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Improving Geotechnical Properties of Expansive Subgrade Using Sugar Cane Molasses and Cement

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Abstract: Soil stabilization using Portland cement is a widely adopted technique. Previous research has demonstrated that molasses, which contains sugars, enhances the reaction between cement and aggregates. This study investigates the impact of adding molasses to soil stabilized with Ordinary Portland Cement (OPC) on geotechnical properties. Expansive clay soil samples from Taru Jabba, District Nowshera, Pakistan, were treated with various combinations of molasses and cement. The concentrations of each stabilizer were varied at 0%, 4%, 8%, and 12% by dry weight of the soil. Additionally, the soil was treated with constant molasses contents of 4%, 8%, and 12%, while varying the cement content at 4%, 8%, and 12% by dry weight. Geotechnical tests, including Proctor compaction, Atterberg limits, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), and swelling potential, were conducted to assess the effects of the stabilizers. The results indicated that the addition of molasses improved soil strength, mitigated shrinkage cracks, and reduced brittleness. Specifically, the CBR value increased from 3.2% in the native soil to 12.3% with 12% molasses and 12% cement. The Plasticity Index (PI) decreased from 14.23% to 8.12%, and the CBR swell value reduced from 9.66% to 3.82%. Furthermore, the UCS of the stabilized soil increased by 64.7% compared to the untreated soil after a 7-day curing period.

Keywords: sugar cane molasses; soil stabilization; geotechnical properties; expansive clay soil; stabilization mechanism

1. Introduction

There are various serious geotechnical problems caused by expansive soil in different parts of the world. Excessive volume changes of the soil profile in the occurrence of change in moisture content are the main problems associated with these soils. Buildings and roads built on such soils faces severe damages to their engineering properties due to the excessive volume changes [1]. Soil stabilization or modification refers to the improvement of the soil physically or chemically by using various techniques including mechanical compaction and the use of various calcium rich chemicals. The selection of proper stabilization technique depends on the soil type and its condition. Expansive soils pose substantial hazards to construction, particularly affecting low-rise buildings, pavements, and shallow services [2]. Therefore, the removal of existing expansive soil or its replacement with non-expansive soil or improvement of its properties through soil stabilization technique is very important. In this area where expansive soils are abundant and suitable fill materials are scarce, roads are not the increased global demand for energy and increasing local demand for aggregates it has become expensive from a material point of view to remove inferior soils and replace them with foreign soils [3]. Expansive soils, or swelling soils, exhibit significant volume changes due to variations in water content, primarily due to the presence of the mineral montmorillonite. These soils, also known as Vertosols, typically contain 30% or more clay and are characterized by high bulk densities and low permeability. The clay forms through the breakdown and alteration of rocks exposed to air and moisture, resulting in complex crystalline structures [4]. Expansive soils pose substantial hazards to construction, particularly affecting low-rise buildings, pavements, and shallow services. These soils are prevalent in arid, semi-arid, and regions with alternating wet and dry

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conditions. Countries significantly impacted by expansive soils include Ethiopia, Kenya, China, India, the USA, and Australia. In these regions, high evaporation rates and seasonal rainfall patterns cause cycles of swelling and shrinkage, leading to structural damage [5].

Research conducted on the effect of sugar containing molasses on concrete have proved that sugar improves the quality of reaction between the cement and the aggregates and reduces setting time of concrete. Sugar cane molasses, a thick byproduct resulting from the sugar cane processing into sugar, is characterized by its viscosity. The growing demand for sugar has led to an increase in the production of cane molasses, accounting for approximately 30%–40% of the sugar volume. Analysis of sugar cane molasses reveals the presence of various components such as lime and sulfur dioxide. These identified elements, along with other nutrients absorbed by the sugar cane from the soil to facilitate its growth, are believed to have interacted with expansive soil, causing alterations in its properties during the stabilization process. With Huang et al. [6] investigated the effect of cement addition by varying cement content on plasticity of expansive clay soil and found that Liquid limit (LL) decreased and Plastic Limit (PL) increased with increasing cement content, thus PI decreased with addition of cement content up to 14% cement content and then increased with further addition of cemen [7]. Cement is used to improve the expansive clay soil, but it is very expensive. Moreover, expansive clay soil treated with cement is prone to shrinkage cracks and rapid setting time of cement makes compaction difficult. The main content is sugar (sucrose) ($C_{12}H_{22}O_{11}$). The various factors which are impacted by the composition of molasses includes the location of cane plantation, its climatic conditions [8]. Similarly, the overall growth process and the conditions of the processing factory also affect the composition of molasses values of expansive clay soil effected by cane molasses was investigated by on both un-soaked and soaked samples for different curing periods which showed that the CBR values were increased by the molasses in expansive clay soil ultimately effecting the bearing ability of the soil [9].

Moreover, it was noticed that swelling tendencies of the soil could be reduced by mixing cane molasses with expansive clay soil. Mechanical stabilization of a material is usually achieved by adding a different material in order to improve the grading or decrease the plasticity of the original material [10]. The physical properties of the original material will be changed, but no chemical reaction is involved. The main methods of mechanical stabilization can be categorized into compaction, mixing or blending of two or more gradations, applying geo-reinforcement and mechanical remediation. The expansive clay soils have caused persistent difficulties in road construction and are a relatively common problem in the country [11]. On the other hand, stabilization refers to the selection of the stabilizer in order to achieve certain target strength/stiffness values in addition to modification.

In conclusion, creating working platform for construction purpose only is part of modification/treatment; whereas stabilization is essential if we are dealing with construction of sub base in pavements. The conventional stabilizing agents commonly used in expansive soils and replacement of the inferior sub-grade soils by foreign soils are fairly expensive. As a result, the proper construction of such roads is not done, requiring frequent and close attention [12]. So, it becomes essential to modify the properties of locally available soil with cheaper stabilizer to the extent that it can be used in the construction of roads and to make best utilization of various industrial by products like molasses as a soil modifying/soil stabilizing agent [13].

The geotechnical properties of the soil in Tehsil Taru Jabba, Nowshera, Pakistan exhibit significant settlement issues, primarily due to the predominant clayey nature of the sub-grade. This characteristic leads to challenges in maintaining the stability and bearing capacity of the soil, which is critical for the foundations of structures built on it. As a result, many subgrade roads and residential housing societies in the area are experiencing foundation settlement problems. This issue is manifested by diagonal cracks observed in the brick masonry walls of several buildings, indicative of excessive and differential settlement of the foundations. Traditional chemical stabilizers, while effective, are often prohibitively expensive, making them less accessible for widespread use in such regions. On the other hand, sugar cane molasses presents a more cost-effective alternative due to its relative abundance as a byproduct of established agricultural practices. The incorporation of

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molasses into the soil not only enhances the workability during compaction, thus improving the efficiency of construction, but also contributes to environmental sustainability. The use of molasses helps in reducing industrial effluents from factories, thereby addressing environmental concerns related to waste disposal. Additionally, unlike manufactured chemical stabilizers, molasses has a minimal environmental impact, making it an eco-friendly option for soil stabilization. This research aims to address the existing gap in the application of agricultural byproducts for geotechnical improvements, offering a sustainable and economical solution to enhance the bearing properties of expansive subgrades while mitigating environmental and economic challenges.

This study highlights the significant benefits of using sugar cane molasses as a sustainable and cost-effective stabilizer in soil stabilization, particularly in expansive clay soils such as those found in Tehsil Taru Jabba, Nowshera. The results demonstrate that the combination of molasses with cement significantly improves the geotechnical properties of the soil, including increased California Bearing Ratio (CBR), reduced plasticity index (PI), and decreased swelling potential. These improvements are crucial for enhancing the bearing capacity and stability of soils used in construction, particularly in regions where traditional chemical stabilizers are economically unfeasible. By effectively utilizing molasses, an agricultural byproduct, not only are the soil properties enhanced, but environmental and economic challenges are also addressed. The findings of this research underscore the potential for integrating agricultural waste products into civil engineering practices, offering a viable solution for sustainable and resilient infrastructure development in areas plagued by expansive soils.

2. Methodology

Drawing upon the research objectives and scope, along with insights from the literature review, the research methodologies employed in this study were structured into five distinct components in Figure 1. Several samples of soil taken from test pits in Taru Jabba, District Nowshera, Pakistan. Ordinary Portland Cement (OPC) and black strap sugar cane molasses, which were suggested as stabilizers for this study, were obtained from Khazana Sugar Factory Pakistan. Due to their close proximity to the study location, the origins of the OPC and sugar cane molasses were selected, respectively. Laboratory experiments were carried out on the native soil to determine its engineering properties, and several tests were also performed to evaluate the stabilizers' physical and chemical composition. The Pakistan Roads Authority's stabilize sub-grade criterion for soil properties was compared to the reestablished properties of the soil following stabilization with molasses and cement combination that Pavement Design Manual [14].

