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Research Article

Application of Ecofriendly Geopolymer Binder to Enhance the Strength and Swelling Properties of Expansive Soils

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The expansive soil swells significantly in the presence of moisture, which often leads to the failure of superstructures. Conventional stabilization techniques are applied in many instances, although environmental issues are of significant concern for such stabilization. Keeping this in mind, an attempt is made to apply a new approach for stabilizing different types of expansive soils, treated with a nonconventional binder geopolymer that utilizes fly ash as the main ingredient. A series of laboratory experiments are run to determine the engineering properties of treated soils with varying percentages of geopolymer from 0% to 30%. The experimental investigation involved tests such as unconfined compressive strength, compaction, Atterberg limits, and swelling pressure. Significant strength development occurs with increasing percentages of geopolymer, and their swelling pressures decrease considerably. Additionally, a series of California Bearing Ratio (CBR) tests were undertaken to assess the suitability for road construction. The optimum dosage of the stabilizing agent is found to be 20%, as justified by studies in the literature. Furthermore, scanning electronic microscope (SEM) images of the treated samples revealed microstructural changes in the soil matrix, which strongly correlate with the improvement of strength and swelling behavior. Hence, based on our experimental results, 20% geopolymer content is sufficient for enhancing the engineering properties of expansive soils, and the treated soils can directly be used as subgrade or sub-base material.

1. Introduction

Problematic soils are always a big concern in the geotechnical engineering arena and are responsible for damages to the structure. Expansive clay, which is considered a problematic soil, is also susceptible to collapse, as reported in many previous studies [1, 2]. Generally, expansive soils contain the montmorillonite mineral, which expands during moisture inhibition and causes severe damage by inducing huge stresses on substructural elements. Structural elements laid on expansive soil strata experience differential swelling and shrinkage upon inundation and drying due to seasonal variations in the water table, rainfall, flooding, etc. [3]. Clay minerals dominate the swelling of soils in an overcompacted state, with the shift from primary to residual shrinkage typically occurring within a water content range of 10%–15% [4, 5, 6]. Differential volumetric changes cause cracking of interior finishes, the heaving of flexible pavements, and other severe damage to overlying structural elements. Expansive soils are typically located at shallow depths, making deep foundation techniques a viable option for high-rise structures to avoid their associated hazards. However, this approach may not be feasible for medium- to low-rise buildings. Additionally, the damage caused to flexible pavements by differential swelling is significant, and it may not always be possible to alter the road alignment to avoid these hazards.

Considering the significant challenges posed by expansive soils, such as their propensity for causing structural damage, it is imperative to find an effective strategy for alleviating such hazards [7]. There are two conventional approaches to mitigate the impact of expansive soil strata: (i) the partial to full replacement of the soil matrix and (ii) the improvement of the existing layer by soil stabilization [8]. The first method, which involves replacing the soil with foreign materials, is common in road construction but comes with high construction costs. In contrast, the latter method has gained significant research interest in recent decades, as it offers a more rational approach to dealing with expansive soils by improving the parent soil through stabilization.

Lime and cement treatments are the oldest ways of stabilizing expansive soils that reduce plasticity index, free swell index, and volume change, as reported in many research studies [9, 10, 11, 12]. Although cement treatment is a popular stabilizing agent owing to its binding nature, as evidenced in many practical applications [13, 14, 15, 16], it is not recommended for ground improvement [17] due to the high cost and environmental threats involved in the production stage. On the other hand, the reaction time of lime with soil is rapid, and in many cases, only a 5% addition can exhibit better strength [18], but the reduction in swelling is not guaranteed in this way [19].

Accepting this state and noting the necessity for rational ground improvement, researchers are devoted to using nonconventional additives in problematic soils [20, 21, 22, 23, 24, 25, 26, 27]. Their main attraction is industrial byproducts, with several research works conducted in recent years to justify their use, although availability is a major issue [28, 29, 30]. Of these various byproducts, fly ash (FA) [31, 32, 33] is a promising material for use in soil stabilization due to its availability as a waste product obtained mainly from coal-based power plants. Although it can effectively improve the plasticity characteristics of expansive clays and prevent their tendency to swell [34, 35], a high volume of it is often required for stabilization due to its low pozzolanic reactivity. Moreover, the slow reaction time of fly ash is a primary constraint of its in situ application for ground improvement. As the addition of catalysts may improve the performances of parent soils, geopolymer would be a rational approach for developing their strengths.

The geopolymer is an inorganic polymer material formed by the alkaline activation of silica materials, including FA, slag, metakaolin, and others [36, 37, 38, 39, 40]. The eco-friendly nature and availability of relevant products support the use of FA as a binding agent in a geopolymer, where sodium sulfate, sodium hydroxide, or other alkaline solutions are used as alkali activators to increase the reaction rate. To understand the behavior of geopolymer made from different activators (NaOH, kOH, $CaOH_2$, etc.), several research were conducted on geopolymer application in black cotton soil, which is classified as highly expensive soil. In recent years, the use of geopolymer has been popular in improving the geotechnical properties of problematic soils [41, 42, 43].

Depending on the degree of expansion, expansive clays are classified as medium, high, and very high expansive soil, and the swelling behavior of such soil greatly depends on the degree of expansion. According to previous literature, most of the experimental research on expansive soils was based on field soil of some specific location [44, 45, 46, 47, 48, 49]. So, a more comprehensive study is still necessary to predict the performance of stabilizers on generalized conditions regardless of the degree of expansion.

Given all the positive aspects of geopolymers and the geotechnical hazards associated with expansive soils, this study aims to find the optimum geopolymer percentage that could be used to improve the strength properties and eliminate the swelling behavior of different expansive soils. In this study, bentonite was blended with soft clay soils to generate synthetic expansive soils of the abovementioned classes. A mixture of sodium silicate and sodium hydroxide was used as activators in the polymerization, along with fly ash in various combinations. An extensive experimental campaign was carried out to evaluate the improvement in soil properties at various percentages of geopolymer, ranging from 0% to 30% of the dry sample weight. The experimental results could unveil the impact of polymerization on expansive soil, allowing for the identification of the optimal binder content. Additionally, selected soil samples were subjected to microscopic image analysis to observe the in-depth microstructural changes resulting from polymerization.

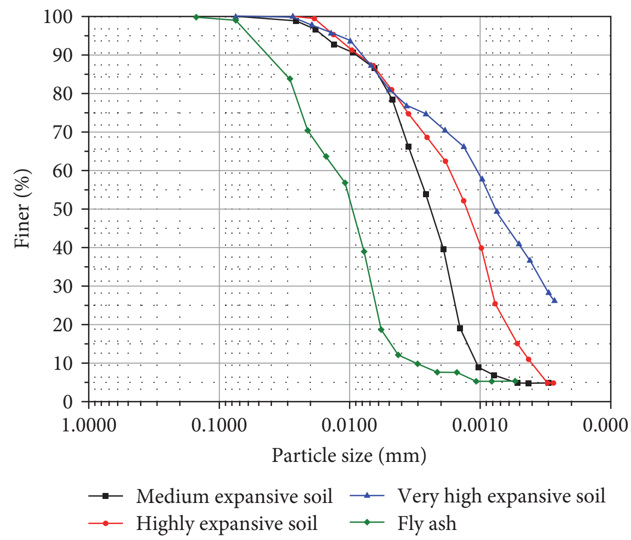


Figure 1: Grain size distributions of expansive soils and FA.

