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Stabilization of Expansive Soil by Improving the Engineering Properties Using Lime and Fly Ash

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Abstract: Soil stabilization stands as a vital process aimed at enhancing the structural qualities of expansive soil to bolster its stability. This involves meticulous compaction control, appropriate mixture ratios, and the introduction of suitable additives and stabilizing agents. Numerous infrastructure endeavors, including roads, railways, water reservoirs, and land reclamation ventures, demand substantial volumes of earth materials. However, regions featuring expansive soil, unfit for construction purposes, necessitate stabilization interventions. Utilizing local resources like sand, silt, lime, and fly ash can effectively stabilize such soil. The current research study centers on investigating the effectiveness of lime and fly ash as additives or stabilizers to heighten the engineering attributes of expansive soil. The research project systematically assesses the impact of lime and fly ash on crucial soil engineering properties, encompassing liquid limit, plastic limit, compaction characteristics, and the California Bearing Ratio (CBR). The experimentation involves varying proportions of lime (ranging from 3% to 12%) and fly ash (ranging from 10% to 40%) within the expansive soil. Outcomes indicate that the introduction of lime elevates the liquid limit, Maximum Dry Density (MDD), and CBR, while diminishing the plastic limit, and Optimum Moisture Content (OMC) of the soil. On the other hand, the inclusion of fly ash reduces the liquid limit, plastic limit, and OMC of expansive soil, concurrently increasing the MDD and CBR values. The primary aim of this research endeavor revolves around determining the viability of lime and fly ash as modifiers or stabilizers for expansive soil in the context of road construction. The study strives to pinpoint the optimal quantities of lime and fly ash that yield optimal performance, particularly in terms of CBR, when the soil functions as a subgrade in highway projects. The findings affirm that the amalgamation of lime and fly ash effectively stabilizes expansive subgrade soils, presenting an economically efficient solution. The results underscore that the incorporation of lime and fly ash augments the geotechnical qualities of expansive soil, rendering it a feasible choice for roadwork and other construction undertakings.

Keywords: Soil Stabilization, Expansive Soil, Fly Ash, Lime Stabilization, Sustainability, Waste Materials, Clay Soil

1. Introduction

Expansive soils are clay soils that experience significant volume changes due to variations in soil moisture. When these soils become wet and then dry, they can cause severe damage to pavements constructed on them. Such pavements on expansive subgrade soils often display early distress, leading to premature failures of the pavement structure. Expansive soils typically exhibit undesirable engineering properties, including low bearing capacity, poor stability, and excessive swelling. These soil characteristics pose serious challenges to civil engineering structures, particularly road pavements built on them.

To address the issues caused by expansive soils, researchers have been extensively studying the problem and exploring remedial measures. Among various solutions, soil stabilization has emerged as the most practical option. Stabilizing such soils can effectively improve their properties and mitigate the negative impacts they pose. Chemical admixtures are widely and commonly used for soil stabilization [1], with lime and fly ash being reported as successful stabilizers for expansive soils [2-5].

The objective of this experimental study is to investigate the improvements in strength characteristics and other properties of expansive soil achieved through the use of lime and fly ash as stabilizers. By analyzing the effects of these stabilizers on the soil, the research aims to provide valuable insights into enhancing the engineering properties of expansive soils, ultimately contributing to more resilient and durable road pavements and other civil engineering structures.

2. Literature Review

Soil stabilization is a crucial process aimed at enhancing specific properties of weak soils, such as expansive clay, to make them stable and suitable for particular purposes. Stabilization leads to notable improvements in engineering properties, including increased soil strength (shearing resistance), stiffness (resistance to deformation), and durability (wear resistance), as well as reduced swelling potential in wet clay soils, among other desirable characteristics [6].