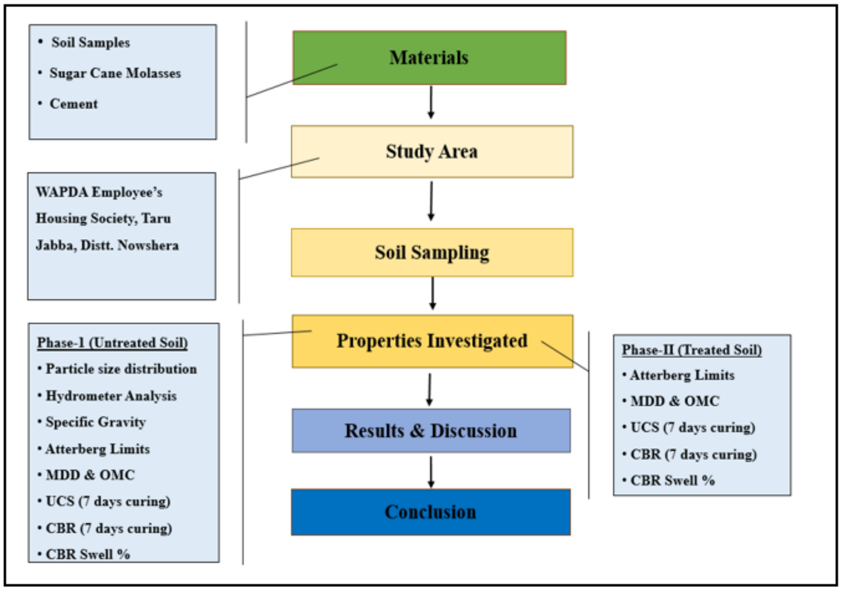

Figure 1. Research Methodology.

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3. Materials

3.1. Expansive Soil

For this investigation, a large sample of soil was collected in Taru Jabba, District Nowshera, Pakistan. The soil samples were taken from 3 different pits at a distance of 1.5 meter below ground level and all the samples used in the study were remoulded in the laboratory according to the available standard procedures (Figure 2). The gradation curve obtained from the sieve analysis and hydrometer analysis revealed that about 61.7% clay, 29.1% silt, and 9.2% sand contents (Figure 3). The soil is classified as Inorganic Clay of low Plasticity because it lies above the A-line of the Unified Soil Classification System (USCS). The untreated soil's properties are shown in Figure 4.

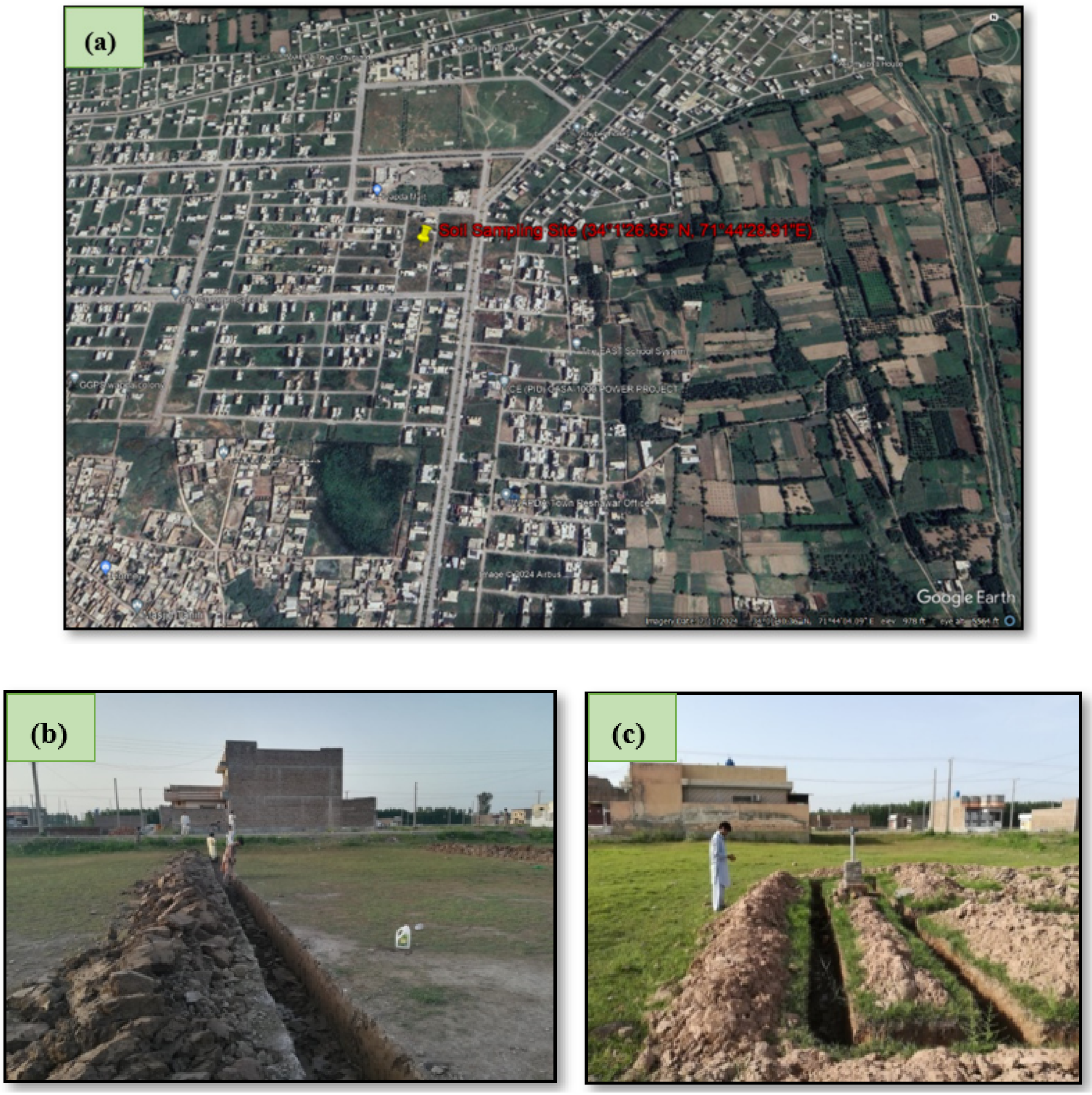

Figure 2. (a) Actual field view of the site; (b) Soil showing desiccation cracks due to wet-dry environment; (c) Pulverized sample.

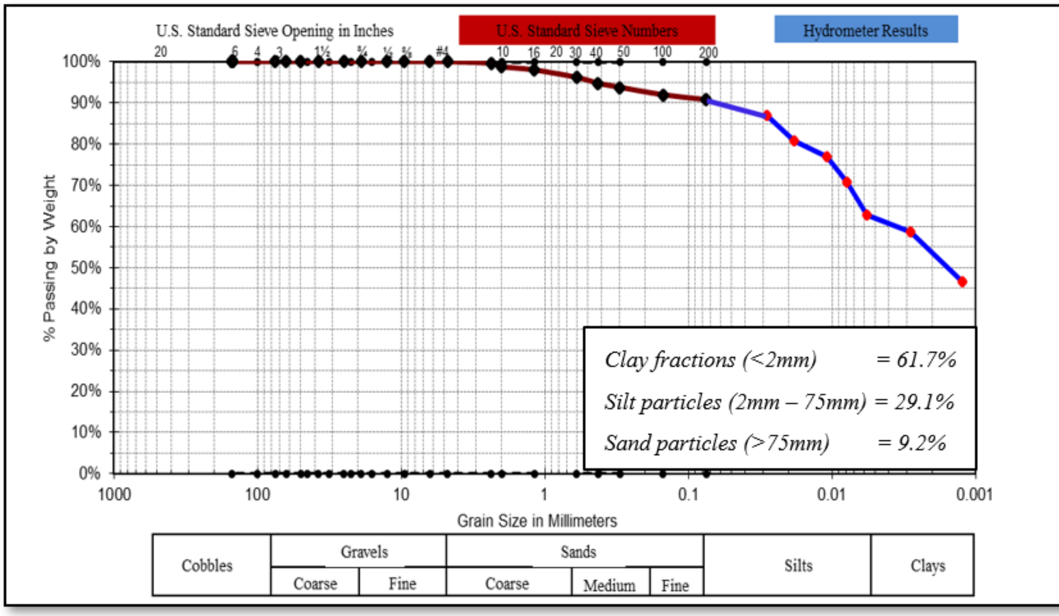

Figure 3. Gradation curve constructed from sieve analysis and hydrometer analysis for native soil.

