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Research Article

Utilization of Coffee Husk Ash on the Geotechnical Properties of Gypsum-Stabilized Expansive Clayey Soil

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Expansive clayey soils (CSs) expand and become softer as moisture content increases, but they get harder and stronger as they dry out. The earth's swelling and shrinkage characteristics under varying moisture conditions make roads built on expansive CS, in particular, vulnerable to early degradation. In this investigation, coffee husk ash (CHA), gypsum, and a blend of the two additives (G-CHA) were used in experimental tests to treat expansive CS. This study aims to evaluate experimentally the potential of expansive soil stabilization using different additives: CHA, gypsum, and a combination of gypsum and CHA. Five different percentages of CHA (5%, 10%, 15%, 20%, and 25%), three percentages of gypsum (3%, 6%, and 9%), and variable percentages of their combinations were used to stabilize the soil for pavement subgrade application. Atterberg limits, compaction, linear shrinkage (LS), swelling, unconfined compressive strength (UCS), and California bearing ratio (CBR) tests were performed on treated and virgin soil specimens at 3, 7, 14, 28, and 56-day curing times. Results showed that CHA additives effectively reduced the plasticity, LS, and swell potential in addition to increasing the maximum dry unit weight, UCS, and CBR. It was determined that the UCS and CBR values for the 6% stabilized gypsum soil increased by 28.95% and 19.54%, respectively, and reduced by 41% of the plastic index parameter after the addition of 15% CHA. Based on the evaluation of the results, an optimum mixture of 6% gypsum and 15% CHA (SG6C15) stabilized soil can be used in pavement subgrade applications as it achieved the minimum strength target. The performance of CHA-treated samples as subgrade material is superior to that of untreated virgin soil. Because of the stronger subgrade, smaller pavement layers result in a thinner pavement structure.

1. Introduction

Environmental sustainability is described as using recycled resources to satisfy short-term requirements without compromising the needs of the next generation, and it has emerged as a key idea of the millennium development targets [1]. Therefore, researchers are striving to explore modern techniques to ensure the sustainability of the environment. Globally, there is growing worry over resource depletion and waste production. Road networks and transportation are essential for achieving environmental sustainability. Transportation systems are the backbone of any economy, and they play a particularly important role in developing countries, including Ethiopia. As a result, it has been discovered that employing waste materials to improve the strength and performance of road pavements is a helpful way to achieve financial effectiveness for a sustainable transportation infrastructure. Highway engineers have recently encountered widespread issues, such as rutting, raveling, stripping, and cracking, which cause flexible pavements to break early. The strength and operational life of the highway are mostly dependent on the subgrade layer [2, 3]. A typical flexible pavement is made up of layers made of various materials, such as a surface layer, a base course layer, a subbase course layer, and a subgrade layer, as

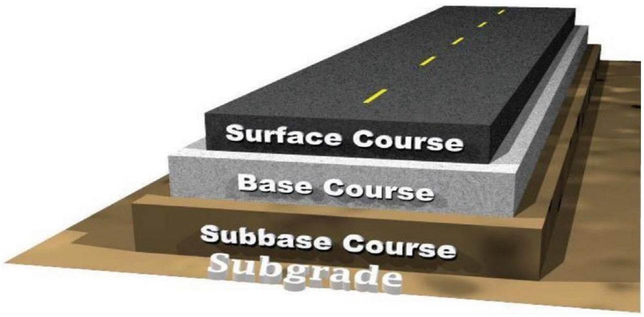

Figure 1: Flexible pavement layers [15].

shown in Figure 1. Through the use of this multilayer structure, the load is transferred to the subgrade layer. The subgrade layer serves as the pavement's foundation [4]. Strength of subgrade soil is the phrase used to describe the pavement's capacity to withstand compressive pressures [5]. If weak subgrade soil is found, soil properties can be corrected utilizing various stabilizing techniques, keeping in mind the economics of roadway construction [6]. Poor subgrade containing expansive soil has a greater tendency to swell and shrink when it comes into contact with water. The abundance of montmorillonite minerals in clay is thought to be the reason for this behavior. Utilizing some chemical or cementitious additions will help decrease this characteristic of expanding soils [7]. Less settlement and eventual soil stability were the results of improving sandy soils utilizing soil injection technology and expandable polyurethane resin [8].

From a financial perspective, composite material-based soil stabilization may be preferable [9]. The liquid limits (LLs), dry densities, swelling pressures, and swelling potential were significantly lowered by using cement and recycled tire rubber [10]. Due to its expensive nature and negative effects on the environment, cement is normally not utilized for soil stabilization. Rice husk ash (RHA), sugarcane bagasse ash, and cow dung ash were all used to stabilize the subgrade for rural roads and stabilized local clayey soil (CS) with a varying percentage of RHA [11, 12]. Nanosilica created soil with more durability and strength than soil stabilized using lime, according to a study on the use of nanoparticles to stabilize poor soil [13]. Soil stabilization is a low-cost method of strengthening fragile soil. The majority of waste materials act as stabilizing agents to improve results and stabilize the weak soil [14]. Since soil supports the pavement from below, as seen in Figure 1 for the flexible pavement layers, soil is an essential component of the structure of road pavements [15].

Natural soils, particularly CSs, usually lack the mechanical and geotechnical characteristics needed for construction projects, requiring treatment to achieve conditions that are acceptable from a geotechnical standpoint [16, 17]. CS currently presents some difficulties for pavement engineering in subgrade soil cross-sectional elements due to their weak subgrade strength, high sensitivity to moisture, and excessive swelling. Due to their poor strength, high sensitivity to moisture, and excessive swelling, clay soils pose certain challenges for geotechnical and civil engineers. Furthermore, CSs that are found above the groundwater table become problematic because they swell with an increase in moisture content and shrink with a reduction in moisture content. Long-lasting rainfall also causes considerable changes in groundwater [18, 19]. Because of their inherent mineralogical characteristics, these soils are well known for their volume change behavior in response to moisture variations. Pavement failures, including cracks, potholes, raveling, and rutting, are some examples of structural failures and fractures brought on by soil expansion [20]. Ethiopian CSs can be problematic for direct subgrade construction. CS applies to soils that have the tendency to swell when their moisture content is increased. Soils containing the clay mineral montmorillonite generally exhibit these properties. Admixing some percentage of cement or cementitious material with soil improves the bearing capacity, but crack formation due to shrinkage cannot be minimized. Hence, highway engineers are making a constant effort to find the right material that really has the potential to improve the bearing capacity as well as improve the shrinkage cracking control. In the present study, efforts have been made similarly in this direction by utilizing CHA as an admixture to improve and strengthen the properties of CS. The long-term performance of the structural properties of soil admixed with CHA was evaluated in the laboratory by conducting tests like the grain size analysis (GSA), LL, plastic index, linear shrinkage (LS), standard Proctor compaction, the California bearing ratio (CBR), and unconfined compressive strength (UCS) test.