There are two primary categories of soil stabilization techniques: mechanical or granular stabilization and chemical stabilization. Mechanical stabilization involves mixing or blending soils to achieve a material that meets the required specifications. On the other hand, chemical stabilization entails mixing or injecting the soil with chemically active compounds, such as Portland cement, lime, fly ash, calcium or sodium chloride, or bitumen materials. Understanding the mechanisms behind the additive's stabilization is crucial for successful soil stabilizer applications [7].

Lime is a widely used additive for improving the properties of expansive soils. The diverse application of lime includes its use in different forms, such as quicklime (calcium oxide), hydrated lime (calcium hydroxide), or lime slurry, to provide soil stabilization for clay soils. Quicklime is produced through a chemical transformation of calcium carbonate (limestone – $CaCO_3$) into calcium oxide. When quicklime reacts chemically with water, hydrated lime is formed [8].

Lime stabilization brings about long-lasting changes in the characteristics of clay soils. When lime is mixed with moist clay, several reactions occur, including cation exchange, pozzolanic reaction, and carbonation [9]. The cation exchange process leads to the aggregation of soil particles, resulting in the early development of strength in the stabilized soil. On the other hand, the pozzolanic reaction takes place more slowly and is responsible for the later development of strength in the stabilized soil.

The properties of soil-lime mixtures are influenced by various factors, including the type of soil, the type of lime used, the percentage of lime added, and the curing conditions (time, temperature, and moisture) [3]. Lime has a significant impact on the behavior of the soil, resulting in notable changes in its characteristics.

When lime is added to the soil, it reduces the plasticity index, making the soil more workable and easier to handle. The reaction between lime and the soil alters the moisture-density relationship, which varies depending on the type of soil and the amount of lime added. This alteration can lead to changes in the compaction curve, with lime-treated soil showing higher values of density and lower moisture content compared to untreated soil.

As per a study investigating three distinct Virginia soils, the incorporation of 3% to 5% hydrated lime resulted in a substantial enhancement of the soaked California Bearing Ratio (CBR), elevating it from less than 5% to nearly 100% [10]. The strength gain in soils stabilized with lime depends on their mineralogical constituents and the surrounding environment [11]. For specific soil types, such as Kaolinite, illite, and montmorillonite, the optimum amount of lime required for maximum strength gain is around 4% to 6%, 8%, and 8% respectively.

Furthermore, lime can effectively reduce the swelling characteristics of stabilized clayey soil [12]. For example, the addition of 6% lime to Oman expansive soil led to a reduction in swelling pressure from 250 kPa to 0. Similarly, the swelling pressure of highly plastic clay was reduced from 2600 kPa to 1700 kPa with the immediate addition of 10% hydrated lime, and further decreased to 0 kPa after 28 days of curing with only 4% hydrated lime [13].

Fly ash is a waste material produced as a byproduct of burning coal for electrical energy generation. It is abundantly available, cost-effective, and environmentally friendly. Unfortunately, in many countries, only a small percentage of fly ash is utilized in the construction industry, and the rest is discarded, causing significant environmental issues. However, fly ash holds great potential as a beneficial material for soil stabilization [14].

Fly ash is classified into two categories: Class F and Class C, based on their chemical composition. Class F fly ash is obtained from the combustion of anthracite and bituminous coals, and it contains a small quantity of lime (CaO). This type of fly ash consists of siliceous and aluminous materials (pozzolans) that possess little or no cementitious value. Nevertheless, when exposed to moisture, these materials undergo a chemical reaction with lime at standard temperatures, leading to the formation of cementitious compounds [15]. Class C fly ash, produced from lignite and sub-bituminous coals, typically contains a significant amount of lime along with pozzolanic materials [16].

It is highly recommended to use fly ash for soil stabilization wherever it is easily and economically available. When fly ash is added to expansive soils, it immediately initiates a cation exchange process, resulting in reduced plasticity, activity, and swelling potential of the soil [17]. The stable exchangeable cations provided by fly ash, such as Ca^{2+}, Al^{3+}, and Fe^{3+}, promote flocculation of the clay particles, leading to improved stability and reduced swelling behavior in the stabilized soil.

