Investigating the Effectiveness of Cement Kiln Dust as an Expansive Soil Stabilizer in Road Construction

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ABSTRACT

This study was conducted to investigate the effect of CKD on weak subgrade soil properties, to characterize the untreated soil and CKD, and to determine optimum CKD content that will achieve effective stabilization. The CKD was obtained from Tororo cement factory and the soil sample was obtained from one of the dumping sites along Kyenjojo-Fort-Portal road at Km 23+700 in Uganda. According to classification tests, the soil is an A-7-6. Using British Standard Heavy (BSH) compaction energy, the effect of varying concentrations of CKD on the soil properties was investigated with respect to compaction characteristics, California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests. The natural soil exhibited medium expansive properties, with a liquid limit of 53.6% and plasticity index of 27.3%. Adding Cement Kiln Dust (CKD) significantly improved soil properties, reducing liquid limit and plasticity index. CKD also enhanced compaction characteristics, unconfined compressive strength (UCS), and California Bearing Ratio (CBR), attributed to pozzolanic reactions and cementitious compound formation. Cement Kiln Dust can stabilize and improve the engineering properties of weak subgrade soils with adequate reactive SiO2 and Al2O3 so that in presence of water the two react with CaO to form cementitious properties.

Keywords: Cement Kiln Dust (CKD), Expansive Soil, Soil Stabilization, Road Construction, Weak Subgrade Soil, Compaction Characteristics.

INTRODUCTION

Cement industry is among the most important and largest industries in the world [1]. However, this industry is considered highly pollutant to the environment due to the large amounts of Cement Kiln Dust (CKD) that is produced during the process of cement manufacturing [2]. Cement manufacturing plants generate about 30 million tons of CKD worldwide per year [3]. The U.S. cement industry generates about 4.1 million tons of CKD every year, 3.3 million tons of which is landfilled and only 0.75 million tons enter commerce as by-products [2]. The Ugandan construction industry depends hugely on Portland cement for almost every type of construction [4, 5]. It is estimated that approximately four million tons was utilized in 2014 [6] and its anticipated that cement consumption may hit a record high of about five million tons by 2020. The Uganda cement market has experienced steady growth in consumption with compounded annual growth (CAGR) rate of 9.8% between 2005 and 2013 and this trend is expected to continue in the short term with CAGR of 10.3% over 9 years [7].

CKD is a fine powdery material produced by cement manufacturing units that is similar in appearance to Portland cement [8]. Its composition is quite variable from source to source due to raw materials and process variations and it is primarily made up of a variable amount of fine calcined and uncalcined feed materials and condensed alkali compounds [9]. The main component of CKD is lime (CaO). Other compounds include silicon oxide, Potassium oxide, sodium oxide and chromium.

CKD is considered one of the most hazardous pollutants which affect the surrounding environment. In 2001, the Environmental Protection Agency (EPA) implemented a regulatory determination on CKD waste and concluded that additional control of CKD is warranted in order to protect the public from human health risks and to prevent environmental damage resulting from current disposal of this waste including damages to ground water and potable water supplies, potential human health risks from inhalation of airborne CKD and ingestion via food chain pathways [10].

Approximately 90,000 metric tons of Cement Kiln Dust are produced annually in Uganda [11] and there is an expected growth of the industry that will be driven by increased public sector investment in infrastructure development projects. Utilization of CKD as a soil stabiliser would not only provide an alternative method of disposing CKD [12] but also reduced energy consumption, greenhouse gas emissions, and landfilling as well as ongoing environmental challenge.

There are large quantities of CKD from cement manufacturing industry released into the environment and this is expected to increase in future [8]. While many facilities are able to reuse a significant portion of CKD in their production lines to form clinker, a large percentage is removed as industrial waste and disposed at landfills increasing the cost of disposal, causing damages to ground water and potable water supplies [13], and potential human health risks from inhalation of airborne CKD and ingestion via food chain pathways yet it can be reused to reduce on its environmental impacts.

The by-product of cement manufacturing process are inevitable [14] unless new and beneficial utilization options, which are economically sound and environmentally friendly are developed and implemented. The use of CKD addresses both the need to identify alternative materials for soil stabilization and methods of disposal that are economical and environmentally friendly. This study was conducted to investigate the effect of CKD on weak subgrade soil properties, to characterize the untreated soil and CKD, and to determine optimum CKD content that will achieve effective stabilization.

