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Research Article

Prediction of Subgrade Strength from Index Properties of Expansive Soil Stabilized with Bagasse Ash and Calcined Termite Clay Powder Using Artificial Neural Network and Regression

Asefachew Belete Tseganeh [1,2] and Emer Tucay Quezon [3]

[1]*Department of Civil Engineering, College of Architecture and Civil Engineering, Addis Ababa Science and Technology University, Addis Ababa, Ethiopia*
[2]*Department of Civil Engineering, Institute of Technology, Woldia University, Woldia, Ethiopia*
[3]*Civil Engineering Department, College of Engineering & Architecture, Cagayan State University, Tuguegarao, Philippines*

Correspondence should be addressed to Asefachew Belete Tseganeh; asefachew.belete@aastu.edu.et

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When moisture levels fluctuate, expansive soils lose a large amount of volume. During the rainy and dry seasons, this type of soil expands and contracts, respectively. As a result, such problematic soils should be avoided or appropriately managed when encountered as subgrade materials. The strength of the subgrade is measured in terms of its California Bearing Ratio (CBR) value which is tiresome, uneconomical, and time-consuming to determine in the laboratory. In the present study, the effect of bagasse ash (BA) and calcined termite clay powder (CTCP) on the strength, index, and microstructural properties of expansive soil was investigated. Laboratory tests such as Atterberg's limits, particle size analysis, moisture-density relationship, and CBR tests were performed on the highly expansive soil and blended with 3%, 5%, 7%, 9%, and 11% bagasse ash (BA), and 5%, 10%, 15%, 20%, and 25% CTCP separately and in combination. In addition, the microstructural properties of the raw highly expansive soil and the soil stabilized with the optimum BA-CTCP combination were analyzed using the Scanning Electron Microscopy (SEM) machine. Soaked CBR prediction models were also developed using multiple linear regression (MLR) and artificial neural networks (ANNs) from the BA fraction (BAF), CTCP fraction (CTCPF), liquid limit (LL), plasticity index (PI), optimum moisture content (OMC), and maximum dry density (MDD). The soil understudy was very weak having a CBR value of 2.2% and a group index (GI) of 64.37 (reported as 20) and highly expansive with a PI of 51.61% and LL of 104.32%. The addition of both BA and CTCP separately and in combination had resulted in the reduction of PI and increased the strength of the soil under study. As compared with the individual effect, the combined effect of BA and CTCP was quite significant. The optimum BA and CTCP combination was determined from the free-swell index test result; a 72.5% reduction was observed when it was blended with a combination of 9% BA and 20% CTCP. Thus, 9% BA and 20% CTCP compositions could be the optimum percentage combination to stabilize the highly expansive soil under study. The PI was decreased by 85.75%, and the CBR became 5.5 times greater when it was stabilized with 11% BA + 25% CTCP. The SEM micrographs showed that the morphology and fabric of the control specimen (raw soil) were significantly changed when the soil was stabilized with the optimum BA-CTCP combination (9% BA + 20% CTCP). The MLR prediction model was shown to be less efficient and accurate than the ANN model.

1. Introduction

Expansive soil is one of the significant problematic soils for any civil or geotechnical engineering application in the whole world [1]. Construction of buildings and other civil engineering structures such as highways, bridges, airports, and seaports on expansive soil is pretty harmful because such soil is particularly susceptible to drying and wetting cycles, potentially causing shrinkage and swelling behavior under pavements and building foundations, resulting in structural and nonstructural element cracking. The cost of structural damage due to shrinkage and swelling is estimated to be £400 million in the UK, $15 billion in the US, and many billions of dollars worldwide on an annual basis [1, 2].

They are mostly found in semiarid tropics with distinct wet and dry seasons. Ethiopia, South Africa, Tanzania, Asia, and a few other African countries have black cotton soils. It may be found all over Ethiopia's central region, following important trunk routes such as Addis-Ambo, Addis-Wolliso, Addis–Debrebirhan, Addis–Gohatsion, and Addis–Modjo. Also, expansive soils cover locations like Mekelle and Gambella [3]. Engineers can deal with these soils in a road, railway, or other civil engineering projects in a variety of ways, including realigning the alignment, stabilizing using additives, or cutting and replacing with specific materials. The first and last options could lead to greater project costs. Using locally available materials to stabilize locations with expansive subgrade soil, on the other hand, has a cost and schedule advantage over the other two options.

Numerous experimental investigations on the stabilization of expansive soil have been performed over the last few decades, and various types of stabilizers have been utilized in highway and other construction projects, such as lime, Portland cement, cement fly ash, and lime fly ash [1]. The addition of chemical or cementitious chemicals can help to stabilize these expansive soils [4]. Fly ash, cement, lime, bagasse ash, medical waste ash [5], and patented chemical stabilizers are examples of additives that range from waste products to manufactured components. Cement stabilization, according to [4], is an effective solution to the problem of fatigue failures produced by recurrent excessive deflection of asphalt surfaces in the presence of a weak subgrade in the pavement structure.

Though many local researchers have been researching the stabilization of expansive soil using locally available stabilizing additives, the majority of them have not been using scientific prediction models like multiple linear regression (MLR), artificial neural network (ANN), fuzzy logic, and other soft computing systems to predict CBR value from easily determinable parameters of a stabilized soil because determining the CBR (subgrade strength) along the length of a road section in the laboratory is quite expensive, laborious, and time-taking.

Several laboratory experiments should always be undertaken during the stabilization of expansive soil using various stabilizers to determine the effect of the stabilizers on the physical, chemical, index, and engineering properties of the soil. The strength of subgrade soil is measured in terms of soaked CBR, which is the actual depiction of subgrade soil under moisture fluctuation [6]. The CBR (subgrade strength) can be measured directly in the laboratory [6]; however, it takes at least four days to conduct the test for each soil sample as well as the longitudinal profile of the road. As a result, determining the subgrade strength (CBR) of a large number of soil samples is complex and time-consuming. This would cause a significant slowdown in the project's progress, resulting in an increase in the project's cost. As a result, it is critical to statistically correlate the CBR of soils with easily determinable independent variables for optimum design, time, and cost considerations. Scientific modeling is also very important. They used multiple regression analysis (MRA) and artificial neural networks (ANN) to determine the soaked CBR value of expansive soil stabilized with bagasse ash and geogrid, and they concluded that the ANN model is more efficient and accurate than the MRA model.

Ethiopian sugarcane production is roughly 350,000 tons per year [7], which means the sugarcane bagasse ash potential is around 84,000 tons. According to Ethiopia's growth transformation strategy, 4.6 million tons of sugar will be produced annually, with more than 1.1 million tons of sugar cane bagasse ash as waste. When used for a variety of productive uses, this quantity of wastage is often useful. In the manufacturing of concrete, it is used as a supplemental cementitious material [7]. According to their observations, partially replacing hard waste materials with cement greatly improved the technical and performance attributes of concrete. According to [8], the pozzolanic property of Termite Hill Clay powder has also been revealed. Those hills also populated Ethiopia's southernmost Borena plain, Dodola, and the Diera towns in high densities [8]. This termite constructs the mound from the clay components required for construction, and it is abundant.

The objective of this study is to investigate how bagasse ash (BA) and calcined termite clay powder (CTCP) affect the strength, index, and microstructural properties of highly expansive soil separately and in combination. It also aims to develop a soaked CBR prediction model from bagasse ash fraction (BAF), calcined termite clay powder fraction (CTCPF), liquid limit (LL), plasticity index (PI), optimum moisture content (OMC), and maximum dry density (MDD) of the BA-CTCP stabilized soil using multiple linear regression (MLR) in the MS-Excel Add-ins data analysis ToolPak and artificial neural networks (ANNs) in MATLAB deep learning toolbox.

1.1. Gaps in the Reviewed Literature, Uniqueness, and Significance of the Study. Many studies, such as [3, 9–11], have been performed and focused solely on the experimental approach. The experimental results of all the studies revealed that the utilized stabilizers have a significant effect on the soil's strength (CBR), but no scientific models were developed to predict soaked CBR from easily determinable stabilized soil parameters in a timely and cost-effective manner, as the laboratory soaked CBR test is tedious, time-consuming, and expensive.

In addition to this, the effect of lime on the properties of clayey soil was also studied by [12], and an ANN model was developed to predict the plasticity index (PI), optimum moisture content (OMC), and maximum dry density (MDD) of lime-stabilized clayey soil. It is obvious that conducting laboratory tests to determine PI, OMC, and MDD is not time-consuming and tiresome, so there is a gap in the research that could have been filled by developing ANN and MLR soaked CBR prediction models from those parameters of the stabilized soil, with CBR as the dependent variable to be explained by PI, OMC, MDD, and a fraction of lime.