Physical Properties	
Silt	29.1 %
Clay	61.7 %
% age Passing #200	90.8 %
L.L	40 %
P.L	25.77 %
P.I	14.23 %
Soil Type (USCS)	CL
Soil Type (AASHTO)	A6
Specific Gravity, Gs	2.75
MDD	86.2 (pcf)
OMC	24.5 %
UCS	0.34 (kg/cm^2)
CBR	4.2 %
CBR Swell	9.66 %

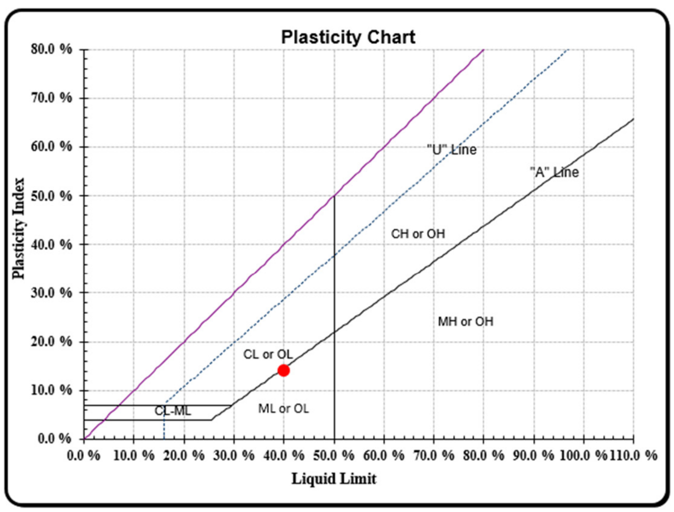

Figure 4. Plasticity Chart for Fine-Grained Soils.

3.2. Sugarcane Molasses

A viscous by-product of converting sugarcane to sugar is cane molasses. The juice extracted from sugarcane is heated during sugar production until the sugar crystallizes and precipitates. Molasses contains numerous compounds, with sugar (sucrose) being a primary component ($C_{12}H_{22}O_{11}$). The sugar cane molasses was collected from Khazana Sugar Factory, Pakistan (Figure 5). The features gained from the laboratory tests are given in the Table 1.

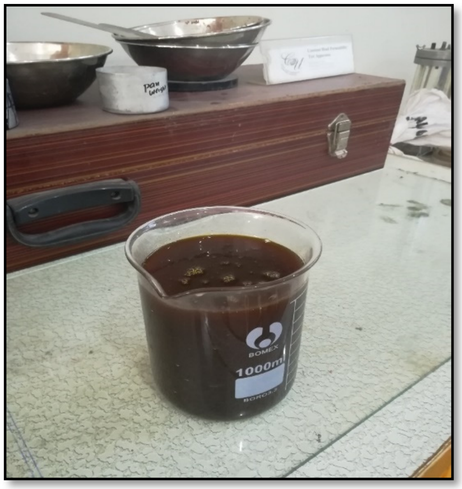

Figure 5. Sugarcane molasses.

Table 1. Constituents of the sample sugar cane molasses.

Sr. No	Constituents	Result
1	Color	Black
2	Brix	84.9
3	pH(1:1at 20^{0}C)	5.5
4	Specific gravity at 20/4^0	1.43181
5	Viscosity @ 30^{0}c (mPa. s)	18400
6	Viscosity @ 60^{0}c (mPa. s)	6600
7	Moisture (%)	23.78
8	Total Sugar (%)	48.46
9	Invert Sugar (%)	10.53
10	Sulphated ash (%)	14.52
11	Ca (%)	1.60

3.3. Ordinary Portland Cement (OPC)

For this research, ordinary Portland cement (OPC), grade 42.5 N, type I cement, was used. The physical and chemical parameters of the OPC as tested in a laboratory are listed in Table 2.

Table 2. Chemical composition of the sample cement.

Sr. No.	Specific Items	Unit	Measured
1	Loss on ignition	%	2.05
2	S_iO_2 (silica)	%	21.63
3	Al_20_3 (alumina)	%	5.52
4	Fe_20_3 (Iron Oxide)	%	3.42
5	CaO (Lime)	%	61.45
6	MgO (Magnesia)	%	1.86
7	$S0_3$ (Sulphur Trioxide)	%	2.71
8	C_3S (ofClinker)-tri silicate	%	>55.0
9	C_2S (of Clinker)—dicalcium silicate	%	>14
10	C_3A (of Clinker)—tricalcium Aluminate	%	<8
11	CAF (of Clinker)-tetracalicium alumina-ferrite	%	>10
12	Free Lime	%	0.45-0.80

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13	Liter Weight	G/Lt	>1310

3.4. Soil Consistency

The soil consistency test was conducted in accordance with the guidelines outlined in ASTM D-4318-17. In order to ascertain the liquid limit (LL), a brass receptacle is elevated to a specific height and then released onto a sturdy rubber surface through the utilization of a manually operated cam. A portion of the soil specimen is placed within the metallic cup and subsequently divided using a grooving implement. The liquid limit represents the moisture content at which the groove closes to a depth of 1/2 inch after 25 iterations of cup dropping. Conversely, the plastic limit is determined by manually shaping a small sphere from moist plastic soil into a 1/8-inch strand following continuous reshaping efforts. Prior to complete formation, the strand starts to disintegrate at the moisture level identified as the plastic limit. The corresponding moisture levels at liquid limit (LL) and plastic limit (PL) were ascertained through the application of the oven-drying technique.

3.5. Compaction Test

Proctor compaction tests were conducted on both untreated and treated soil in accordance with the guidelines set by ASTM (ASTM D-698) to ascertain the maximum dry density (MDD) and optimum moisture content (OMC) for each soil specimen. This procedure entails compacting soil samples at a specified moisture level within a 4-inch-diameter mold using standard compaction energy. Initially, the soil underwent air drying and was subsequently divided into 4 to 6 samples, with the moisture content of each sample being adjusted through the incremental addition of water ranging from 3 to 5 percent. Subsequently, the soil was uniformly mixed with the desired proportions of molasses, cement, and water. The prepared soil samples were then sealed in polyethylene bags within the laboratory environment for 24 hours at ambient temperature (27 ± 2°C) to achieve water equilibration. Following this, the soil was placed and compacted in the compaction mold in three layers, each subjected to 25 blows per layer utilizing standard compaction energy. Ultimately, the moisture content and dry density of the untreated and treated soil, incorporating varying percentages of molasses and cement, were determined.

3.6. Unconfined Compressive Strength (UCS)

Uniaxial compression tests were conducted in accordance with the guidelines outlined in ASTM D-2166. The soil specimens, both untreated and treated, designated for the unconfined compression strength (UCS) analysis, were meticulously crafted within a cylindrical mold measuring 76 mm in height and 38 mm in diameter. These samples underwent compaction at their respective maximum dry densities (MDDs) and optimum moisture contents (OMCs) before being subjected to natural air-drying. Subsequent to the stipulated period of maturation, the specimen was positioned onto the base plate of the digital compression machine that operated under a controlled strain regime, facilitating the investigation of stress-strain characteristics of the soil specimens at a loading rate of 0.8 mm/min.

3.7. California Bearing Ratio (CBR)

A CBR test was carried out using the Digital CBR Test Machine in accordance with ASTM D-1883. During the CBR testing process, the soil samples were compacted within a CBR mold with specified dimensions (inner diameter of 152.4 mm, height of 177.8 mm) through a modified compaction procedure. To replicate the confining loads of pavement and base course, a surcharge weight of 43.64 N was placed on top of the compacted soil specimen within the CBR mold. For the soaked CBR test, the mold with surcharge weights was fully submerged in water for a soaking period of 4 days to ensure complete infiltration of water into the soil specimen. A swelling gauge was affixed during the soaking period to monitor the swelling characteristics of both untreated and treated soil specimens under inundation conditions. The CBR test was conducted on all soil mixtures at a consistent loading rate of 1.27 mm/min.

4. Material Testing

4.1. Sample Preparation

The soil sample collected is initially dehydrated under direct sunlight; the clumps are fragmented in order to obtain a homogeneous sample. Subsequently, the soil sample undergoes a meticulous process to eliminate organic substances, small aggregates, and fragmented wooden materials. The sample is then placed in an oven for the purpose of drying, intended for testing at a temperature of 105°C for a duration of 24 hours. The quantity of soil sample utilized for the test is substituted by the percentage of molasses and cement combination.

