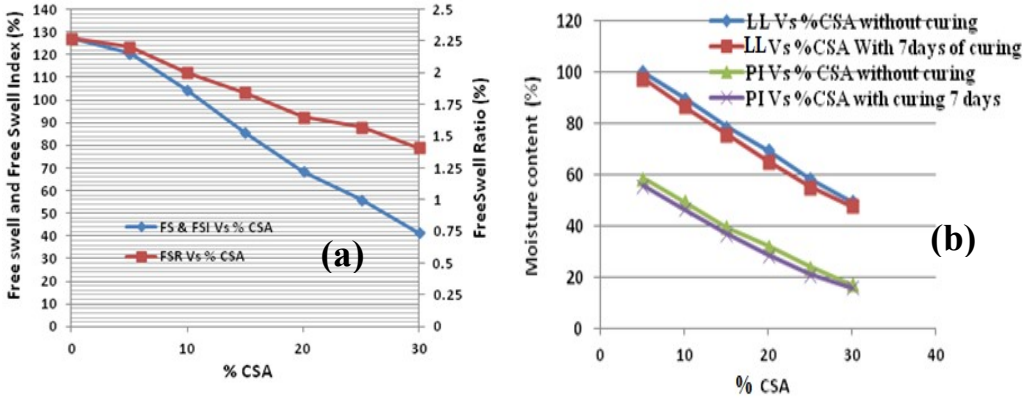


Figure 4 (a) Variation of FSI and FSR with CSA content (b) Effect of curing on treated Atterberg limit values

The shrinkage limit of the treated soil was significantly decreased by 54.5% compared with untreated soil. This is due to the shrinkage limit could be attributed to the flocculation and aggregation phenomena of clay particles and the presence of free CaO. The CSA caused a decrease in the surface of clay particles then formed the clay particles coarser, and eventually enhanced the friction and the strength of treated expansive soil. As a result, the finer clay particles were replaced by relatively coarser particles (Dang et al., 2016). The Effect of CSA on shrinkage limit of expansive soil is shown in Figure 5 (a).

3.3.3 Effect of CSA Content on Specific Gravity

The specific gravity of the soil decreased from 2.74 to 2.43 while the percentage of CSA increased from 5% to 30% as shown in Figure 5 (b). The main reason for the reduction of specific gravity is the addition of low specific gravity of CSA into the high specific gravity of soil (Zha et al., 2008).