Owing to the abovementioned gaps, the present study is focused on the experimental, statistical, and artificial intelligence approach to investigate the effect of bagasse ash and calcined termite clay powder on the strength, index, and microstructural properties as well as to develop soaked CBR prediction models using a statistical approach called multiple linear regression (MLR) and artificial neural networks (ANNs).

2. Materials and Methods

2.1. Materials. The materials utilized for the present study are bagasse ash (BA), calcined termite clay powder (CTCP), and expansive soil. The expansive soil used in this study was obtained from the Koye Feche square-Tulu Dimtu square stretch in Addis Ababa's Akaki-Kality Subcity. The sugarcane bagasse ash utilized for this study was obtained from the Wonji sugar factory, which is located around the capital of the Eastern Shewa zone, Adama, Oromia Regional State, Ethiopia, around 130 km away from the capital, Addis Ababa. The clay powder utilized for the study was obtained around Deira town, Oromia regional state, Ethiopia. It was calcined with a muffle furnace with the best calcination temperature of 650–850°C [13]. Figure 1 shows the materials utilized in the study.

2.2. Methods. The research aim was achieved by performing basic laboratory tests such as index properties, moisture-density relationship (compaction), CBR, and microstructural properties. In addition, artificial neural network (ANN) and multiple linear regression (MLR) soaked CBR prediction models were also developed in MATLAB deep learning toolbox and MS-Excel Add-ins data analysis ToolPak, respectively, to predict CBR from bagasse ash fraction (BAF), calcined termite clay fraction (CTCPF), liquid limit (LL), plasticity index (PI), optimum moisture content (OMC), and maximum dry density (MDD).

The following laboratory tests were conducted on the raw highly expansive soil, blended with 3%, 5%, 7%, 9%, and 11% of BA, and 5%, 10%, 15%, 20%, and 25% CTCP separately and in combination. All the tests were conducted as per the corresponding standards listed and references (cited) in Table 1.

In addition to the above laboratory tests, the Scanning Electron Microscopy (SEM) test to analyze the microstructural properties of the raw highly expansive soil and stabilized soil was also conducted and explained below.

2.2.1. Scanning Electron Microscopy (SEM) Test. The microstructural properties such as the configuration of the sample, structural arrangement (bonding), and particle boundary relationship of a soil specimen can be investigated by the SEM imaging device [1]. The microstructural properties of the raw highly expansive soil and the soil blended with the optimum content of BA and CTCP combination of 9% BA + 20% CTCP (determined from the free-swell index test result) which was powdered and sieved to get a sample passing 150 μm sieve can be easily investigated by the SEM machine. A JCM-6000 PLUS Bench Top SEM JEOL SEM machine was used to conduct the test. The test was conducted at the microbiology laboratory of Adama Science and Technology University, Adama, Ethiopia.

The SEM imaging device used to analyze the microstructural properties of the raw highly expansive soil and soil stabilized with the optimum combination of BA and CTCP is shown in Figure 2.

In addition to the investigation of the effect of BA and CTCP on the strength, index, and microstructural properties of the highly expansive soil, soaked CBR prediction models from index properties of the stabilized soil were also developed using artificial neural network (ANN) and multiple linear regression (MLR) techniques, described below.

2.2.2. Multiple Regression Technique (MLR and ANN). A regression model was developed to correlate soaked CBR of the highly expansive soil stabilized with various percentages of BA and CTCP from liquid limit, plasticity index, maximum dry density, optimum moisture content, percentage of calcined termite clay powder, and bagasse ash using ANN in MATLAB deep learning toolbox and MLR in MS-Excel Add-ins data analysis ToolPak. Sixteen datasets were used in the analysis for both models.

A feed-forward backpropagation neural network, with Levenberg-Marquardt algorithm and PURELIN layer type ANN model, was developed using the MATLAB software deep learning toolbox and MLR model in MS-Excel Add-ins data analysis ToolPak to predict CBR for the highly expansive stabilized soil under study. The models have input layers that accept the inputs (BAF, CTCPF, LL, PI, OMC, and MDD), hidden layers that process the input variables, and the output layer which produces the result (soaked CBR).

For the prediction models' applicability and validity, the CBR values for the highly expansive stabilized soil determined from the MLR analysis in the MS-Excel Add-ins data analysis ToolPak and ANN in MATLAB deep learning toolbox prediction models were compared with the actual (experimental) CBR values determined in the laboratory-based on the determination coefficient (R^2). It is obvious that the overall MLR and ANN CBR prediction models' performance is measured in terms of its determination coefficient (R^2); i.e., the model having the R-squared coefficient closer to +1 or −1 is referred to as the best model having a strong positive and strong negative relationship between the dependent and independent variables that are used to develop the prediction model [20].

(1) Sampling Technique and Sample Size. This study's sampling technique is purposive sampling, which is a nonprobability sampling technique. Six test pits at a depth 1.5 m below the normal ground surface were excavated to obtain an expansive soil sample, and the highly expansive one based on the expansiveness index value from those pits was selected for further investigations and used for the development of the ANN and MLR soaked CBR prediction models.

(a) (b) (c)

Figure 1: Materials utilized in the study: (a) BA, (b) CTCP, and (c) soil.

Table 1: Laboratory tests conducted for the study.

Laboratory tests	Standards used	Reference
(1) Particle size analysis	ASTM D 422-63	[14]
(2) Specific gravity	ASTM D 854-98	[15]
(3) Free-swell index	IS: 2720 (part XL)	[16]
(4) Atterberg limits	ASTM D 4318-98	[17]
(5) Compaction	ASTM D 698-91	[18]
(6) CBR	ASTM D 1883-99	[19]

Figure 2: JCM-6000 PLUS Bench Top SEM JEOL SEM machine [5].

(2) Study Variables. The soaked California Bearing Ratio (CBR) for the stabilized soil is a dependent variable for the regression-based model developed by the Artificial Neural Networks (ANNs) model in MATLAB deep learning toolbox and the MLR model in MS-Excel Add-ins data analysis ToolPak.

The bagasse ash fraction (BAF), calcined termite clay powder fraction (CTCPF), liquid limit (LL), plasticity index (PI), optimum moisture content (OMC), and maximum dry density (MDD) are independent (explanatory) variables for the stabilized soil.

3. Discussion of Results

3.1. Characteristics of the Soil Sample and Properties of the Stabilizers

3.1.1. Characteristics of the Natural Soil Samples. The soil sample used for the study was obtained from six test pits around the Koye Feche square-Tulu Dimtu square stretch, Akaki-Kality Subcity, Addis Ababa, Ethiopia. The test pits are designated as TP-1, Tp-2, Tp-3, TP-4, TP-5, and TP-6.

The results of the laboratory investigations performed on the natural soil from each test pit are summarized in the following tables and figures.

Table 2 shows the number and designation of test pits, the depth at which the samples were taken, and the percentage of passing through representative sieve sizes.

Figure 3 shows the particle size distribution of the soil samples obtained from each test pit.

As can be inferred from Figure 3 and Table 2, the percentage of passing No. 200 (0.075 mm) sieve of the soil sample obtained from Tp-1, TP-2, TP-3, TP-4, TP-5, and TP-6 is 94.32%, 97.20%, 96.17%, 97.12%, 94.77%, and 97.17%, respectively, which is greater than 50% (silt and clay). Thus, according to the AASHTO soil classification system, the soil is commonly classified as A-7-5 (20), and as per the USCS, from the plasticity chart, the soil is classified as MH & OH (organic clay of high plasticity and silt with high plasticity) depending on the value of LL and PI; i.e., the soil has a poor quality to be used as subgrade material. The number "20" in the bracket from the AASHTO classification system indicates the group index (GI) of the soil. As shown in Table 3, the group index of the soil sample from each test pit was determined by

$$\mathrm{GI} = (F-35)[0.2+0.005(\mathrm{LL}-40)] + 0.01(F-15)(\mathrm{PI}-10), \quad (1)$$

where "F" is the percentage of soil that passes through a 0.075 mm (No. 200) sieve expressed as a whole number, and LL and PI are the liquid limit and plasticity index of soil, respectively. As the GI value increases, the quality of material

Table 2: Characterization of expansive soil and particle size distribution.