4.2. Planning for Laboratory Tests

The expansive soil that was supposed to be used as sub-grade soil had been modified through the addition of molasses and cement in varying amounts. The mix of expansive soil and combination of molasses and cement are designated as in the Table 3 [15].

Table 3. Mixtures composition of native and treated soil**.**

Mix Types	Soil	Molasses	Cement
$S_{0,0}$	100%	-	-
$S_{4,4}$	92%	4%	4%
$S_{4,8}$	88%	4%	8%
$S_{4,12}$	84%	4%	12%
$S_{8,4}$	88%	8%	4%
$S_{8,8}$	84%	8%	8%
$S_{8,12}$	80%	8%	12%
$S_{12,4}$	84%	12%	4%
$S_{12,8}$	80%	12%	8%
$S_{12,12}$	76%	12%	12%

5. Results and Discussions

5.1. Effect of Stabilizers on pH values

Several specimens were produced in the manner described in Table 4 and the soil-stabilizer slurries pH values have been measured in line with ASTM D-6276. The table presents the pH values of soil samples following a one-hour mix with varying percentages of molasses and cement as stabilizers. The native soil, with a baseline pH of 8.20, serves as a reference point. The data demonstrates a clear trend in which the addition of stabilizers influences the soil's pH, with specific combinations of molasses and cement yielding distinct results. For instance, the $S_{4,4}$ combinations, consisting of 4% molasses and 4% cement, reduces the pH slightly to 7.84, making the soil less alkaline than the native sample. As the cement percentage increases, the pH also rises, as seen in the $S_{4,8}$ (8.07) and $S_{4,12}$ (9.11) combinations. This trend continues with higher percentages of molasses, where the $S_{8,4}$ (13.19) and $S_{8,12}$ (13.74) combinations exhibit significant increases in pH, indicating a strong alkalizing effect. Notably, the highest pH values occur when both stabilizers are used in substantial quantities, such as in the $S_{12,8}$ (13.18) and $S_{12,12}$ (13.48) samples, reflecting a synergistic interaction between molasses and cement that amplifies the alkaline reaction in the soil. These findings highlight the impact of varying stabilizer concentrations on soil pH values, providing critical insights for soil stabilization practices in civil engineering.

Table 4. pH values after one-hour mix of Soil and Stabilizers**.**

Percent of Stabilizer	pH Value
Native	8.20
$S_{4,4}$	7.84

$S_{4,8}$	8.07
$S_{4,12}$	9.11
$S_{8,4}$	13.19
$S_{8,8}$	13.63
$S_{8,12}$	13.74
$S_{12,4}$	12.75
$S_{12,8}$	13.18
$S_{12,12}$	13.48

5.2. Effect of Stabilizers on Atterberg Limits

Consistency limits for soils treated with molasses and cement combination for 7-day curing periods are determined according to ASTM D-4318 and presented in Table 5.

Table 5. Atterberg Limits Value for the Native/Untreated Soil and Treated Soil**.**

Limit	Native soil (%)	Soil treated with molasses and cement (%)								
		$S_{4,4}$	$S_{4,8}$	$S_{4,12}$	$S_{8,4}$	$S_{8,8}$	$S_{8,12}$	$S_{12,4}$	$S_{12,8}$	$S_{12,12}$
LL	40	37	35	32	34	33.5	30	33	31	27
PL	25.77	23.38	22.33	22.3	21.1	20.81	20.24	19.87	19.64	18.88
PI	14.23	13.62	12.67	9.7	12.9	12.69	9.76	13.13	11.36	8.12

Figure 6 shows the effect of molasses, the initial reduction in the liquid limit (LL) observed up to the $S_{4,12}$ treatments can be attributed to the cation exchange and adhesive properties of molasses. However, when the molasses content increases to 8% and 12%, the LL also rises. This increase occurs because the higher concentration of molasses in clay soil leads to a reduction in the size of individual soil aggregates. The values of Plastic Limit (PL) slightly declines with addition of sugar cane molasses in addition to cement up to 12%, as shown in Figure 7. Eventually, this causes the soil to revert to a finer state, which enhances its water-holding capacity and results in an increased LL and plasticity index (PI). The PI values for soils treated with molasses range from 9.7% to approximately 12.9%, aligning with the findings of M'Ndegwa [16].

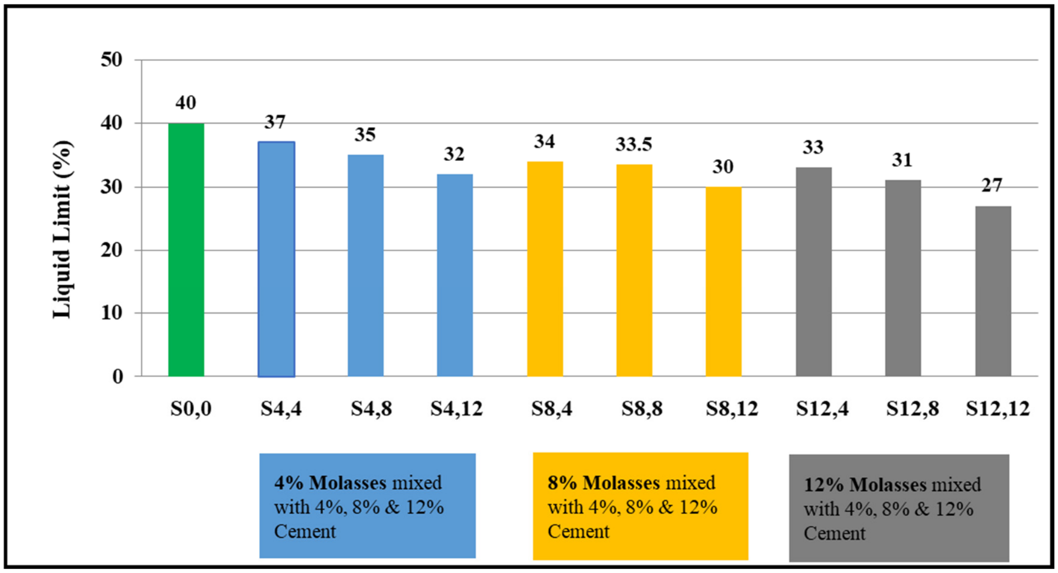

Figure 6. Liquid Limit result in terms of constant amount of Molasses and varying amounts of Cement.

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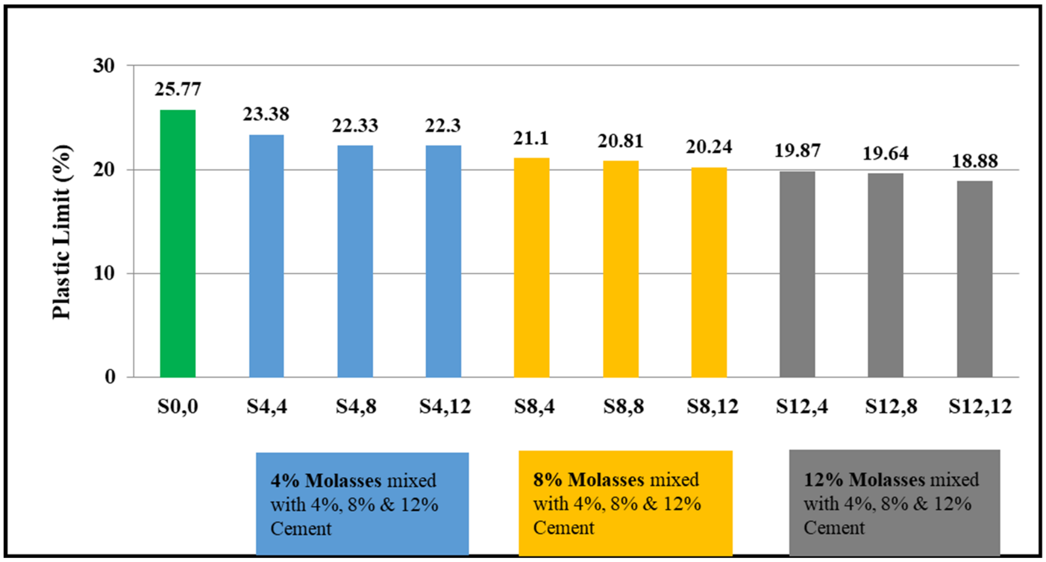

Figure 7. Plastic Limit result in terms of constant amount of Molasses and varying amounts of Cement**.**

Regarding cement, the initial reduction in the soil's water-holding capacity and LL is due to the cation exchange process between the soil's cations and those in the cement. This exchange suppresses the thickness of the double layer by increasing the cation concentration, as noted by Yu et al. [17]. Conversely, the decrease in LL with 8% cement can be attributed to a reduced pozzolanic reaction, which occurs due to the high concentration of $Ca(OH)_2$ when the cement content exceeds 4%. This pozzolanic reaction decreases the soil's water-holding capacity, thereby lowering both the LL and PL, as discussed by Bhattacharya [18].