MATERIALS AND METHODS

The materials used in the study included;

a) Lime, Cement Kiln Dust
b) Expansive soils.

Cement Kiln Dust was obtained from Tororo cement factory approximately 153km from Kampala city. This source was chosen due to its vast amount of CKD produced. It was obtained in bags and stored in air tight containers.

Soil samples used in this research were expansive soils, obtained by method of disturbed sampling from a test pit dug to a depth of 1000 mm. The source selected soil sampling is located along Kyenjojo-Fort Portal road at km 23+700.

Chemical tests on Cement Kiln Dust were carried out from the Tororo cement factory's materials analytical laboratory mainly to ascertain if it contained chemical components required for stabilization purposes. The oxide composition of CKD was assessed through X-ray florescent test (XRF). The following oxides were tested for; calcium Oxide Magnesium oxide, potassium oxide, sodium oxide silicon oxide and aluminum oxide.

The preliminary tests (to consistency tests, compaction and classification tests) for identification of the natural soil and the geotechnical properties of the soil treated with CKD were carried out in accordance with BS 1377. The standard Proctor energy level was used for compaction test which was also used to determine the moisture content for the CBR and UCS specimens.

The test was performed to determine the particle size distribution of the soil samples to help in classifying the soil using the USCS and AASHTO classification systems. Grading was essential for determination of the percentage by mass of particles within different size ranges. From this, it's possible to establish to a limited extent which sieve range is likely to influence the engineering properties of the soil. The test was performed in accordance to BS 1377: Part 2:1990

Consistency limits consist of the Atterberg limits which are the basic measure of the nature of a fine-grained

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soil. Atterberg limits contains three tests that is the liquid limit, plastic limit and linear shrinkage.

Liquid limit: The liquid limit was empirically determined to establish moisture content at which a soil passes from the liquid state to plastic state**.**

Plastic Limit test: The plastic limit is the empirically established moisture content at which a soil becomes too dry to be plastic. This test was used together with the liquid limit test to determine the Plasticity Index which when plotted against the liquid limit on the plasticity chart provides a means of classifying cohesive soils.

Linear shrinkage: This was determined was performed as a way of quantifying the amount of shrinkage likely to be experienced by clayey materials.

The Atterberg Limit tests were performed in accordance to BS 1377: PART 1990. Figure 4 shows preparation of material for the Atterberg tests. Figures 3 show material preparation before any test was carried out.

Figure 1:Sample preparations and Weighing

California Bearing Ratio (CBR)Test

The California Bearing Ratio (CBR) test is a penetration test that was used to evaluate the potential strength of pavement subgrade. This test was done in accordance with BS1377: Part 4:1990. Figures 5 and 6 show soaking and penetration of CBR specimens respectively.

Modified Proctor Test

The objective of this test was to obtain relationships between compacted dry density and soil moisture content, using two magnitudes of manual compactive effort. These tests helped to determine the change in moisture content and the dry density. The test was performed in accordance to BS 1377: Part 4:1990.

Unconfined Compressive Strength Test

The unconfined Compressive Strength (UCS) of un stabilized or stabilized material is the load in KN/m^2 (kPa) required to crush a cylindrical specimen 127 mm high and 152.4 mm in diameter to total failure at rate of application of load of 140 kN/m^2 per second.

The test was performed in accordance with BS 1924: Part 2:1990

Figure 2: Soaking of CBR specimens

Determination of the effect of Cement Kiln Dust on soil properties

The effectiveness of Cement Kiln Dust on properties of weak subgrade soil was evaluated through testing a soil after being mixed with different contents of CKD. The maximum content of CKD was limited to 5% in this investigation. Four test soils with CKD contents of 0.0, 3.0, 4.0, and 5.0% by weight were prepared and tested. The soil with zero CKD content was considered for use as a control soil for the purpose of comparison with the other soils mixed with CKD and lime. The following general tests were conducted in accordance to BS 1377 testing methods;

1. Modified Proctor test,
2. Consistency tests
3. Unconfined Compressive Strength (UCS) test
4. California Bearing Ratio (CBR) test

Same test procedures were followed in all tests and the only variable was the kind of stabiliser (CKD or Lime) and its content in each mix relative to the dry weight of soil.