2. Experimental Program

This section briefly overviews expansive soil synthesis, including its physical properties, detailed geopolymer preparation, soil–geopolymer mixing process, specimen preparation, and test procedures.

2.1. Materials Used

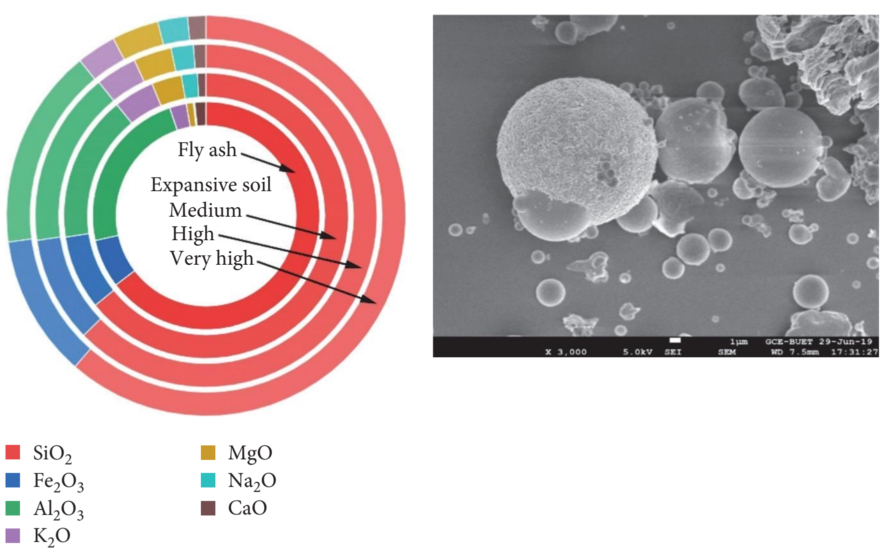
2.1.1. Expansive Soil. Soft clayey soils were collected from the eastern bank of the Karnaphuli River in Chattogram, Bangladesh. The collected soil was dried, pulverized, and sieved through a 425-μm standard sieve at the beginning of this experimental campaign, and then commercially available bentonite was blended to prepare different states of expansive clay soils. Initially, the percentage of bentonite was varied from 0% to 50% in 5% increments, and the index properties were determined to set the optimum bentonite content for the preparation of synthetic expansive soils, with the degree of expansion selected as per IS-1498 [50]. The particle size distributions of the soils and class F FA used for the present research are shown in Figure 1, and their properties are

Table 1: Properties of expansive soils.

Expansive soil (degree of expansion)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Free swell index (%)	Specific gravity	Swelling pressure (kPa)
Medium	45	22	23	75	2.56	81
High	58	27	31	143	2.53	121
Very high	70	31	39	215	2.44	157

Table 2: Chemical compositions of fly ash and expansive soils.

Oxides	Fly ash	Expansive soil		
		Medium	High	Very high
SiO_2	64.6	64.2	62.7	61.4
Fe_2O_3	6.9	8.4	10	11.5
Al_2O_3	23.3	16.6	16.5	16.2
K_2O	2.4	4.6	3.9	3.2
MgO	1.0	3.4	3.6	3.8
Na_2O	0.2	1.8	2.1	2.4
CaO	1.6	1.0	1.2	1.5



(a) (b)

Figure 2: (a) Chemical composition of fly ash and soils and (b) SEM image of fly ash.

enlisted in Tables 1 and 2, respectively. Notably, the specific gravity of soils follows a decreasing order for the medium to very high expansive soil conditions. The prime reason for such a trend is the relatively low specific gravity value of bentonite (measured as 2.3). Adding a significant amount of bentonite yields the lower specific gravity of very high expansive soil. Referring to Figure 1, all classes of expansive soils have silt and clay content of 90% or above. The free swell index values were 75, 143, and 215 for medium, high, and very high expansive soil.

2.1.2. Geopolymer. This study used class F fly ash as the primary ingredient of geopolymer. The specific gravity of fly ash was found to be 2.25. The oxide composition of the fly ash (FA) and expansive soils was determined using X-ray fluorescence (XRF) analysis, as listed in Table 2 and plotted in Figure 2(a). Three major constituents of FA are approximately 65% silicon dioxide, 23% aluminum oxide, and 7% ferric oxide, which reasonably satisfied the standard requirements ($SiO_2 + Al_2O_3 + Fe_2O_3 > 70\%$) of ASTM C618. Figure 2(b) shows the SEM micrographs of the fly ash sample. The alkali activator solution consisted of NaOH and Na_2SiO_3, both sourced from local suppliers. Sodium silicate is an inorganic liquid chemical with a brownish color and a density of 1.55 g/L. In contrast, sodium hydroxide is a solid material in pallet form, with a bulk density of 9.12 kN/m^3.

Table 3: Details of soil–geopolymer mixes.

Degree of expansion	SL no.	Designation	Details of the mix	OMC (%)	γ_{dmax} (kN/m^3)
Medium	1	MFA0	Untreated soil	18.90	16.55
	2	MFA10	Soil + 10% geopolymer	18.80	16.59
	3	MFA15	Soil + 15% geopolymer	18.70	16.64
	4	MFA20	Soil + 20% geopolymer	18.60	16.71
	5	MFA25	Soil + 25% geopolymer	18.10	16.75
	6	MFA30	Soil + 30% geopolymer	17.70	16.79
High	7	HFA0	Untreated soil	20.20	16.37
	8	HFA10	Soil + 10% geopolymer	19.80	16.39
	9	HFA15	Soil + 15% geopolymer	19.61	16.44
	10	HFA20	Soil + 20% geopolymer	19.45	16.54
	11	HFA25	Soil + 25% geopolymer	18.56	16.61
	12	HFA30	Soil + 30% geopolymer	17.40	16.69
Very high	13	VHFA0	Untreated soil	22.80	15.54
	14	VHFA10	Soil + 10% geopolymer	22.60	15.59
	15	VHFA15	Soil + 15% geopolymer	22.10	15.67
	16	VHFA20	Soil + 20% geopolymer	21.40	15.80
	17	VHFA20	Soil + 25% geopolymer	20.80	15.89
	18	VHFA30	Soil + 30% geopolymer	18.70	15.94

The sodium hydroxide was first dissolved in water to create a sodium hydroxide solution; upon dissolution, the NaOH solution achieved a molar concentration of 6.5 mol/L. This solution was mixed with an equal proportion of sodium silicate to create the alkali activator solution and stirred continuously by a glass rod to prevent coagulation. The mixture was then allowed to rest for approximately 15–20 min to eliminate the heat generated from the chemical reaction. Freshly prepared alkali activator solution was then used for each batch of the soil–geopolymer mixture; hence, the excessive solution was discarded after completing every batch mix.

