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Research Article

Study on the Performance of Expansive Subgrade Soil Stabilized with Enset Ash

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This paper deals with the effect of Enset ash on the mechanical property of expansive soil used as a subgrade material in road construction works. To investigate the influence of Enset ash on the behavior of expansive soils, laboratory tests were conducted according to AASHTO, ASTM, IS, and BS standards. The laboratory results show that the expansive soil belongs to the A-7-5 class of soil in AASHTO and CH class in the USCS. The liquid limit, plasticity index, free swell index, and free swell ratio of the soil have decreased with the increasing content of Enset ash. The strength test result shows CBR and UCS, and OMC increases and decreases in MDD value with increasing content of Enset ash. The microstructural properties of natural soil and stabilized soil were selected based on strength properties and were observed by a scanning electron microscopy (SEM) imaging device, and the result clearly shows the alteration in the fabric and morphology of the natural soil. The mineralogical composition of expansive soil is identified by XRD, and the result shows that the expansive soil in the study area is mainly composed of quartz and montmorillonite, which separately take up 50% and 38.5% of the total air-dried sample, while the percentage of kaolinite was 11.5%. From this study, it has been found that Enset ash stabilized soil that satisfies the minimum requirement of the Ethiopian Road Authority pavement manual specification for use as a subgrade material in road construction works.

1. Introduction

Expansive soil is plastic clay soil that exhibits high volume changes when subjected to moisture variations due to seasonal climatic conditions or artificial causes. The degree of expansiveness depends on the presence of active clay minerals like montmorillonite [1, 2]. The primary issue with expansive soil is the significant volume change of the soil mass when subjected to moisture variations. This volume change can generate cracks and damage to lightweight structures, roads, and other civil structures directly placed on this type of problematic soil. Pavements are also highly susceptible to damage because of their relatively lightweight nature. Expansive soils are widely distributed and found in more than 40 countries and regions [3]. The distribution of expansive soils depends on the regional geological background, climate, hydrology, and geomorphology. Expansive soils, mainly black cotton soils, cover nearly 40% surface area of Ethiopia [4] and are common soil types, particularly in Addis Ababa [5]. Thus, expansive soil is the main source of concern in the construction of highways in the Highlands of Ethiopia where a significant part of that area is covered by this soil [6, 7].

To reduce the problem associated with expansive soil, so many treatment techniques, for instance, removal and replacement with nonexpansive fill, ponding the use of moisture barriers or membranes, and soil stabilization methods were known so far [8]. In the past, different studies were conducted on soil stabilization using chemical methods, and it is a common practice as it becomes uneconomical to replace the foundation material with good quality soil. Chemical stabilization of clay soil using lime, cement, or fly ash has been used to improve the workability and mechanical characteristics of the soil in geotechnical engineering [9]. Conventional stabilizers such as lime, cement, and fly ash are not always acceptable. They can cause adverse effects on the environment by changing the pH level of treated soil and its surrounding areas [10]. The increment in pH level could rise above 12. When the rise of pH level is above 9, then the solubility of silica and alumina increases exponentially as a function of pH and favors pozzolanic reactions necessary for strength gain in lime stabilization [11].

Although several researchers studied the improvement in engineering properties of stabilized soil at the macro level (e.g., shear strength, unconfined compressive strength, swell behavior), very few studies discussed the changes in a soil-stabilizer matrix at the microlevel [12]. This challenge made the issue get due attention and triggered the need for investigation and introduction of innovative soil stabilization approaches that can improve engineering properties in a cost-effective way. The prime objective of this study is to investigate the performance of Enset (Abyssinian banana) ash on the mechanical and microstructural properties of subgrade soil.

2. Materials and Methods

2.1. Location of the Study Area. A soil sample was collected from Addis Ababa, Kality, a subcity near Addis Ababa Science and Technology University (AASTU). The city is located in the central highlands of Ethiopia, covering an area of about 527 km^2 with an average elevation of 2600 m above mean sea level (ASL). The city is bounded by 9°00′N and 10°00′N latitudes and 37°30′E and 39°00′E longitudes (Figure 1).

2.2. Expansive Soil. A disturbed soil sample was taken at 1.2 m depth from the natural ground surface. The approximate location of the test pit is shown in Figure 1. Sample preparation was done as per the ASTM-D421 standard. The geotechnical properties of the expansive soil are listed in Table 1.

2.3. Enset Ash. The Enset was cut and dried in the sun to facilitate easy burning. The dried Enset was burned in the open air to ashes and then collected in polythene bags to protect it from moisture and contamination of other materials before being stored at room temperature until it was used. Furthermore, the ashes from the burnt Enset were sieved through an ASTM Sieve 425 μm to get the very fine ash. Ash analysis is carried out to obtain the elemental content of a material. The samples of ash for analysis were prepared from portions of the raw materials following the British Standards [13]. The resulting ashes were manually ground and sieved to 200 mesh. The samples were analyzed using an X-Thermo ARL Advant XP sequential X-ray fluorescence spectrometer. The chemical composition of the ash was determined by X-ray fluorescence analysis (XRF). XRF is a technique used to determine the composition of various chemical oxides in EA in which the material reemits the X-ray at lower energy after being bombarded with higher energy X-rays. The analytical result is presented as a percent in Table 2.

2.4. Methods and Standard Testing Procedure. Standards and specifications for this study were adapted from AASHTO, ASTM, IS, and BS (Table 3). In this study, the specimen particle size is generally below 4.75 mm; therefore, the sieve size below 4.75 mm is used for the determination of particle size, and distilled water is used for the hydrometer analysis. After the particle size determination and Atterberg limit calculation, the untreated and treated soil samples are classified based on the unified soil classification (USCS) and AASHTO system. Table 4 shows the mix design adopted in this study.

2.5. Microanalysis (SEM). By scanning the surface with a focused beam of electrons, SEM will be used to characterize the microstructure and surface morphology of raw soil specimens and qualitatively identify the microstructural development in the matrix of the stabilized soil specimens. SEM imaging was carried out in the central laboratory of Addis Ababa Science and Technology University, Addis Ababa, Ethiopia. SEM was conducted for rows of natural soil and soil mixed with Enset ash. Before SEM analysis, unconfined compressive strength testing was conducted. To make sure of the development of cementitious bonds, a tiny representative piece was extracted from samples that were used for the UCS test. The representative samples were oven dried for 24 hours and sieved to 150 μm. The detailed procedure of this test has been discussed in a previous study [14].