The preparation of the test samples was made in the following order:

The natural soil was air dried.

The dried soil and stabiliser were carefully weighed for a predetermined content of stabiliser.

The weighed soil and the predetermined amount (3%, 4% or 5% by dry weight of soil) of stabiliser were thoroughly mixed to provide for a sufficiently homogeneous mixed soil.

Samples were taken from the mixed soil for the any of above laboratory tests.

This procedure was followed in preparing all the test samples. The only variable was the content of CKD

Determination of Optimum Cement Kiln Dust content achieving effective stabilization.

The pH of soil and the CKD were determined separately. The optimum amount of CKD was determined using Eades and Grims test. The sufficient amount of CKD to be added to the soil must produce a pH of 12.4 or a pH of CKD itself. A graph was plotted between pH and CKD percentage and optimum CKD content corresponding to the maximum PH of CKD –soil mixture determined.

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RESULTS

Identification of soil and CKD

The index properties of natural soil before addition of stabilizer are shown in table 2. The particle size distribution is shown in Figure 6. The geotechnical properties of natural soil showed that it has a liquid limit and plasticity index of 53.6 and 27.3 respectively and classified as a medium expansive soil. The soil is classified as A-7-6 based on the AASHTO Soil Classification System and CH on the Unified Soil Classification System (USCS).

Table 1:Index Properties of Natural soil sample

Description	**Results**
Liquid Limit (%)	53.6
Plastic Limit (%)	26.3
Plasticity Index (%)	27.3
Linear Shrinkage (%)	11.5
Percent passing BS NO.200 sieve	70
AASHTO classification	A-7-6
USCS classification	CH
UCS (MPA)	-
Maximum Dry Density (kg/m^3)	1606
Optimum Moisture Content (%)	17.4
CBR at 95% of MDD (after 4 days of soaking)	3

The oxide composition of CKD was assessed through X-ray florescent test (XRF) the result is shown in Table 2. The composition of calcium oxide (CaO) alone is 48.8 %. This is responsible for the ion exchange between soil and the CKD resulting in the formation of more granular material and strength development. It contained inadequate percentages reactive SiO_2 (silica oxide) and $Al2O_3$ (aluminum oxide) but with adequate percentage of reactive CaO (Calcium Oxide). This implies that CKD can only stabilize soils with adequate reactive SiO_2 and Al_2O_3 so that in presence of water the two react with CaO to form cementitious properties.