Numerous investigations have been done on the effectiveness of clay stabilization by CHA admixing. In this context, Munirwan et al. [21] conducted research on the shear strength improvement of clay soil stabilized by coffee husk ash (CHA). They evaluated the geotechnical properties of clay soil treated with CHA to minimize the construction cost and develop environmentally friendly alternative compositions. It was observed that CHA reduced the plasticity of soils and changed the soil classification in accordance with soil classification system standards. In general, 5%–25% of CHA is the optimum amount to reduce the plasticity of the soil. They observed that the stabilization of CHA increased the optimum moisture content (OMC) and reduced a certain amount of maximum dry densities (MDDs) that corresponded to an increased CHA percentage. It has been reported that the optimum CHA content is 20%. The maximum CBR value determined was at 4% cement and 5% CHA soil mixtures. According to the compressive strength and plasticity index (PI) parameters, 5%–25% CHA showed the optimum amount required to improve the properties of soil. According to Atahu [22], for stabilized clay soil with CHA, laboratory experiments such as Proctor density, swelling index, consistency limits, and UCS tests were performed for different percentages of 5%, 10%, 15%, and 20% of CHA. Standard Procter tests were conducted to evaluate the compaction behavior, and unconfined compressive tests were performed on samples of 5 cm in diameter and 10 cm in height after curing for 1, 7, and 14 days. The laboratory test results showed that the addition of CHA increased compressive strength and decreased swelling ratio and shrinkage; the PI and OMC decreased in the Atterberg limit and Proctor tests, while dry density increased as the CHA percentage increased. Munirwan et al. [23] investigated the potential of CHA to stabilize CS. CS was stabilized using different amounts of CHA, such as 3%, 6%, 9%, and 12% by a 3% increment. The performance of CHA-modified soils was evaluated using different performance tests, namely, specific gravity, GSA, and Atterberg limits and indexes. Mamuye and Geremew [24] investigated the effects of CHA in soil-stabilized subgrade pavement construction materials. They observed that the amount of CHA strongly influences the strength of the stabilized mixes, with a range of 5%–25%, varying by 5% increment. According to Mamuye and Geremew [24], the results showed that the stabilization of CHA reduced the PI, swelling, and OMC, with an increase in MDD and CBR with all increased CHA contents. According to Fattah et al. [25], an experimental study using RHA to improve CS characteristics was conducted. The samples of these soils were collected from a different site in Al-Nasiriyah, a city south of Iraq. The soil was stabilized using 3%, 6%, and 9% percentages of RHA. For both unstabilized and stabilized soils, tests for the Atterberg limits, specific gravity, compressibility, UCS, and consolidation were conducted. The results showed that the three soils' LLs decreased by about 11%–18% with the addition of 9% RHA, while the PI reduced by about 32%–80%, and the soil's rice husk content increased to its maximum at RHA between 6% and 8%. Irshayyid and Fattah [26] compared two methods for enhancing the parameters of the soil: the first method used steel fibers to enhance the soil, and the second method used plastic waste to enhance the strength and volume fluctuations of the soil. The effects of adding varying amounts of steel fiber and plastic trash (4%, 8%, and 12%) by dry weight of soil were investigated in a number of tests. The results showed that, in addition to the physical characteristics of expansive clay soil that is susceptible to swelling, the steel fiber and plastic waste material considerably improved the soil strength and volume changes. Al-Gharbawi et al. [27] investigated the laboratory study of stabilizing expansive soil using three percentages of lime, cement, and silica fume (5%, 7%, and 9%), and the work used a consolidation test to record the free swell and swell pressure for the untreated and treated soils, and the grouting technique is used as a process that can be applied in the field to maintain the improvement in the bearing capacity. It was determined that, in comparison to virgin soil, soil stabilized with various concentrations of lime, cement, and silica fume shows a reduction in both free swell and swelling pressure of about 65% and 76%, respectively. In comparison to virgin soil, silica fume-grouted soil enhances the bearing capacity of footings lying on the soil by roughly 64%–82% for soil treated with 5% and 9% silica fume, respectively. Fattah et al. [28], a study was conducted on the effects of different additives. The swelling soil from the Hamamuk earth dam, which was located in Koya town north of Iraq, was treated with four types of additives: cement, steel fibers, gasoline fuel, and cement grout injection. The treatment of the expansive soil with 5% of cement or steel fibers or the injection with cement grout revealed a better improvement, while 4% of gasoline oil is sufficient to reveal the optimum treatment by this material. The angle of internal friction is not affected by the treatment, while the cohesion between particles is slightly affected by these additives due to a change in the adhesion between the additive and soil particles. To investigate the effect of the changes in the soil suction on volume changes, expansion index, swelling pressure, shear strength, and the coefficient of permeability, small-scale experiments were conducted by Fattah et al. [29] on pure bentonite and bentonite mixed with sand with different proportions at different initial water contents and dry unit weights that were chosen from the compaction curves. The results showed that the swelling potential decreased with an increase in sand content from 14% to 2.4% by adding 50% sand to pure bentonite. The swelling percent found from the large-scale model is higher than that obtained from the oedometer swelling test for the same soil. This result applies well on the BS5 (50 : 50, bentonites : sand) soil sample, for which the swelling potential from the large-scale model is 8.3% and from the conventional swelling test is 3.6% only. The measured swelling pressure from the swelling test at small soil samples is much higher than that measured from the large-scale model. Previous research has primarily focused on RHA, steel fibers, plastic waste, sugarcane bagasse ash, and sawdust ash, but the stabilization of clay soils with CHA is rather limited. This article mainly deals with assessing the usefulness of CHA for modifying the soil structure to improve load-bearing capacity by evaluating the effects of CHA on various geotechnical properties of expansive CSs ranging from 5% to 25% by weight of soil as well as the blending effects of CHA with gypsum addition in CS on plasticity, compaction, free swell index (FSI), CBR value, UCS test, and shrinkage characteristics.

2. Materials and Methods

Highway engineers are interested in the basic engineering properties of soils because soils are used extensively in highway construction. Soil properties are of significant importance when a highway is to carry high traffic volumes with a large percentage of trucks and are used as support for the highway pavement. Therefore, several transportation agencies have developed detailed procedures for investigating soil materials used in highway construction. This article presents materials used for the study and experimental programs that were utilized to evaluate the characteristics and engineering properties of untreated soils and treated soils that are important to highway engineers, including the GSA of soils, soil classification, and soil testing methods.

2.1. Materials

2.1.1. CHA. The coffee husk utilized in this investigation was sourced from factories and the nearby towns of Zege, Gojam, Amhara regional state province, Ethiopia. It was then heated to 550°C in a furnace for 5 hr to produce the ash. After stabilizing with CHA, [30] has already investigated the expansive soil behavior of compressibility and strength in geotechnical engineering. The criteria for the soil's good strength following treatment with CHA are indicated by the results. Moreover, calcium oxide (CaO), magnesium

Table 1: Chemical compositions of CHA [30].