2.6. X-Ray Diffraction (XRD). The XRD was performed on untreated black cotton soil. The analysis was carried out to identify the changes in mineralogical phases presented in the samples using a Bruker CCD diffractometer. The XRD was carried out using CuKa radiation. The samples were scanned at an angle of 2θ, and its range from 15° to 60° was chosen to provide enough X-ray diffraction peaks to identify the most common soil minerals. The minerals identified for this research are montmorillonite, kaolinite, and quartz.

Powder X-ray diffraction will be used to characterize the mineralogy of the clay soil sample and identify the mineral content of clay by the use of a diffractogram. The minerals will also be identified by the use of diffractograms. First, samples were oven dried for 24 hours and later filtered through a sieving mesh no. 250 (58 μm). Ethylene glycol will be added during sample preparation for later placement within the X-ray diffractometer. This does not inhibit the clay's expansion but eliminates organic matter to obtain a clearer diffractometry. The result will be presented as a diffractogram that is a plot of the 2θ (incidence angle between the Rontgen beam ray at the exit and the receptor) versus its intensity. The various minerals present in each soil sample will be identified by comparing the diffraction pattern with standard pattern data files using DIFFRAC software provided by the manufacturer of the instrument. The detailed procedure of this test will be supported by the following literature [15, 16]. The Match! (Crystal Impact) software was used to analyze the data obtained from the diffractometer.

3. Results and Discussion

3.1. Engineering Properties of Expansive Soil. The soil is grayish-black in color. The natural moisture content of the soil is 43.5%. The result of the wet sieve analysis indicated

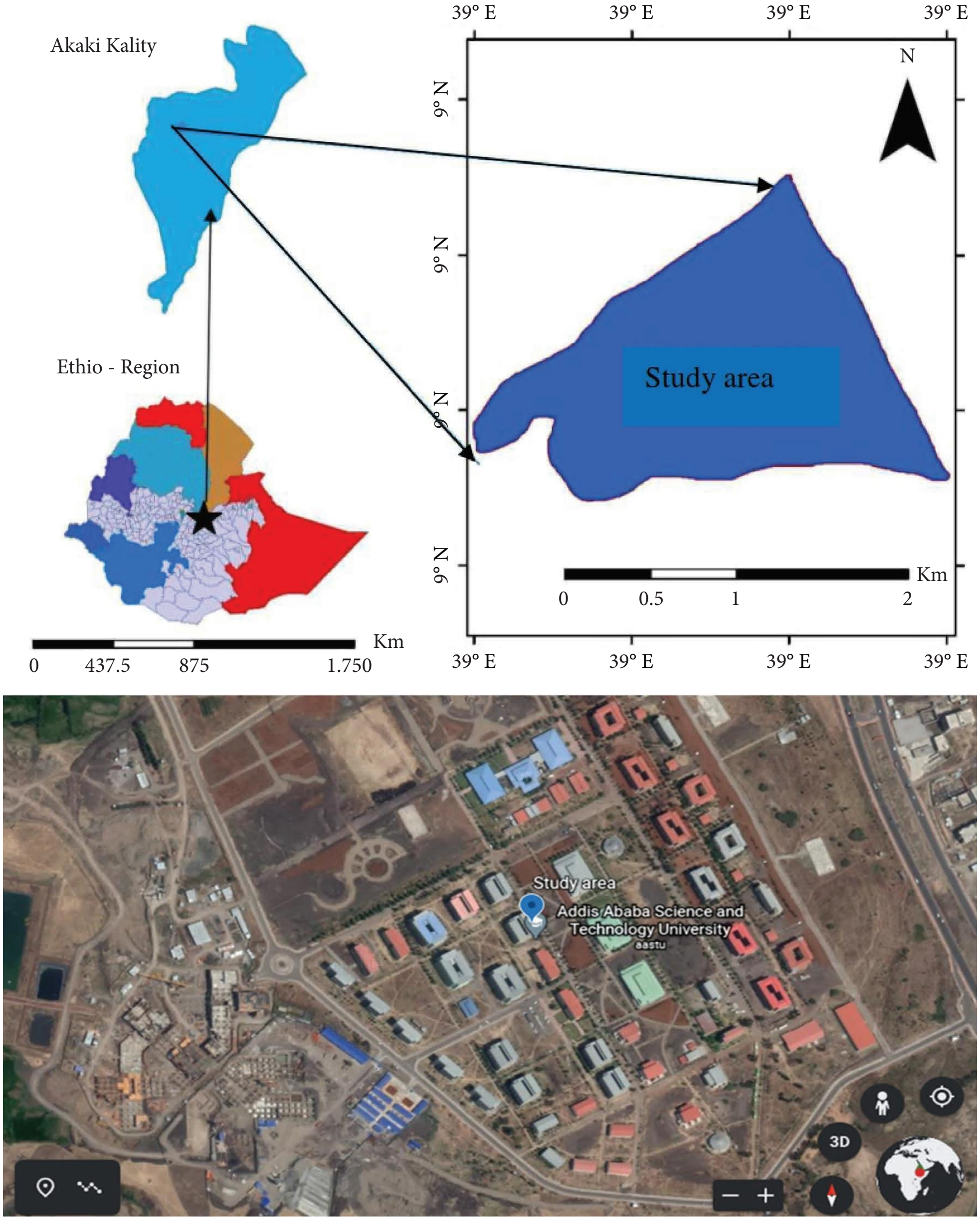


Figure 1: Study area location.

that 91% of the soil was passing through the No. 200 sieve. Based on the USCS soil classification system, the soil is CH (high plastic clay). According to AASHTO, the soil falls under the A-7-5 soil class. Soils under this class are generally classified as materials of poor engineering property to be used as subgrade materials. The index property test result shows a liquid limit of 96.88%, a plastic limit of 57.11%, and a plasticity index of 39.75%. During the construction of roads, the strength of the soils to be used is usually evaluated by their CBR values. The soaked CBR of the expansive soil used in this study is 1.7%. Subgrade materials having a CBR value of less than 2% need special treatment [17]. Table 1 shows the overall geotechnical properties of the expansive soils considered in this study.