Table 2: Oxide composition of Cement Kiln Dust

Oxides	**Percentage %**
$Si0_2$	14.2
Al_20_3	3.8
Fe_20_3	3.2

Ca0	48.8
Mg0	2.2
Na_20	0.18
K_2O	2.4
LOI	6.8
SO_3	1.48
Na_2O	0.5
K_2O	1.5

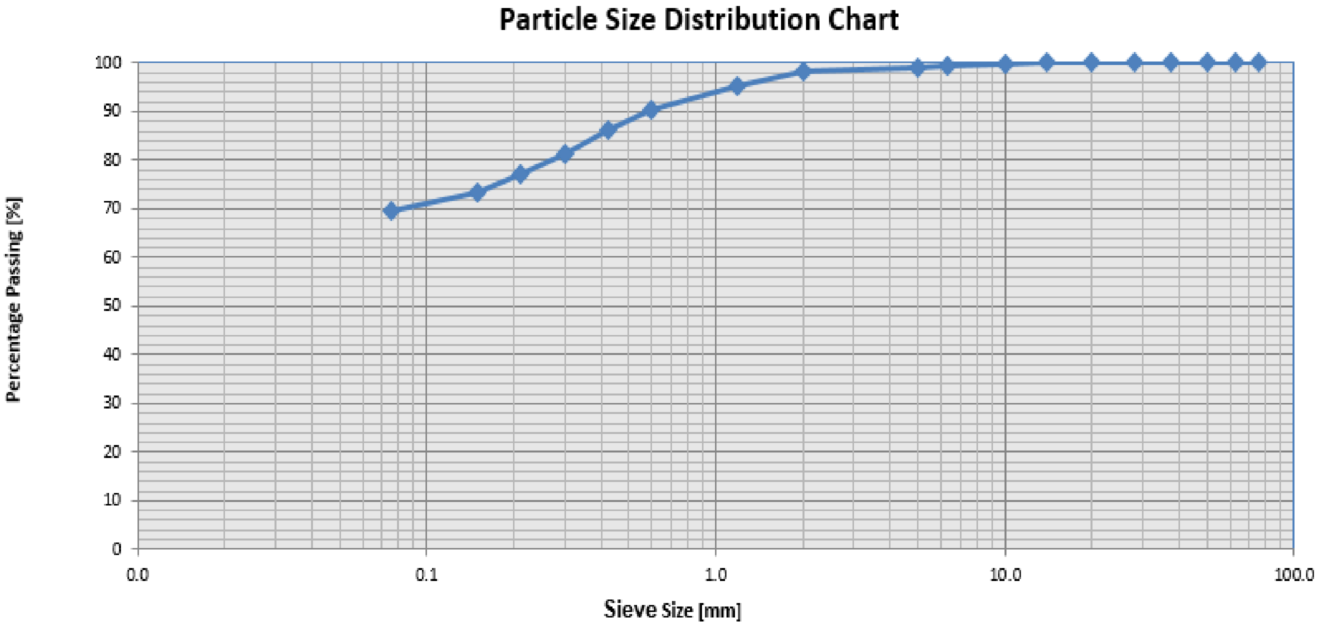

Figure 3: Particle size distribution curve of natural expansive soil

Effect of varying CKD content on soil properties

Effect of CKD on Consistency limits

The variation of liquid limit with CKD is shown in figure 7. The liquid limit decreases with the addition of CKD. This improvement of liquid limit attributed that more water is required for the cement treated soil to make it fluid and the increase of plastic limit implies that cement treated soil required more water to change it plastic state to semisolid state.

Figure 8 shows the relationship between plastic limits and CKD content. The trend is similar to that of the liquid limit. The reasons for the variation of the liquid limit with CKD content are also similar to that of the variation of plastic limit with CKD content.

Plasticity Index and CKD content relationship is shown in figure 9. Plasticity index decreases with increased concentration of CKD. This trend may be attributed to the replacement of the finer soil particles by CKD with consequent reduction in plasticity. The reduction in the Plasticity index causes a significant decrease in swell potential, removal of some water that can be absorbed by clay minerals. and this means increase in the workability of the soil having less affinity for water. This is considered to be an improvement in the geotechnical properties of the soil.