The combined effects of molasses and cement on the Atterberg limits suggest a significant reduction in the soil's water-holding capacity, which may result from interactions among molasses, cement, clay, and water. As previously mentioned, the cation exchange and adhesive properties of molasses contribute to this reduction, while the hydration and pozzolanic reactions of cement have a similar effect in soil-cement mixtures, as supported by Estabragh et al. [19]. Stabilizing expansive clay soil with a combination of molasses and cement is a relatively new concept, and the literature on the interactions among these components is limited. Therefore, the observed reduction in the Atterberg limits may be due to one or more of the following mechanisms: cation exchange, hydration reaction, pozzolanic reaction, or the adhesive properties of molasses. Research indicates that the combination of molasses and cement effectively stabilizes subgrade soil, with all tested mixtures yielding PI values below 20%, as shown in Figure 8. This threshold is significant as it meets the criteria for adequate soil stabilization, which is crucial for construction and infrastructure projects. For instance, one study demonstrated that the addition of molasses to cement significantly improved the mechanical properties of the soil, resulting in enhanced stability and reduced plasticity [20].

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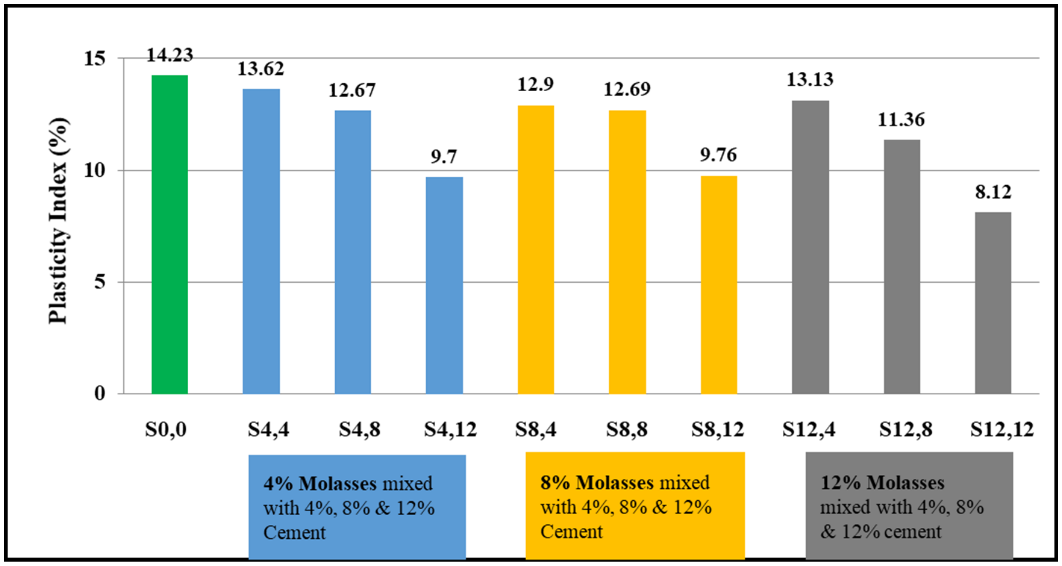

Figure 8. Plasticity Index result in terms of constant amount of Molasses and varying amounts of Cement.

5.3. Effect of Stabilizers on Standard Proctors

For optimum combinations of molasses, and cement with clay soil, standard proctor tests were performed in order to determine the MDD (maximum dry density) and OMC (optimum moisture content) of the soil during this research. The MDD and OMC of clayey soil were found to be 86.2 lb/ft^3 and 24.5 percent, respectively (Figures 9 and 10). Standard Proctor tests were conducted on both the native subgrade soils and the treated/stabilized soils following ASTM D-1557, as illustrated in Figure 12. Figure 11 presents a comparison of the compaction curves for the native subgrade soils and those treated with the specified stabilizers.

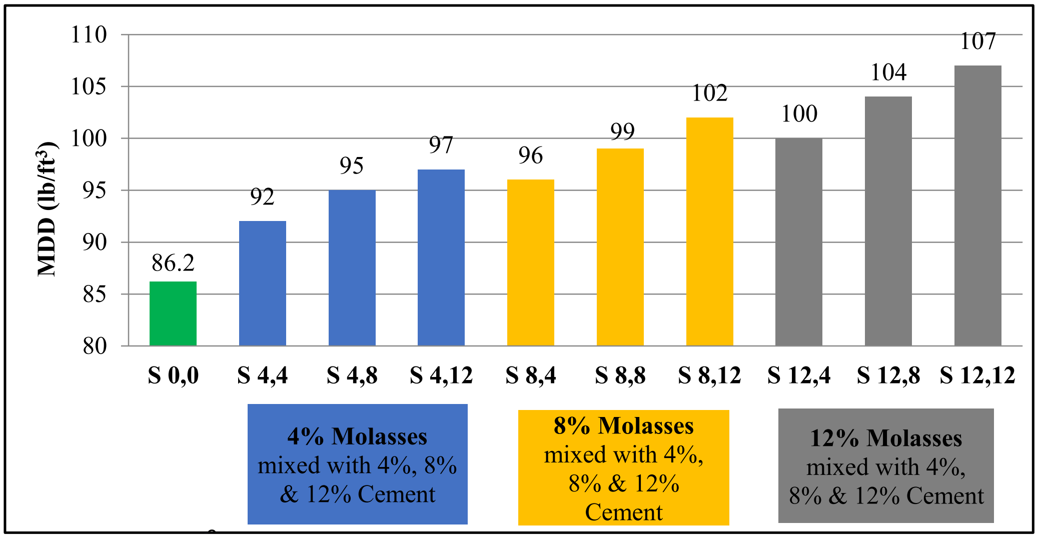

Figure 9. MDD result in terms of constant amount of Molasses and varying amounts of Cement.

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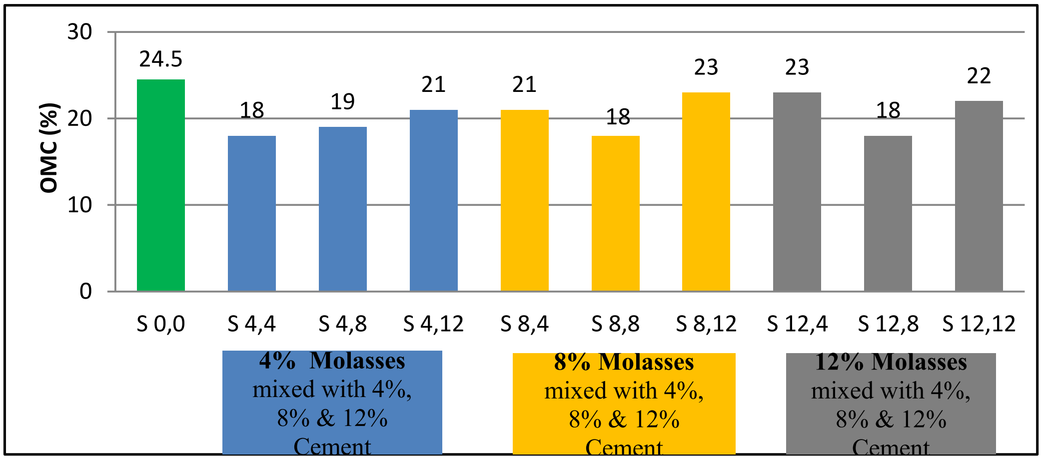

Figure 10. OMC result in terms of constant amount of Molasses and varying amounts of Cement.