3.2. Characterization of Enset Ash. The chemical composition of the ash was determined by X-ray fluorescence analysis. The result is presented in Table 2. The XRF analysis revealed that potassium oxide (K_2O) was the most abundant chemical property, accounting for 29.04% of the total. The concentration of silica (SiO_2) in the ash was 18.58% by weight. The analysis also showed that EA has a substantial amount of calcium oxide ($CaO = 9.52\%$), which makes the ash self-cementitious. The high value of LOI could be attributed to the unburnt carbon or other volatile materials during the open-air burning process.

3.3. Effect of Additive on Index Property. The laboratory tests which include the Atterberg limit, linear shrinkage limit, sieve analysis, free swell index, and free swell ratio were

Table 1: Geotechnical properties of expansive soil.

Property	Quantity
Percentage passing no. 200 sieve %	91
Liquid limit %	97
Plastic limit %	57
Plasticity index %	40
Linear shrinkage %	24.3
Volumetric shrinkage %	58.5
Shrinkage index %	38.4
AASHTO soil classification	A-7-5
USCS	CH
Natural moisture content %	43.5
Specific gravity	2.74
Free swell index %	140
Free swell ratio	2.4
Maximum dry unit weight kN/m^3	11.6
Optimum moisture content %	36.2
UCS (kPa)	49.41
Soaked CBR value %	1.7

Table 2: Chemical properties of Enset ash.

Elemental oxides	Concentration (%)
Silica (SiO_2)	18.58
Alumina (Al_2O_3)	<0.01
Iron oxide (Fe_2O_3)	0.52
Calcium oxide (CaO)	9.52
Magnesium oxide (MgO)	2.44
Sodium oxide (Na_2O)	0.08
Potassium oxide (K_2O)	29.04
Manganese oxide (MnO)	0.32
Phosphorus pentoxide (P_5O_5)	2.70
Titanium dioxide (TiO_2)	<0.01
Loss on ignition (LOI)	30.43

conducted for both natural black cotton soil and treated soil samples. A summary of index properties for treated and untreated soil samples is presented in Table 5. As the amount of EA increases from 0–10%, the liquid limit of the soil decreases by 14%. A reduction in liquid limit is generally due to a decrease in the thickness of the double layer developed. A reduction in liquid limit generally indicates an increase in frictional resistance and a decrease in the cohesion of soil as stated in the study by [18].

3.4. Effect of Additive on Compaction Characteristics. With the addition of varying percentages of the stabilizers EA to the soil sample, changes in the values of maximum dry density (MDD) and optimum moisture content (OMC) are observed as shown in Figure 2. Thus, the value of MDD decreased and OMC increased as the percentage of EA stabilizer increased. This is due to the low specific gravity of EA [19]. The increase in OMC is due to the pozzolanic reaction of silica and alumina in EA and soil with calcium to form calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), which are the cementing agents. Another reason for this occurrence is due to structural changes in which the dispersed structure changes to a flocculated structure, and as a result, the mixture absorbs more moisture. An increase in OMC values implies that more water is needed to compact the soil [20]. The observed decrease in MDD values can be attributed to the mixture of the soil and stabilizer, which has lower specific gravity compared to the soil [21].

3.5. Effect of Additive on Unconfined Compressive Strength. The addition of different percentages of EA has considerable effects on the unconfined compressive strength (UCS) of the expansive soil. The variation of UCS value with the addition of EA has been shown in Figure 3. The UCS had the highest value when the percentage of Enset ash was 10%. The unconfined compressive strength of untreated expansive soil was 49.41 kPa. Hence, after the addition of 10% Enset ash additives, the unconfined compressive strength increased to 76.62 kPa. The unconfined compressive strength value of the treated soil is increased as the percentage of stabilizer is increased. The increment of UCS is mainly due to the flocculation, enhanced pozzolanic reaction, and formation of cementitious materials in the stabilized soil sample [22].

3.6. Effect of Additives on CBR Value. During the construction of roads, the strength of subgrade soils is usually evaluated by their CBR values. According to AASHTO M 145 (1999), the expansive soil used in this study is classified as A-7-5 in the silt-clay groups. These groups range from fair to poor in quality as a subgrade material. After stabilization, it can be concluded that the CBR value increases with the percentage of EA (Figure 4). The CBR value of untreated soil is 1.7% for soaked conditions. The CBR values of soils treated with 10% EA were found to be 6.8% in cases of soaked conditions. From the test results, it has been observed that the stabilization of expansive soil with EA improves the CBR value. Based on these results, it can be concluded that the expansive soil treated with EA performs better as a subgrade material; hence, a relatively lower thickness of the base course is required as compared to the untreated BC soil to meet the standard.

3.7. Microstructural Property. In this section, SEM has been used in soil research as a practical and effective instrument for analyzing the mechanical and physical properties of soils [23, 24]. Its mechanical behavior and physical properties are predicted by the arrangement of elementary particles, as well as their sizes and shapes [25]. Micrographs of the natural expansive soil and treated samples with Enset ash were taken at magnifications of ×100, ×500, and ×1000. Figure 5 shows a micrograph of expansive soil, and Figure 6 shows a micrograph of 10% EA-treated soil. The micrograph of expansive soil at a magnification of ×100 indicates the presence of many small particles with different shapes. At higher magnification (×1000), the number of large and small pores in various shapes can be seen. The micrograph of BC soil treated with 10% EA shows few pores and continuous clay matrices. Large pores in expansive soil particles are reduced in samples treated with 10% EA. The reason for observing a more stable microstructure in EA-treated samples

Table 3: Standards and specifications employed in the study.