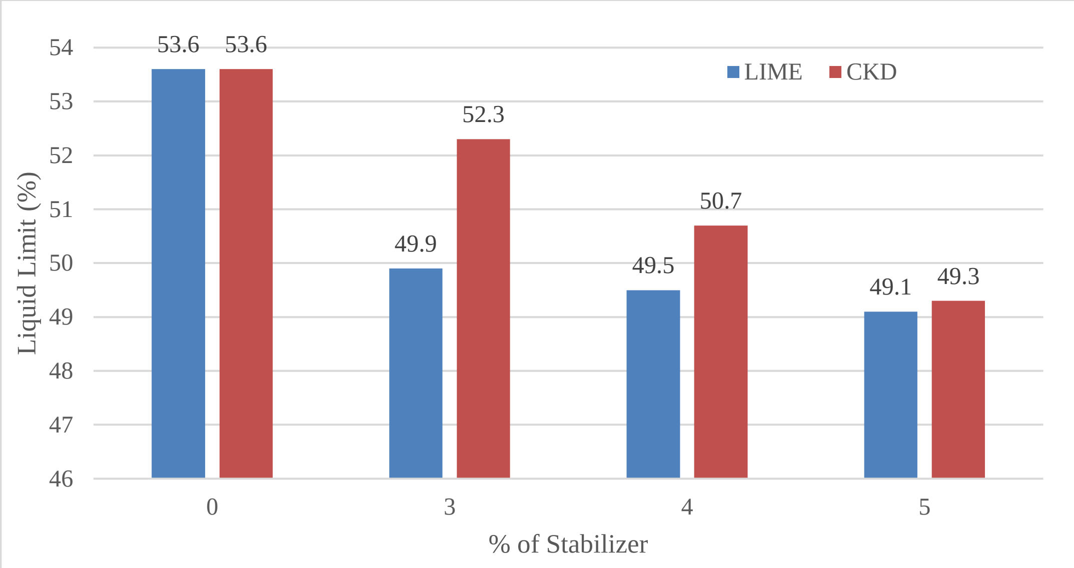

Figure 4: A graph of Liquid limit against Stabilizer content

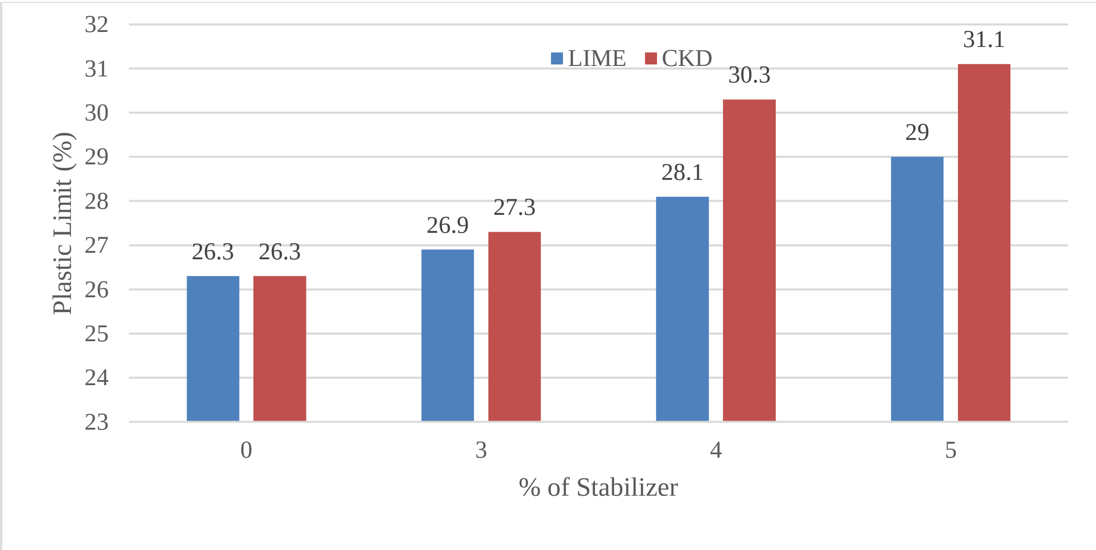

Figure 5: A graph of Plastic Limit against % stabilizer

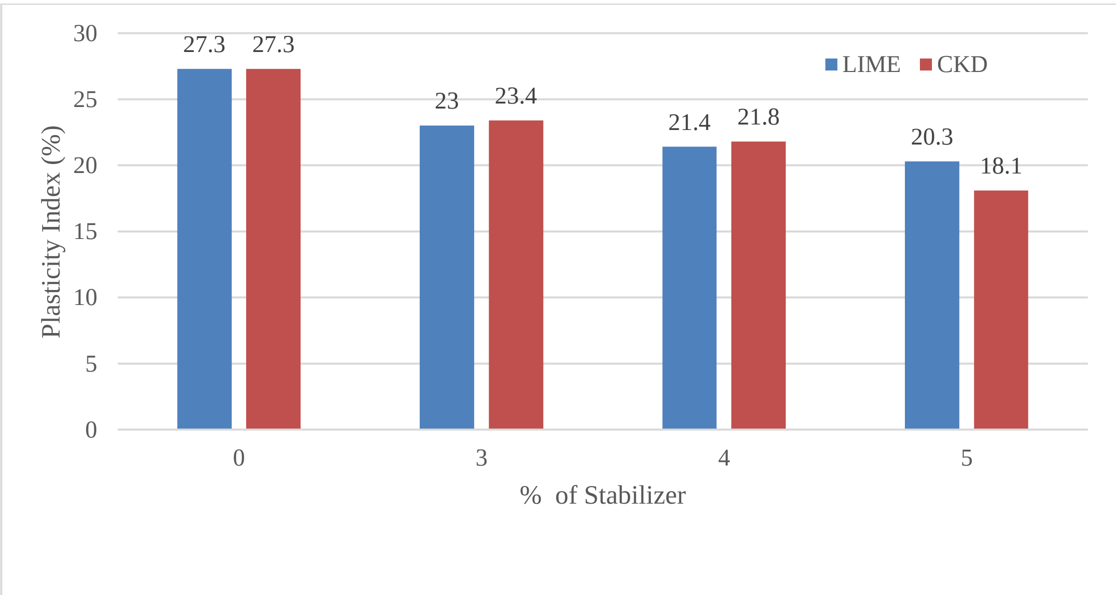

Figure 6: A graph of Plasticity Index against % of stabilizer

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Effect of CKD on Compaction characteristics of soil