2.2. Sample Preparation. The geopolymer dosages were denoted as 10%, 15%, 20%, 25%, and 30% of fly ash (FA) by weight of dry soil with 10% by weight of the alkali activator solution. For example, 20% geopolymer mixed soil denotes that the mixture contains 20% FA, 10% alkali activator solution, and the remaining portion of soil (70%). To ensure the homogeneity of mixing, first, the calculated amount of dry ingredients (fly ash and soil) was blended separately, and the activator solution made by mixing an equal proportion of Na_2SiO_3 and NaOH solution was then spread uniformly over the dry ingredients and mixed thoroughly. The NaOH pallets are dissolved in the necessary amount of water determined by the compaction test, which yields the molar concentration varying in the range of 6.0–7.0 mol/L depending on mixes, and an average of 6.5 mol/L can be taken as the molar concentration of alkaline activator.

At the early stage of the experimental campaign, a series of compaction tests was conducted on both untreated soil and different soil–geopolymer mixtures to determine their maximum dry unit weight (γ_{dmax}) and optimum moisture content (OMC). Table 3 summarizes the detailed composition of soil–geopolymer mixes with their OMC and γ_{dmax}. Afterward, the soil specimens were prepared with the corresponding optimum moisture content for each mixture. This ensured that the soil–geopolymer mixtures had the desired compaction properties and would perform well in subsequent tests.

2.3. Test Procedures. According to ASTM D4609 [51], evaluating the effectiveness of chemical additives in enhancing the engineering characteristics of fine-grained soils involves comparing the unconfined compressive strength (UCS) and moisture–density relationships of treated and untreated soils. As mentioned in the previous section, the OMC and γ_{dmax} of each soil–geopolymer mix are determined by the proctor test; these values were maintained throughout the experimental campaign. Additionally, swelling pressure, Atterberg limits, and CBR tests were conducted to evaluate the strength and swelling properties of geopolymer-treated expansive soils. Figure 3 illustrates the experimental setup used in the present study. Throughout all laboratory experiments, a minimum of three samples were prepared and tested. Subsequently, the average value was computed to ensure the reliability and accuracy of the experimental data.

The present study used a different approach for preparing laboratory compacted UCS samples. Unlike the conventional method, which entails compacting soil mixes in a proctor test mold and then trimming them to the desired specimen size, our method utilized a customized mold having 142 mm height, 71 mm diameter, and an extended collar of 50 mm [52]. This customized mold allowed for the direct preparation of UCS samples with dimensions of 71 mm × 142 mm, eliminating the need for trimming. In contrast, the conventional sample preparation method often requires trimming from a proctor test specimen, which can result in cracks and uneven shapes. Thus, our approach streamlines the sample preparation process and ensures the uniformity

Figure 3: Illustration of various experiments: (a) liquid limit test, (b) mechanical compaction device, (c) swelling pressure test assembly, (d) curing of UCS specimens, (e) UCS test device, (f) typical failure of UCS specimens, and (g) CBR test.

and time-efficient preparation of the UCS samples. The soil–geopolymer mixes were put in the mold in three layers and 15 blows at each layer to maintain the standard compaction energy [53]. Excess soil was then removed by trimming, and the sample was extruded using a sample extruder. A series of UCS specimens were prepared for each soil–geopolymer mix and wrapped with thin polyfilm and then stored at room temperature until the desired curing period. For each UCS test, three samples were tested, and the average compressive strength was recorded as the UCS result. One set of samples was tested immediately after preparation and recorded as 0 day UCS, while the other two sets were tested after 7 and 28 days, respectively. The UCS tests were carried out using a motorized compression machine, wherein an axial strain rate of 1–1.5 mm/min was maintained [54]. Figure 3(f) illustrates the typical untreated and geopolymer-treated specimen at failure.

After the final curing period (28 days), the index properties of each sample, that is, the liquid limit (LL) and plastic index (PI), were tested. Also, a swelling pressure test was performed to investigate the expansive nature of the treated soils and to check the suitability of the proposed approach for road construction. The test method "A" described in ASTM D4546-08 [55] was adopted for swelling pressure determination. Samples of swelling pressure tests had 50 mm diameter and 25 mm height, which were prepared by maintaining compaction criteria of corresponding mixes and kept up to 28 days curing in moisture-sealed condition.

Swelling pressure tests were performed using six one-dimensional odometer units, each equipped with a cell diameter of 50 mm. The identical soil samples of each mix were assembled, and varying loads were applied to generate different vertical stress levels. The swelling pressure was interpreted from the stress vs. wetting-induced strain relationship. CBR tests in both soaked and unsoaked conditions were also performed following the standards test procedure [56] with a uniform penetration rate of 1.27 mm/min. Furthermore, at the end of laboratory experiments, the morphological change of selected treated and untreated soils was observed by SEM image analysis.

3. Results and Discussions

In this study, fly ash-based geopolymer binder is used to enhance the strength and swelling characteristics of expansive soil. A series of laboratory tests were conducted on three classes of expansive soils with different geopolymer content varying from 10% to 30%. Improvement of strength properties is evaluated using the results of the compaction test, UCS, and CBR. Similarly, the improvement of swelling properties is recorded in terms of Atterberg limits and swelling pressure. The results of these experiments are discussed in the following subsections.

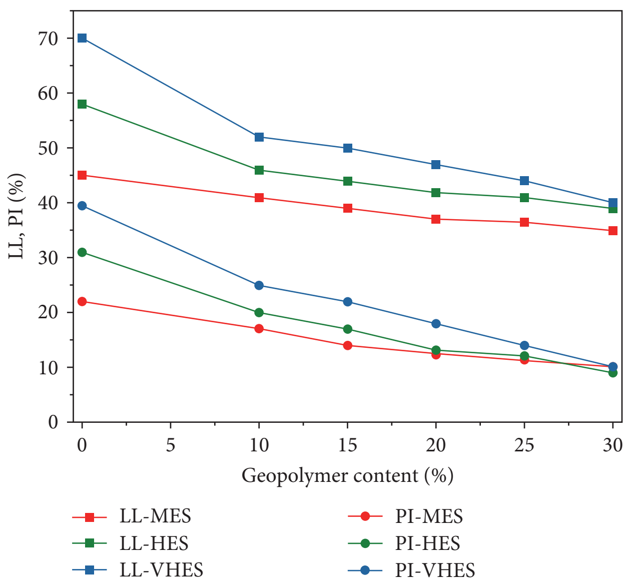


FIGURE 4: Variation of index properties of geopolymer-treated expansive soils. LL (solid square), liquid limit; PI (solid circle), plasticity index; MES, medium expansive soil; HES, high expansive soil; VHES, very high expansive soil.

