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Improvement Of Soil Using Cement Kiln Dust

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Abstract: Clayey soils, characterized by high plasticity and low shear strength, pose significant challenges in geotechnical engineering applications. This study investigates the effectiveness of Cement Kiln Dust (CKD), an industrial by-product with high calcium oxide content, as a stabilizing agent for clayey soils. Laboratory experiments focused solely on CKD-treated samples at varying dosages (3%, 6%, 9%, 12%, and 15%) to evaluate improvements in engineering properties. Standard Proctor Compaction tests were conducted to determine changes in Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), while Unconfined Compressive Strength (UCS) and Triaxial shear tests were used to assess strength parameters, including cohesion and internal friction angle, over curing periods of 0, 7, and 28 days. Results demonstrated that increasing CKD content led to notable improvements in MDD and reductions in OMC, indicating better compaction characteristics. UCS and Triaxial test outcomes revealed enhanced soil strength and stability with increased CKD content, particularly at extended curing durations, due to pozzolanic reactions and cementitious bonding. The findings support the viability of CKD as a cost-effective and sustainable stabilizer for improving the structural performance of clayey soils.

Index Terms – Soil-Improvement, CKD, Clay

I. Introduction

In geotechnical engineering, the improvement of weak or problematic soils is essential to ensure the safety, durability, and functionality of civil engineering structures. Natural clayey soils, in particular, often exhibit undesirable characteristics such as high plasticity, low shear strength, and significant volume changes due to moisture fluctuations. These properties make them unsuitable for direct use in foundations, road subgrades, and other load-bearing applications without appropriate treatment. Among the various techniques for enhancing soil properties, chemical stabilization has proven to be one of the most effective. However, conventional stabilizers such as lime and cement, while effective, are associated with high production costs and adverse environmental impacts due to their energy-intensive manufacturing processes and carbon emissions. In light of growing concerns over sustainability and material cost, attention has shifted towards the utilization of industrial by-products for soil stabilization. One such material is Cement Kiln Dust (CKD), a fine, powdery by-product generated during the manufacture of Portland cement. CKD contains significant quantities of calcium oxide (CaO), along with other alkalis and reactive compounds, making it a potential alternative to traditional binders. The high free lime content in CKD enables it to undergo hydration and pozzolanic reactions when mixed with clayey soils, resulting in improved strength and reduced plasticity. Several studies have documented the positive effects of CKD on soil behavior, highlighting its potential to increase unconfined compressive strength, enhance compaction characteristics, and modify shear strength parameters. Miller and Zaman (2000) indicated that CKD greatly enhanced the strength and lowered the plasticity of clay soils. Kumar et al. (2023) reported that the combined use of CKD and Recon fibre significantly improves the strength and CBR value of clayey soils, making them suitable for subgrade applications. Anil Kumar and Singh (2017) demonstrated that adding up to 30% CKD improves soil compaction, strength, and permeability, making it a viable stabilizer for poor soils. Adeyanju and Okeke (2019) highlighted the effectiveness of CKD as a sustainable stabilizer for clayey soils, improving strength and reducing environmental impact. However, the effectiveness of CKD as a stabilizer depends on various factors, including its chemical composition, the type of soil treated, and the dosage applied. Moreover, while its influence on strength and compaction has been explored, a detailed understanding of how CKD affects the shear strength parameters of clayey soil particularly cohesion and internal friction angle under varying curing conditions remains limited.

This study focuses on evaluating the impact of CKD on the shear strength behavior of clayey soils using triaxial shear testing. By analyzing changes in shear strength parameters at different CKD contents and curing periods (0, 7, and 28 days), the research aims to assess CKD's suitability as a sustainable and effective stabilizer for problematic soils.

II. Clayey Soil

It is the finest and most active portion of the soil material and is generally characterized by high to very high dry strength. The grains have a size less than 0.002 mm. CL soil, also known as Low Plasticity Clay, is a type of clay soil that exhibits relatively low plasticity and strength.

Table 1: Physical Properties of Soil

Properties	Typical values
IS Classification	CL
Liquid Limit	24.4 %
Plastic Limit	15.07 %
Plasticity Index	9.33%
Uniformity coefficient, C_u	2.93
Gradation coefficient, C_c	0.95

III. Cement Kiln Dust (CKD)

Cement Kiln Dust (CKD) is a powdery, fine-grained by-product formed during cement production. CKD forms when raw materials like limestone and clay are subjected to high temperatures in a cement kiln, producing a dusty by-product. CKD is a combination of calcium oxide, silica, alumina, and other elements, and its chemical composition may change according to the cement manufacturing process. CKD has been utilized as an admixture, supplementary cementitious material, and soil stabilizer, among other uses, with possible environmental and economic advantages.