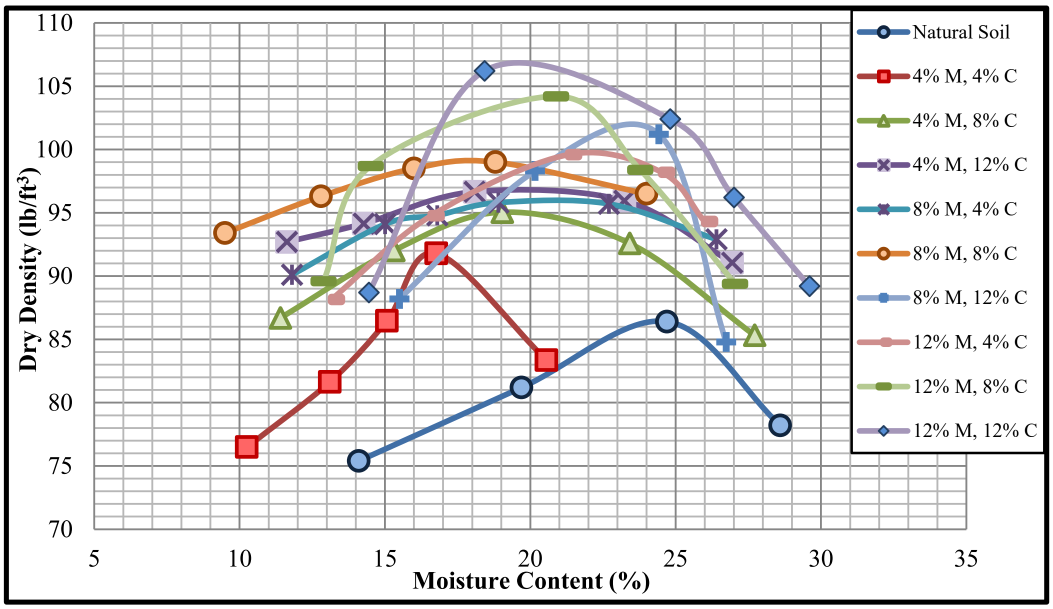

Figure 11. Compaction curve for the natural soil and stabilized soil with different additives.

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Figure 12. Standard Proctor Test.

Soils treated with molasses exhibit a characteristic bell-shaped curve in their moisture-density relationship, as shown in Figure 11. These curves shift to the left compared to untreated soils, indicating that molasses treatment increase the maximum dry density (MDD) and reduce the optimum moisture content (OMC). This observation aligns with the findings of Shirsavkar [21]. The increase in density can be attributed to the positive charge of molasses, which is readily attracted to the negatively charged surfaces of clay minerals. The adhesive properties of molasses further enhance its attraction to soil particles, binding them together. Suriadi [22] also reported that the addition of cane molasses to clay soil reduced the clay content.

Soils treated with cement display the usual bell-shaped curve in the moisture-density relationship, although these curves shifted to the left compared to untreated samples, as shown in Figure 11. The reduction in density might be due to the flocculation and agglomeration of clay particles, which occupy more space, resulting in a lower dry density. This observation is consistent with the effect of cement on the specific gravity of soils mixed with various cement concentrations, as reported by Wahab et al. [23].

Soils treated with a combination of molasses and cement exhibit the typical bell-shaped curve in the moisture-density relationship, although these curves shifted leftward compared to untreated soils. The increase in density could be linked to the reorganization of flocculated and agglomerated clay particles into a more compact arrangement due to the higher amount of plastic paste in soil-cement-molasses mixtures compared to soil-cement mixtures (Roshan) [24]. Additionally, the enlargement of clay particles transformed the fine soil into coarse soil, which may explain the reduction in optimum moisture content (OMC), as shown in Figure 10.

5.4. Effect of Stabilizers on UCS values

The stress-strain curves for untreated and treated soils using molasses and cement are determined in accordance with ASTM D-2166. Figure 15 illustrates the various stages of the UCS test execution. The results are presented in Figures 13 and 14, which compare the UCS values of the treated soils with those of the untreated soils.

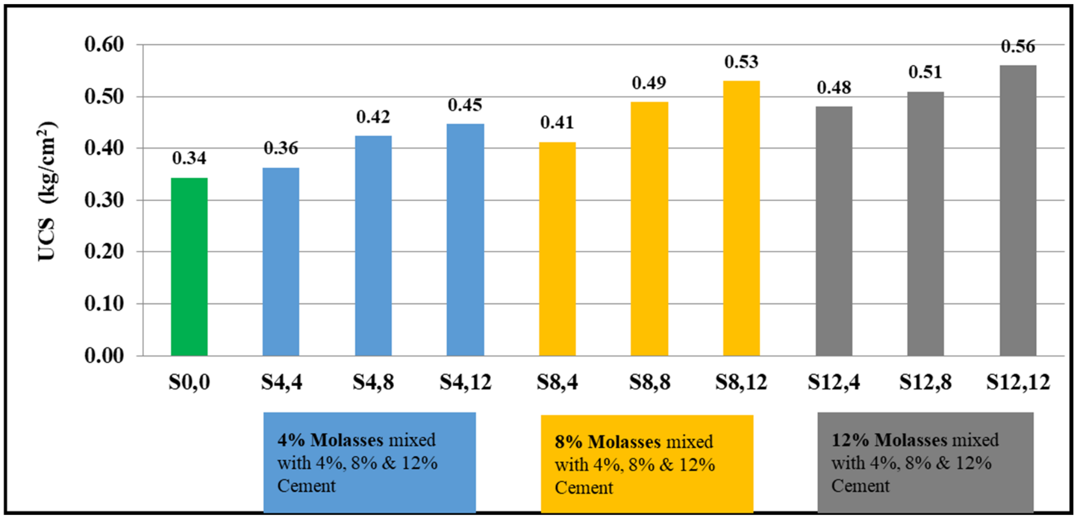

Figure 13. UCS values comparison of native soil with stabilized soil samples.

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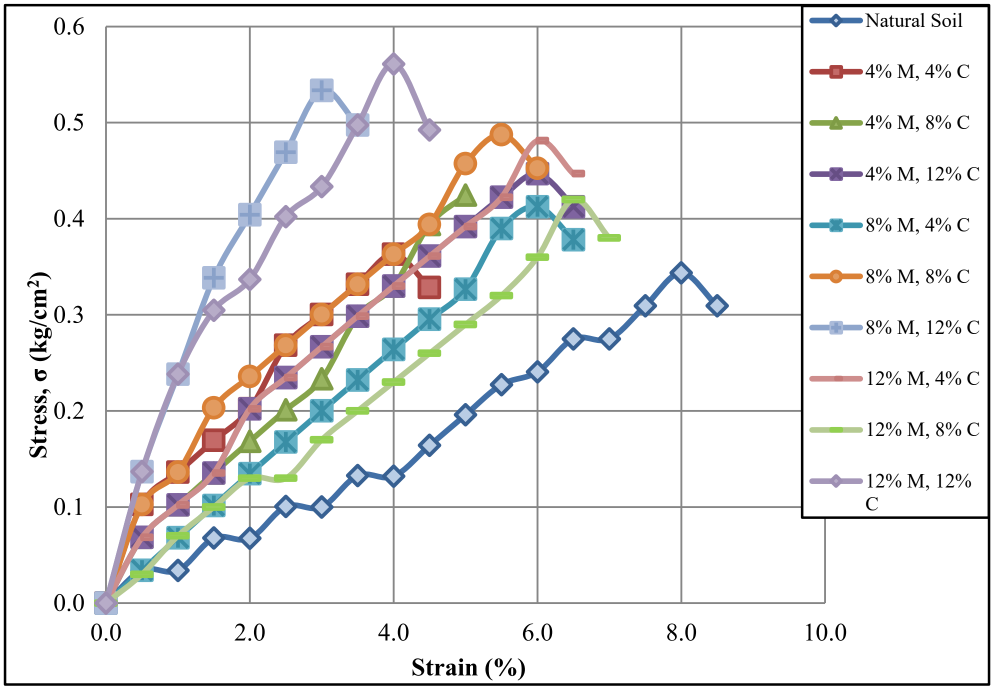

Figure 14. Summary of Stress-Strain curves for untreated soil and treated soil with different stabilizers.

(a)

(b)

(c)

(d)

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Figure 15. Unconfined Compression Test (a) Hand mixing of the soil-molasses-cement mixture; (b) Prepared soil sample coming out of UCS mold; (c) Appearance of shear planes in the soil after testing; (d) Specimens after UCS test.

The incorporation of molasses into untreated soils significantly enhances their strength while also improving their durability and cohesion, resulting in increased ductility as axial strain rises with higher molasses content. As shown in Figure 14, the stress-strain curves for soil specimens with varying molasses content shift to the right, indicating that the strain at failure increases with the addition of stabilizers. This suggests that molasses-treated soils exhibit greater ductility compared to untreated soils. This observation aligns with the findings of (Tsutsumi, 2022; Nabil, 2019) [25,26]. The observed increase in UCS values for soils treated with molasses is likely due to cation exchange reactions, flocculation, and agglomeration effects. However, a decrease in UCS values at higher molasses concentrations may be due to the coating of individual soil particles with molasses. It is generally observed that UCS values increase with higher cement content. The stress-strain curves for soil specimens with varying cement levels, as shown in Figure 14, reveal a shift to the left, indicating a decrease in failure strain with the addition of stabilizers [27]. Furthermore, the failure mode of the treated material displays a brittle behavior, as illustrated in Figure 15.