Figures 10 and 11 show the results of the modified proctor tests performed on the four test soils. It is seen that adding CKD to the soil resulted in significant changes in its compaction characteristics; it should be noted that all the test samples in the performed modified Proctor tests were subjected to exactly the same compactive effort. The use of CKD resulted in significant increases in the optimum water content and the reduction in the maximum dry unit weight. The increasing water content, as intuitively expected, is essentially attributed to the increasing CKD content, which results in a finer test soil and thus necessitates more water to reach the maximum dry unit weight. The optimum moisture content also increased with increase in the percentage of CKD because more water was needed for the soil-CKD immediate chemical reaction (pozzolanic process).

The general drop in MDD could be a result of the flocculated and agglomerated fine particles occupying larger spaces leading to corresponding decrease in dry density. As the CKD content increases, more hydrated calcium ions are released into solution resulting in more flocculation and agglomeration of clay particles. Also it is because of the cation exchange and the short term reaction that takes place when the reactive calcium oxide in CKD reacts with silica oxide and aluminum oxide in the soil in presence of water.

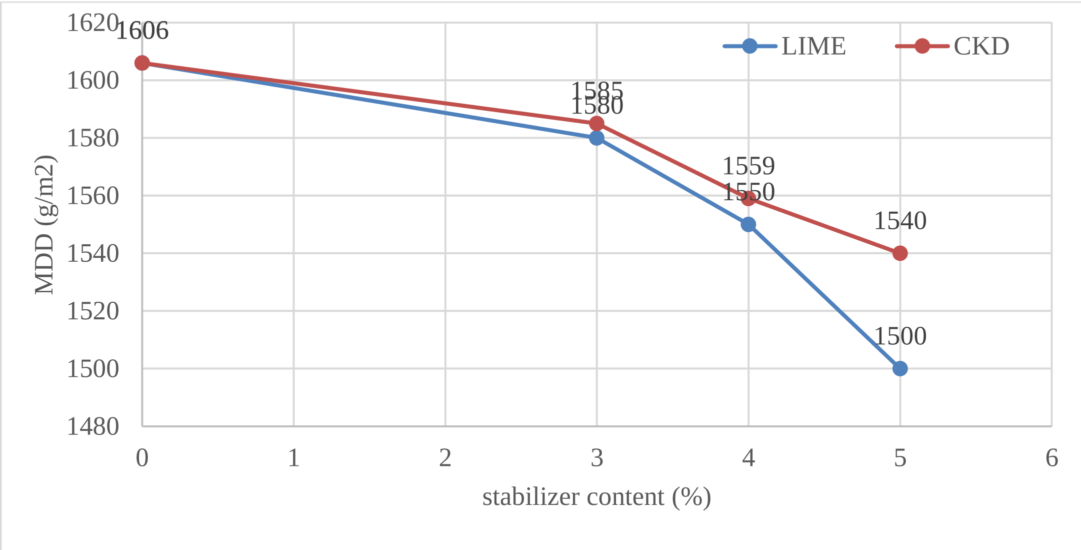

Figure 7: A graph of MDD against % of stabilizer

The advantage of the increase in OMC with higher stabilizer content and corresponding decrease in MDD of the soil is that it allows compaction to be easily achieved with wet soil. Thus, there is less of a need for the soil to be dried to lower moisture content prior to compaction in the field.