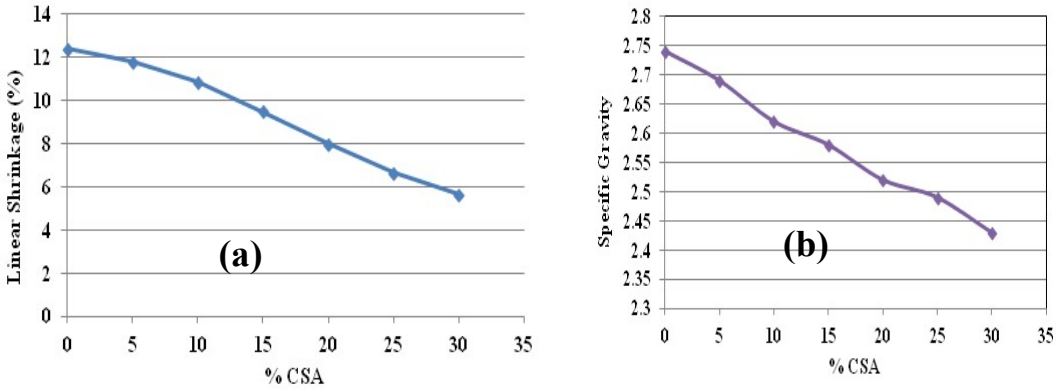


Figure 5 Effect of CSA content on: (a) shrinkage limit; (b) specific gravity

3.3.4 Compaction Characteristics of Treated Soil

The OMC increased from 26.1% to 32.1% as the MDD decreased from 1.513 to 1.419 g/cm^3 with increasing CSA. The effect of CSA content on the moisture-density relationship of the clay soil is shown in Figure 6. This may be due to the comparatively low specific gravity value (2.28) of the CSA compared to soil of 2.74 value. A similar relationship was reported by (Ferguson, 1993; Nicholson and Kashyap, 1993). On the other hand, the OMC increased with higher CSA treatment due to the ion exchange process between the soil particles and the formation of lumpy mass, which needs additional moisture, the soil becomes crumbly for compaction requiring slightly higher moisture content for attaining maximum density (Mohammed et al., 2018).

The optimum percentage of CSA can be determined as 30%, based on the moisture-density relationship and other properties met. As illustrated in Figure 6, the OMC consistently increases while MDD decreases with increasing CSA content. However, the MDD of the soil treated with 30% CSA was found to be only 6.2% lower than the MDD of the untreated soil. This reduction falls within the acceptable range, as specified in ERA (2013). A CSA percentage can be considered acceptable if the MDD remains within a tolerable reduction threshold (less than or equal to 10% of untreated soil's MDD). The optimal percentage of CSA is not solely defined by MDD and OMC trends but rather by a holistic assessment of all relevant engineering properties such as CBR, UCS, and swelling potential reduction.