The UCS results, as depicted in the Figure 13, indicate that the soil's strength improves with the addition of molasses and cement. The native soil ($S_{0,0}$) exhibits the lowest UCS value of 0.34 kg/cm². With the incorporation of 4% molasses and varying cement percentages, the UCS gradually increases, reaching up to 0.45 kg/cm² for the $S_{4,12}$ sample. This trend continues with higher molasses content; for instance, the $S_{8,12}$ sample, containing 8% molasses and 12% cement, achieves a UCS of 0.53 kg/cm². The highest UCS value of 0.56 kg/cm² is observed in the $S_{12,12}$ sample, indicating a significant enhancement in soil strength. The stress-strain curves for soil specimens with varying molasses and cement content, as shown in Figure 14, demonstrated a leftward shift, indicating a decrease in failure strain with the addition of these stabilizers. The natural soil shows the least resistance to stress, while samples with higher molasses and cement content, particularly the 8% molasses and 12% cement combination, demonstrate superior stress resistance and less strain before failure. Overall, the study reveals that higher percentages of molasses and cement substantially enhance the soil's compressive strength, with the most effective treatment being 8% molasses combined with 12% cement.

5.5. Effect of Stabilizers on CBR Values

CBR tests were carried out on untreated and treated soils, in accordance with ASTM D-1883. The tests, which included stabilizer contents up to 12%, involved a 4-day soaking period and a 7-day curing period, with the results displayed in Figure 16.

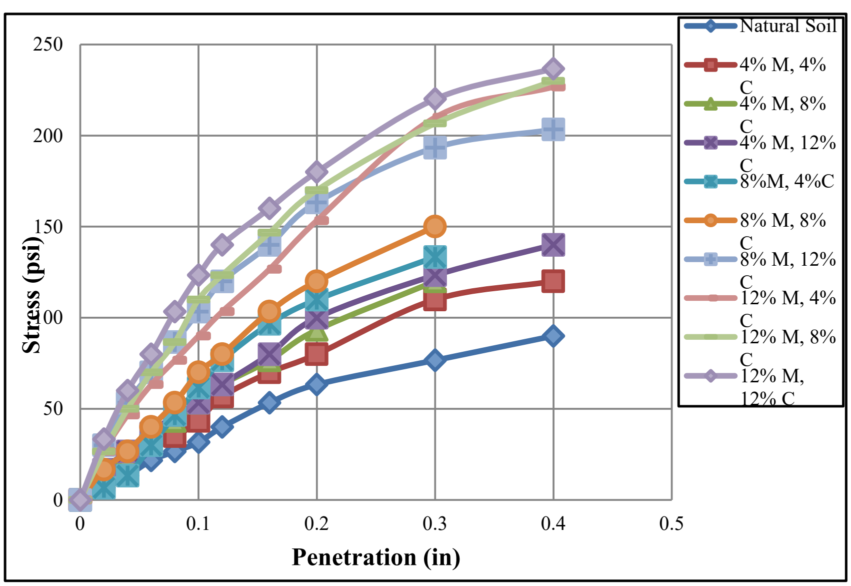

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Figure 16. CBR combine graph of Stress versus Penetration of native and stabilized soil.

Figure 17 illustrates that the CBR of treated soil increases with molasses content up to 8%, after which it declines as the molasses content continues to rise. The highest CBR value is observed with a combination of 12% molasses and 12% cement. These findings align with those reported by Ndegwa [28]. The increase in CBR values for soils treated with molasses is attributed to cation exchange reactions, as well as the flocculation and agglomeration effects. Taye et al. [29] explained that the decrease in soil pH is due to calcium and magnesium cations from cane molasses replacing weaker monovalent sodium ions at the clay particle surfaces. The decline in CBR values when molasses content exceeds a certain threshold may be due to the coating of individual soil particles with molasses [30].

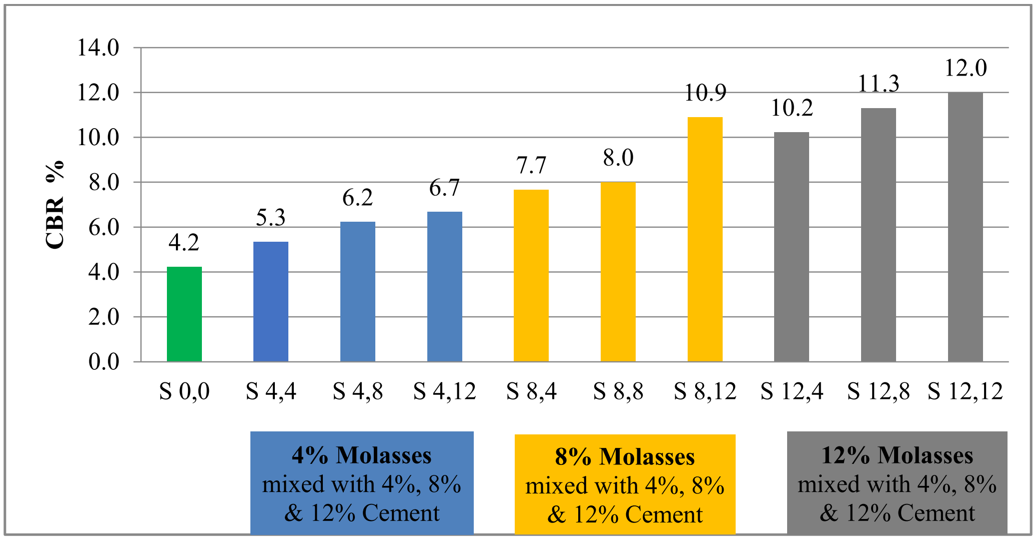

Figure 17. CBR values comparison of native soil with stabilized soil samples.

The results indicate that the CBR value of soils treated with cement increases as the cement content rises. This improvement may be attributed to the formation of secondary cementitious materials, which are produced by the reaction between free lime $Ca(OH)_2$ released during cement hydration and the pozzolanic reaction between the lime and soil.

The significant increase in CBR value can be attributed to the interactions between molasses, cement, clay soil, and water. As discussed earlier, the cation exchange reaction and the adhesive properties of molasses contribute to the enhanced load-bearing capacity of the soil. Additionally, the hydration of cement and the pozzolanic reaction further improve the soil-cement mixture [31]. Soils stabilized with $S_{12,4}$, $S_{12,8}$, and $S_{12,12}$ after 7 days of curing and 4 days of soaking, achieved CBR values of 10.2%, 11.3%, and 12%, respectively. The peak California Bearing Ratio (CBR) values recorded at 12% indicate a slight compliance with the Engineering Research Association (ERA) specification, which mandates a minimum CBR value of 10% after a 7-day curing period for effective sub-grade soil stabilization. All the stages of sample preparation for CBR testing are presented in Figure 18.