Sample designation	Depth of pit (m)	Sample description (color)	Percent of passing				
			4.75	2.36	0.425	0.075	0.002
TP-1	1.5	Greyish-black	100	100	99.91	94.32	57.52
TP-2	1.5	Dark-grey	100	99.4	98.15	97.2	58.4
TP-3	1.5	Black	100	100	99.47	96.17	56.2
TP-4	1.5	Dark-grey	100	100	98.32	97.12	54.33
TP-5	1.5	Greyish-black	100	99.3	98.15	94.77	48.22
TP-6	1.5	Dark-grey	100	99.6	98.4	97.17	55.3

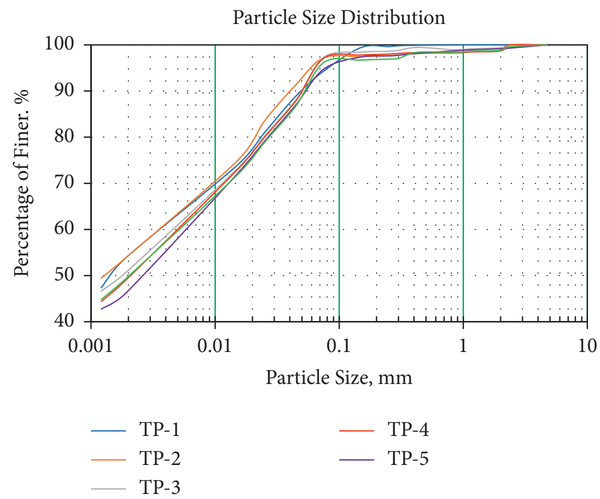


Figure 3: Particle size distribution curve.

Table 3: Soil expansiveness based on [21].

Sample designation	w_p	w_s	% Passing #40 sieve	Expansiveness index based on ERA manual	Remark on expansivity	GI	Reported GI
TP-1	35.50	18.98	99.91	43.66	Moderately expansive	48.73	20
TP-2	32.82	16.69	98.15	46.20	Moderately expansive	46.81	20
TP-3	27.54	14.92	99.47	40.41	Moderately expansive	40.25	20
TP-4	36.43	17.70	98.32	50.91	Highly expansive	52.87	20
TP-5	50.66	21.59	98.15	69.86	Highly expansive	64.37	20
TP-6	40.13	23.62	98.40	36.70	Moderately expansive	53.64	20

for subgrade becomes very poor. A GI of zero implies that the material has a good quality in its group for subgrade construction. The GI values of soils greater than or equal to 20 are generally poor subgrade materials.

Atterberg's limit test results of the raw expansive soil obtained from each test pit (TP-1, TP-2, TP-3, TP-4, TP-5, and TP-6) are shown in Table 4.

As can be inferred from Table 4, all the samples have a high plasticity index and liquid limit which shows that the soil is highly plastic containing more fines (silt and clay). The soil samples from all test pits are commonly classified as A-7-5 (20) and MH & OH as per the AASHTO and USCS, respectively.

As shown in Table 3, the group index (GI) value of the soil in all test pits is greater than 20 which means the soil is very weak and could not satisfy the requirements to be used as road subgrade material. The expansiveness index (ϵex) is correlated with the plasticity index, shrinkage limit, and percent of particles finer than the No. 40 (0.425 mm) sieve. Based on the expansiveness index from those parameters' soils are classified from low to high expansive range. The expansiveness index of the soil was calculated by the empirical formula shown in

$$\epsilon_{ex} = 2.4w_p - 3.9w_s + 32.5, \tag{2}$$

where ϵ_{ex} is the expansiveness index, $w_p = \text{PI} * (\text{% passing } 0.425\text{ mm sieve})/100$, $w_s = \text{SL} * (\text{% passing } 0.425\text{ mm sieve})/100$, PI is the plasticity index, and SL is the shrinkage limit.

As shown in Table 5, based on the calculated expansiveness index, a soil can be classified as low, moderately, and highly expansive.

The soil sample from TP-4 and TP-5 falls under the range of expansiveness index greater than 50. Thus, based on [21], the samples are highly expansive but the expansiveness index of the soil taken from TP-5 has a higher expansiveness

Table 4: Atterberg limit test results of the raw expansive soil for each test pit.

Sample designation	Natural moisture content (%)	Atterberg limits				Soil type	
		LL (%)	PL (%)	PI (%)	SL (%)	AASHTO	USCS
TP-1	39.81	96.02	60.49	35.53	19	A-7-5 (20)	MH & OH
TP-2	34.86	88.56	55.12	33.44	17		
TP-3	32.12	84.65	56.96	27.69	15		
TP-4	28.16	98.7	50.59	37.05	18		
TP-5	42.29	104.32	52.71	51.61	22		
TP-6	38	91.2	50.42	40.78	24		

Table 5: Soil expansivity based on expansiveness index.

Expansiveness index, ϵ_{ex}	Classification
<20	Low expansive
20–50	Moderately expansive
>50	Highly expansive

index than the one obtained from TP-4. Therefore, the soil sample from TP-5 was selected for further investigation by blending with BA and CTCP in terms of its index properties, shrink-swell, strength, and microstructural properties that were analyzed using Scanning Electron Microscopy (SEM). Besides, the selected soil specimen was also used to develop a CBR prediction model using MLR in MS-Excel Add-ins data analysis ToolPak and ANN in MATLAB deep learning toolbox.

The free-swell index test results and the specific gravity of the raw expansive soil at each test pit are also summarized in Table 6.

Like the expansiveness index, the soil specimen taken from TP-5 has the maximum free-sell index test result among the other samples from the remaining test pits. It is thus clearly visible that the soil from TP-5 is highly expansive and weak with a high swell-shrink behavior under moisture fluctuation. That is why further investigation and characterization of this soil sample on its index, engineering, and microstructural properties was made by blending with the two famous locally available pozzolanic materials, BA and CTCP. The pozzolanic properties and the oxide compositions of the two materials are shown and discussed below.

3.1.2. Properties of BA Sample. The BA sample utilized for the study was obtained from the Wonji sugar factory, Wonji, East Shewa, Oromia Regional State, Ethiopia. The complete silicate analysis was conducted at the Geological Survey of Ethiopia central laboratory, and the chemical compositions in percent are tabulated as shown in Table 7.

BA is a highly pozzolanic material that has a good percentage of silicon dioxide. According to [18]'s specification of the chemical composition of fly ash, the material's major oxide composition ($SiO_2 + Fe_2O_3 + Al_2O_3$) is equal to 82.66%, which is greater than the minimum requirement of 70%. Thus, BA meets the requirements for both class F and N fly ash pozzolanic materials. As a result, it can improve soil strength by creating calcium silicate hydrate (CSH) and calcium aluminate hydrate compounds (CAH).

Table 6: Free-swell index (FSI) and specific gravity of the soil sample from all test pits.

Sample designation	Free-swell index, FSI (%)	Specific gravity (G_S)
TP-1	75	2.70
TP-2	82	2.67
TP-3	83	2.70
TP-4	83	2.66
TP-5	120	2.65
TP-6	100	2.72
BA	—	2.18
CTCP	—	2.42

Table 8 shows the standard chemical compositions of fly ash according to the ASTM standard ASTM C 618-04a.

3.1.3. Properties of CTCP Sample. The termite clay powder used for the present study was obtained from the highly abundant termite hill around Dera town, East Shewa, Oromia regional state, Ethiopia. It was then pulverized to the required size and calcined with a muffle furnace with an average best calcination temperature of 650–850°C [13]. The complete silicate laboratory analysis was determined at the Geological Survey of Ethiopia's central laboratory, and the test results are summarized in Table 9.

Like the bagasse ash material, the calcined termite clay powder is also highly pozzolanic with 62.00% of silicon dioxide. Thus, according to [22]'s specification, the material's major oxide composition ($SiO_2 + Fe_2O_3 + Al_2O_3$) is equal to 83.60% which is 1.14% greater than that of bagasse ash's pozzolanic nature as a class F and N fly ash material. Therefore, both materials have significant effect on the reduction of plasticity and expansiveness of the raw highly expansive soil under the study.

The effects of each and combined pozzolanic stabilizers on the strength, index, and microstructural properties of the raw extremely expansive soil (TP-5) selected for further investigations are summarized in the following sections.

3.2. Effect of BA and CTCP on the Properties of the Highly Expansive Soil

3.2.1. Effect of BA and CTCP on Atterberg's Limits. The individual and combined effects of the two pozzolanic stabilizers on Atterberg's limit (liquid limit, plastic limit, plasticity index, and shrinkage limit) are presented and discussed hereinafter. The individual effect of BA on

Table 7: Chemical compositions of BA.