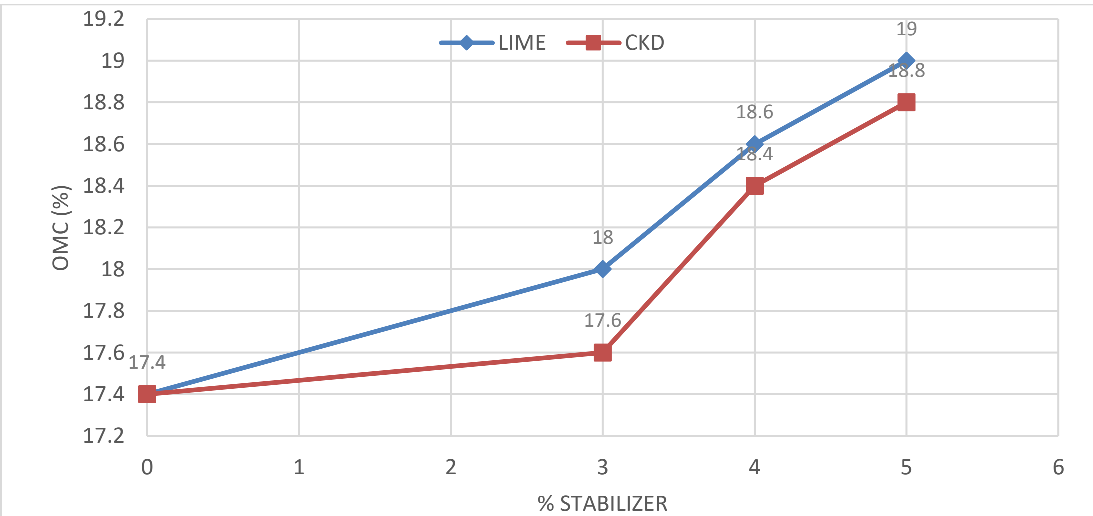

Figure 8: Variation of Optimum Moisture Content with lime and CKD content

Unconfined Compressive Strength

Unconfined compressive strength (UCS) is the most common and adaptive method of evaluating the strength of stabilized soil. Results of variation of UCS with increase in CKD for 14days of curing are shown in fig 12. The UCS values increases as the percentage of CKD increases from 0% to 5. The increase in the UCS is attributed to the formation of cementitious compound between CaOH present in the soil and the CKD. The increase in UCS of the stabilized material is also due to the pozzolanic reactions of cement with soil which results in agglomeration and flocculation in large size particles, carbonation and pozzolanic reaction that takes place when the calcium oxide in the stabiliser reacts with silica oxide and aluminum oxide to for cementitious properties and causes the increase in compressive strength. According to Jawad (2014), Cation exchange and flocculation agglomeration reaction takes place immediately after mixing and these reactions cause immediate changes in strength, plasticity index, and workability of the soils.

Effect of CKD on California Bearing Ratio of soil

Figure 13 shows CBR results obtained for four mixtures. The data indicates that as Cement Kiln Dust content is increased, there is an increase in the CBR and a decrease in swelling.

The increase in CBR could be due the pozzolanic reaction that takes place when the reactive calcium oxide (CaO) released by CKD reacts with silica oxide and aluminum oxide released by the clay soil. This results into agglomeration and flocculation of the soil particles which consequently leads to the increase in the internal friction between the flocculated soil particles (larger particle agglomerates).