Table 2: Properties of CKD (Mith, J., & Rao, K. (2017))

Sl No	Property	Value
1	Limestone (%)	80-95
2	Clay (%)	0-20
3	Quartz (%)	5-9
4	Type	Powdery
5	Colour	Grey

IV. Research Methodology

To evaluate the geotechnical performance of clayey soil stabilized with varying proportions of Cement Kiln Dust (CKD), a comprehensive laboratory testing program was undertaken. The experimental work involved the preparation and testing of soil-CKD mixtures at different percentages to assess changes in compaction characteristics, unconfined compressive strength (UCS), and shear strength parameters. CKD was added to the native clayey soil at incremental contents of 3%, 6%, 9%, 12%, and 15% by dry weight of soil. All laboratory procedures were carried out in accordance with the relevant parts of the Indian Standard (IS) Code 2720.

1. Proctor Compaction Test

The compaction characteristics of the CKD-stabilized soil were determined using the Standard Proctor Compaction Test in accordance with IS: 2720 (Part 7) – 1980. The objective of this test was to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for each CKD-soil mixture.

Soil samples were thoroughly mixed with CKD at the designated percentages (0%, 3%, 6%, 9%, 12%, and 15%), and each mixture was compacted in a standard Proctor mould using a 2.6 kg rammer dropped from a height of 310 mm. The test results were used to identify how CKD content influences the compaction behavior of clayey soil, which is critical for field applications.

2. Unconfined Compressive Strength (UCS) Test

The Unconfined Compressive Strength test was carried out on CKD-treated samples to evaluate strength development over time. UCS testing was conducted as per IS: 2720 (Part 10) – 1991. Samples were prepared by mixing the soil with CKD at 3%, 6%, 9%, 12%, and 15%, compacted at OMC, and moulded into cylindrical specimens.

Three sets of samples were prepared for each CKD percentage and cured for different durations:

- 0 days (immediate testing)
- 7 days curing
- 28 days curing

The specimens were cured in sealed conditions to promote pozzolanic reaction and strength gain. After the respective curing periods, the samples were subjected to axial compression until failure without lateral confinement. The maximum axial stress at failure was recorded as the unconfined compressive strength. This test provided insight into the time-dependent strength behavior of CKD-stabilized clayey soil.

3. Triaxial Shear Test (UU Test)

To assess the shear strength parameters of the CKD-stabilized soil, Unconsolidated Undrained (UU) Triaxial Tests were conducted according to IS: 2720 (Part 11) – 1993. Cylindrical samples (38 mm × 76 mm) were prepared for each CKD content (3%, 6%, 9%, 12%, and 15%) using the respective OMCs obtained from the compaction tests.

After moulding, specimens were cured under moist conditions for 7 and 28 days to allow for the development of cementitious bonds due to pozzolanic activity. Post-curing, the samples were saturated and consolidated under controlled confining pressures before being subjected to axial loading under undrained conditions.

During the test, deviator stress and axial strain were recorded continuously until failure. From the Mohr-Coulomb failure envelope, the shear strength parameters -cohesion (c) and angle of internal friction (φ) were determined for each CKD content and curing period. These parameters are essential for understanding the improved shear resistance of CKD-treated clayey soils under loading conditions.

V. Results and Discussion

I. Variation of OMC and MDD with different percentages of CKD

The graph shows that the Optimum Moisture Content (OMC) of clayey soil initially decreases with increasing Cement Kiln Dust (CKD) content, dropping from 12.5% at 0% CKD to a minimum of 10.89% at 9% CKD, and then increases to 13.89% at 15% CKD. The initial decrease in OMC is due to the filler effect of CKD, which improves soil particle packing and reduces voids, along with the consumption of water in pozzolanic reactions between CKD and clay minerals. However, beyond 9% CKD, the OMC increases because the excessive fines from CKD raise the surface area, increasing the water demand for coating particles and sustaining further chemical reactions. Additionally, higher CKD content can reduce mix workability, necessitating more moisture for proper compaction. This results in a parabolic trend with an optimum CKD content around 9% for efficient moisture utilization.