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI
(%)	**66.04**	**12.18**	**4.44**	1.96	1.08	2.12	6.76	0.16	0.77	0.14	0.66	3.51

Table 8: Standard chemical compositions of fly ash [22].

Chemical requirements	Class of fly ash	
	N	F
$SiO_2 + Fe_2O_3 + Al_2O_3$, min, (%)	70	70
Loss of ignition (LOI), max, (%)	10	6
Moisture content, max, (%)	3	3

Table 9: Chemical compositions of CTCP.

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LO I
(%)	**62.00**	**13.80**	**7.84**	3.96	2.44	1.60	3.16	0.16	0.30	0.41	<0.01	3.35

Atterberg's limit of the highly expansive soil understudy is shown in Figure 4.

Figure 5 shows the variation of Atterberg's limit of the highly expansive soil understudy when it was blended with CTCP alone.

As can be seen from Figures 3 and 4, with every 2% and 5% increment of BA and CTCP stabilizers separately and in combination, a significant decrease in liquid limit and shrinkage limit and hence plasticity index is observed to decrease significantly, indicating the stabilizing potential of the pozzolanic sugar factory waste and the termite hill calcined powder whereas the plastic limit was initially kept on increasing and became slightly decreased when the soil was treated separately with 11% and 25% BA and CTCP, respectively. The decrease in liquid limit, shrinkage limit, and plasticity index is due to the percentage replacement of fine particles by the pozzolanic materials, and physiochemical and pozzolanic reaction between the soil mass and the additives.

The combined effect of BA and CTCP with the specified percentage is also shown in Figure 6.

As can be inferred from Figure 6, like the individual effect of BA and CTCP on Atterberg's limit, the combined effect of both stabilizers (3% BA + 5% CTCP, 5% BA + 10% CTCP, 7% BA + 15% CTCP, 9% BA + 20% CTCP, and 11% BA + 25% CTCP) was also quite significant. The liquid limit, plasticity index, and shrinkage limit of the soil stabilized with 11% BA + 25% CTCP were decreased by 41.6%, 88.81%, and 68.38%, respectively. The combined effect of the stabilizers on Atterberg's limits is much more significant than the individual effect. This is mainly due to the fact that the chemical reaction takes place between the clay mineral in the highly expansive soil and the cations like sodium, magnesium, and aluminum (monovalent, divalent, and trivalent, respectively) in the stabilizers.

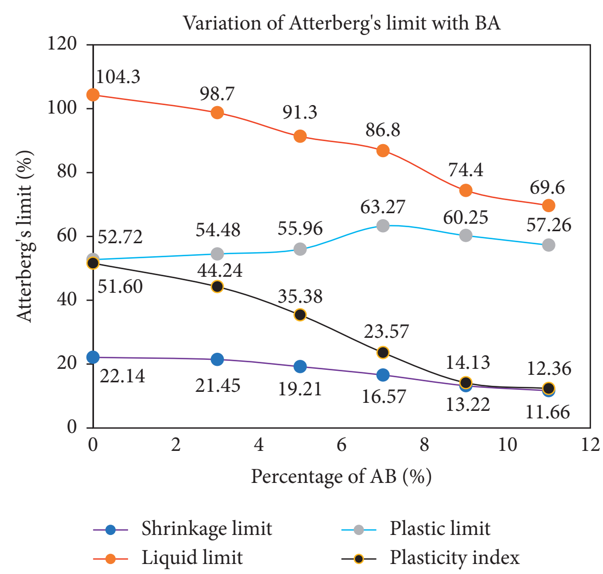


Figure 4: Effect of BA on Atterberg's limit.

3.2.2. Effect of BA and CTCP on Swelling Characteristics. The stabilizing potential of the BA and CTCP is further demonstrated by the significant reduction of the free-swell index test results that are summarized in the figures shown hereinafter. The individual effect of BA on the free-swell index of the highly expansive soil is shown in Figure 7.

The stabilizing behavior of the BA was demonstrated by the significant reduction of the free-swell index; a 61.67% decrease was obtained when the extremely expansive subgrade soil was blended with 9% of BA. That means that 9% BA alone could be the optimum percentage that can reduce the swelling potential of the highly expansive soil by balancing the negative charge (anion) by the exchangeable cation found in the BA.

The variation of the free-swell index of the highly expansive soil stabilized with CTCP alone is shown in Figure 8.

As can be inferred from Figure 8, the stabilizing performance of the calcined termite clay powder is significantly demonstrated by the substantial decrease in the free-swell index test results. There was a 66.67% decrease in the swelling potential of the highly expansive subgrade when it was blended with 15% CTCP alone which is almost 5% better than the stabilizing performance of 9% BA (61.67%). It could be concluded that the optimum content of CTCP alone to

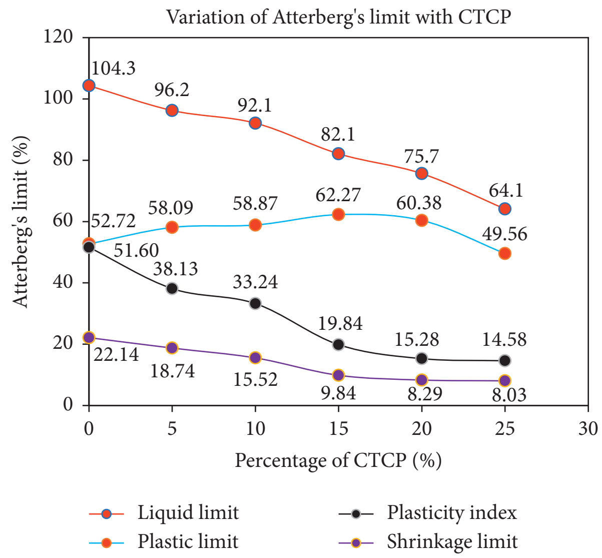


Figure 5: Effect of CTCP on Atterberg's limit.

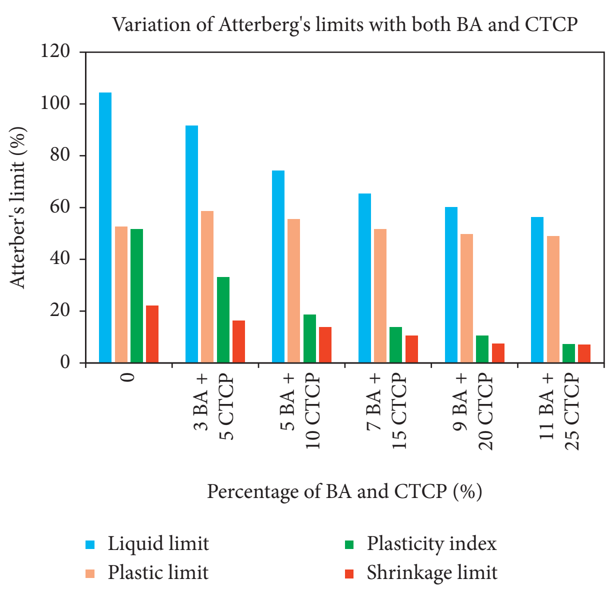


Figure 6: Combined effect of BA and CTCP on Atterberg's limit.

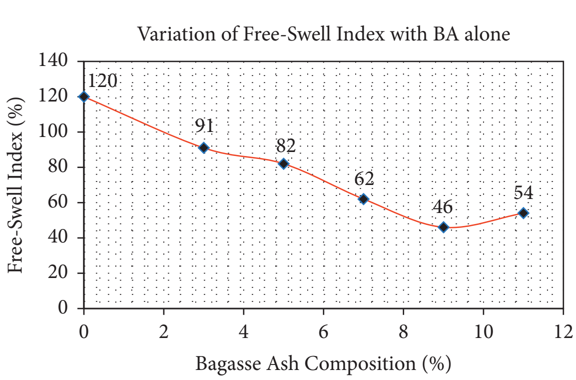


Figure 7: Effect of BA on the free-swell index.