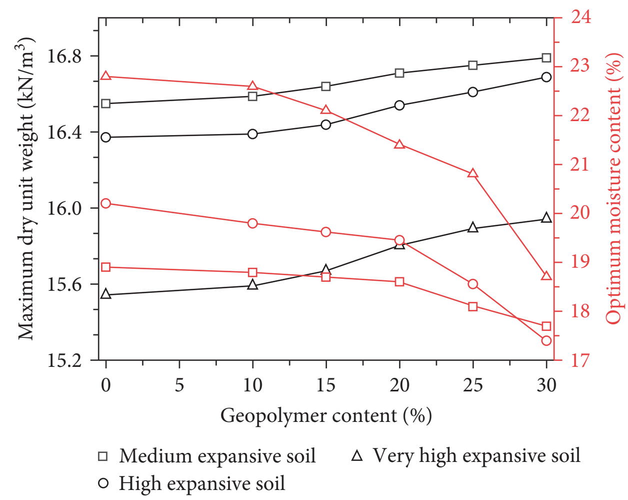


FIGURE 5: Variation of compaction parameters (γ_{dmax} and OMC) with geopolymer content.

3.1. Effect of Geopolymer on Index Properties of Treated Soil. After the final stage (28 days) of curing, the index properties of the treated soils were tested to determine their improvement, including the liquid limit and plasticity index. Figure 4 plots the variation in the liquid limit and plasticity index of three expansive soils with geopolymer contents. The liquid limit and plasticity index of untreated expansive soils ranged from 45% to 70% and 23% to 39%, respectively. A significant reduction of index properties was noted for 10%–20% geopolymer dosages, and their rates became slower for higher percentages (25% and 30%). Expansive soils contain montmorillonite clay minerals that cause them to exhibit high plastic behavior [57].

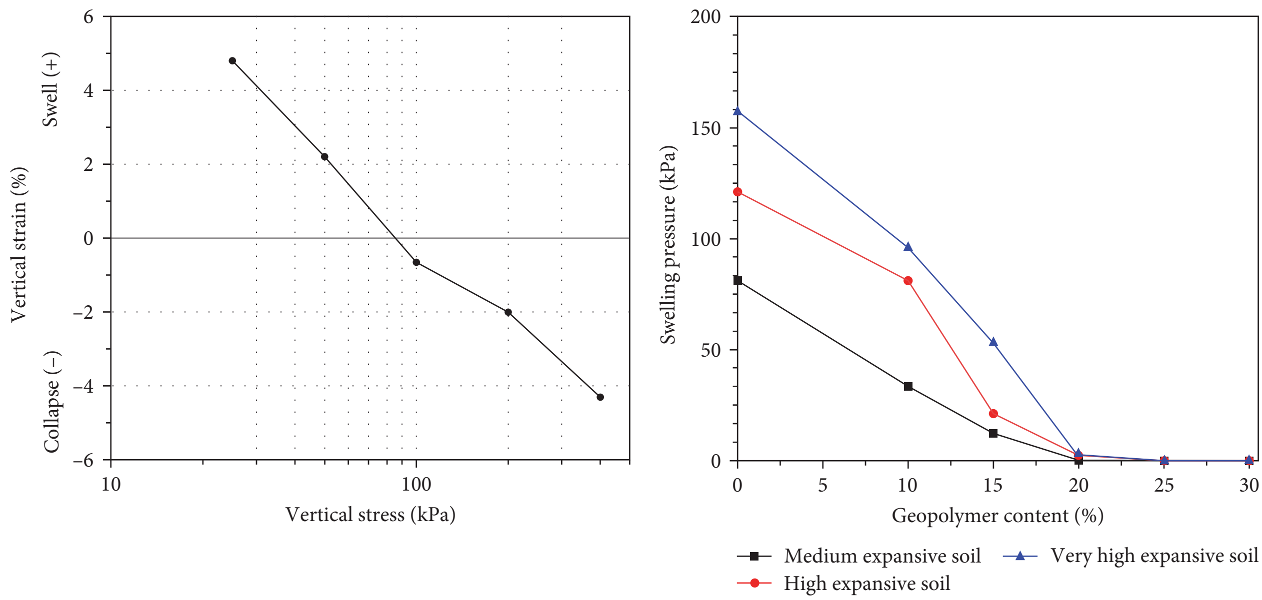
However, during the geopolymer treatment process, a major portion of the soil is replaced by fly ash, which is enriched with silica (65%) and is nonplastic in nature. Such replacement leads to an increase of nonplastic substances in the soil matrix, resulting in an improvement in the soil's plasticity characteristics. Thus, the geopolymer treatment rapidly changed the soil classification from the range of high plasticity clay to low plasticity silt; consequently, the swelling nature is also eliminated.

3.2. Compaction Characteristics of Treated Soil. The compaction parameters of untreated and treated expansive soils with varying percentages of geopolymer were determined using the proctor test. Table 3 summarizes the optimum moisture content (OMC) and maximum dry unit weight (γ_{dmax}) of individual mixes, which are also presented in Figure 5. The γ_{dmax} of untreated expansive soils varied from 15.54 to 16.55 kN/m^3, and the OMC varied from 18.9% to 22.8%. The γ_{dmax} of treated soil increased gradually with increases in the percentage of geopolymer, with the highest density observed in the 30% geopolymer-treated soil, indicating densification of the soil matrix due to polymerization. The reason for such variation is due to the density of used materials; the density of stabilizing agents is higher than the expansive clay, and as a result, the increment of binder content gradually increases the density of the soil matrix.

On contrary, the OMC shows a decreasing trend with the increment geopolymer percentage with the least moisture content at 30% geopolymer-treated soil. Among three untreated soils, the very high expansive soil exhibited maximum water absorption, followed by the high and medium expansive soil. Such a trend is expected as the untreated soils were prepared by blending varying amounts of bentonite with clay. However, the addition of geopolymer reduces the OMC because of the nonplastic behavior of fly ash and its low water absorption. Therefore, as the amount of geopolymer increases, the water absorption of the treated soil decreases. Consequently, this allows for the compaction of the soil mixture to its maximum density with a reduced water content. Such improvement is highly significant for enhancing the compaction characteristics.

Previous research [32, 41, 58] on expansive soil using different stabilizers also confirms a similar evolution trend of compaction parameters (OMC and γ_{dmax}) with increasing binder content. In general, the soil-stabilizing agents are nonswelling in nature and are composed mainly of silt-sized particles. Their addition to the soil caused substantial reductions in the soil's resistance for the same compaction level, allowing the particles to come closer and resulting in higher density. In parallel, the flocculation process led to reductions in the OMC [29], while the soil-binder mix became well-graded due to the increased percentage of the binder, resulting in continuous increases in γ_{dmax}.