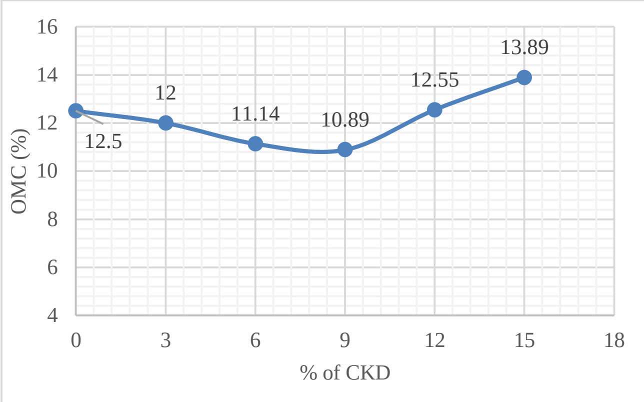

Figure 1: Optimum Moisture Content vs percentage of Cement Kiln Dust

The graph illustrates the variation in Maximum Dry Density (MDD) of clayey soil with increasing percentages of Cement Kiln Dust (CKD). The MDD rises from 1.975 g/cc at 0% CKD to a peak of 2.42 g/cc at 9% CKD, after which it gradually declines to 2.29 g/cc at 15% CKD. The initial increase in MDD up to 9% CKD can be attributed to the filler effect of CKD, which improves particle packing by occupying the voids between soil grains, resulting in a denser soil matrix. Additionally, the presence of reactive lime content in CKD contributes to the formation of cementitious compounds that bind soil particles more tightly. However, beyond 9% CKD, the MDD starts to decrease due to the excessive addition of fines, which disrupts the optimal gradation and increases water demand, leading to less efficient compaction. Furthermore, higher CKD content may reduce the overall specific gravity of the mix, contributing to the decline in dry density. Thus, 9% CKD appears to be the optimal content for achieving maximum compaction and density.

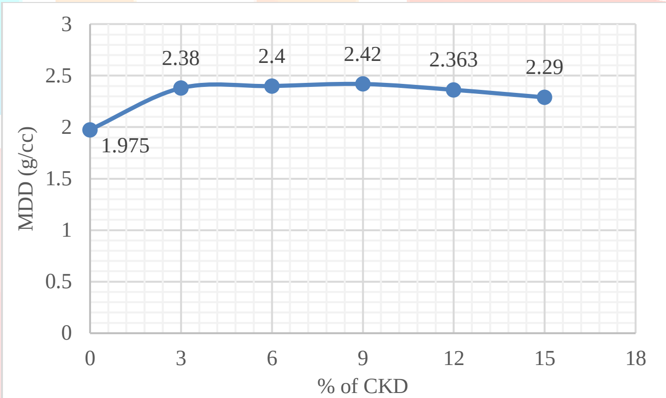

Figure 2: Maximum Dry Density vs percentage of Cement Kiln Dust

II. Variation of Cohesion and internal friction with different percentages of CKD for 0,7 and 28 days

Curing duration has a significant impact on cohesion, with values increasing from 0 days to 7 days and reaching their highest at 28 days. This trend reflects the progressive development of cementitious bonds from CKD, which strengthen the soil matrix over time. In all curing periods, cohesion improves with CKD addition up to an optimum at 9% CKD, where bonding between particles is most effective. When CKD content exceeds this level, cohesion declines, likely due to surplus unreacted material disrupting the dense packing of particles and reducing the overall bonding efficiency.

Similarly, internal friction increases with curing time, with 28-day curing showing the highest values followed by 7-day and 0-day curing, due to the gradual improvement in particle bonding and surface roughness from CKD's cementitious action. For all curing periods, the internal friction angle rises with CKD content up to a peak at 9% CKD, where particle interlocking and bond strength are maximized. Beyond this optimum, internal friction decreases slightly as excess CKD can create a smoother particle matrix and reduce the effectiveness of interparticle contact, lowering shear resistance.

These findings highlight the importance of both optimal CKD content and sufficient curing time to achieve maximum shear strength improvement in soil stabilization. The results also suggest that over-stabilization, through excessive CKD addition, may counteract the benefits of the cementitious reactions by altering the soil structure and increasing brittleness or porosity. Therefore, maintaining a balanced mix design is crucial for achieving a well-compacted and durable stabilized soil. The consistent trend across curing periods emphasizes the long-term effectiveness of CKD in improving both cohesion and internal friction angle when used in appropriate proportions.