No	Laboratory test	Standards			
		AASHTO	ASTM	IS	BS
	Grain size analysis		D1140		
	Initial moisture content of soil		D2216		
	Atterberg limits testing		D4318		
	Linear shrinkages				2720 (part 40)
	Free swell tests			2720 (part 40)	
	Specific gravity		D854		
	Standard Procter compaction	T99			
	Unconfined compressive strength		D2166		
	California bearing ratio	T193			

Table 4: Mix designation of raw soil with stabilizers.

Sample label	Mix description	ES%	EA%
ES	Expansive soil	100	0
ES + EA	Expansive soil + Enset ash	98	2
ES + EA	Expansive soil + Enset ash	96	4
ES + EA	Expansive soil + Enset ash	94	6
ES + EA	Expansive soil + Enset ash	92	8
ES + EA	Expansive soil + Enset ash	90	10

Table 5: Summary of index properties of treated and raw soil samples.

Sample	Liquid limit (%)	Plastic index (%)	Free swell index (%)	Free swell ratio	Linear shrinkage limit (%)
ES	97	40	140	2.4	24.3
ES + 2%EA	96.5	36.5	110	2.1	23.9
ES + 4%EA	96	35	90	1.9	23.6
ES + 6%EA	89	25	80	1.8	22.1
ES + 8%EA	87	28	70	1.7	22.4
ES + 10%EA	83	25	60	1.6	19.3

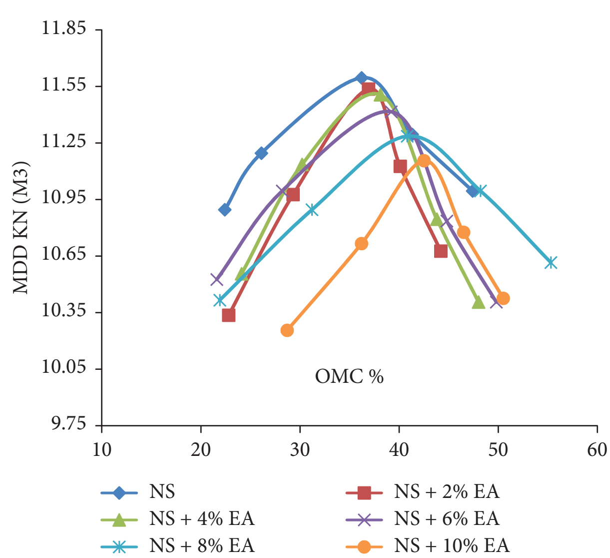


Figure 2: Compaction curve of natural soil (NS) treated with various percentages of Enset ash (EA).

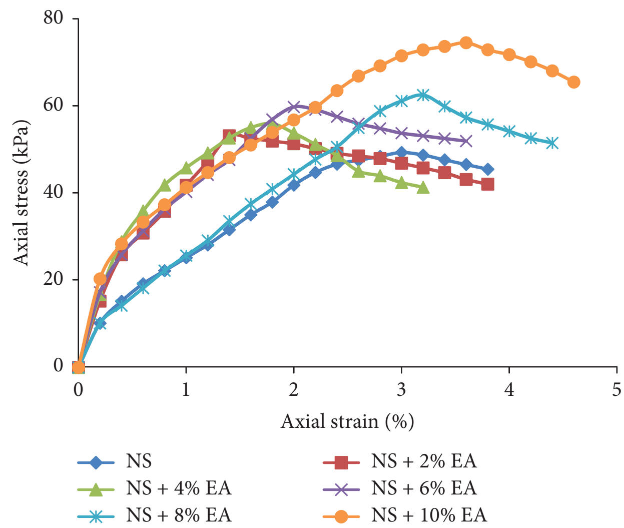


Figure 3: Unconfined compressive strength curves of natural soil (NS) treated with Enset ash (EA).

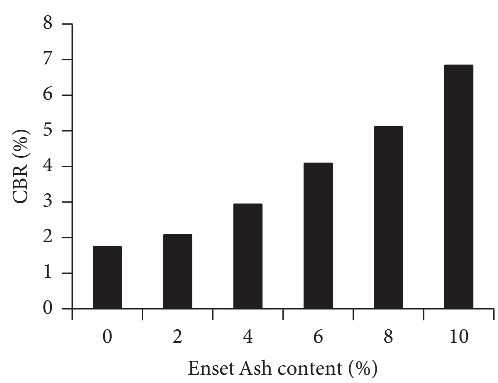


Figure 4: Variation of CBR value with a percentage of Enset ash (EA) content.

compared to untreated samples could be attributed to the formation of cementitious products resulting from the reaction between expansive soil and EA particles.

3.8. X-Ray Diffraction Analysis. In this section, XRD analysis has been employed to identify the minerals present in black cotton soils and also identify the major elemental constituents of the soil. The result of XRD shows that a high percentage of quartz minerals are present in the soil (Figure 7(a)). The expansive soil in the study area is mainly composed of quartz and montmorillonite, which separately take up 50% and 38.5% of the total air-dried sample, while the percentage of kaolinite is 11.5% (Figure 7(b)). In Figure 7(b), the highest peak at 26.71° of the soil confirms the presence of quartz mineral, while the second peak is at 19.70° indicating the presence of montmorillonite mineral, and the lowest peak of the XRD pattern at 11.51° showing the presence of kaolinite mineral (Figures 7(c) and 7(d)).

The XRD pattern of EA-treated soil shows the formation of calcite (Figure 7(e)). In addition, reductions in the intensity of some minerals for EA-treated samples are also observed. For instance, a decrement in the intensity of quartz and montmorillonite is observed for samples treated with 10% EA. Apart from the reduction in peak intensity of quartz and the appearance of calcite, the disappearance of kaolinite is also observed in the samples treated with 10% EA. These changes in XRD pattern and peak height could be attributed to the reactions between clay mineral and additive.

3.9. Experimental Results When Compared with ERA Specification. The CBR value of untreated soil is 1.7% for soaked conditions, which indicates very poor quality for subgrade. Therefore, the expansive soil used for this study requires initial modification and/or stabilization to improve its workability and engineering property. Therefore, the addition of 10% of EA modifies the soil into a suitable subgrade material for pavement construction. According to Ethiopian Road Authority [17], the subgrade class for the natural soil and natural soil blended with different percentages of EA is tabulated in Table 6.