Moreover, the time-dependent cementation process, known as the pozzolanic reaction, leads to the formation of cemented compounds characterized by high strength and minimal volume change [18]. Studies have shown significant reductions in the free swell index when Class C fly ash is added to expansive soils. For example, a 60% reduction was observed for expansive soil A, and a 63% reduction for expansive soil B when treated with 15% Class C fly ash.

Other research reported notable decreases in swelling potential when expansive soils were stabilized with fly ash.

For instance, treating expansive soil composed of 85% sodium bentonite and 15% kaolinite with 25% of fly ash-1 and fly ash-2 (both Class C fly ashes) resulted in reductions of 52.6% and 58.3%, respectively [19]. Similarly, the addition of 20% fly ash led to a 65% reduction in swelling potential, a result similar to that achieved with 8% lime stabilization [4]. These findings demonstrate the effectiveness of fly ash in mitigating swelling issues in expansive soils.

Research also revealed that treating expansive soils with 12% fly ash led to a decrease in swelling pressure from 120 kPa to 90 kPa for expansive soil A and from 160 kPa to 105 kPa for expansive soil B. Both soils exhibited high plasticity and were classified as CH soils [18]. Additionally, the use of fine fly ash mixture resulted in 25% higher peak strength compared to coarse fly ash [20]. Furthermore, the addition of lime and fly ash as admixtures to expansive soil improved its California Bearing Ratio (CBR) value and reduced its hydraulic conductivity [21]. This combination of stabilizing admixtures proves beneficial for soils with lower plasticity and higher silt content. From a material cost perspective, using less expensive fly ash can reduce the overall amount of lime required for stabilization, making the process more cost-effective. These findings emphasize the practical advantages of employing fly ash and lime in soil stabilization projects to improve soil properties and mitigate the challenges associated with expansive soils.

3. Materials and Methodology

In this study, expansive clayey soil was collected from Charghat, Rajshahi, Bangladesh, at a depth of 1.0m below the ground surface, from an open excavation site. Prior to testing, the soil was air-dried and sieved through a 4.75mm sieve for further preparation. Standard test procedures, as per ASTM guidelines, were conducted to determine the index properties and compaction parameters of the soil, and the results are presented in Table 1.

Table 1. *Characteristics of the clayey soil.*

Property	Value
Liquid Limit (%)	39.73
Plastic Limit (%)	15.33
Plasticity Index (%)	24.40
Maximum Dry Density (gm/cm^3)	1.66
Optimum Moisture Content (%)	21.71
Specific Gravity	2.69
Soaked CBR (%)	2.85

Based on the ASTM classification, the soil was identified as inorganic clay, categorized as CL.

The fly ash used in this research was sourced from Maowa Orion Coal Power Plant in Munshiganj, Dhaka Division, Bangladesh. The fly ash was air-dried and pulverized before being utilized in the experiments. Fly ash represents a residual byproduct generated from thermal power plants. Although it possesses little cementitious value on its own, when exposed to moisture, it undergoes a chemical reaction and forms cementitious compounds. This reaction contributes to the enhancement of strength and compressibility characteristics of soils when used as a stabilizer.

The grade of the fly ash used in this study is classified as "F" grade, and the chemical compositions are provided in Table 2 below.

Table 2. *Chemical compositions of fly ash.*

Ingredient	Percentage
Silicon Oxide, SiO_2	61.00%
Aluminium Oxide, Al_2O_3	27.26%
Ferric Oxide, Fe_2O_3	4.95%
Calcium Oxide, CaO	2.65%
Magnesium Oxide, MgO	1.47%
Titanium Oxide (TiO_2)	1.03%
Sodium Oxide, Na_2O	0.63%
Phosphorus Pentoxide (P_2O_5)	0.60%
Potassium Oxide (K_2O)	0.35%
Sulfur trioxide (SO_3)	0.06%

The lime used in this research as a stabilizer and binder has been sourced locally and meets the general requirements for construction purposes. The basic constituents of lime are presented in Table 3 below.