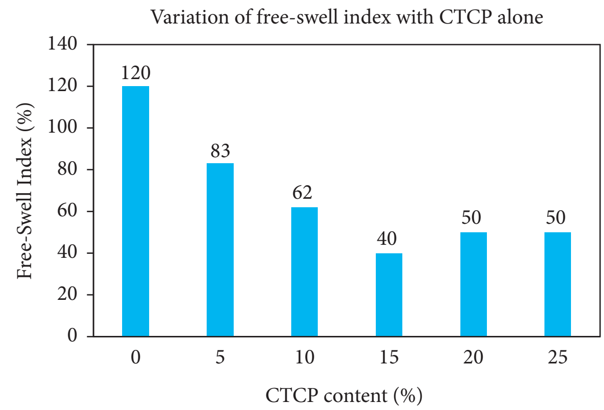


Figure 8: Effect of CTCP on the free-swell index.

stabilize the cyclic shrink-swell property of the highly expansive subgrade soil is 15% because the free-swell index test result for the last two percentages of CTCP became a little bit increased and the same as each other although the free-swell index has decreased by 58.33% when it was blended with 20% and 25% CTCP.

In order to further investigate the effect of BA and CTCP in detail, a combination of the two pozzolanic stabilizers was made and a significant effect on the swelling potential has been demonstrated. The combined effect of BA and CTCP on the swelling potential of the highly expansive soil under the present study is shown in Figure 9.

As can be seen in Figure 9, the combined effect of BA and CTCP is quite significant and the swelling potential of the raw highly expansive soil was reduced from 120% to 33% with a 72.5% reduction when it was blended with a combination of 9% BA and 20% CTCP. Thus, 9% BA and 20% CTCP compositions could be the optimum percentage combination to stabilize the cyclic swell-shrink behavior of the soil under study due to moisture fluctuation. When the soil was blended with 9% BA and 20% CTCP, there was a 28.6% and 17.5% of free-swell index reduction when it was stabilized with the optimum BA (9%) and CTCP (15%) alone, respectively. Thus, it can be concluded that the combined effect of BA and CTCP is quite significant and its effect on the swelling potential of the highly expansive soil in the present study is very promising.

3.2.3. Effect of BA and CTCP on Moisture-Density Relationship. In this study, the standard laboratory compaction test was conducted for the raw highly expansive soil, the soil blended with 3%, 5%, 7%, 9%, and 11% BA, the soil blended with 5%, 10%, 15%, 20%, and 25% CTCP, and the soil blended with both BA and CTCP in combination (3% BA + 5% CTCP, 5% BA + 10% CTCP, 7% BA + 15% CTCP, 9% BA + 20% CTCP, and 11% BA + 25% CTCP).

The maximum dry density (MDD) and optimum moisture content (OMC) of the highly expansive soil understudy (TP-5) were found to be 1.56 g/cc and 32.57%, respectively. The effect of BA alone on the maximum dry density of the study soil is shown in Figure 10.

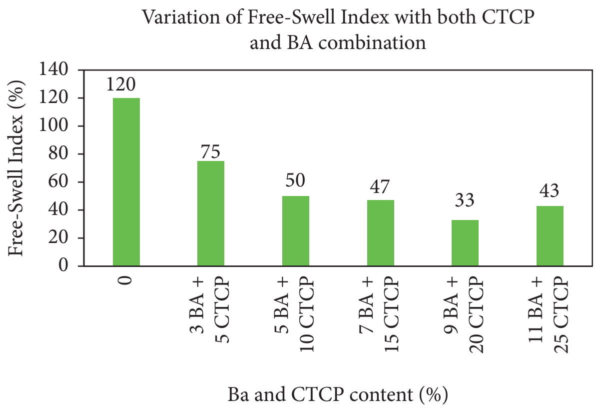


Figure 9: Combined effect of BA and CTCP on the free-swell index.

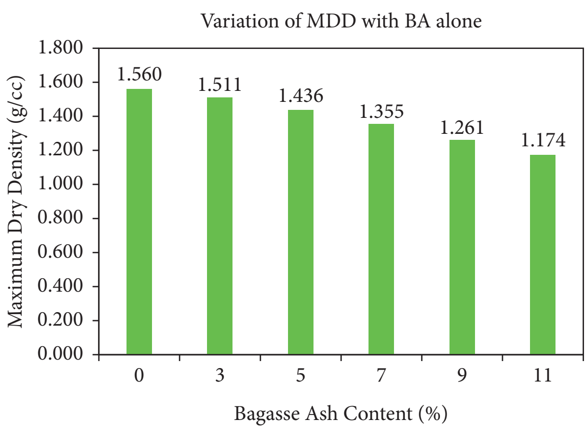


Figure 10: Effect of BA on MDD.

As can be seen from Figure 10, the addition of BA has slightly reduced the maximum dry density of the highly expansive soil. The MDD of the raw soil was 1.56 g/cc but it was decreased by 3.14%, 7.95%, 13.14%, 19.17%, and 24.74% when the highly expansive subgrade soil blended with 3%, 5%, 7%, 9%, and 11% BA. The study performed by [23] on expansive soil stabilization using rice husk ash also showed a decrease in the maximum dry density as the content of rice husk ash increased. The reduction in MDD is mainly due to the percentage replacement of the relatively heavier soil by the lighter bagasse ash sample with a specific gravity of 2.65 and 2.18, respectively. The variation of optimum moisture content (OMC) with the addition of the percentage of BA alone is also shown in Figure 11.

Unlike the MDD, the OMC of the highly expansive soil was kept on slightly increasing when it was blended with various percentages of BA as shown in Figure 11. The OMC of the highly expansive soil was increased by 11.85%, 17.81%, 26.56%, 30.1%, and 39.51% when it was stabilized with 3%, 5%, 7%, 9%, and 11% of BA, respectively.

The variation of maximum dry density of the study soil stabilized with CTCP alone is shown in Figure 12.

Like the effect of BA on OMC and MDD, the addition of CTCP has also increased the OMC and decreased the MDD of the highly expansive soil treated with 5%, 10%, 15%, 20%, and 25% CTCP for the same reason stated above.

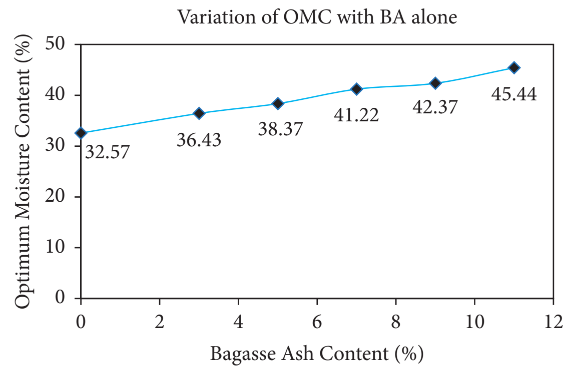


Figure 11: Effect of BA on OMC.

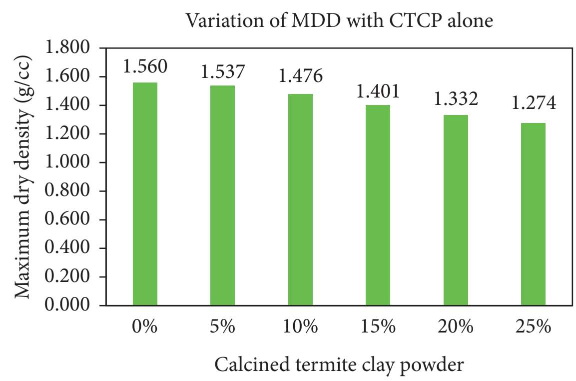


Figure 12: Effect of CTCP on MDD.

Figure 13 shows the variation of the optimum moisture content of the study's highly expansive soil stabilized with CTCP alone.

As can be inferred from Figure 13, the MDD and OMC of the untreated highly expansive soil were 1.56 g/cm^3 and 32.57%, respectively. But, when it was treated with 25% CTCP, the MDD was decreased by 18.33% whereas the OMC was increased by 33.22%. The variations of MDD and OMC for the stabilized soil with BA and CTCP combination (3% BA + 5% CTCP, 5% BA + 10% CTCP, 7% BA + 15% CTCP, 9% BA + 20% CTCP, and 11% BA + 25% CTCP) are shown in Figures 14 and 15, respectively.

The combined effect of BA and CTCP on the maximum dry density of the highly expansive soil understudy is shown in Figure 14.

Generally, as can be seen from all the above graphs, the optimum moisture content was kept on slightly increasing whereas the maximum dry density was kept on decreasing with the addition of BA and CTCP separately and in combination (blended simultaneously with the highly expansive soil). In particular, the combined effect of both the BA and CTCP on the maximum dry density and optimum moisture content of the treated soil was comparatively significant. Figure 15 shows the combined effect of BA and CTCP on the optimum moisture content of the soil under the study.