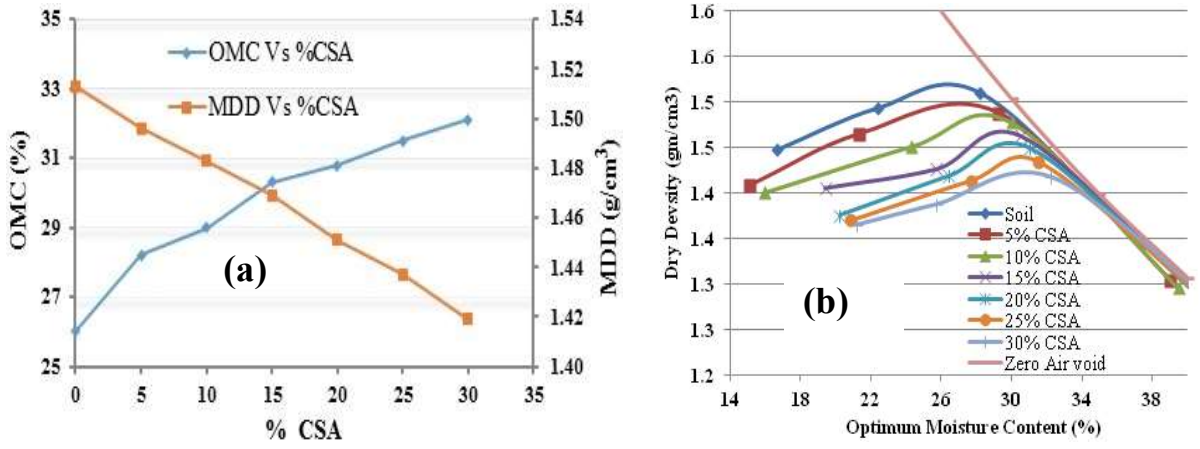


Figure 6 Effect of CSA content on: (a) MDD and OMC; (b) Compaction curve of soil

3.3.5 Effect of CSA Content on UCS Value

The percentage of CSA and curing time are directly related to the values of UCS. The effects of CSA content and curing times on UCS and cohesion values are depicted in Figure 7. The maximum value of UCS at 30% of CSA, and uncured, 7 and 14 days cured respectively were found to be 295.25 kPa, 324.92 kPa, and 342.44 kPa. The main reason for increasing UCS with the increase of the percentage of CSA is the formation of cementitious products under pozzolanic reaction and additional strength is mobilized by granular packing in the matrix formed with CSA act as filler (Consoli et al., 2001). Similar UCS test results for untreated expansive soil are also depicted in these figures for comparison purposes. As can be seen, the undrained cohesion increased considerably for each increment of time in the curing process. The UCS results cured at 14 days indicated that the UCS values apparently increased as the CSA contents were increased, as shown by the slope of the linear line if compared to that of treated soils cured at 7 days. The increase in UCS values for treated soils with 30% CSA content, cured at 14 days was 255.6%. However, for the treated soils cured at 7 days with the same amount of CSA content, the increase in UCS value obtained to be nearly 242.5%. The effect of CSA contents on the UCS values are represented by strong coefficient of correlation as indicated by both treated soil samples cured at 7 and 14 days.

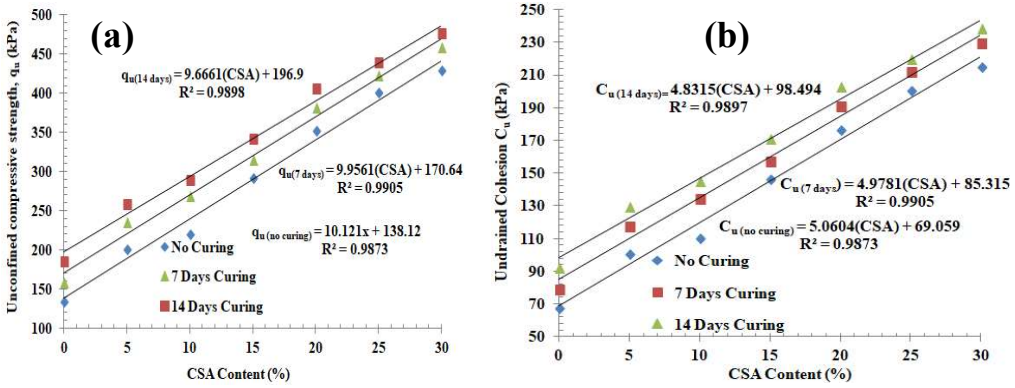


Figure 7 UCS test results at different curing times: (a) Variation of UCS with CSA content; (b) Variation of cohesion with CSA content

The curing time has a significant effect on UCS of the stabilized soil. Curing required a time to the dissolution of SiO_2 and Al_2O_3 from the ash (Sivapullaiah et al,. 1998) and/or soil, and pozzolanic reactions between CaO, SiO_2, and Al_2O_3 (Dayioglu et al., 2017). Thus, pozzolanic reactions are known as time dependent. As time progresses, cementitious materials, calcium-silicate-hydrate and calcium-aluminate-hydrate gels, are formed during the pozzolanic reactions and strengthen the inter-particle connections by acting as filling gels (Little and Nair, 2009; Cetin et al., 2010; Zumrawi, 2015). This improved linking between the soils particles increases the strength (Zhu and Liu, 2008). Thus, the general trend is that a longer curing period yields stronger soil materials (Pflughoeft-Hassett et al., 2000; Su, 2012). Relatively higher UCS values were observed in the specimens cured for 14 days compared with the specimens uncured in all the mixtures.

Different researchers in the past reported that the strength of stabilized expansive soil significantly improved as the curing periods were further extended. The comparison of UCS values for various expansive soils treated with different stabilizers are given in Table 7. As can be seen in this table, the UCS value of the treated soil is comparable to those achieved using different stabilizers such as lime, cement, sawdust, fly ash, coffee husk ash, and rice husk ash which are often utilized in higher mix percentages to achieve optimum results. The ability to reduce plasticity, compressibility, and swelling potential while increasing shear strength serves as a practical criterion for selecting a stabilizer for problematic local soils, considering cost and availability. In this study, the improvement in the engineering behavior of expansive soil using CSA aligns with the performance of other commonly used additives.