Table 3. *Chemical compositions of lime.*

Properties	Value
Calcium Oxide, CaO	64.10%
Silicon Oxide, SiO_2	20.76%
Aluminium Oxide, Al_2O_3	6.35%
Ferric Oxide, Fe_2O_3	3.60%
Magnesium Oxide, MgO	0.67%
Potassium Oxide (K_2O)	0.01%
Sodium Oxide, Na_2O	0.01%
Carbon (C)	4.50%

The index tests conducted in this study involved Atterberg limits tests, specific gravity analysis, and grain size analysis. The soil was subjected to index property tests, a modified compaction test, and the California Bearing Ratio (CBR) test after stabilization with varying percentages of lime and fly ash separately.

The purpose of these tests was to assess the soil's basic characteristics, plasticity, consistency, and particle size distribution. Furthermore, the study aimed to evaluate how the addition of different percentages of lime and fly ash affected the soil's engineering properties, including compaction behavior, strength, and load-bearing capacity. By performing these tests separately with lime and fly ash, the research seeks to determine the optimal stabilizer percentages for improving the soil's suitability for construction applications.

4. Result and Discussion

Figure 1 illustrates the variation of the liquid limit of the soil with the addition of different percentages of fly ash. Based on the test results, it has been observed that the liquid limit of the soil decreases gradually from an initial value of 39.73% to a lower value of 30.82% as the percentage of fly ash increased from 0% to 40%.

The liquid limit of expansive clayey soil decreases with the addition of fly ash content due to the pozzolanic reaction between fly ash and the clay minerals present in the soil. This reaction leads to the formation of additional cementitious compounds, which contribute to the stabilization of the clayey soil. As a result of this pozzolanic reaction, the clay particles tend to flocculate and become more stable. This reduces the plasticity of the soil, as indicated by the decrease in the liquid limit. A lower liquid limit means that the soil has a reduced tendency to undergo excessive volume changes upon wetting and drying, which is a desirable property for construction purposes.

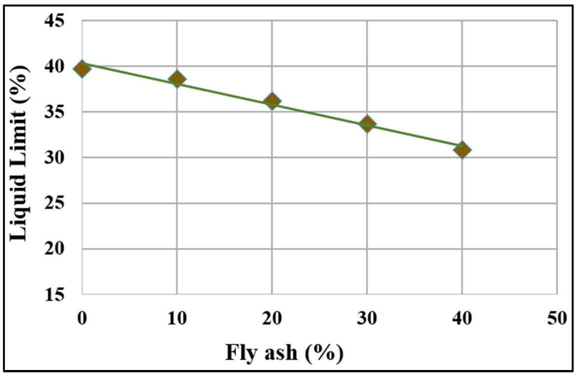

Figure 1. *Variation of Liquid Limit with percentage of fly ash.*

Figure 2 demonstrates the correlation between the plastic limit of the soil with the addition of different percentages of fly ash. The test results clearly show that as the percentage of fly ash increases from 0% to 40%, the plastic limit of the soil undergoes a reduction from an initial value of 15.33% to a lower value of 11.68%. The addition of fly ash can lead to improved particle packing in the soil matrix. The fly ash particles fill the voids between the soil particles, resulting in a more densely packed soil structure. This increased particle packing reduces the void spaces available for water to be retained, leading to a reduction in the water content required for the soil to exhibit plastic behavior.