As stated above, the MDD and OMC of the untreated raw soil were 1.56 g/cc and 32.57%, respectively. But the MDD was decreased by 5.32%, 14.3%, 17.9%, 25.38%, and

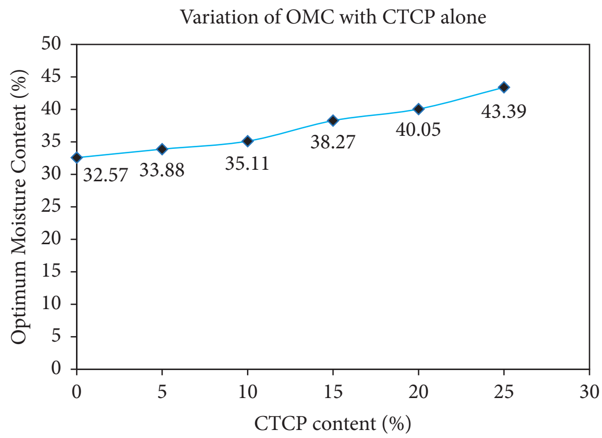


Figure 13: Effect of CTCP on OMC.

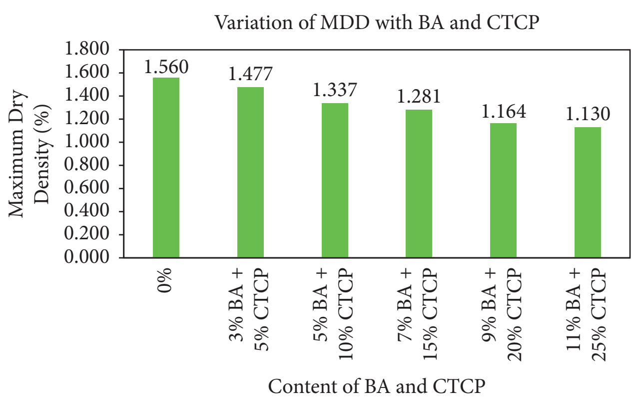


Figure 14: Combined effect of BA and CTCP on MDD.

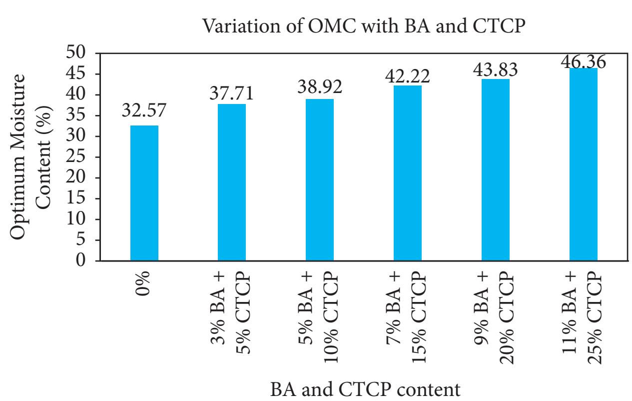


Figure 15: Combined effect of BA and CTCP on OMC.

27.56% whereas the OMC was increased by 15.78%, 19.5%, 29.63%, 34.57%, and 42.34% when the soil was treated with the combination of BA and CTCP. The result of the decrease in maximum dry density and an increase in the optimum moisture content is also again in line with the findings of the study conducted by [24] on the stabilization of expansive soil using bagasse ash with an amendment of lime. According to the conclusions drawn by [24], the increase in OMC is due to the pozzolanic reaction of silica and alumina in bagasse ash and soil with calcium of the lime to form calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) which are the cementing agents. Additional water is needed to saturate the enormous surface area of the fine bagasse ash particles, or it is absorbed by the fine bagasse ash particles.

3.2.4. Effect of BA and CTCP on Soaked CBR. The CBR value of the highly expansive soil was found to be 2.2% which is less than 3%; thus according to the [25]'s standard specification, the strength of the soil is very poor to be used as subgrade material. The effect of Ba alone on the strength of the highly expansive soil is shown in Figure 16.

In addition to the above parameters, the stabilizing performance of the bagasse ash and calcined termite clay powder is demonstrated by the significant improvement of the strength of subgrade soil. As can be seen in Figure 16, the strength of the highly expansive soil was significantly improved with the addition of BA. The CBR of the soil was doubled, tripled, and five times greater than that of the CBR of the untreated soil when it was stabilized with 7%, 9%, and 11% of BA, respectively.

Figure 17 shows the individual effect of CTCP on the strength (CBR) of the highly expansive soil.

As shown in Figure 17, the effect of CTCP on the strength of the soil is much more significant as compared with the effect of BA. The CBR of the natural soil was increased by 79.1%, 160.45%, 283.64%, 326%, and 406.36% when the highly expansive soil was blended with 5%, 10%, 15%, 20%, and 25%, respectively.

The combined effect of both the BA and CTCP on the strength of the highly expansive soil understudy was also investigated and shown in Figure 18.

As can be inferred from Figure 18, as compared to the effect of BA and CTCP on the strength of the soil separately, the combination of the two pozzolanic resulted in a significant improvement. The combination of 11% BA + 25% CTCP has increased the CBR of the untreated weak soil from 2.2% to 12.81% which is six times greater than the original (untreated) strength of the soil.

3.2.5. Effect of BA and CTCP on the Microstructural Properties. The following images (SEM images) for the natural highly expansive soil (control specimen) and the optimum mixture (soil + 9% BA + 20% CTCP) at different sizes and magnification rates were captured. Figure 19 shows the SEM images of the raw highly expansive soil without the addition of neither BA nor CTCP.

The optimum combined effect of BA and CTCP (9% BA & 20% CTCP) on the microstructural properties of the highly expansive soil was also investigated using an SEM machine, and the resulting SEM images at different sizes and magnification rates are shown in Figure 20.

As can be inferred from Figures 19 and 20, the JCM-6000 PLUS Bench Top SEM JEOL machine gives a clear image of both the highly expansive soil sample taken from TP-5 and the soil treated with 9% BA + 20% CTCP at different sizes and magnification rate. As shown in Figures 19(a) and 19(b), the highly expansive soil under study shows a dispersed,

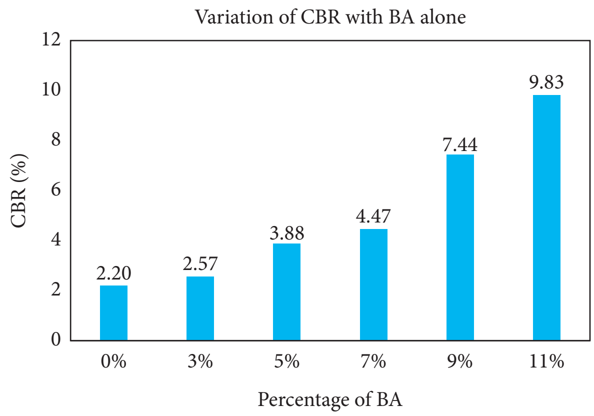


Figure 16: Effect of BA on CBR.

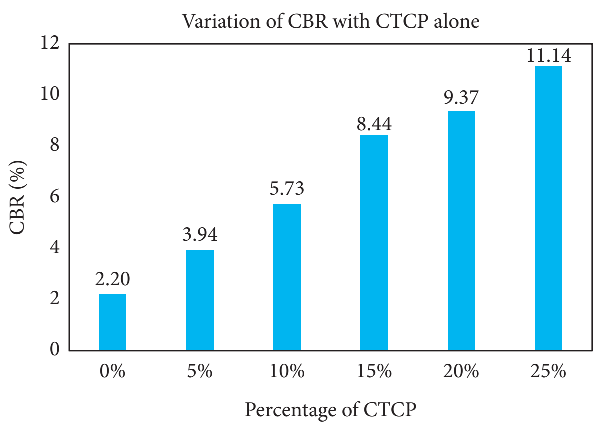


Figure 17: Effect of CTCP on CBR.

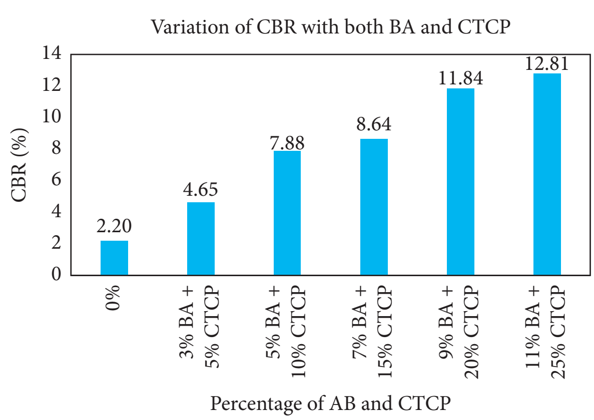


Figure 18: Combined effect of BA and CTCP on CBR.

loosened, and scattered type of fabric with many pores and less interlock and bond between particles having an opened (floated) arrangement of a disintegrated layered structure. But, when it was blended with 9% BA + 20% CTCP, the negatively charged clay surfaces attract the cations (monovalent, divalent, trivalent, etc.) in the highly pozzolanic additives (BA and CTCP) and a more flocculated, aggregated and well-integrated layered structure that seems a white strong plastic material with fibers is shown in Figures 20(a) and 20(b), and the microsized particles act as a single homogeneous mass with no any visible hole (pore) in between when it was seen by 10 μm size and ×2000 magnification rate as shown in Figure 20(b).