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	TiO_2	P_2O_5	SO_3	LOI
Value (%)	1.24	0.58	0.56	17.70	4.51	0.14	46.46	0.06	0.08	3.85	3.75	21.07

Table 2: Oxide composition of the hydrated gypsum [31].

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	TiO_2	P_2O_5	SO_3	LOI
Value (%)	6.21	2.18	3.57	59.47	3.91	0.61	0.79	0.32	0.20	0.27	0.58	17.04

Table 3: Chemical compositions of expansive clayey soil.

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	TiO_2	P_2O_5	LOI
Value (%)	49.18	13.30	7.80	6.32	2.28	0.12	1.28	0.24	0.44	0.08	10.90

oxide (MgO), and potassium oxide (K_2O) are the primary mineral components of CHA. Table 1 displays the chemical makeup of the CHA stabilizer components.

2.1.2. Gypsum (G). The stabilization of expansive CS involved the application of gypsum (G) obtained from the local market, which is the production of the Debre Berhan gypsum factory in North Shewa, Ethiopia. It is a soft sulfate mineral composed of calcium sulfate dihydrate with the chemical formula $CaSO_4.2H_2O$. It is a two-water-molecule-attached calcium sulfate mineral, which is 150 times more soluble than limestone and has 23% calcium and 18% sulfur. A range of 2.30–2.40 was found for the specific gravity value. According to the American Society for Testing and Materials (ASTM) C977, hydrated lime used for soil stabilization should not retain more than 3% on a 590-μm filter or more than 25% on a 75-μm sieve. Table 2 shows the oxide chemical compositions of hydrated gypsum [31] used in this study.

2.1.3. ECS. The Gondar–Debark Road Project test location in Gondar, Ethiopia, provided the vast CS that was employed in this investigation. The soil samples were collected at a depth of 1.50 m below the surface and stored in a plastic bag to preserve their initial moisture content. The Gondar–Debark Road project is located in the Amhara regional state in northern Ethiopia, between latitudes 12°35′60″N and 13°09′22″N and longitudes 37°28′00″E and 37°53′53″E, at an elevation of 2527.5 m. Based on the standard procedures of the Ethiopian Road Authority (ERA), the American Association of State Highways and Transportation Officials (AASHTO), and the ASTM, investigations on the examined soils were carried out. Table 3 displays the expansive CS's chemical composition.

The ASTM D422 standard [32] was used to determine the GSA of the expansive CS. The GSA, which included sieve analysis and hydrometer measurements, revealed that the sample has a consistent size distribution. The soil is composed of 55.33%, 37.46%, and 7.26% particles of clay, silt, and sand, respectively. The physical parameters of untreated expansive CS are shown in Table 4. The LL, plastic limit (PL), and PI of natural expansive CSs are 94%, 40%, and 54%, respectively. According to Atterberg limit results using the plasticity chart, the expansive CS is classified as A-7-5 and CH according to AASHTO and USCS, respectively.

2.2. Methods. In this experimental study, CHA, gypsum, and the blending stabilization of gypsum-CHA in the virgin soil sample were utilized to assess the change in geotechnical qualities of expansive CS in compliance with AASHTO T87-86. The produced samples contain both gypsum and CHA stabilizers. The percentages of each vary from 0% to 25% CHA depending on the dry weight of the expansive clay soil, with a 5% increase. The percentages of gypsum range from 3% to 6% to 9%. The experiments were carried out in the geotechnical laboratory of the Department of Civil Engineering, Faculty of Civil and Hydraulic Engineering, Bahir Dar University, Bahir Dar, Ethiopia. The different gypsum concentrations (0%, 3%, 6%, and 9%) and CHA mixture concentrations (0%, 5%, 10%, 15%, 20%, and 25%) were applied to the soil in a total of 24 combinations, as indicated in Table 5. After that, laboratory tests are performed on the 24 samples to assess their specific gravity, UCS, Atterberg limits, FSI, CBR and CBR swelling, and GSA.

2.2.1. Sample Preparation. In this study, the physical and mechanical characteristics of expansive CS were determined through a series of laboratory experiments. The samples are prepared with expansive clayey soil (ECS), gypsum, and coffee husk ash oven-dried separately, then the oven-dried ECS is mixed with gypsum (G) and CHA in varying proportions of 0%, 3%, 6%, and 9%; and 0%, 5%, 10%, 15%, 20%, and 25% by dry weight of the ECS, respectively. The formed dry mixes are blended together with water in order to get a homogeneous blend, then kept aside for 24 hr to be oven-dried. The dried mix samples are then conducted for laboratory testing and treated as samples in accordance with ASTM, AASHTO, and other standards.

2.2.2. GSA. The GSA is carried out for the ECS, CHA, and gypsum (G). Materials passing through a 4.75-mm sieve and retained on 75-μm sieves are subjected to the sieve analysis method, whereas the hydrometer analysis method is adopted for the soil particles passing through a 75-μm sieve. Wet sieving tests were performed to obtain the grain size

Table 4: Summary of geotechnical properties of untreated expansive clayey soil.

Tests parameters	Properties	Test results	Test methods
Grain size analysis	Gravel (%)	0.00	AASTO T-87 and T-88
	Sand (%)	7.26	
	Silt (%)	37.41	
	Clay (%)	55.33	
Percentage of passing no. 200, (%)		92.74	
Atterberg limits	Liquid limit (%)	94	AASTO T-89
	Plastic limit (%)	40	AASTO T-90
	Plasticity index (%)	54	
	Linear shrinkage (%)	26.26	AASHTO T-92
Soil classification	AASHTO	A-7-5	AASHTO M145
	USCS	CH	ASTM D2487
	Color	Black	
Specific gravity	—	2.68	ASTM D854
Compaction	OMC (%)	37.20	BS 1377
	MDD (g/cm^3)	1.24	BS 1377
UCS	UCS (kPa)	89.31	ASTM D2166
CBR	CBR unsoaked (%)	12.53	AASHTO T193
	CBR soaked (%)	1.53	ASTM D1883
	CBR swell (%)	10.08	
Swell	Free swell index	116	IS: 2720

Table 5: Matrix of the percentage proportion of the proposed soil mixture (S, CHA, and G).

CHA (%)	Gypsum (%)			
	0	3	6	9
0	100	97	94	91
5	95	92	89	86
10	90	87	84	81
15	85	82	79	76
20	80	77	74	71
25	75	72	69	66

S = expansive clayey soil, CHA = coffee husk ash, and G = gypsum.

distribution (GSD) of fine particles according to ASTM D 422 [32]. According to AASHTO M 146 [33], the particle size distribution determines the gravel, sand, silt, and clay fractions by considering wet sieve testing and hydrometer analysis. The GSD curve has been plotted to determine the gravel, sand, silt, and clay contents in the test samples, as shown in Figure 2.