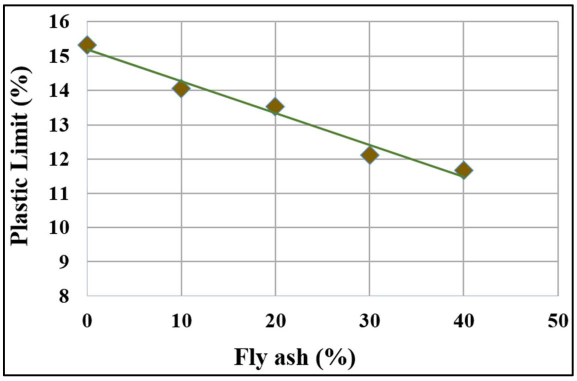

Figure 2. *Variation of Plastic Limit with percentage of fly ash.*

The relationship between the plasticity index and the addition of fly ash is illustrated in Figure 3. It is evident from the figure that as the percentage of fly ash increases, the plasticity index of the soil consistently decreases. Specifically, the plasticity index decreases from an initial value of 24.40% to a lower value of 19.14% as the percentage of fly ash is increased from 0% to 40%.

The decrease in the plasticity index is a result of the combined effects of fly ash on the soil's plastic and liquid limits. As discussed earlier, fly ash acts as a pozzolanic material and promotes the flocculation of clay particles, reducing the soil's plasticity. Additionally, the chemical reactions and particle packing effects of fly ash contribute to the reduction in the liquid limit.

As a result, the plasticity index, which is the difference between the liquid limit and the plastic limit, decreases as both limits decrease with the inclusion of fly ash. This decrease in the plasticity index indicates that the soil becomes less prone to volume changes and displays improved engineering properties as a stabilizer.

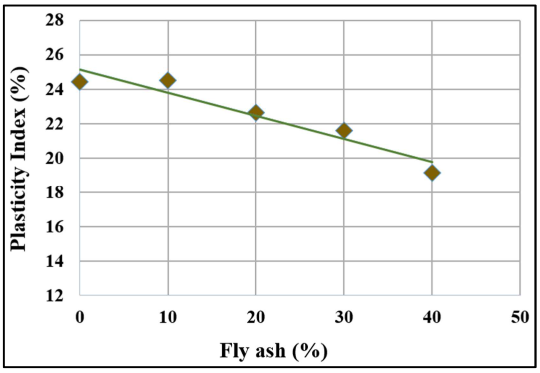

Figure 3. *Variation of Plasticity Index with percentage of fly ash.*

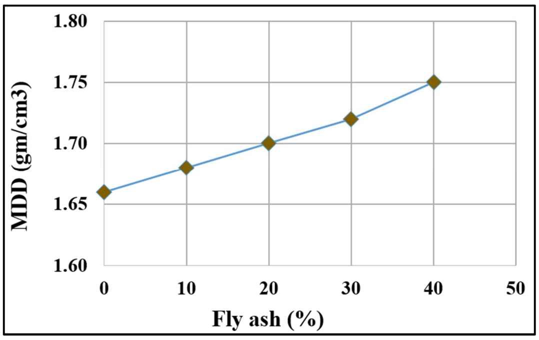

Figure 4. *Variation of MDD with different percentages of fly ash.*

The variation of the Maximum Dry Density (MDD) with the inclusion of fly ash at different percentages is depicted in Figure 4. The test results indicate that as the percentage of fly ash increases, the MDD of the soil increases as well. Specifically, when 40% fly ash is added to the parent soil, the MDD increases from 1.66 gm/cm^3 to 1.75 gm/cm^3. Fly ash acts as a filler material, reducing the void spaces between soil particles. This filling effect leads to a more compacted arrangement of particles, resulting in increased dry density. Fly ash particles can mechanically interlock with soil particles, providing additional stability and promoting densification during compaction.