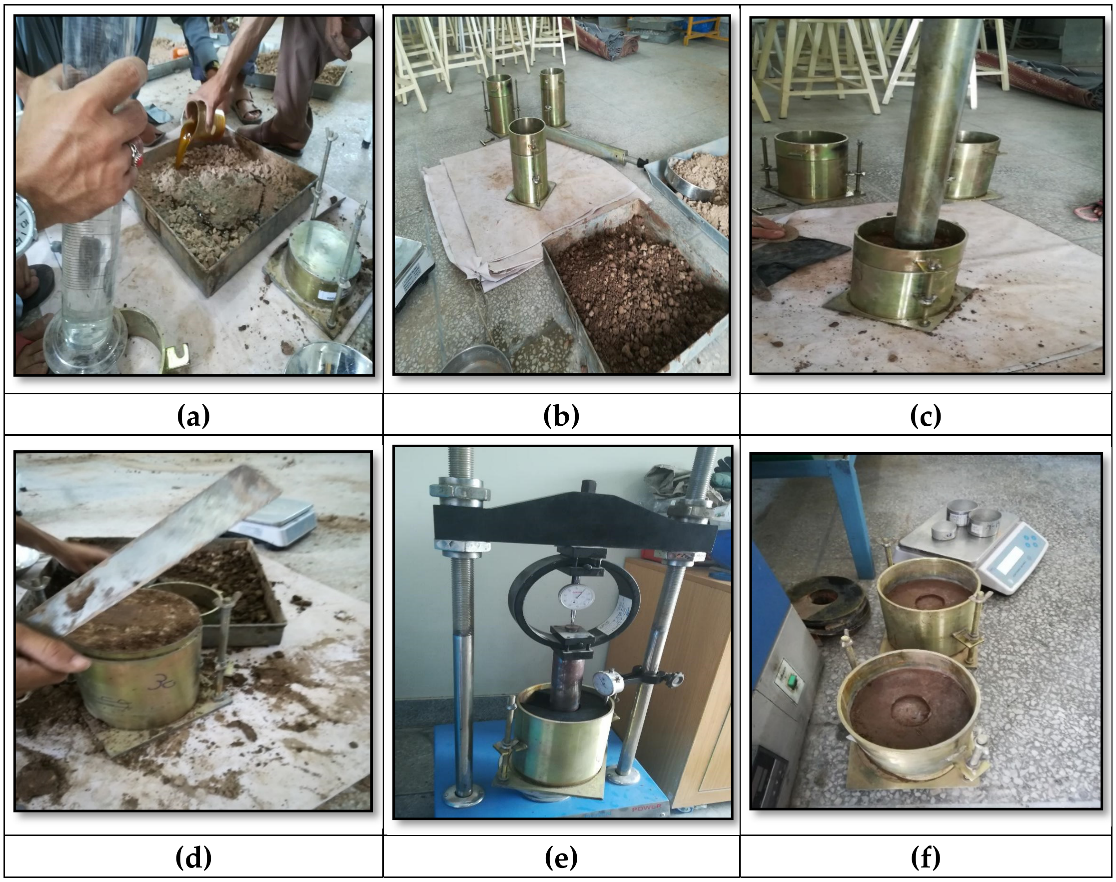

Figure 18. Stages of sample preparation for CBR testing (a) Hand-mixing of soil, molasses and cement; (b) Sample pouring in CBR mold for compaction; (c) Layer-by-layer compaction of soil mix with molasses and cement in CBR mold by modified proctor hammer; (d) Trimming and leveling of the mix by spatula; (e) Prepared mold placed in the machine for CBR testing; (f) Tested CBR samples.

5.6. CBR Swell of Expansive Clay Soils

Soil treated with molasses exhibits a reduction in CBR swell compared to the 9.66% observed in untreated soil, as shown in Figure 19 and Table 6. Additionally, it is noted that the swelling potential decreased with increasing molasses content up to 4%, but began to rise again beyond 8% molasses content, leading to an increase in swelling potential. Amrisha et al. [32] observed a similar trend in his study on the effects of cane molasses on the strength of expansive soil, finding a comparable relationship between molasses content and swelling potential in terms of CBR swell, although with lower CBR swell values than those reported in this research. This discrepancy could be attributed to differences in the clay mineralogy of the expansive soils [33]. The addition of molasses and cement significantly reduced CBR swell. Furthermore, it is observed that the swelling potential of expansive soils treated with molasses and cement decreases as the percentage of stabilizers is increased. These reduced swell characteristics are generally attributed to the lower water affinity of calcium-saturated clay and the formation of a cementitious matrix that resists volumetric expansion [34]. Figure 20 shows dial gauges mounted on top of molds soaked in water to measure swelling after a 4-day period.

Table 6. CBR swell results with additives.

Soil Type	Mould Height (mm)	Change in Length in mm during soaking	CBR Swell (%)	% Change
$S_{0,0}$	116.43	11.25	9.66	0.00
$S_{4,4}$	116.43	8.5	7.30	-24.43
$S_{4,8}$	116.43	8	6.87	-28.88

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$S_{4,12}$	116.43	6.75	5.80	-39.95
$S_{8,4}$	116.43	7.4	6.36	-34.16
$S_{8,8}$	116.43	6.6	5.67	-41.30
$S_{8,12}$	116.43	5.2	4.47	-53.72
$S_{12,4}$	116.43	7	6.01	-37.78
$S_{12,8}$	116.43	4.95	4.25	-56.0
$S_{12,12}$	116.43	4.45	3.82	-60.45

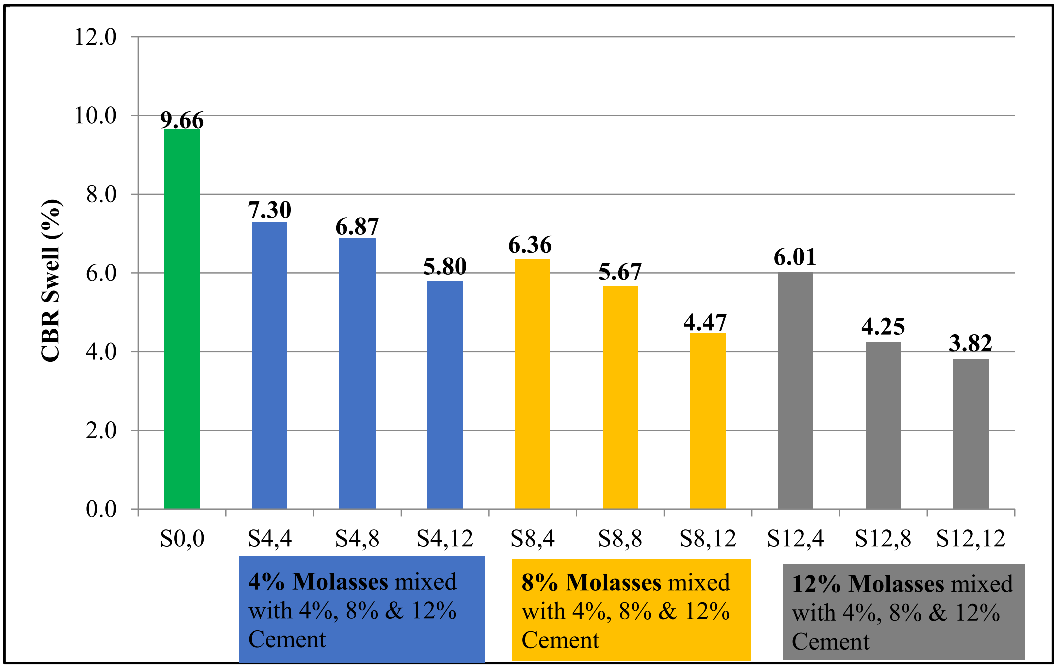

Figure 19. CBR swells for treated and untreated soils.

Figure 20. Dial gages placed on top of mold soaked in water for swell measurement after 4 days.

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6. Conclusions and Recommendations

This research rigorously investigated the effectiveness of sugar cane molasses and cement in addressing the challenges posed by expansive soils. An extensive array of geotechnical assessments was performed to ascertain the soil's consistency, compaction characteristics, and California Bearing Ratio (CBR) performance while taking into account its long-term stability. Moreover, molasses, being economical by-products of industrial processes, contribute to a reduction in environmental pollution when utilized in the construction of pavement subgrades. The following conclusions are drawn from this research study.

i. The values of Liquid Limit decline with the addition of sugar cane molasses and cement up to 12%. For the stabilized soil, the Liquid Limit value decreased from 40% to 27% compared to the unstabilized soil. The values of Plastic Limit also slightly decline with the addition of sugar cane molasses and cement up to 12%. Additionally, the values of the Plasticity Index decrease with the addition of sugar cane molasses and cement.

ii. The values of MDD increase with the addition of sugar cane molasses and cement up to 12%, while the values of OMC decrease with the increasing percentages of sugar cane molasses and cement in the soil sample.

iii. In the unconfined compression test, it is observed that the compressive strength of the stabilized soil increased by 64.7% with the addition of sugar cane molasses and cement up to 12%, after curing for 7 days, compared to the strength of the native soil. Soil treated with molasses exhibits a plastic nature, while soil treated with cement shows a brittle nature, with shrinkage cracks observed. The addition of molasses to cement reduces the soil's brittleness.

iv. The addition of 12% sugar cane molasses to 12% cement increases the CBR value from 4.2% in the native soil to 12.3% in the stabilized soil and reduces the swell value from 9.66% in the native soil to 3.82% in the stabilized soil, after curing for 7 days. Thus, the geotechnical properties of the soil are improved.

It is recommended that sugar cane molasses and cement additives be used up to 15% for soil stabilization. Since the stabilization of expansive soil with a cement and molasses mixture is a relatively new concept, the chemical interactions and mechanisms involved among cement, sugar cane molasses, water, and expansive clay soil should be studied further. Additionally, the effect of the curing period on soils treated with the molasses and cement combination should also be investigated.

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