2.2.3. FSI. Soil swelling is a volume increase that causes significant issues, serious injury, and negative economic consequences in the construction industry, particularly in road construction. The FSI test was conducted on the EC soil and CHA-treated samples in accordance with IS: 2720. According to the Bureau of Indian Standards [34], the EC soil (see Table 4) and CHA-treated samples (see Figure 3) can be summarized based on FSI value.

$$\mathrm{FSI} = \frac{V_\mathrm{f} - V_\mathrm{i}}{V_\mathrm{i}} \times 100. \tag{1}$$

where V_i = initial dry volume of poured soil and V_f = final volume of poured soil.

2.2.4. LS. In accordance with AASHTO T-92 [35], LS is a parameter used in pavement engineering projects and is defined as the decrease in one dimension of a soil mass, expressed as a percentage of the original dimension, when the water content is dropped from a certain value to the shrinkage limit. It describes the length change caused by drying a cylindrical soil sample that is near its LL, where the sample's length (LD) after drying is close to the LL of 140 mm for standard mold.

2.2.5. Atterberg Limits Testing. The Atterberg limit tests were performed on treated and untreated ECS according to the ASTM 4318 [36] and AASHTO T 88 [37] and T90 [38] standards. PI is defined as the numerical difference between the LL and the PL, and it is one of the most commonly used parameters in geotechnical and pavement engineering for subgrade soils. Subgrade soil materials with a high PI value ($\mathrm{PI} > 40$) are unsuitable for pavement foundations, such as clayey, silty, and sand-silt materials. The subgrade soil is classified based on GSD, consistency limits, and indexes in accordance with the AASHTO soil classification system and the unified soil classification system (USCS). In the plasticity chart for the AASHTO and USCSs, the samples are classified in accordance with AASHTO M145 [39] and ASTM D2487

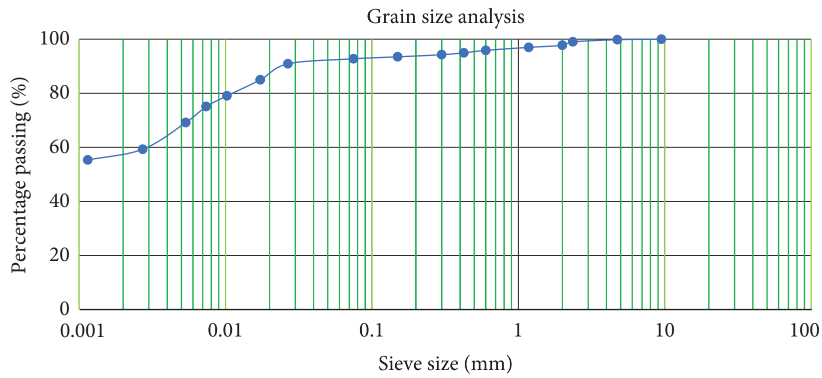

Figure 2: Grain size distribution (GSD) of the untreated expansive clayey soil.

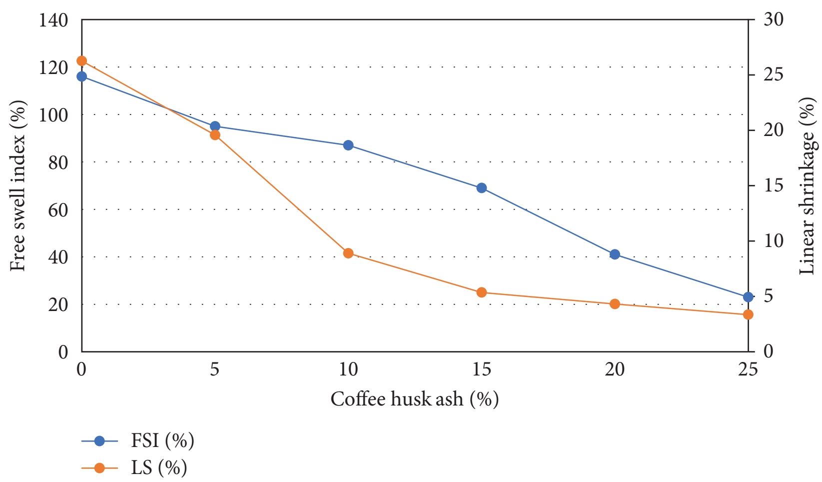

Figure 3: Effect of CHA on FSI and LS at various percentages.

[40], respectively. The basic index properties of plasticity are the LL (x-axis) and plastic index (y-axis).

2.2.6. Specific Gravity. The ratio of the masses of water and soil solids in an equal volume is known as specific gravity. A crucial factor in establishing the weight–volume correlations of soils is specific gravity (G_s), which is required for many computations in soil mechanics. The water pycnometer method was used to determine the soil-specific gravities in accordance with accepted test procedures for the specific gravity of soil solids ASTM D854 [41]. In this study, the specific gravity of existing natural CS is 2.68. The specific gravity, G_s, of a soil sample is calculated as follows:

$$G_s = \frac{W_0}{W_0 + (W_A - W_B)}. \quad (2)$$

where W_0 = weight of a sample of oven-dry soil, W_A = weight of pycnometer filled with water, and W_B = weight of pycnometer filled with water and soil.

2.2.7. Standard Compaction. In order to ascertain the maximum density at a particular moisture content known as the OMC, the standard compaction test establishes the link between soil density and moisture content. The soil's geotechnical characteristics, such as CBR and UCS, are influenced by the moisture content and compacted soil density. High soil compaction typically improves the soil's geotechnical characteristics. The Proctor test, also known as the moisture-density test, was used to find the OMC and MDD of soil mixtures that included gypsum and CHA or that blended gypsum and CHA. In this context, heavy compaction testing was employed in accordance with AASHTO D698 and BS 1377 [42]. According to Flaherty et al. [43], the MDD of the CS sample at the OMC is 1.555 g/cm^3 and 28%, respectively.