3.3. Swelling Behavior of Treated Soil. The high swelling potential is always a big concern for expansive soils as it can cause cracks and stresses in overlying structures. To measure the improvement in the swelling behavior of treated expansive soils, the swelling pressure test was conducted after the 28-day curing period. As described in the test process [55], varying vertical stress ranging from 0 to 400 kPa



(a) (b)

Figure 6: (a) Typical wetting-induced strain vs. stress plot. (b) Variations in swelling pressures of geopolymer-treated soils.

are applied to each soil sample, and the stress corresponding to zero axial strain is taken as the swelling pressure of that soil. Figure 6(a) illustrates the typical stress vs. wetting-induced swell/collapse strain plot of one sample. The variation of swelling pressure with varying geopolymer content is then plotted in Figure 6(b). Initially, swelling pressures of the untreated medium, high, and very high expansive soils were found to be 81, 121, and 157 kPa, respectively. Swelling pressure sharply decreases with the increasing geopolymer content, and no swelling pressure is observed at or above 20% geopolymer content. This observation justified that the use of a 20% geopolymer binder is sufficient to improve not only the strength requirement but also the swelling characteristics of all classes of expansive soils.

As discussed in the compaction characteristics of geopolymer-treated expansive clays, the inclusion of nonplastic binders in the soil decreases absorption; the clay particles have less chance to exhibit free swelling. This mechanism can be revealed by microstructural analysis of treated soils. From the microscopic point of view, the untreated soil structure is loosely spaced, allowing it to expand under wetting. Conversely, a dense fabric is observed in treated soil, and such interlocking provides sufficient resistance against swelling. The following section describes this phenomenon in more detail with microscopic images.

3.4. Unconfined Compressive Strength (UCS) of Treated Soil. The ultimate objective of any ground improvement application is to enhance the soil's load-bearing capacity. Among various parameters, the UCS is inherently linked to the undrained shear strength of soil and serves as a rational indicator in this regard. A total of 162 UCS samples were prepared for three expansive soils with varying geopolymer content, maintaining the compaction parameters discussed in the previous section. The UCS samples underwent testing at intervals of 0, 7, and 28 days of curing to evaluate the strength development attributed to polymerization. Figure 7(a) illustrates the typical stress–strain curve of untreated and 20% geopolymer-treated soils. The peak compressive strength from this curve is taken as the UCS value of the corresponding mix. Figures 7(b) and 7(c) illustrates the UCS values of medium, high, and very high expansive soils at different ages, demonstrating the significant improvement in UCS of the expansive soils with geopolymer treatment. Initially ($t = 0$ day), the impact of variations in geopolymer dosage was minimal, as there were only slight fluctuations in the UCS at this stage. However, over time, and with higher geopolymer contents, the UCS of the soils exhibited a gradual increase. The peak strength was found for 20% geopolymer-treated soils, and the UCS values showed a slightly decreasing trend afterward, features that were seen for all types of expansive soils.

After the 28-day curing period with 20% geopolymer, the UCS value of medium, high, and very high expansive soils was found to vary from 380 to 414 kPa, which was initially 69–90 kPa for untreated soil. Several researchers have conducted similar studies, and their findings align well with the results of the present study [59, 60, 61, 62]. The addition of stabilizing agents initiates the cementation process and increases the density of the soil matrix, and this process continues when stabilizing agents are increased up to a specific limit. Further increase of the additive beyond the optimal percentage leads to saturation of the reaction process, leaving residual additive unbonded and decreasing compressive strength. Such phenomena are also observed in earlier studies [63, 64, 65] for other stabilizing agents such as cement, zeolite, metakaolin, and plastic straps.

For further comparison, the percentage improvement of UCS is computed with respect to the UCS value of untreated soils. For example, the untreated 0 day compressive strength