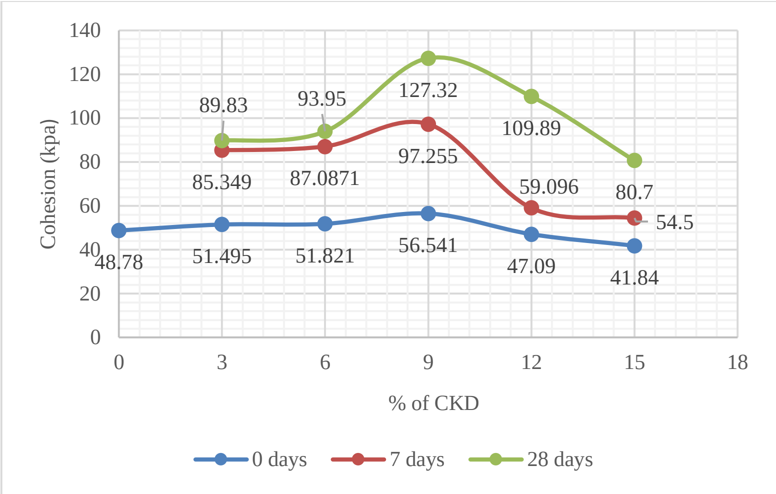

Figure 3: Cohesion vs percentage of Cement Kiln Dust

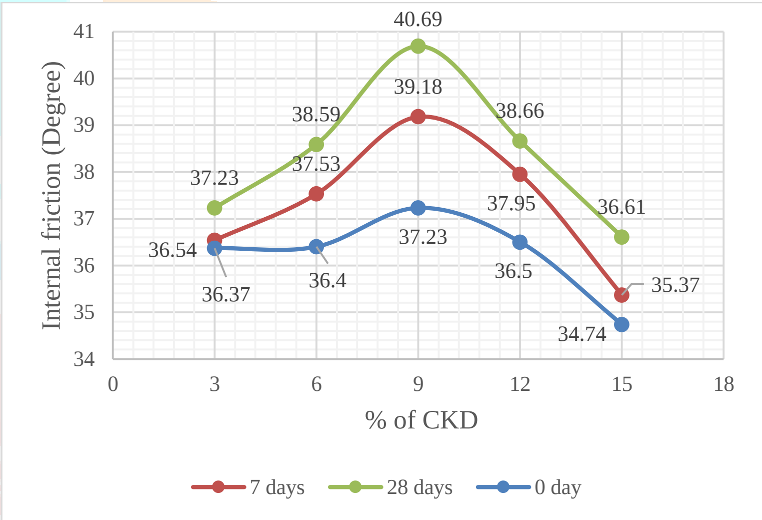

Figure 4: Internal friction vs percentage of Cement Kiln Dust

III. Variation of shear strength with different percentages of CKD for 0,7 and 28 days

At 0-day curing, the unconfined compressive strength of clayey soil increases with the addition of Cement Kiln Dust (CKD), reaching a peak value of 164.095 kPa at 9% CKD. This improvement is attributed to the initial pozzolanic activity and the presence of calcium compounds in CKD, which promote early-stage bonding and enhance the compactness of the soil structure. The strength increases progressively from 87.4375 kPa at 0% CKD to 116.051 kPa at 3%, and 137.55 kPa at 6%, before peaking at 9%. However, beyond this point, the strength begins to decline, with values of 151.558 kPa at 12% and 135.309 kPa at 15%, likely due to excess CKD disrupting particle interaction and leading to reduced density. At 7 days of curing, the compressive strength shows a significant increase due to more developed pozzolanic reactions, which form additional cementitious compounds that strengthen the soil matrix. The strength rises from 169.751 kPa at 0% CKD to 234.078 kPa at 6%, peaking at 357.146 kPa at 9%, indicating this as the optimum content. A slight reduction is observed beyond this point, with 337.84 kPa at 12% and 327.201 kPa at 15%, possibly due to poor bonding from excessive CKD. At 28 days of curing, the compressive strength increases further, reflecting the effects of prolonged pozzolanic and cementitious reactions. The strength improves from 239.56 kPa at 0% CKD to 289.0 kPa at 6%, and reaches a maximum of 528.726 kPa at 9%. Slight reductions to 511.321 kPa at 12% and 502.562 kPa at 15% may result from unreacted CKD or suboptimal compaction. Across all curing periods, 9% CKD consistently delivers the highest compressive strength, confirming it as the optimum content for stabilization.