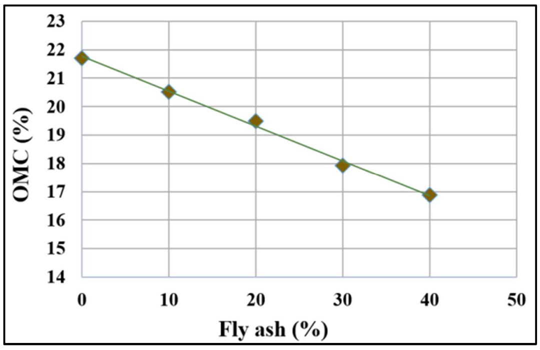

Figure 5. *Variation of OMC with different percentages of fly ash.*

Figure 5 displays the relationship between the Optimum Moisture Content (OMC) and the inclusion of fly ash at different percentages. Fly ash is a pozzolanic material that reacts with the clay minerals in the soil, causing particle agglomeration and reducing the water content needed for compaction. This leads to a decrease in OMC as less water is required to achieve the maximum dry density (MDD) during compaction. The decrease in OMC results in a more compacted and denser soil structure with better engineering properties.

The variation of soaked California Bearing Ratio (CBR) values with the increasing percentages of fly ash is displayed in Figure 6. The CBR value increases with the addition of fly ash because of the beneficial effects of fly ash on soil properties. When fly ash is mixed with the soil, it chemically reacts with the soil particles, leading to improved bonding and strength characteristics. As a result, the soil-fly ash mixture exhibits higher CBR values compared to the untreated soil. The increase in CBR indicates an enhancement in the load-bearing capacity and overall strength of the stabilized soil, making it more suitable for engineering applications, such as road construction and pavement design.

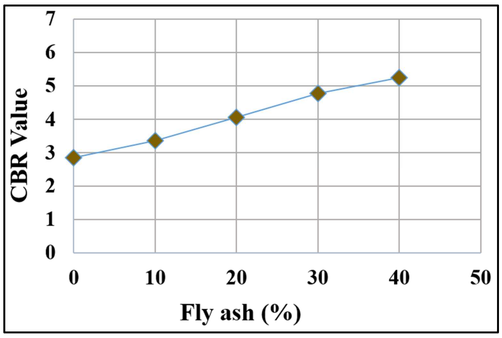

Figure 6. *Variation of CBR value with different percentages of fly ash.*

Table 4 presents the test results for different percentages of fly ash mixed with clayey soil.

Table 4. *Test results for different percentages of fly ash mixed with soil.*

Sl No	Types of soil	Liquid Limit	Plastic Limit	OMC	MDD	CBR (Soaked)
1	Soil	39.73%	15.33%	21.71%	1.66	2.85
2	Soil+10% Fly ash	38.57%	14.06%	20.52%	1.68	3.37
3	Soil+20% Fly ash	36.18%	13.54%	19.49%	1.70	4.06
4	Soil+30% Fly ash	33.69%	12.11%	17.93%	1.72	4.77
5	Soil+40% Fly ash	30.82%	11.68%	16.87%	1.75	5.24

Figure 7 typically demonstrates how the liquid limit of the soil changes as lime is added in different proportions. Lime has a drying effect on the soil, which means it reduces the soil's ability to retain water and decreases its plasticity. Plasticity refers to the soil's ability to change shape and retain its form under different moisture conditions. So, with the addition of lime, the soil becomes less flexible and more stable.

As a consequence of reduced plasticity, the liquid limit of the soil increases. The liquid limit represents the moisture content at which the soil transforms from a plastic, moldable state to a liquid state. With decreased plasticity, the soil requires more water content to reach this liquid-like behavior. The increase in liquid limit occurs because the lime-stabilized soil has a lower capacity to hold water, making it closer to the liquid state at higher moisture content.

To sum it up, lime reduces the soil's ability to retain water and makes it less plastic. This reduction in plasticity leads to an increase in the liquid limit, as the soil needs more water content to reach its liquid state. The overall effect of lime stabilization is to enhance the soil's stability and reduce its susceptibility to moisture-related issues.