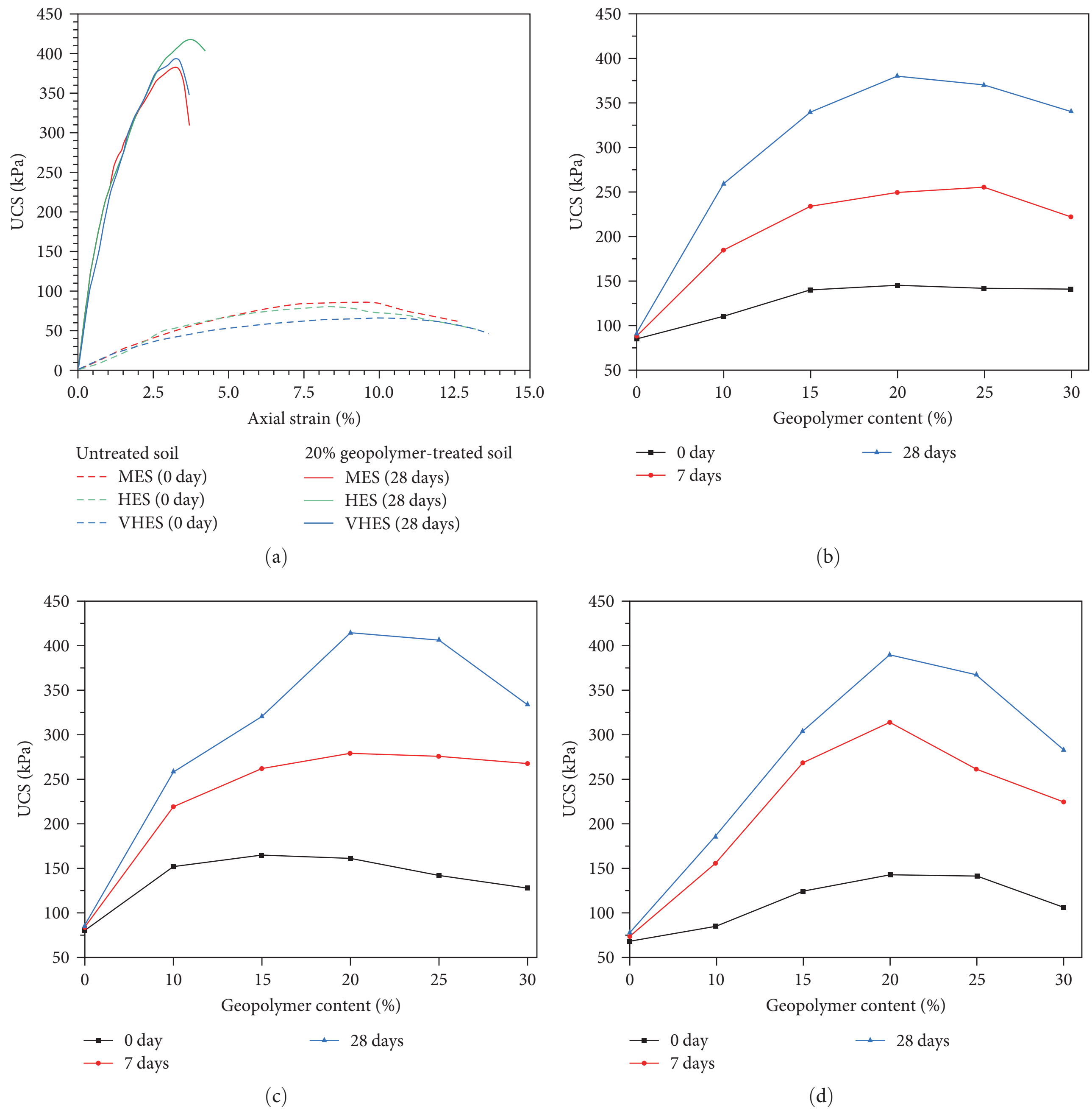


Figure 7: (a) Typical stress–strain curve of untreated and geopolymer-treated soils; (b–d) UCS of medium, high, and very high expansive soil at different curing ages. MES, medium expansive soil (b); HES, high expansive soil (c); VHES, very high expansive soil (d).

of medium expansive soil is $UCS_0 = 85.46$ kPa, and the peak strength at 20% geopolymer is 145.38, 249.5, and 380.21 kPa at 0, 7, and 28 days respectively. Taking 85.46 kPa as base strength, the percentage of improvement is computed as 100x $(UCS–UCS_0)/UCS_0$. Figure 8 represents the maximum percentage improvement of UCS at 20% geopolymer content for three expansive soils; the compressive strength was increased by approximately 350%–450% compared to the corresponding untreated soil. This indicated that the geopolymer binder could sufficiently increase the mechanical strength of expansive soils and, at the same time, offer an ecofriendly solution for the safe recycling of industrial byproducts like fly ash.

Bankowski et al. [66] reported that the maximum strength development of expansive soil was achieved with 20% of a precipitator FA (PFA)-based geopolymer. Meanwhile, other binders, such as lime and rice husk ash (RHA), exhibit much lower strength improvement, approximately 1.7 times that of untreated soil [18]. A similar trend of strength improvement was obtained for stabilizing volcanic ash, 20% of which could be used with a small quantity of natural lime to improve the mechanical strength and durability of soil [67]. Therefore, based on this, a geopolymer dosage of 20% could be considered an optimum amount. However, justifying using the UCS as a strength criterion is needed to address the effect of the

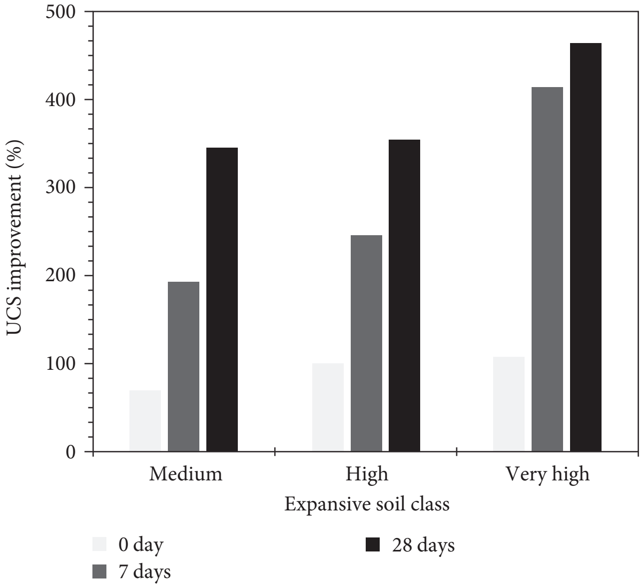


Figure 8: UCS improvement at 20% geopolymer for different soils.

degree of saturation of treated soil and to represent it as the undrained strength of soil required adequate degrees of saturation on different curing days. Although the remolded samples were prepared at the OMC and did not represent a 100% saturation level, an attempt was made to determine the degree of saturation after 28 days of curing, with a saturation level greater than 94% for all cases providing satisfactory results which implicitly justified the actual strength development of treated soils.

3.5. California Bearing Ratio (CBR) of Treated Soil. The CBR test is a widely used method to evaluate the strength of subgrade layers, which also helps to determine the necessary thickness of overlying layers such as sub-base and pavement. CBR value of natural soils varies depending on the presence of moisture. Usually, if the natural soil is in a saturated condition, its CBR value reduces compared to that of the soil if there is no moisture in it. In this study, CBR tests (ASTM D1833 [56]) were conducted on untreated and geopolymer-treated soil samples with a modified compaction effort maintained by an automatic mechanical loading device, and the test was conducted in both soaked and unsoaked conditions. Figure 9 displays the standard load penetration curve for untreated soils and soils treated with 20% geopolymer. The solid lines depict the results of unsoaked CBR tests, whereas the dashed line represents data from soaked CBR tests. The CBR values were determined according to ASTM D1833 and further considered for comparison.

Figures 10(a) and 10(b) present the variation of unsoaked and soaked CBR values of the medium, high, and very high expansive soils. The test results showed a gradual improvement in CBR values as the geopolymer content increased, with a sharp increase observed between 10% and 25% of geopolymer content, which became almost flat with further increases in the geopolymer content. Notably, the soaked CBR values of the medium, high, and very high expansive soils were initially 3.2%, 2.1%, and 2.2%, respectively, which, due to the geopolymer treatment, increased to 39%, 43%, and 41%, respectively. The unsoaked CBR test results showed a similar trend of improvement but with slightly higher percentages, with the maximum being 50.2% for a very high expansive soil treated with 30% geopolymer, while the soaked CBR value was 43.1% for the same. The reason for such improvement is due to the increasing amount of binder in the soil mixes, which contributes to continuous improvement by enhancing gradation, resulting in a higher bearing capacity.

The CBR value of subgrade soil is a critical factor in pavement design as it directly affects the thickness requirements of the overlying pavement layers. When the soaked CBR value of the subgrade soil is high, the thickness requirements for overlying pavement layers will be low [68]. According to the technical specifications outlined by the Bangladesh Roads and Highways Department [69], if the soaked CBR value of soil is less than 5%, an additional layer of improved subgrade must be used. On the other hand, if it is greater than 25%, the soil can be directly used as sub-base. The results of the current study demonstrate that initially, the soaked CBR of expansive soils were less than 5%. However, the geopolymer treatment significantly improves the CBR values, and all the expansive soils attain soaked CBR values greater than 32% at 20% geopolymer content, which is sufficient to fulfill the standard requirements [69] for both the subgrade and sub-base materials. On the contrary, traditional soil stabilizers have limited capacity for CBR improvement; for example, marble dust and waste plastic stabilization [59, 65, 70] can attain soaked CBR values up to 12.9% and meet the requirements of subgrade only.