2.2.8. UCS. To determine the amount of additive needed for soil stabilization, the primary test advised is the UCS test. Both the undrained shear strength and the maximum stress measured at failure are equivalent. 100-mm-long and 50-mm-diameter cylindrical specimens were manufactured at OMC and MDD for the UCS test. Each sample was immediately placed in a polyethylene bag to retain the necessary moisture level after compaction. The samples were then cured for 3, 7, 14, 28, and 56 days to shield them from 5% to 25% by 5% increments of the dry weight of the soil sample. The test was conducted in accordance with ASTM D2166 [44]. The results of the UCS of soil admixed with

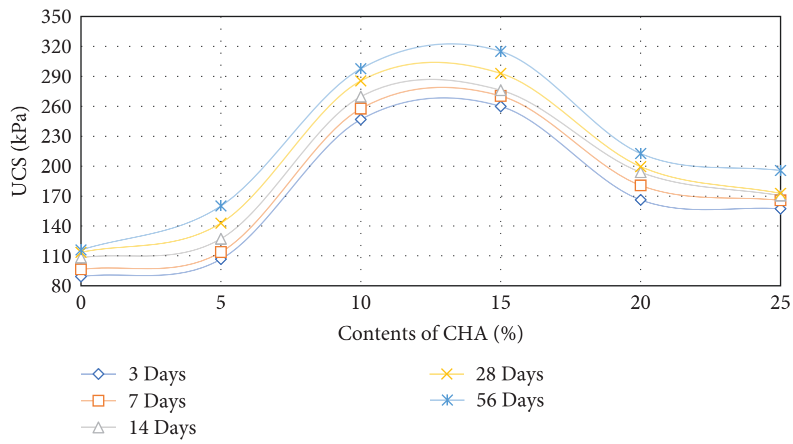

Figure 4: Unconfined compressive strength (UCS) with contents of CHA.

CHA varying from 0% to 25% tested at 3, 7, 14, 28, and 56 days of curing are shown in Figure 4.

2.2.9. CBR and CBR-Swell. The ratio of the load needed to cause a specific penetration of the plunger into the soil material to the load needed to obtain the same penetration on a specimen of standard material is known as the CBR test. In pavement engineering, the CBR is used to represent the strength of the soil material that the pavement will be built over. Since many pavement design procedures, including those used by the ERA, rely on these criteria, they are particularly helpful. On the other hand, the CBR value indicates performance whether utilizing gypsum-CHA-treated or untreated soil material. The CBR laboratory test can be carried out according to ASTM D 1883 [45] or AASHTO T 193 [46]; other equivalent national specifications may have been developed. The treated and untreated samples were prepared for testing, and then a penetration piston with a diameter of 4.9 cm was pushed into the samples at a loading rate of 1.27 mm/min. The CBR was calculated as the stress for 2.5- or 5.0-mm penetration divided by standard penetration for 6.89 or 10.34 MPa, respectively. The value received must be higher than the value corresponding to a penetration of 5.0 mm in order for the CBR value, which corresponds to a 2.5 mm penetration, to be determined.

2.2.10. CBR-Swell. The CBR swell of the soil is measured by placing the tripod with the dial indicator on top of the soaked CBR mold. The initial dial reading of the dial indicator on the soaked CBR mold is taken just after soaking the sample. At the end of 96 hr, the final dial reading of the dial indicator is taken. CBR tests also provided data on swelling. A swell dial gauge was mounted on the CBR mold. Then, the initial height of the samples was recorded before immersing the samples in the water, and the final height was taken after the samples had been soaked for 4 days.

3. Results and Discussion

3.1. GSA. Table 4 shows that the GSD analysis indicates that the soil has a silt and clay content of 92.74% in soil passing through the No. 200 sieve, an LL of 94%, and a PI of 54%. The soil is highly expansive clay with an FSI of 116%, which indicates the soil sample was expansive clay soil in accordance with IS: 2720 (part-40) [47]. The soil has an MDD of 1.24 g/cm^3 at an OMC of 37.20% within a maximum specification of [43], an LS of 26.26%, a soaked CBR value of 1.53%, and a CBR swelling of 10.08%. Figure 2 displays the GSD of the ECS. The ASTM D422 [32] standard was used to evaluate the ECS GSD. The sample exhibits a consistent size distribution, according to the GSD analysis, which comprised hydrometer readings and sieve examinations. In this study, the three main constituents of soil are sand, silt, and clay, with relative percentages of 7.26%, 37.41%, and 55.33%. The size-based classification of the soil indicates that clay makes up the majority of the soil.

3.2. Atterberg Limits and Soil Classification. The Atterberg limit and index tests were performed on untreated expansive clay and CHA-treated soil samples according to the ASTM 4318 standard [36]. The plasticity characteristics of untreated clays and treated samples are illustrated using index properties such as LL, PL, and PI, as shown in Figures 5 and 6 by using USCS and AASHTO classification systems, respectively. The LL, PL, and PI of virgin soils are 94%, 40%, and 54%, respectively. According to the grain size ASTM D422 [32] and the USCS ASTM 2487 [40] (Figure 5), the ECS is classified as high plastic clay (CH) and A-7-5 according to the AASHTO M145 [39] classification system (Figure 6), which may be considered an expansive clay soil.

According to the Atterberg limit findings from the laboratory test, the rate of reduction in the plastic index with respect to virgin soil is 36%, 54%, and 63%, with 3%, 6%, and 9% gypsum of the weight of the soil, respectively, as the proportion of gypsum at varied 3% increment intervals. The cause of this result is that the positive ions in the gypsum were sufficiently replaced by calcium ions to decrease the gap in the clay surface of the soil [17]. The rates of reduction in the PI relative to virgin soil for 5%, 10%, 15%, 20%, and 25% are 2%, 19%, 50%, 56%, and 69%, respectively. The samples treated with gypsum and CHA mixtures show a decrease in the parameters of the plasticity chart. Reducing the elasticity of newly created soil may be achieved by treating it with