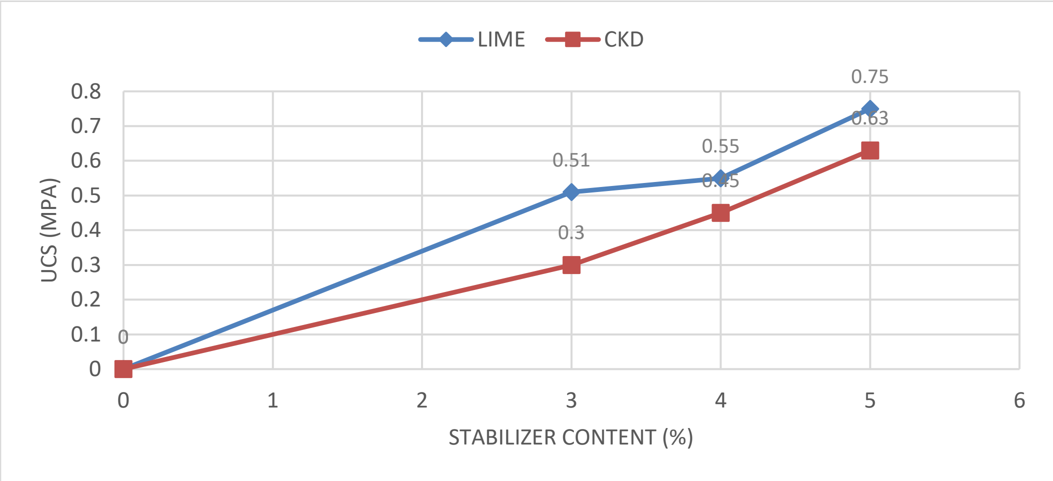

Figure 9: Variation of unconfined compressive strength with lime and CKD content

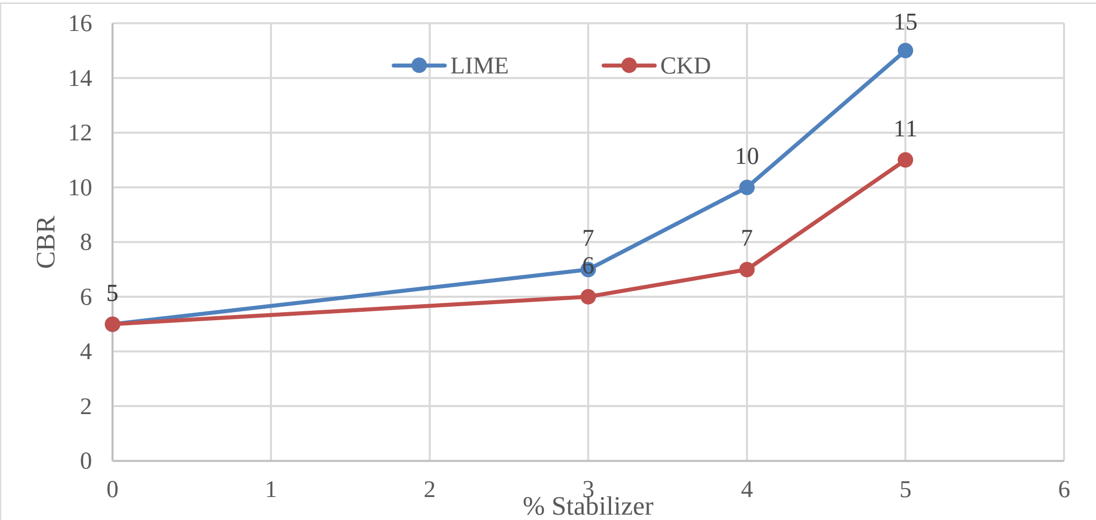

Figure 10: Variation of California Bearing Ratio with lime and CKD content

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DISCUSSIONS

The natural soil's geotechnical properties indicate a medium expansive soil with a liquid limit of 53.6% and plasticity index of 27.3%. This classification aligns with findings on expansive soils [15]. The addition of CKD significantly improved soil properties, reducing liquid limit and plasticity index [16]. Similar results were reported, highlighting CKD's effectiveness in stabilizing soils [17-19].

CKD addition increased optimum moisture content and reduced maximum dry unit weight. This agrees with previous studies [20], which attributed these changes to increased fines content and pozzolanic reactions.

UCS values increased with CKD content. The formation of cementitious compounds and pozzolanic reactions contributed to strength gains. CBR values increased with CKD content. Improved CBR is attributed to enhanced internal friction between flocculated soil particles [21].

The results align with previous studies on CKD-stabilized soils, demonstrating improvements in geotechnical properties, compaction characteristics, UCS, and CBR [22, 23]. The findings support the effectiveness of CKD as a soil stabilizer.

CONCLUSION

The study revealed significant improvements in geotechnical properties of cement-treated soil. The natural soil was classified as medium expansive with high plasticity, categorized as A-7-6 according to the AASHTO soil classification system or CH in the Unified Soil Classification System (USCS). Chemical analysis of Cement Kiln Dust (CKD) showed adequate calcium oxide content, but low silica and aluminum oxide levels, indicating suitability for stabilizing soils with sufficient silica and alumina.

The addition of CKD effectively enhanced soil properties, particularly California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS), making it suitable for subgrade material in road construction. Optimal improvement occurred at 5% CKD content. CKD also altered soil plasticity, significantly reducing plasticity. Furthermore, CKD addition increased optimum moisture content and slightly decreased maximum dry density. Overall, the findings demonstrate CKD's efficacy as a stabilizer for weak subgrade soils.

RECOMMENDATIONS

There is a need to Incorporate CKD at an optimal content of 5% to achieve the most significant improvements in geotechnical properties of subgrade soils, as indicated by the study. This study also Advocates for policies encouraging the use of CKD as a soil stabilizer to minimize environmental hazards and support sustainable construction practices.

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