Table 7 Comparison of UCS values for various expansive soils treated with different stabilizers

Ar	Type of Stabilizer (%)	UCS (kPa) Curing time (day)			
		3	**7**	**14**	**28**
Al-Taiea et al. (2016)	8% Lime	--	--	--	573
Rahman et al. (2016)	20% Cement	30	--	--	50
Raviteja et al. (2014)	20% Fly ash and 9% lime	--	--	--	702
Niyomukiza et al. (2019)	3% Sawdust and 3% lime		735	1044	1348
Ma et al. (2020)	12% Rice husk ash and 3% lime		2000	2420	2830
Atahu (2020)	15% Coffee husk ash		247	251	
This study	30% Cotton stalk ash	--	458.9	476.42	--

3.3.6 Effect of CSA Content on CBR

According to AASHTO T193, unless specified by the requiring agency, or it has no effect on the test results for the material being tested, all specimens shall be soaked before penetration. To simulate the worst field conditions like high rainfall and complete saturation of the entire soil mass due to near ground water table the CBR specimens should soaked for four days. However, in most parts of Ethiopia, the groundwater table is much lower than the

annual moisture fluctuation depth, 'active zone' (commonly 2-3 m) and the annual rainfall intensity is not as high as the worst condition considered for the soaked CBR test. This study area is located near Lake Tana and Abay River and hence the groundwater table is at a lower depth. Thus, soaked CBR tests are conducted on the natural subgrade soil and compared with CBR of treated soil using 10%, 20%, and 30% CSA.

The effect of soaked CBR on pavement thickness is investigated by considering an ideal section of expansive subgrade soil. The CBR values of CSA treated soil were substantially increased while the percentage of additive and curing time increased. The CBR values of CSA stabilized expansive soil increased from 0.98% to 5.47% with increasing CSA from 0 to 30%. The amount of CBR increase was almost 379% compared with the CBR of untreated soil without curing. Moreover, the CBR values were increased with curing time of 7 days at different percentages of CSA. The CBR values of CSA treated soil at CSA content of 30% increased by nearly 452% compared with that of untreated soil. The CBR increased by about 17% compared to the same CSA content treated soil after 7 days of curing. Therefore, it can be concluded that the CBR value was not only affected by CSA content but also by the curing time. The continuous increase in the CBR value with rising CSA content is primarily due to enhanced soil granularity, pozzolanic reactions, and reduced plasticity, due to better interlocking of soil-CSA particles, and improved compaction characteristics. These factors synergistically contribute to a progressively stronger and more load-resistant soil structure. The increase in CBR values may be due to cementation and pozzolanic reaction in the form of frictional resistance contributed by CSA. The CBR value of subgrade soil is not less than 3% determined at MDD and OMC (Anupam, et al. 2017).

3.3.7 Effects of CSA Content on CBR Swell

The swelling potential tests were conducted on 4 days of soaked CBR samples to estimate the expansive nature of the subgrade soils. The CBR swell at 10%, 20%, and 30% CSA treated soil samples was measured from the CBR mould before and after soaking. The CBR swell test results of untreated and treated, and uncured and cured soil samples are shown in Figure 8. The CBR swell was decreased from 11.24% of untreated soil to 1.67% at 30% CSA on treated uncured samples. Also, curing played a significant role in decreasing the CBR swell values from 11.24% to 1.28%. The main reasons for the reduction of CBR swell are the pozzolanic reaction produces Calcium silicate hydrate and calcium aluminate hydrate gel. This gel helps with flocculation and agglomeration of the soil particles by strong bonds. And then the water absorbency capacity of the soil is reduced. The CBR swell value of subgrade soil should be less than 2% determined at MDD and OMC (ERA 2013).