3.3. *Prediction of Soaked CBR Using Multiple Regression Technique.*

In the present study, two prediction models, (1) the artificial neural network (ANN) model and (2) the multiple linear regression (MLR) model, have been developed to predict the soaked CBR values of the highly expansive soil stabilized with bagasse ash and calcined termite clay powder. It is obvious that various studies have been conducted by many researchers in the world to predict soaked CBR from easily determinable parameters using ANNs and MLR. The present study is unique because no one has done such kinds of research using the two highly pozzolanic materials to stabilize expansive soil separately and in combination globally and locally and to predict soaked CBR from representative easily determinable parameters of the stabilized soil. Nowadays, the major problem that civil engineers are facing is the shortage of selected fill material to cut and replace expansive soils and to conduct representative CBR tests along the length of the road as it is quite expensive, laborious, and time-taking; thus, the research has a potential to resolve the shortage of selected fill materials to replace sections where an expansive soil exists and to aware local or international researchers to apply soft computing systems to the field of civil engineering.

3.3.1. *Development of the Multiple Linear Regression (MLR) Model.*

The MLR model was developed in the MS-Excel data analysis ToolPak by taking soaked CBR as a dependent variable and the bagasse ash fraction (BAF), calcined termite clay powder fraction (CTCPF), liquid limit (LL), plasticity index (PI), optimum moisture content (OMC), and maximum dry density (MDD) as input (independent) variables. The model has the form shown in

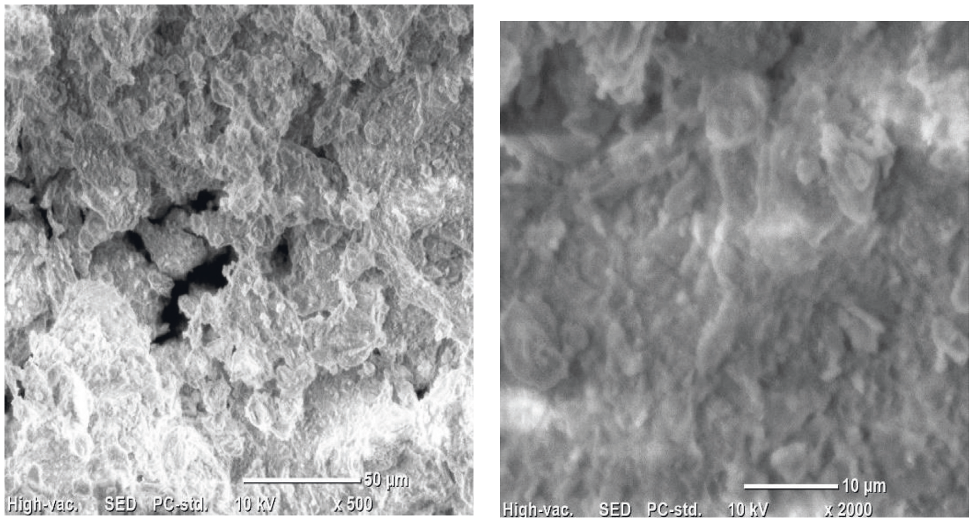
$$\% \; Y = b + b1X1 + b2X2 + b3X3 + b4X4 + b5X5 + b6X6, \tag{3}$$

where Y is the dependent variable (soaked CBR) and $X1$, $X2$, $X3$, $X4$, $X5$, and $X6$ are the dependent variables. The term b is the coefficient of intercept whereas $b1$, $b2$, $b3$, $b4$, $b5$, and $b6$ are the coefficients of the independent variables. The independent variables are those parameters described above for all of the sixteen datasets shown in Table 10.

The coefficients of each variable from the MLR model summary output were substituted in equation (3) correspondingly, and the model shown in equation (4) was developed.

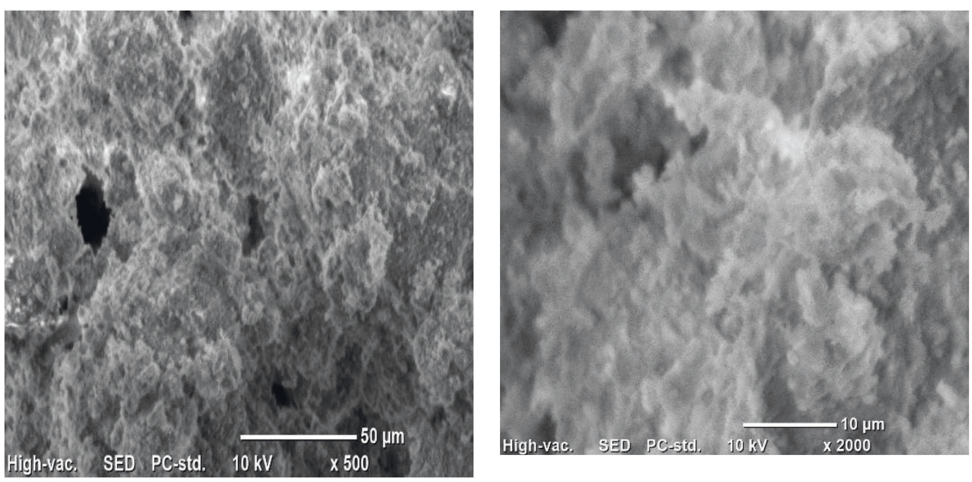
$$\begin{aligned} \text{CBR } (\%) = {} & 40.399 - 0.164\,\text{BAF} + 0.132\,\text{CTCPF} \\ & + 0.096\,\text{LL} - 0.044\,\text{PI} \\ & - 0.056\,\text{OMC} - 28.061\,\text{MDD}, \end{aligned} \tag{4}$$

where CBR is the California bearing ratio (%), CTCPF is the calcined termite clay powder fraction (%), LL is the liquid



(a) (b)

Figure 19: SEM images of the highly expansive soil at different sizes and magnification rates. (a) 50 μm, ×500. (b) 10 μm, ×2000.



(a) (b)

Figure 20: SEM images of the (soil + 9% BA + 20% CTCP) at different sizes and magnification rates. (a) 50 μm, ×500. (b) 10 μm, ×2000.

Table 10: Experimental results of the BA and CTCP stabilized soil.

No. of observations	BA fraction (%)	CTCP fraction (%)	LL (%)	PI (%)	OMC (%)	MDD (g/cc)	CBR (%)
1	0	0	104.3	51.60	32.57	1.560	2.20
2	3	0	98.7	44.24	36.44	1.511	2.57
3	5	0	91.3	35.38	38.37	1.436	3.88
4	7	0	86.8	23.57	41.22	1.355	4.47
5	9	0	74.4	14.13	42.37	1.261	7.44
6	11	0	69.6	12.36	45.44	1.174	9.83
7	0	5	96.2	38.13	33.88	1.537	3.94
8	0	10	92.1	33.24	35.11	1.476	5.73
9	0	15	82.1	19.84	38.27	1.401	8.44
10	0	20	75.7	15.28	40.05	1.332	9.37
11	0	25	64.1	14.58	43.39	1.274	11.14
12	3	5	91.7	33.14	37.71	1.477	4.65
13	5	10	74.3	18.74	38.92	1.337	7.88
14	7	15	65.4	13.77	42.22	1.281	8.64
15	9	20	60.0	10.43	43.83	1.164	11.84
16	11	25	56.2	7.32	46.36	1.130	12.81

limit (%), PI is the plasticity index (%), and MDD is the maximum dry density (g/cc). $R^2 = 0.987$ which is closer to +1, which means the dependent variable (CBR) could be explained by those six independent variables about 98.6%, and the MLR model performance is very high according to [16], and again according to [26], the model is an efficient model to predict CBR values because the R-value (0.993) > 0.8. The observed (experimental) CBR versus the predicted CBR by the MLR model is plotted in Figure 21.