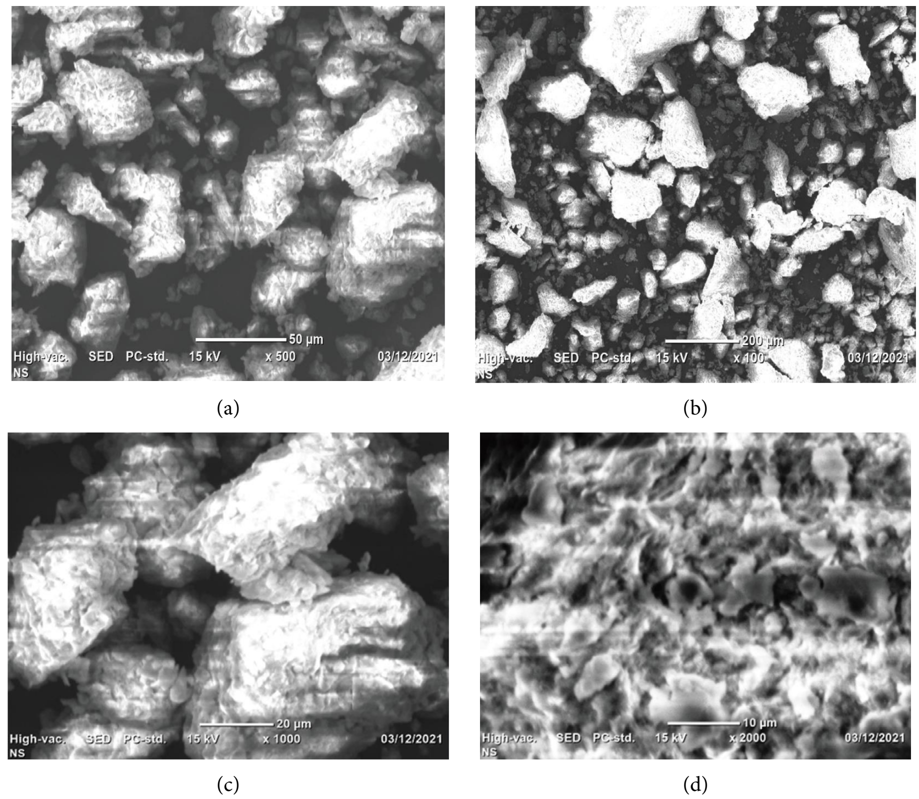


Figure 5: SEM image of natural soil at different magnification factors. (a) ×100. (b) ×500. (c) ×1000. (d) ×2000.