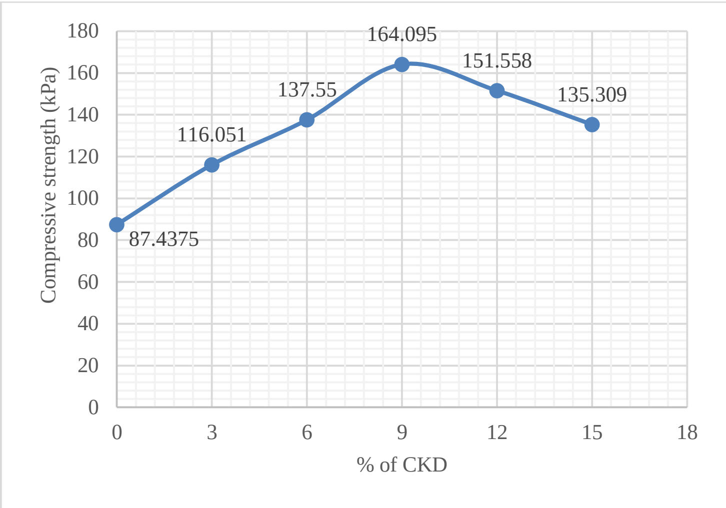

Figure 5: Compressive strength vs percentage of Cement Kiln Dust at 0 day

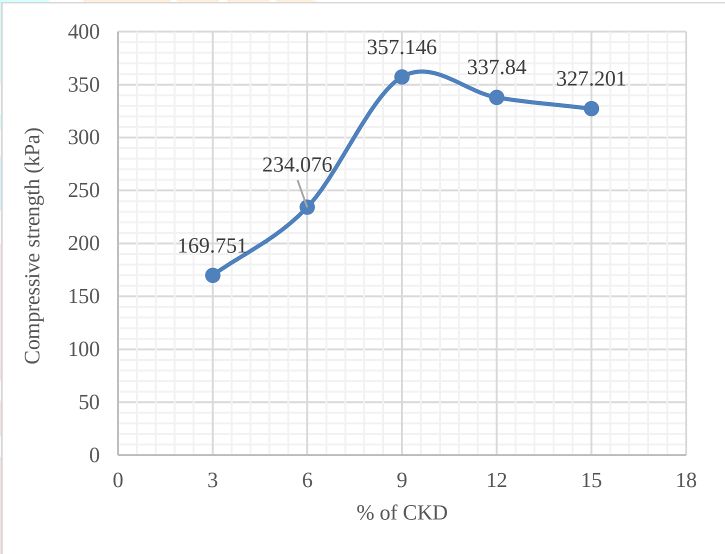

Figure 6: Compressive strength vs percentage of Cement Kiln Dust at 7 days

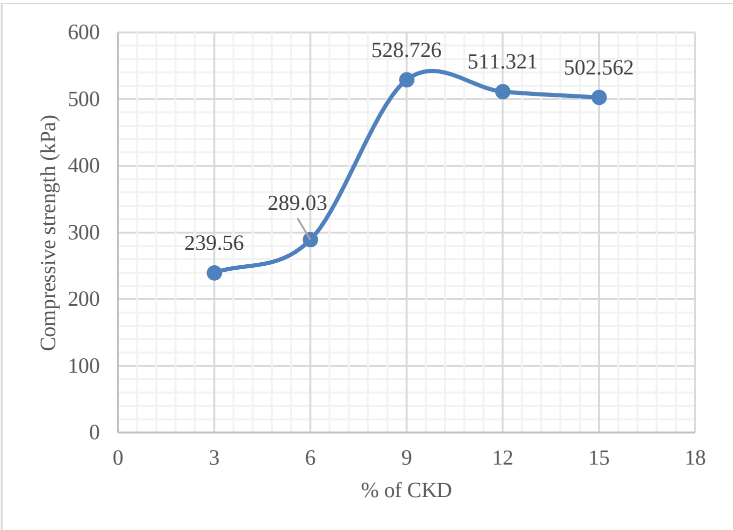

Figure 7: Compressive strength vs percentage of Cement Kiln Dust at 28 days

VI. CONCLUSION

1. The Optimum Moisture Content (OMC) decreased with the addition of CKD, indicating improved workability and reduced water demand for achieving maximum compaction.
2. A significant increase in Maximum Dry Density (MDD) was observed with CKD-treated soils, suggesting better particle packing and enhanced soil strength.
3. The cohesion of the soil increased progressively over time, with the highest improvement noted at 28 days, indicating the ongoing pozzolanic reaction and binding effects from the calcium content in CKD.
4. The internal friction angle also improved with curing duration (0, 7, and 28 days), reflecting enhanced inter-particle bonding and shear resistance due to CKD stabilization.
5. The Unconfined Compressive Strength (UCS) values showed a significant increase at 28 days compared to 0 and 7 days, demonstrating long-term strength development from cementitious and pozzolanic reactions.
6. CKD alone is proven to be an effective stabilizer for enhancing the engineering properties of clayey soil through improved strength, compaction, and shear parameters.

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