3.6. Microstructural Characteristics of Treated Soil. As seen from Figure 6(b), the 20% geopolymer content performed best in improving the swelling characteristics of all expansive soils; the microstructural analysis was performed on some selected samples of this group. In this study, we used the SEM technique to capture the change in the microstructure of geopolymer-treated samples, and a qualitative comparison was made with untreated expansive clays. A portion of the UCS test sample, after 28 days of curing, was used to prepare the SEM specimen. The soils were air-dried and pulverized in powder format to make them suitable for SEM analysis. Then, a dense layer of powdered samples was put in the SEM sample holder and scanned as per standard procedure.

Figure 11 shows the microscopic images of untreated and geopolymer-treated medium- and high-expansive soil. Referring to Figure 11(a), the expansive clay exhibits a sheet-type clay structure with random space (red circles) among them; these loosely compacted sheets of clay minerals are mainly responsible for higher values of index properties (LL and PI) of expansive soil. Numerous voids of uneven shapes are also visible in the microstructure of raw expansive soils (Figures 11(a) and 11(c)), which can be ascribed as a prime reason for the low mechanical strength, less density, and higher water absorption of untreated expansive clays. Similar formation in microstructure was also observed for natural expansive and collapsible soils [15, 71, 72, 73].

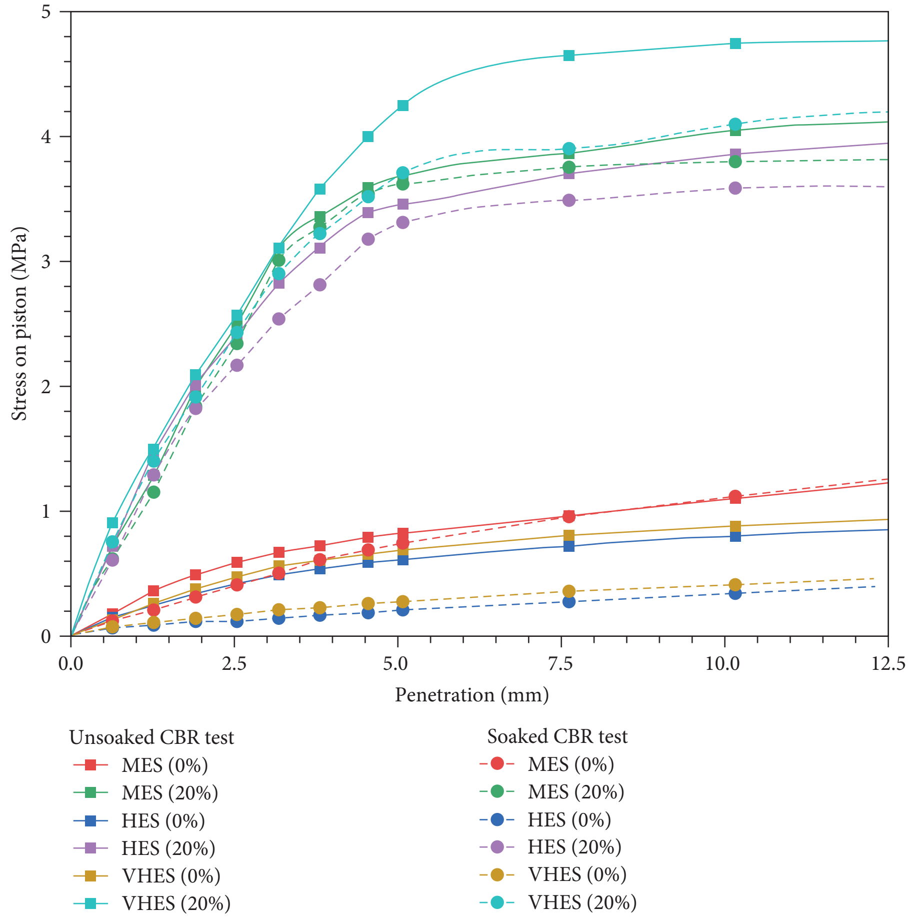
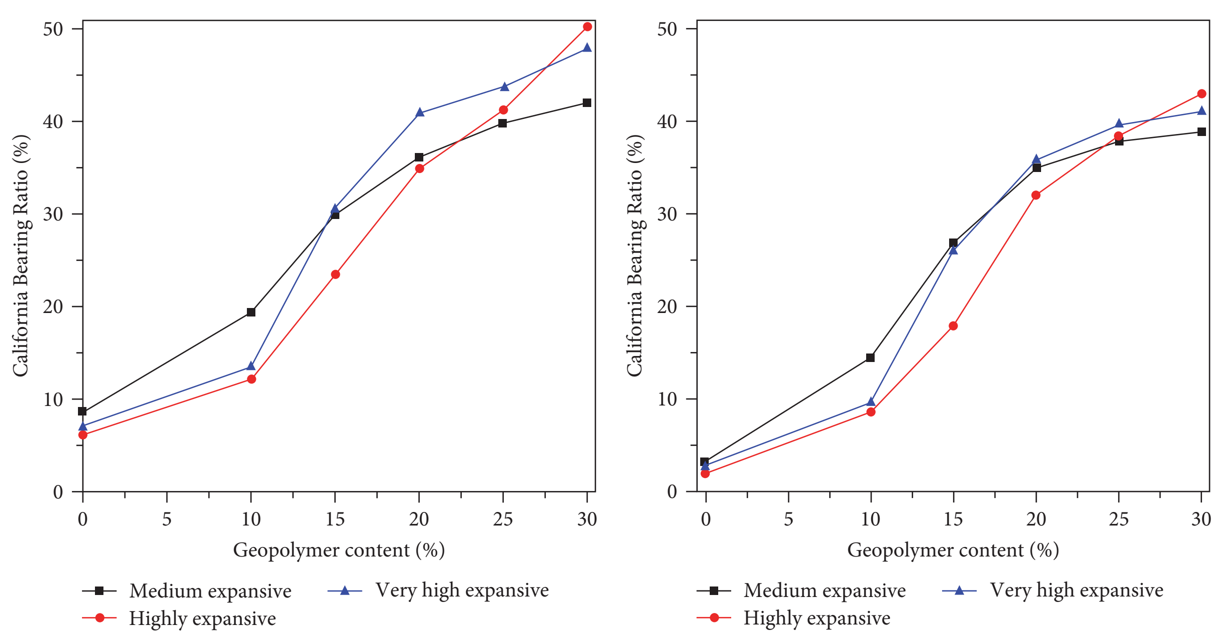


Figure 9: Load penetration curve of untreated and 20% geopolymer-treated samples in soaked and unsoaked conditions. MES, medium expansive soil; HES, high expansive soil; VHES, very high expansive soil.