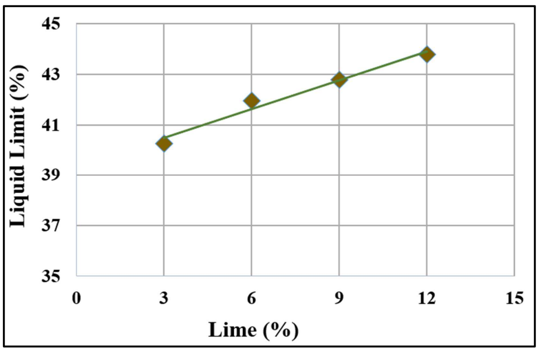

Figure 7. *Variation of Liquid Limit with percentage of Lime.*

Figure 8 presents the relationship between the plastic limit and the amount of lime added to the soil. The addition of lime to the soil decreases its plastic limit.

The cementitious compounds formed due to lime stabilization increase the cohesion between soil particles. This cohesion makes the soil more stable and less prone to deformation under loading, contributing to the decrease in the plastic limit.

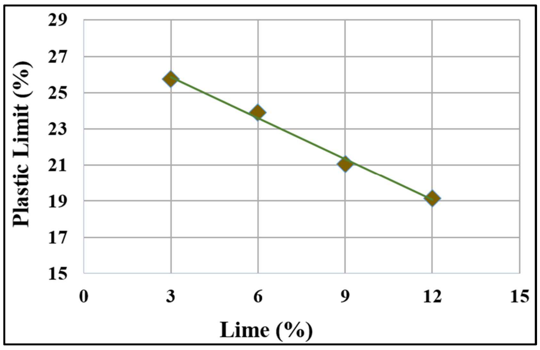

Figure 8. *Variation of Plastic Limit with percentage of Lime.*

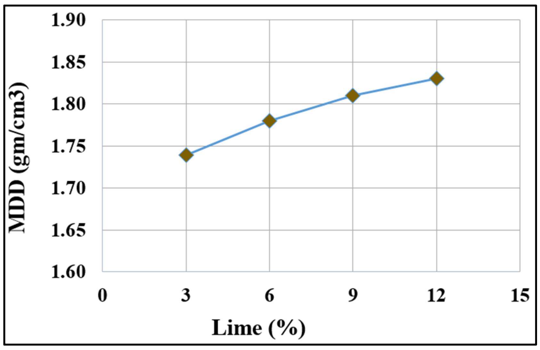

Figure 9. *Variation of MDD with different percentages of Lime.*

The addition of lime to the soil increases its Maximum Dry Density (MDD) due to the reaction with clay minerals, causing particle aggregation and bonding. This results in a more compacted and denser soil structure. Lime has a higher specific gravity than most soil particles, and its presence increases the overall specific gravity of the soil-lime mixture, contributing to higher dry density. Moreover, lime treatment improves the soil's engineering properties, making it stiffer and less prone to deformation, which further enhances the dry density as the soil becomes more resistant to compaction.

Figure 10 shows the variation of the Optimum Moisture Content (OMC) with the addition of lime with the expansive soil.

With the addition of lime to the soil, the soil particles tend to bind together, reducing the void spaces between them. This binding effect improves the compaction ability of the soil, meaning it can be compacted to a denser state with less water content. As a result, the Optimum Moisture Content (OMC) decreases, indicating that the soil-lime mixture requires less water to achieve maximum compaction.