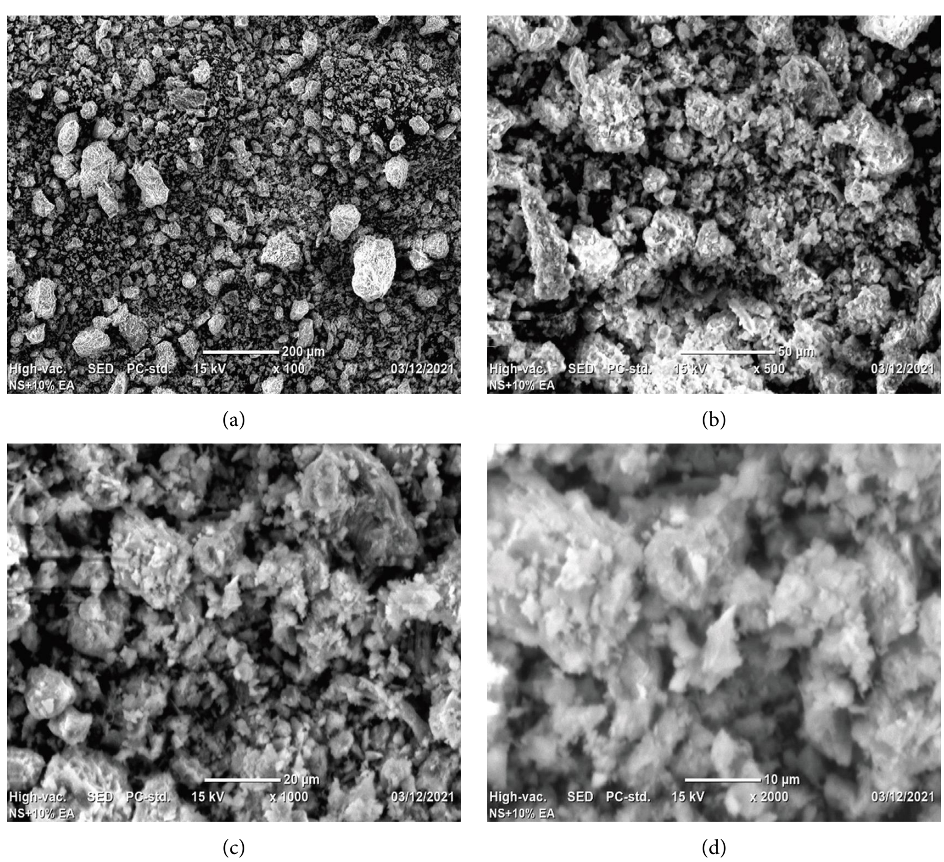
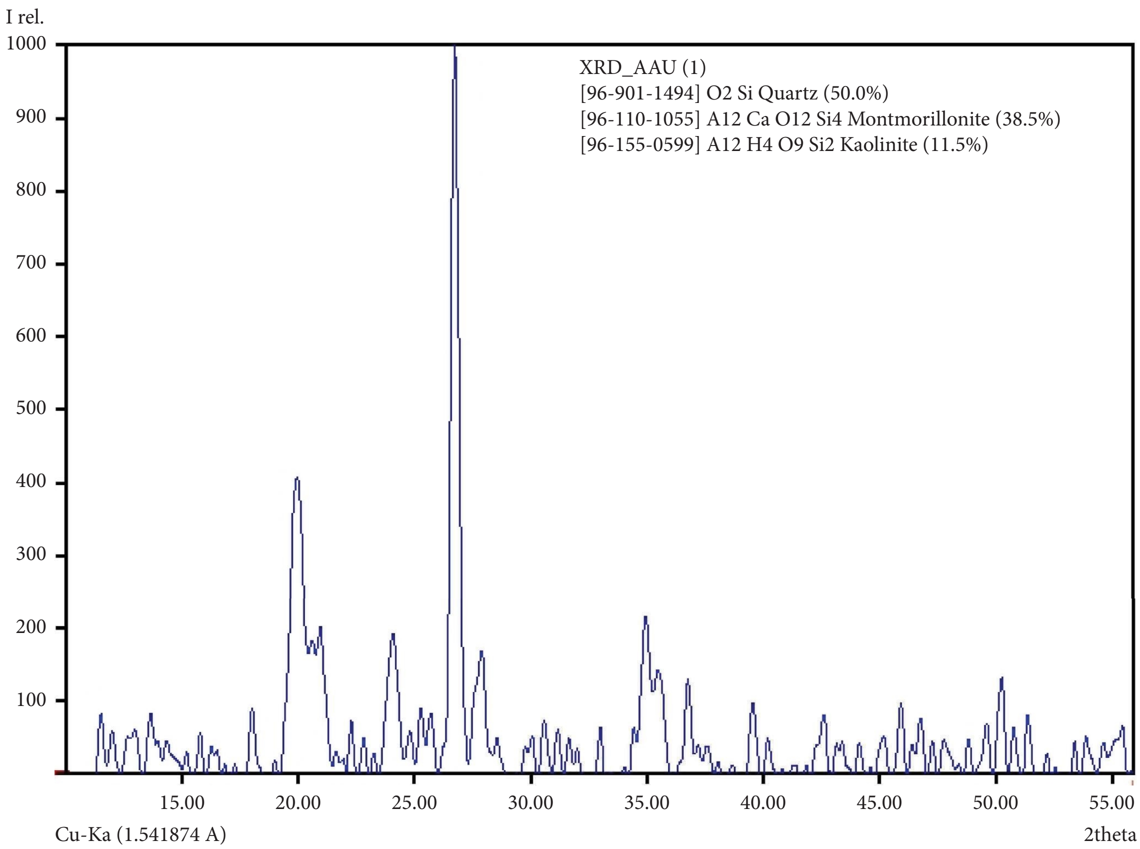
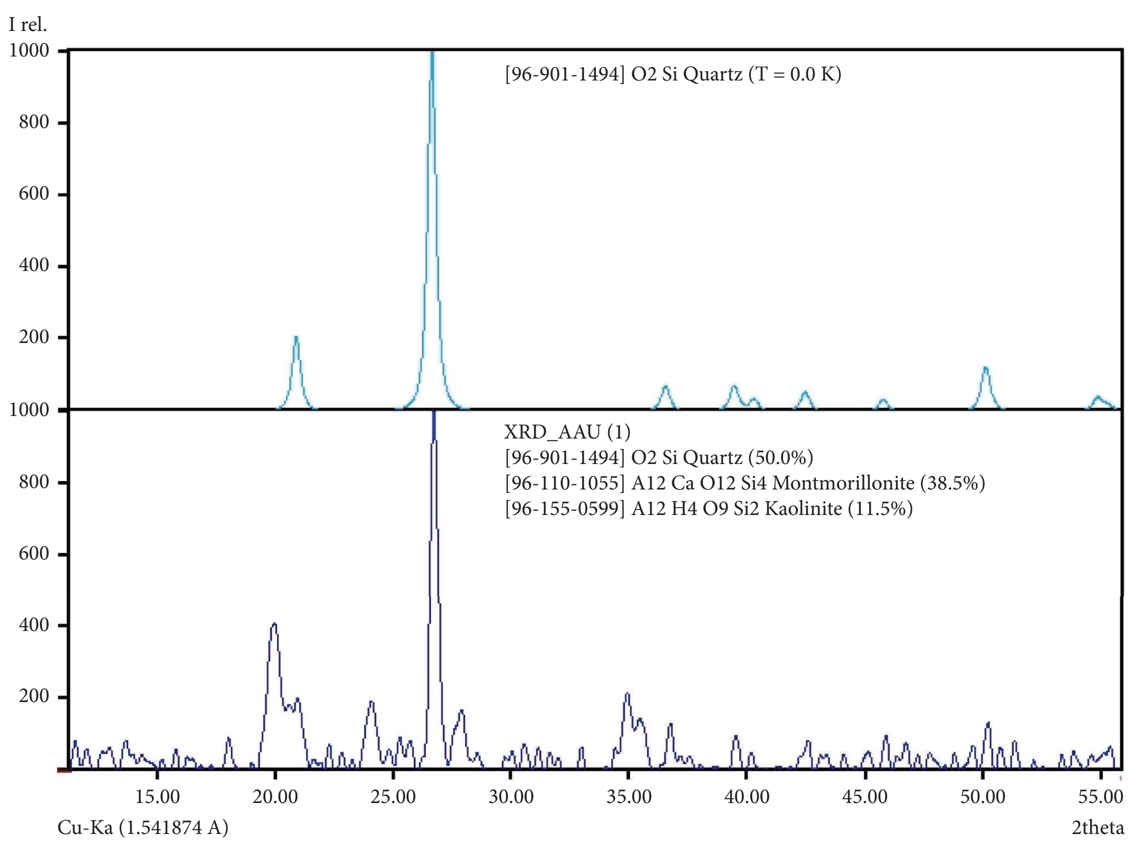


Figure 6: SEM image of 90% natural soil with 10% Enset ash at different magnification factors. (a) ×100. (b) ×500. (c) ×1000. (d) ×2000.