The determination coefficient (R^2) between the predicted and observed CBR values is 0.9875 which is closer to +1. This is again an indicator of the high performance (efficiency) of the MLR model and shows that there is a strong positive relationship between the dependent and independent variables.

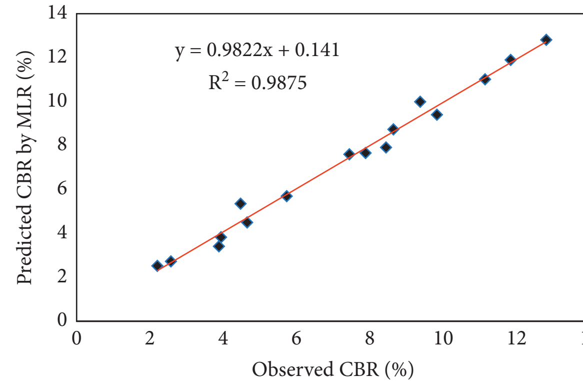


Figure 21: Predicted CBR by MLR versus experimental CBR.

3.3.2. Development of Artificial Neural Network (ANN) Model. The ANN model used to predict the soaked CBR value was developed using the MATLAB deep learning neural network toolbox. The feed-forward back propagation artificial neural network with various algorithms like Levenberg-Marquardt Neural Network (LMNN), Bayesian Regularization Neural Network (BRNN), and Scaled-Conjugate Neural Network (SCGNN) have been developed and trained many times. The neural network model constructed with the LMNN algorithm was found to be the most efficient model with the highest determination and correlation coefficients R^2 and R, respectively, after many training attempts. Figure 22 shows the architecture of the developed ANN model.

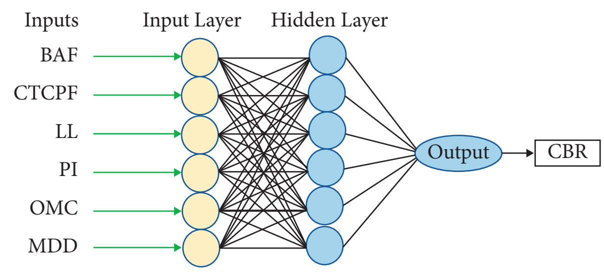


Figure 22: Architecture of the developed ANN model.

As can be seen in Figure 22, for the neural network modeling (ANN), the bagasse ash fraction (BAF), calcined termite clay powder fraction (CTCPF), liquid limit (LL), plasticity index (PI), optimum moisture content (OMC), and maximum dry density (MDD) of the stabilized highly expansive soil were used as input parameters for the ANN modeling. The model has one hidden layer with six neurons. According to [6], there are no general rules to define the number of hidden layers and the number of neurons in each hidden layer, but for earning time, it is preferable to use a simple architecture of one hidden layer with a limited number of neurons. The feed-forward back propagation neural network architecture with Levenberg-Marquardt Neural Network (LMNN) algorithm (the fastest training algorithm with high accuracy) was used to develop the ANN prediction model shown in Figure 22. Two extra algorithms, namely, the Bayesian Regularization Neural Network (BRNN), and Scaled-Conjugate Neural Network (SCGNN), have been also substituted instead of the LMNN algorithm, but the accuracy and performance of the models were found to be low as compared with the prediction model developed with the LMNN algorithm in terms of determination and correlations coefficients as well as the mean squared error. Thus, the feed-forward backpropagation neural network model with the LMNN algorithm was only considered and the regression plot of the model (with $R^2 = 0.9925$) is shown in Figure 23. The predicted CBR values by the ANN model were compared with the observed (experimental) CBR as shown in Figure 24.

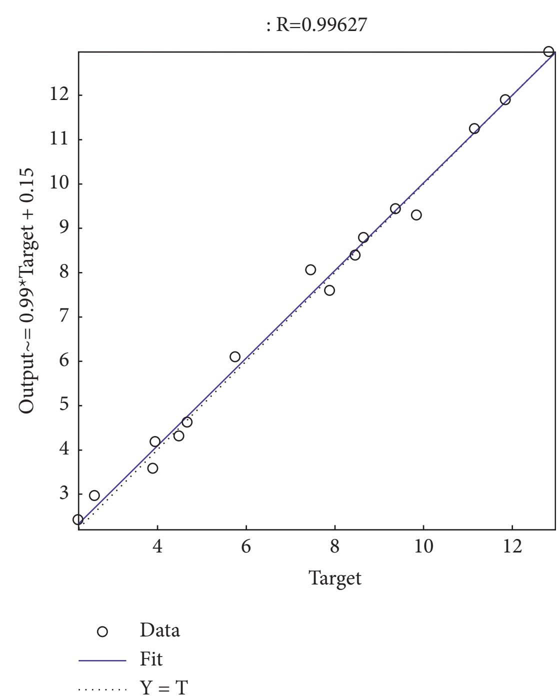


Figure 23: The regression plot of the ANN model.

As can be inferred from Figure 23, the correlation coefficient ($R = 0.99627$) is very close to +1, and the determination coefficient ($R^2 = 0.9925$) is also closer to +1. Thus, the ANN regression-based model is efficient and shows a perfect positive relationship between the dependent variable (soaked CBR) and independent (BAF, CTCPF, LL, PI, OMC, and MDD) variables.

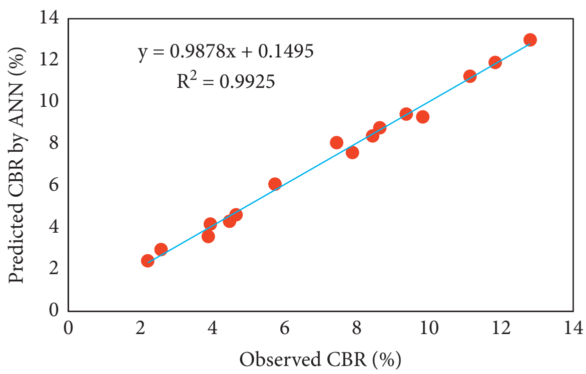


Figure 24: Predicted CBR by ANN versus experimental CBR.

The determination coefficient of the MLR model ($R^2 = 0.9875$) is lower than that of the ANN model ($R^2 = 0.9925$) as compared to the ANN model. Thus, the ANN model showed comparatively better values of CBR with satisfactory values of prediction parameters as compared to the MLR model for the prediction of soaked CBR of stabilized highly expansive soil under study. The modeling results of the present study are in line with the findings of [27] where the soft computing ANN prediction model is comparatively better than that of the Simple Linear Regression (SLR) and MLR prediction models. Figure 24 shows the correlation between the predicted CBR using ANN and the experimental CBR values of the stabilized highly expansive soil.

4. Conclusions

The present study has mainly focused on the stabilization of highly expansive soil using an industrial waste called sugarcane bagasse ash (BA) and calcined clay powder from termite mounds. In addition to this, microstructural analysis was also investigated using SEM test, and soaked CBR prediction models were also developed using MLR and ANN.

According to the [22]'s specification of the chemical composition of fly ash, the material's major oxide composition ($SiO_2 + Fe_2O_3 + Al_2O_3$) is equal to 82.66%, and 83.60%, respectively, greater than the minimum requirement of 70%. Hence, both stabilizers satisfy the criteria of class F and N fly ash pozzolanic materials.

The natural soil understudy is classified as MH and OH and A-7-5 (20) as per the USCS and AASHTO classification systems, respectively, which is a typical indicator of highly expansive soil that is of poor quality to be used as a road subgrade material.

The combined effect of BA and CTCP is quite significant, and the swelling potential of the raw highly expansive soil was reduced from 120% to 33% with a 72.5% reduction when it was blended with a combination of 9% BA and 20% CTCP. Thus, 9% BA and 20% CTCP compositions could be the optimum percentage combination to stabilize the highly expansive soil under study.

A significant improvement in the strength (CBR) was demonstrated when the soil was treated with every separate and combined dosage of BA and CTCP. The effect of CTCP on the strength (CBR) of the soil is much more significant as compared with the effect of BA.

The SEM micrographs show that the raw expansive soil understudy was scattered (nonflocculated) loose particles with an open arrangement, but it became a single homogenous and flocculated layered structure when it was stabilized with the optimum BA-CTCP combination (9% BA + 20% CTCP).

The R^2 of both the MLR and ANN prediction models is closer to +1, but the ANN model is found to be more significant and efficient than the MLR prediction model.

Data Availability

The corresponding author is very glad to share any necessary supporting files via the provided e-mail address.

Conflicts of Interest

The authors declared that there are no conflicts of interest concerning the publication issues.

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