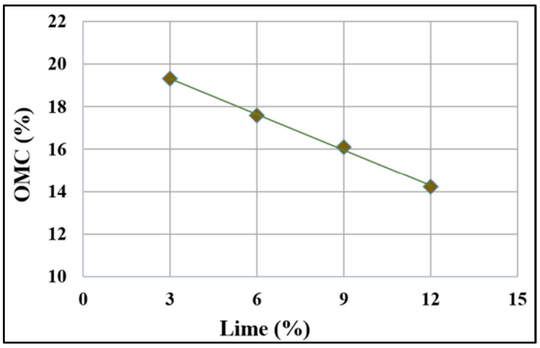

Figure 10. *Variation of OMC with different percentages of Lime.*

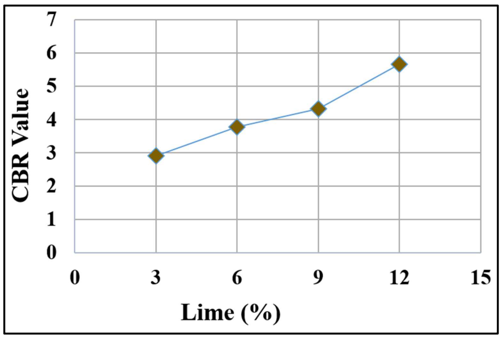

Figure 11. *Variation of CBR value with different percentages of Lime.*

The California Bearing Ratio (CBR) value of soil typically increases with the addition of lime. And Figure 11 also demonstrates that. Lime has a cementitious property that reacts with the soil particles, leading to the formation of stable cementation compounds. This reaction improves the strength and load-bearing capacity of the soil.

In accordance with the findings of another study, it has been demonstrated that the CBR values of BC soil exhibit a positive correlation with the incremental addition of lime. The CBR value reaches its zenith when the lime content reaches 12%. This observation aligns with previous research outcomes and underscores the efficacy of lime as a stabilizing agent for enhancing the engineering properties of soil [22].

Table 5 presents the test results for different percentages of lime mixed with the clayey soil.

Table 5. *Test results for different percentages of lime mixed with soil.*

Sl No	Types of soil	Liquid Limit	Plastic Limit	OMC	MDD	CBR (Soaked)
1	Soil+3% Lime	40.27%	25.73%	19.32%	1.74	2.92
2	Soil+6% Lime	41.94%	23.89%	17.59%	1.78	3.78
3	Soil+9% Lime	42.78%	21.07%	16.09%	1.81	4.33
4	Soil+12% Lime	43.79%	19.15%	14.23%	1.83	5.66

Table 6 presents the test results for different percentages of fly ash and lime mixed with the clayey soil.

Table 6. *Results for varying percentages of fly ash and lime with soil.*

Sl No	Types of soil	Plasticity Index	OMC	MDD	CBR (Soaked)
1	Soil+10%FA+ 9% Lime	21.89%	18.37%	1.73	3.81
2	Soil+10%FA+ 12% Lime	24.88%	17.26%	1.75	4.44
3	Soil+20%FA+ 9% Lime	22.47%	17.53%	1.78	4.21
4	Soil+20%FA+ 12% Lime	23.94%	16.99%	1.81	5.83

5. Conclusion

The present investigation yields the following conclusions:

1) Both the liquid limit and plastic limit of the expansive clayey soil decrease with an increasing percentage of fly ash. This indicates that fly ash reduces the soil's plasticity and makes it less susceptible to moisture-induced changes.
2) The addition of lime to the soil increases its liquid limit but lime treatment reduces the soil's plastic limit, meaning that it requires less moisture to exhibit plastic behavior.
3) The Maximum Dry Density (MDD) of the soil typically increases with the addition of fly ash, indicating an improvement in the compacted density.
4) The CBR value of expansive soil increases with an increasing percentage of lime, reaching its best value at 12% lime content (CBR value of 5.66). Lime stabilization significantly enhances the soil's load-bearing capacity.
5) The CBR value of the clayey soil further increases when both lime and fly ash are added. The optimum combination of 12% lime and 20% fly ash provides the best CBR value of 5.83, making it the most suitable mix for subgrade applications.

It can be concluded that the addition of waste materials like fly ash can be effectively used in civil engineering construction to improve the geotechnical properties of expansive clayey soil. The effectiveness is further enhanced when lime is combined with fly ash, leading to improved workability, increased load-bearing capacity, and greater stability of the soil [23]. These findings support the sustainable utilization of waste materials in engineering projects, offering potential cost savings and environmental benefits.

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Biography

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