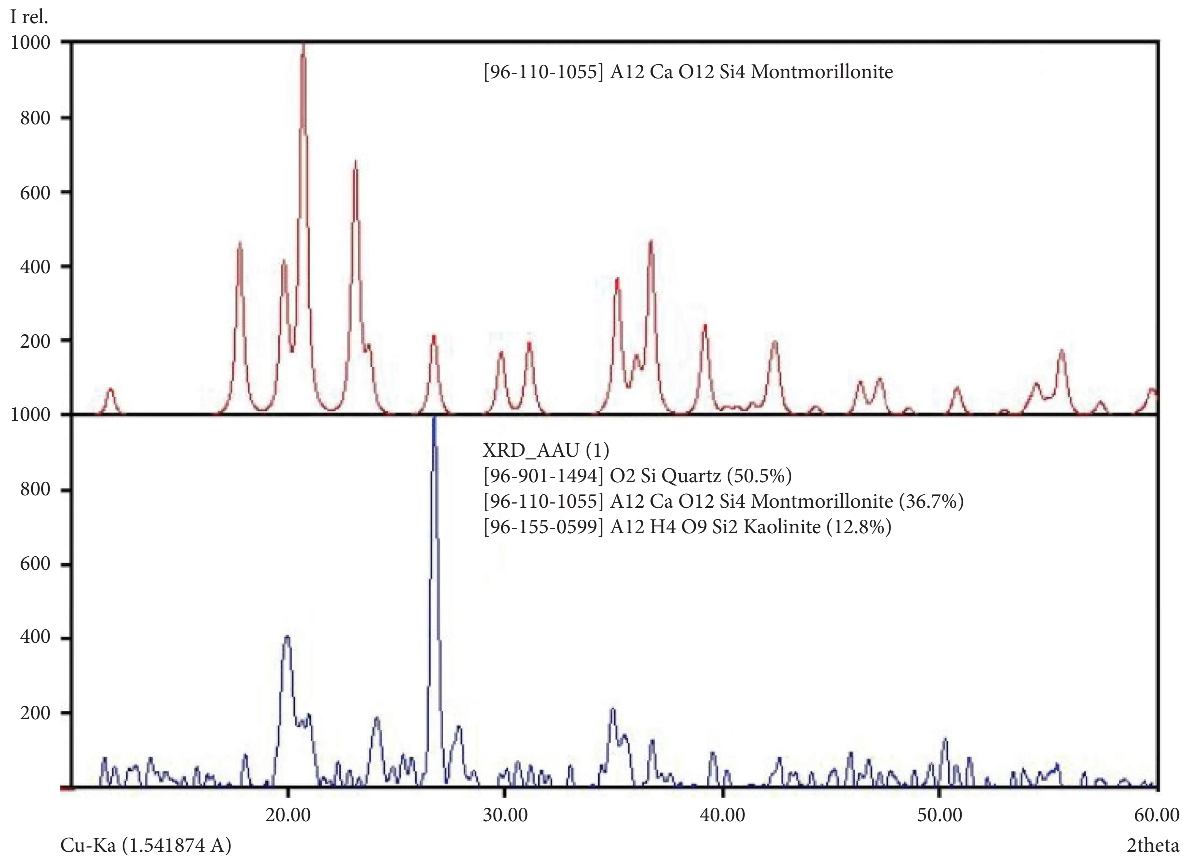


(a)

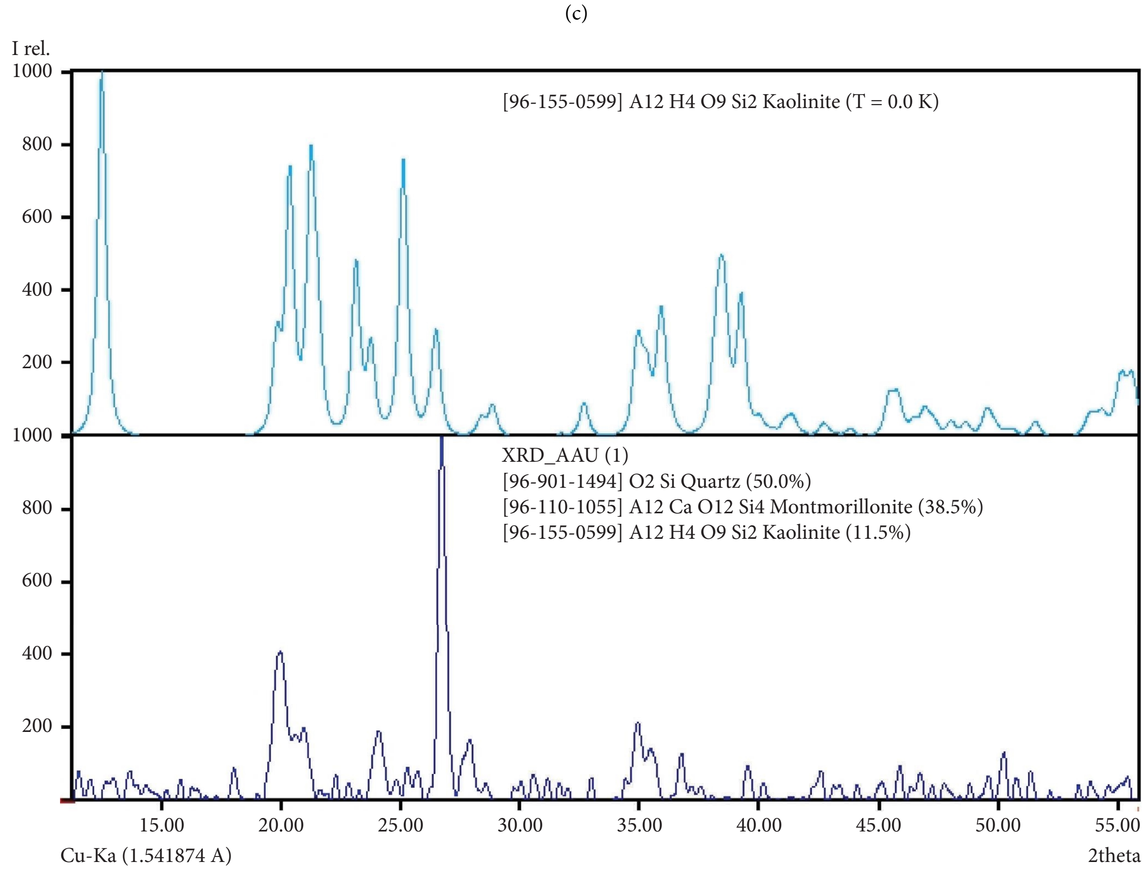


(b)

Figure 7: Continued.