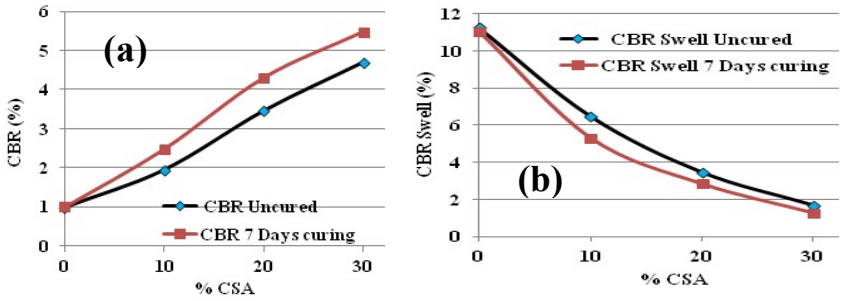


Figure 8 (a) Effect of CSA on soaked CBR values (b) Effect of curing on CBR swells

As per the current standards, it can be noted that the 30% CSA can be used for a subgrade class of S3 which is rated as 'nearest to fair' subgrade material. The application of CSA has a significant effect on the engineering properties of the expansive soil. The LL and PI respectively reduced from 109.4% to 47.9% and 65.15% to 16.2% at 30% of CSA. Moreover, the CBR value was increased from 0.98 to 5.47 at 30% of CSA. The direct and indirect swell test results indicated that the potential swell of the soil was significantly reduced by increasing the percentage of CSA and curing period. The potential swell at 30% CSA was reduced from 11.24% of the natural soil to 1.67% and 1.28% for uncured and cured cases respectively. Thus, it can be concluded that the CSA is a good material to be used as an additive for expansive subgrade soils. All the test results are in reasonable agreement with the previous study data. Ensuring that treated soil complies with ERA standards is essential for its suitability in engineering applications, particularly road construction. This study results demonstrated that soil treated with CSA significantly meets ERA requirements by enhancing key engineering properties, including plasticity, CBR, UCS, swelling potential, and compaction. These improvements enable the treated soil to achieve the necessary benchmarks for road construction, presenting a sustainable and effective solution for overcoming the challenges posed by expansive soils.

The use of CSA in this study is justified due to its potential as an eco-friendly and cost-effective soil stabilizer. CSA is a by-product of agricultural waste generated from cotton stalks, which are abundant in many regions. Its utilization aligns with sustainable development goals by promoting waste recycling and reducing environmental pollution. CSA is rich in pozzolanic compounds, such as silica and alumina, which enhance soil stabilization through pozzolanic reactions. These reactions improve the strength, durability, and compressibility of expansive soils, making them more suitable for use as road bedding material. It mitigates the challenges of expansive soils, such as high shrink-swell potential, and increases load-bearing capacity, making the soil suitable for road bedding. Its low cost and availability make CSA an accessible alternative to traditional stabilizers like lime or cement, particularly in resource-constrained regions. Its application in this study demonstrates its viability as a sustainable solution to improve soil properties while addressing agricultural waste management challenges.

4. Conclusions

An experimental study was carried out to investigate the effect of CSA on the engineering properties of an expansive soil. Based on the test results the following conclusions have been drawn.

- The summation of important elements found in CSA (Al_2O_3, CaO and SiO_2, and Fe_2O_3) is more than 70%; thus, it is a good pozzolana that could help to mobilize the

calcium ion with the combination of clay to form pozzolanic reaction.

- The swelling potential of the natural soil has been reduced from high to low by applying 30% of CSA. A 30% CSA may be selected as sufficient content to stabilize the expansive soil for the road sub-grade material.
- Atterberg limit values have significantly improved as the percentage of CSA was increased. When the percentage of CSA was increasing, the OMC was increased but the MDD values decreased due to the specific gravity of CSA being lower than this soil.
- The CBR-swell and free swell values of the soil showed a significant reduction as the percentage of CSA increased in the case of uncured and 7-day cured samples. At 30% of CSA, the soaked CBR value was found to be a suitable subgrade material that can reduce pavement thickness and overall project cost.
- The UCS value was significantly improved concerning the curing period at 30% of CSA. Curing played an important role in improving the shear strength parameters and index properties of the treated soil.

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