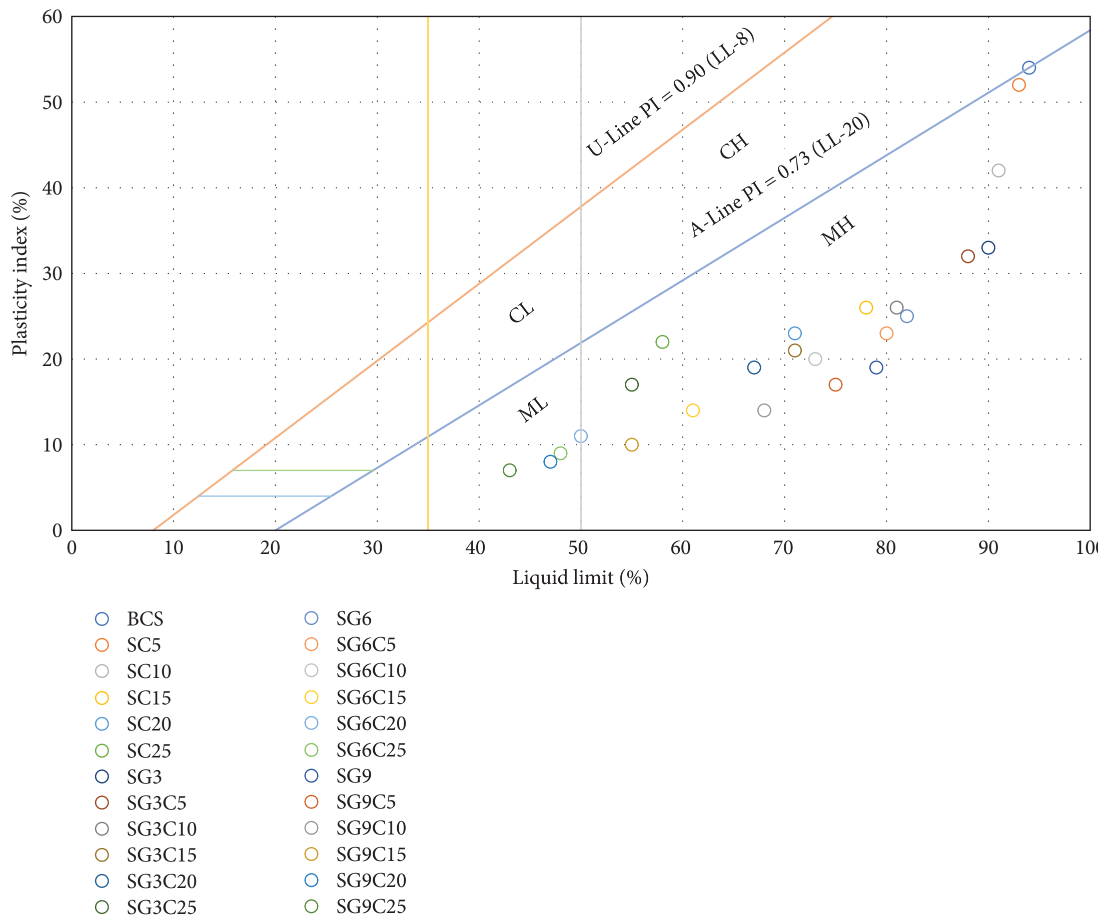

FIGURE 5: Plasticity chart by USCS for untreated and treated samples.

CHA. Nevertheless, gypsum and CHA work better together to lower LL and PI. A PI of less than 15% was found for samples containing the combined mixtures of SG6C15, SG6C20, SG9C10, SG9CHA15, VSG9C20, SG6C25, and SG9C25. The USCS and AASHTO classification schemes for untreated and G-CHA-treated samples, respectively, are shown in Figures 5 and 6. Figure 5 illustrates how the USCS classified the virgin soil as CH. The samples moved away from an area of high plasticity clay and toward high and low plasticity silt on the LL axis, as indicated by a drop in the plasticity chart features of LL and PI. The AASHTO soil classification system chart, which is seen in Figure 6, classifies the virgin soil as A-7-5. When 6% gypsum and 15% CHA are added, the soil changes to A-5 and progresses to the left as the quantity of additions increases.

3.3. Swell-Shrink. Soil swelling is an expansion in volume that causes significant problems, leading to serious damage and economic consequences in the construction sector, mainly in road construction. The FSI test was performed on the virgin soil and CHA-treated samples according to IS: 2720 [47]. The FSI value decreases by 40% and 65% by adding 15% and 20% CHA, respectively, as shown in Figure 3. Figure 3 also shows that the rates of reduction in the LS with respect to virgin soil for 5%, 10%, 15%, 20%, and 25% are 25%, 66%, 80%, 84%, and 87%, respectively. The LS decreases as the percent of CHA added to the virgin soil increases [48], the reason for this was that stabilization through cation exchange does not depend on the dose of additives but on the elemental composition.

3.4. CBR and CBR-Swell. During the construction of flexible pavement roads, the strength of the soils to be used is usually evaluated by their CBR values and CBR swell. The soaked CBR of the virgin soil used in this study is 1.53% for the subgrade materials, which have a CBR value of less than 2% and require special treatment [49]. As can be seen in Figure 7, the CBR value grew for both soaked and unsoaked situations, the CBR swell increased for their respective proposed percentages of CHA, and the percentage of CHA increased from 5% to 25%. The CBR swell grows as the proportion of CHA increases, and for all samples, the laboratory result of the CBR value was more than 3%, which is the minimal threshold as per ERA subgrade specification. The findings demonstrate that the minimum CBR, the minimum CBR swell, and more than 10% CHA were reached. Therefore, in both situations, a large dose of the additive was preferred.

3.5. Standard Compaction. Moisture density and the type of compactions used have an impact on soil geotechnical parameters such as the triaxial test, veUCS, and CBR.

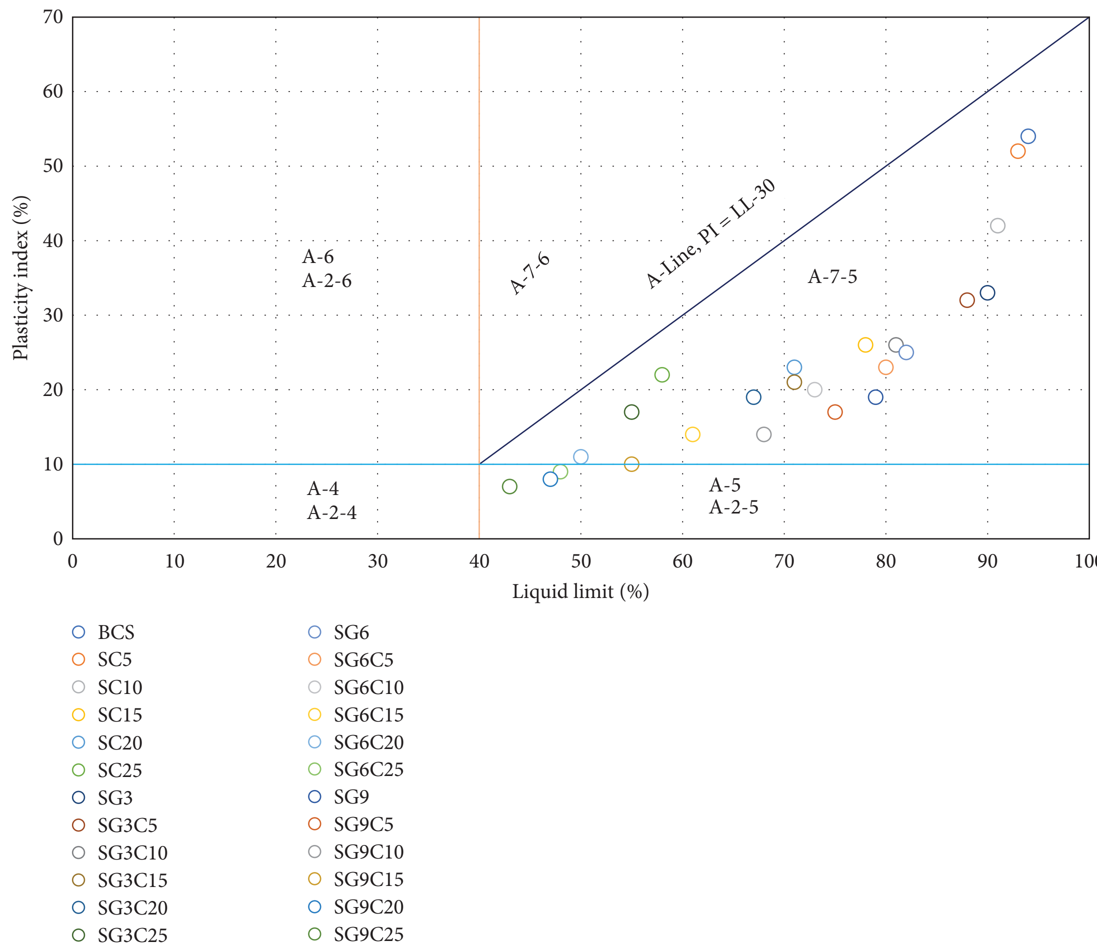

Figure 6: Plasticity chart by AASHTO for untreated and treated samples.