(a) (b)

Figure 10: Variations of (a) unsoaked and (b) soaked CBR values of geopolymer-treated soils.

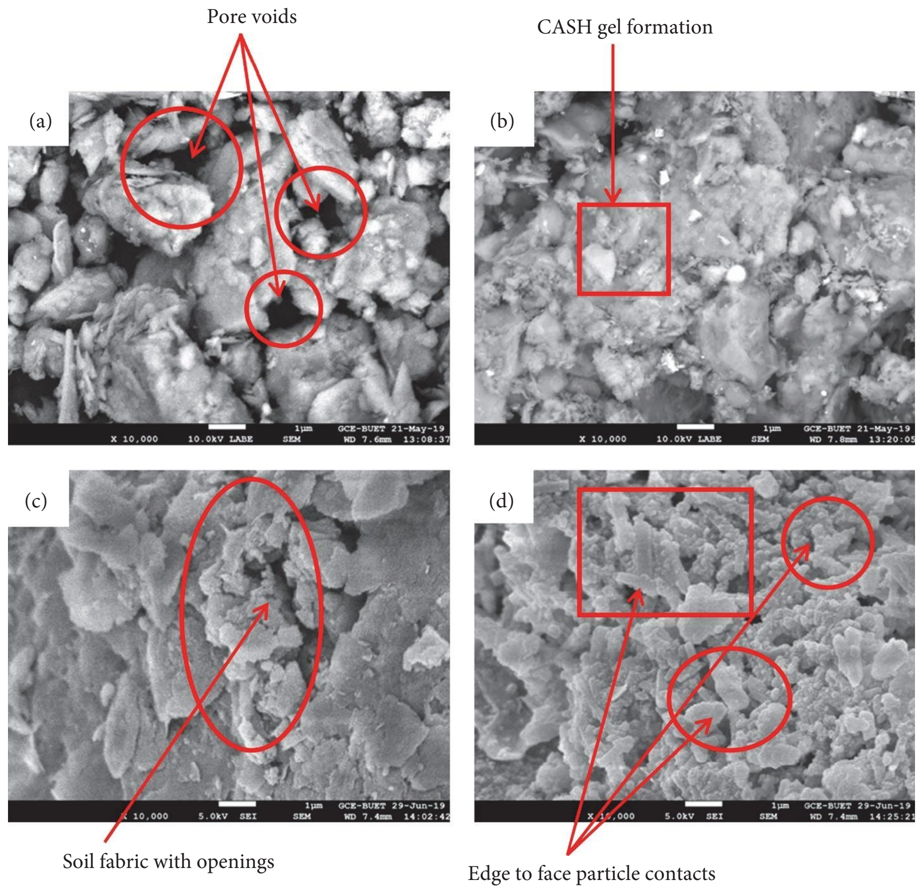


FIGURE 11: SEM images of medium expansive soil, (a) untreated and (b) 20% geopolymer-treated, and highly expansive soil, (c) untreated and (d) 20% geopolymer-treated.

However, the images of geopolymer-treated soil show a uniform, dense fabric with fewer pores in its microstructure compared to untreated soil, as observed in the microscopic image of 20% geopolymer-treated medium expansive soil. In this microscopic image, the amount of sheet-type elements was almost absent. Such reduction of sheet-type microstructural elements is due to the advancement of polymerization (red square in Figure 11(b)) in a clay matrix, resulting in a higher density of geopolymer-treated soil, as found in the compaction test. Shi et al. [74] also observe a similar improvement for metakaolin-based geopolymer; they confirm that the formation of silicoaluminate gel enhances the bonding between soil particles and reduces the micropores. Thus, geopolymer-treated soil attains a more compact structure.

In close view of 20% geopolymer-treated highly expansive soil, a dense state of a needle-type structure (marked by red rectangle in Figure 11(d)) with an irregular shape and a rough surface was visualized. This microstructural element indicated the advancement of polymerization reaction that increases the interlocking in the soil matrix. The dense needle-type structure provides sufficient resistance against the swelling tendency. Previous studies on lignosulfonate-treated expansive soil [75] also obtained a similar microstructure of soil particles with sharp edges. Agglomerations of such polymerized particles provided adequate interlocking in the clay matrix, which is the prime reason for the strength gaining of geopolymer-treated expansive soil compared to untreated conditions. So, the morphological transformation, like the reduction of voids and the presence of interlocked microstructure, can be attributed to the polymerization reaction in the clay-geopolymer mix.

4. Conclusions

The presence of expansive soils in a shallow subsoil often creates a problem for setting foundations and road construction. To overcome this, this research attempted to highlight the use of waste products as stabilizing agents by adding a mixture of fly ash and an alkali activator, called a geopolymer, to different classes of expansive soils. Laboratory experiments were conducted to quantify the improvement in mechanical strength and swelling properties, and the following conclusions are drawn based on the experimental findings of geopolymer-stabilized expansive soils:

(1) The index properties, specifically the liquid limit and plasticity index, showed visible decreases with increasing binder contents, which implicitly indicated that the expansive nature of the soils had disappeared.

(2) It is evident that the high swelling pressure of the expansive soils is drastically reduced with increasing

geopolymer content and dropped to nearly zero at the optimum geopolymer content.

(3) The experimental results showed significant improvements in the unconfined compressive strength of geopolymer-treated expansive soils; the UCS of 20% geopolymer-treated soil increased nearly 400% within a 28 days curing period compared to untreated soils.

(4) A similar trend of improvement is also evident in the CBR test results. Notably, the soaked CBR value of 20% geopolymer-treated soil improved above 32% and reasonably satisfied the standard requirements of road construction guidelines. Thus, the geopolymer treatment of expansive soil is an environmentally friendly and economical solution for road construction rather than replacing them with costly foreign materials.

(5) The microscopic images demonstrate that the treated soil has attained uniform, dense fabric with fewer pores due to polymerization, and the formation of irregular-shaped microstructure provides sufficient interlocking within the clay matrix. Such transformation in geopolymer-treated expansive soil reveals the better advancement of mechanical strength and swelling properties.

In summary, the current study confirmed that 20% alkali-activated fly ash-based geopolymer binder is optimum for all classes of expansive soils regardless of the degree of expansion, and these findings can offer valuable options for academics and professionals. This study justified the applicability of geopolymer-treated soil based on experimental findings.

However, future investigations should focus on assessing the field performance of geopolymer binders, considering differences in mixing and curing conditions between laboratory and field conditions. Furthermore, the exact dosages of fly ash need to be verified through multiple field trials before designing for pavement application, as the curing criteria will be different from laboratory conditions. To fully understand soil–geopolymer field performance as a part of the pavement layer, checking its durability under dynamic loading, resilient modulus, and the effect of alternate drying–soaking is required and hence recommended for further research.

Data Availability

The data used in this study are included within the article and can be available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors have no conflict of interest.

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