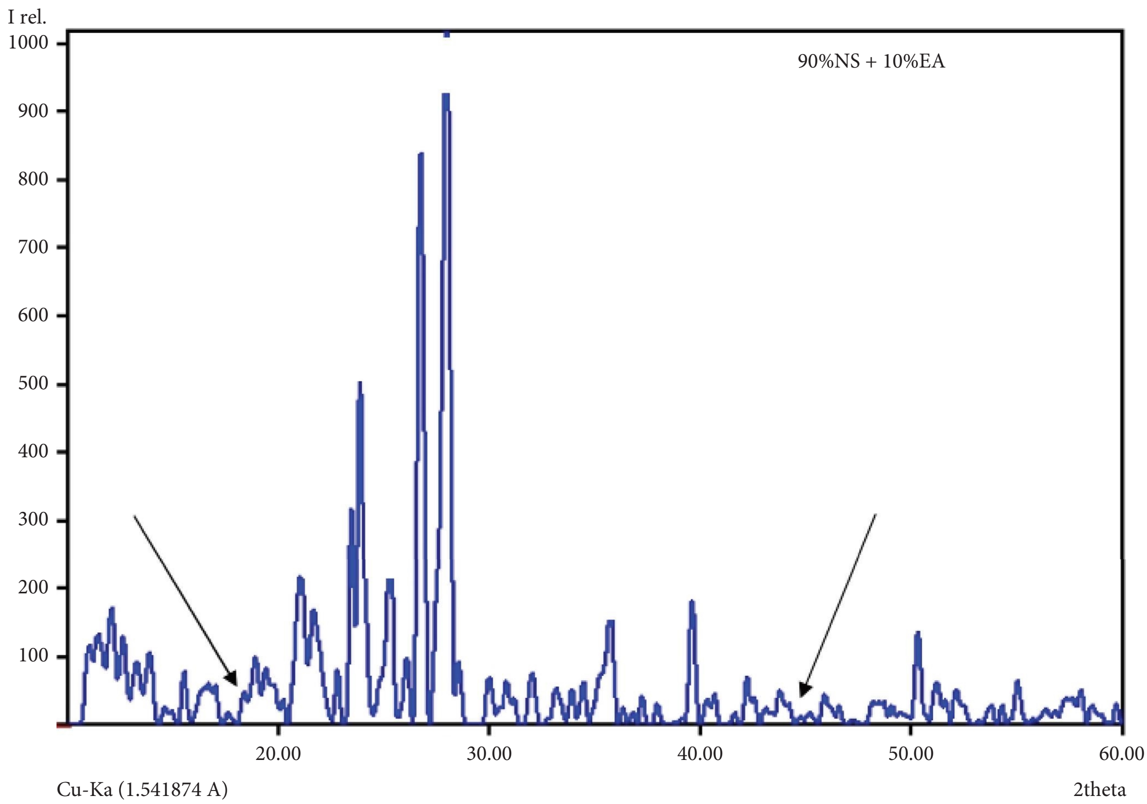


(c)



(d)

Figure 7: Continued.



(e)

FIGURE 7: XRD analysis results: (a) percentage of mineral present in the soil, (b) quartz peak, (c) montmorillonite peak, and (d) kaolinite peak, and (e) when natural soil is treated with 10% EA.

TABLE 6: Subgrade class of soil with Enset ash.

Additive content	Subgrade class
Natural soil	Inappropriate to lay a pavement
Natural soil + 2% EA	Inappropriate to lay a pavement
Natural soil + 4% EA	S2
Natural soil + 6% EA	S3
Natural soil + 8% EA	S3
Natural soil + 10% EA	S3

4. Conclusion

This study aims to investigate the effects of Enset ash (EA) on the properties of expansive soil. Based on the results obtained in the experimental investigation, the following conclusions have been drawn:

(i) The natural subgrade soil of the study area was generally classified as a material of poor engineering properties to be used as a subgrade material. It requires initial modification and/or stabilization to improve its property to satisfy the ERA standard specification for subgrade material.

(ii) The expansive soil used in this study was classified as high plasticity clay (CH) according to USCS, and the soil falls under the A-7-5 soil class according to AASHTO.

(iii) As the content of EA additives increased, both LL and PI decreased. Based on the free swell index and free swell ratio, the potential expansiveness of the natural soil has decreased with increasing content of EA.

(iv) With the addition of Enset ash content increasing from 0 to 10%, the linear shrinkage of Enset ash mixed with expansive soil significantly decreased by a substantial amount of 20.6% in comparison with that of a virgin soil specimen.

(v) The compaction characteristics show an increase in optimum moisture content and a slight decrease in maximum dry density with an increase in the percentage of Enset ash.

(vi) After stabilization, it can be concluded that the CBR and UCS values increase as the percentage of Enset ash increases. The addition of 10% of EA modifies the soil to a suitable subgrade material for pavement construction, increasing the value of CBR by 300%. The subgrade class of the stabilized soil by 10% of EA falls under the class of S3.

(vii) The result of XRD shows that the expansive soil in the study area is mainly composed of quartz and montmorillonite, which separately take up 50% and 38.5% of the total air-dried sample, while the percentage of kaolinite was 11.5%. The micrograph of the untreated soil indicated a discontinuity in its structure and more visible voids. The micrograph of soil treated with 10% EA shows few pores and continuous clay matrices.

(viii) In expansive soils treated with Enset ash, 10% by dry weight of the soil was found to be a better performance of stabilizer. The highest values for strength tests (UCS, CBR) are at this percentage.

(ix) Based on the overall laboratory test results, the natural soil did not satisfy the requirements of ERA standard specifications for subgrade construction. However, after blending with 10% EA, the mix proportion satisfied ERA standard specifications for subgrade construction.

5. Recommendation

(i) Further studies should be conducted to determine the effect of Enset ash on the mineralogical properties of the expansive soil by X-ray diffraction (XRD) analysis

(ii) Further studies should be carried out to identify the long-term effects that Enset ash has on the durability of road pavement structures

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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