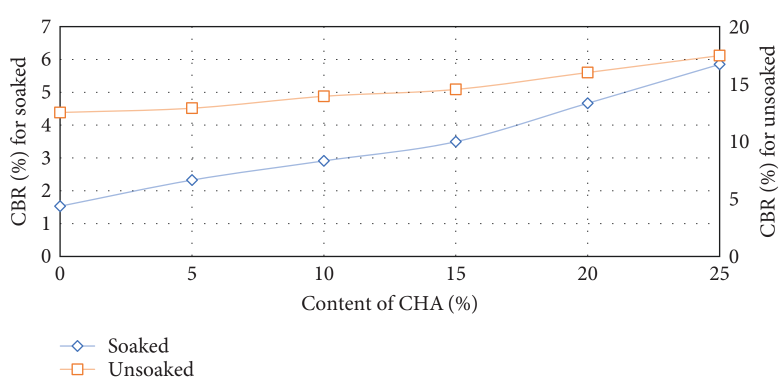

Figure 7: CBR (%) value of clay–CHA-treated mixtures.

The deliberate improvement of the soil's geotechnical characteristics is known as compaction. This test was designed to find the MDD and eOMC of soil mixtures, including gypsum, CHA, blending G-CHA, or without additives. Figures 8 and 9 show the OMC and MDD for stabilizing soil with CHA and G, respectively. As can be observed in Figure 8, the current data show that OMC reduces when CHA concentration increases. The rate at which moisture content decreases appears to be linear and gradual, up to 25% CHA. However, Figure 9's depiction of the rate of moisture content increase from 0% to 9% G content indicates that it is obviously linear and progressive. The decrease in OMC following CHA admixing may be mostly attributable to the soil-CHA mixes' decreased need for water for the hydration reaction.

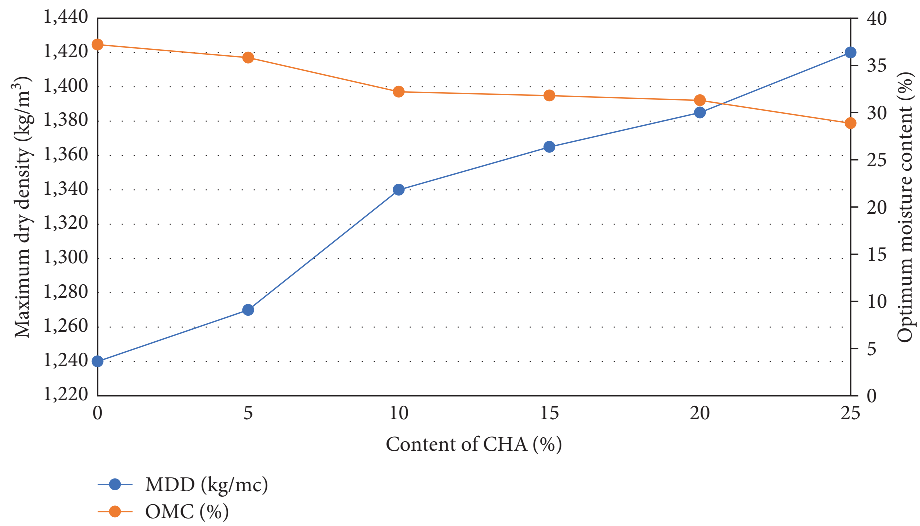

Figure 8: Standard compaction parameter of the clay–CHA mixture.

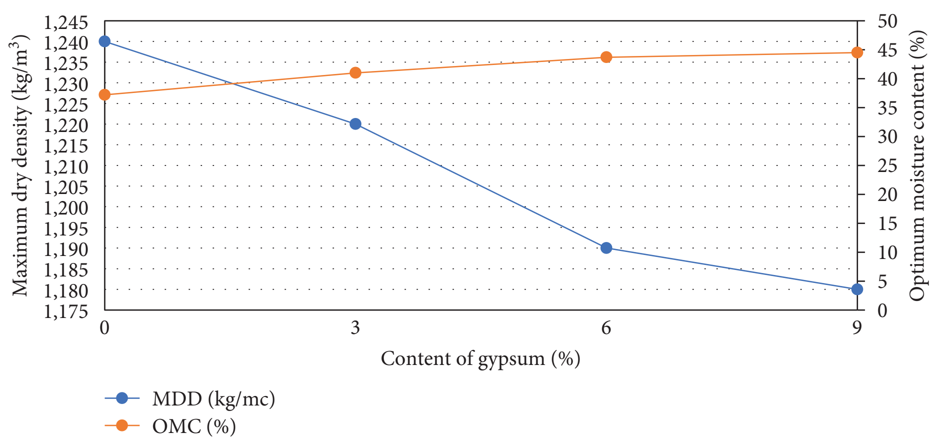

Figure 9: Standard compaction parameter of the clay–G mixture.

Contrary to popular belief, the addition of CHA to soil increases dry density. The rates of increase in dry density with respect to virgin soil for 5%, 10%, 15%, 20%, and 25% are 2.42%, 8.06%, 10.08%, 11.69%, and 14.52%, respectively. The increase in the MDD was attributed to the replacement of soil with a higher weight material (CHA). The agglomeration and flocculation of clay particles caused a quick cation exchange in the CHA–clay mixture, which is what caused the increase in clay MDD. Also, higher dry density results in increased particle interlocking. Moreover, as was previously discovered, the improvement in clay gradation brought on by the addition of CHA is responsible for the increase in MDD of the clay. However, as the CHA concentration increased, the OMC of the treated clay decreased slightly. The soil water solubility appears to have been lowered by the CHA addition, causing the OMC to fall [50]. According to the previous researchers' reports [21], there is an increase in MDD and a decrease in OMC when CHA is added.

In order to investigate the effects of altering the quantity of CHA applied to the proposed subgrade soil on the correlations between moisture and density, typical compaction tests were conducted. The test's findings, which examined the impact of the suggested clay–CHA treated soil sample on MDD and ideal moisture content, are shown in Figure 10. When CHA is incorporated into the soil, the MDD rises. The ideal moisture level also decreased as compared to natural subgrade soil, suggesting that CHA had water-absorbing properties.

3.6. UCS. The UCS test is a standard and the most common strength test used in evaluating the effectiveness of stabilizers. Cylindrical specimens of 50 mm in diameter and 100 mm in length were created at OMC and MDD for the UCS test. Each sample was compacted, immediately sealed in a polyethylene bag to preserve the required moisture level, and then allowed to cure for 3, 7, 14, 28, and 56 days to prevent free moisture in a room with a 100% relative humidity at 21°C, in accordance with ASTM D1632 [51], and the test was carried out according to ASTM D2166 [52]. Figure 4 displays the UCS findings of the virgin soil and CHA-treated samples with various CHA concentrations and cure durations from 0% to 25% at 3, 7, 14, 28, and 56 days after curing.

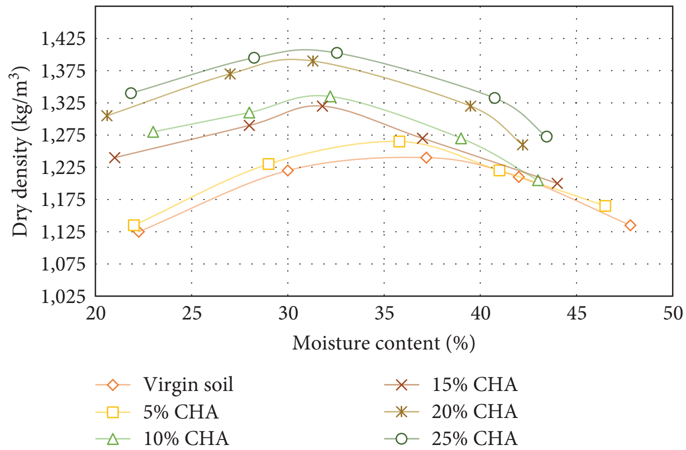

FIGURE 10: Standard compaction curve for clay–CHA-treated soil sample.

Adding CHA to soil sample results reveals a significant improvement. The virgin soil achieved a UCS of 89.31 kPa, as can be revealed. The UCS has increased to 247 kPa as the percentage of CHA increases from 0% to 10%, and it increases to 260 kPa for 15% CHA after 3 days of curing. For all curing conditions, the additional CHA that was not mobilized in the reaction, which subsequently occupies spaces inside the sample and weakens the link in the soil-CHA mixes, may be the cause of the drop in UCS after 15% CHA content. The UCS of virgin soil treated with 15% CHA increased by more than double compared to that of the untreated virgin soil. CHA and samples of CS mixed together significantly improved the UCS (Figure 4). When the CHA was admixed at 5%, 10%, 15%, 20%, and 25%, the improvements compared to CS samples at 7 days were 18%, 167.11%, 180.35%, 87.34%, and 71.80%, respectively. Similarly, for CHA replacement level with respect to CS samples, improvements on UCS increased by 17.49%, 149.15%, 155.08%, 79.13%, and 57.51% at 14 days. Further improvement was observed for higher curing periods, i.e., 25.77%, 151.34%, 157.92%, 75.65%, and 52%, and 38%, 156.66%, 171.65%, 83.36%, and 68.69% for 28 and 56 days, respectively. The pozzolanic materials increase the strength of the clay–CHA blend. Similar findings have also been reported by other researchers [53, 54]. Based on the findings, it has been observed that the strength increased by 7.97%, 12.24%, 4.94%, and 2.1% from 3 to 7 days, 7 to 14 days, 14 to 28 days, and 28 to 56 days, respectively, for untreated virgin soil.

4. Conclusions

In this article, the potential use of CHA for the treatment of geotechnical properties such as the Atterberg limit, swelling parameters, compaction characteristics, CBR, and UCS of ECSs was investigated. In addition, the effect of the gypsum and CHA mixture on the geotechnical engineering parameters of the studied soil was investigated. The following conclusions have been drawn from the present laboratory study.

The present study results reveal that the addition of CHA reduces the plasticity of the soil. The LL and plastic index were reduced by 24.5% and 57.4%, respectively, with the addition of 20% CHA. Similar trends were observed in the sample treated with 9% gypsum; the LL was reduced by 16%, with a 64.8% reduction in the plastic index. For the gypsum-CHA mixture treatment, it was noted that the LL was reduced by 41.5%, with a corresponding reduction in the plastic index of 81.5% for the additive content of 15% CHA and 9% gypsum. Since PI is a good indicator of the swelling behavior of soils, the reduced PI helped to decrease the swelling potential of the treated soil.

From the compaction test results, the MDD of CHA-treated samples increased, and the OMC decreased as the contents of CHA increased. The MDD of gypsum-treated samples slightly decreased, and the OMC increased as the gypsum content increased. In contrast, the addition of CHA to gypsum-treated soil slightly increases the MDD and decreases the OMC. The OMC increased by 19.6%, and the MDD decreased by 4.8% when the 9% gypsum content was added to the virgin soil sample. Similar trends were observed in the sample treated with 20% CHA; the MDD showed an increase of 14.52%, with a 17.20% reduction in the OMC. For the gypsum-CHA mixture treatment, it was noted that the MDD was reduced by 3.23%, with a corresponding increase in the OMC of 11.60% for the additive content of 15% CHA and 9% gypsum.

The addition of CHA improved the bearing capacity of the virgin soil. The CBR values of the virgin soil increased with the increase in CHA content from 5% to 25%. The CBR value of gypsum and gypsum-CHA treated samples increases as the additive content increases. The highest CBR values were found for the BC soil treated with a mixture of gypsum and CHA (SG6C15). The quality of the virgin soil to be used as subgrade material was very poor; after treatment with CHA, the quality improved to fair. For gypsum and gypsum-CHA mixture treatment (6% and 9% gypsum content for gypsum treatment, and 6% and 9% gypsum mixed with 5%, 10%, 15%, 20%, and 25% CHA for mixture treatment), the quality became good.

In samples treated with CHA, the UCS increased as the CHA level increased from 5% to 15%. When compared to the virgin soil, the UCS values of all samples treated with the gypsum and G-CHA combination improved. When the CHA content exceeded 15%, a decline in these values was seen. Samples stabilized with 15% CHA and 6% gypsum had the highest UCS value. The enhancement is a result of the additives creating cementitious chemicals, which result in a stiffening reaction.

This study illustrates CHA's potential utility for building road subgrades. In comparison to BC soil that has not been treated, CHA-treated samples perform better as subgrade material. A thinner pavement structure is produced by thinner pavement layers because of the stronger subgrade. One advantage is that it saves money on construction costs as well as construction materials. It can significantly contribute to lowering the environmental effect caused by garbage storage in addition to the socioeconomic benefits it brings to infrastructure development.

Data Availability

The data that support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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