Performance Assessment of Cement Kiln Dust Stabilized Clayey Soil Reinforced with Steel Fibers

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Abstract - The increasing generation of industrial by-products and the growing demand for sustainable ground improvement techniques have created a need for innovative methods of utilizing waste materials in geotechnical engineering. Cement kiln dust (CKD), a fine-grained by-product generated during cement manufacturing, possesses significant stabilizing potential due to its alkaline and cementitious characteristics. The present study therefore focuses on the performance assessment of CKD-stabilized clayey soil reinforced with steel fibers, with particular emphasis on its strength and load-bearing characteristics. In the proposed investigation, clayey soil will be treated with different proportions of CKD to determine its influence on the index and compaction characteristics of the soil. Steel fibers will subsequently be incorporated into the CKD-treated soil at selected dosages to provide mechanical reinforcement and improve resistance to tensile deformation and cracking. The stabilized mixtures will be evaluated through laboratory tests including Atterberg limits, standard Proctor compaction, unconfined compressive strength (UCS), and California Bearing Ratio (CBR). Selected specimens will also be subjected to different curing periods to examine the development of strength with time. The interaction between CKD and steel fibers is expected to produce a more stable soil matrix in which the chemical stabilization provided by CKD is complemented by the reinforcing and crack-bridging action of steel fibers. The study aims to establish the optimum combination of CKD and steel fiber that provides significant improvement in the engineering performance of clayey soil. The findings may provide a cost-effective, resource-efficient, and environmentally sustainable approach for improving weak clayey soils used in subgrades, embankments, and other geotechnical construction applications.

***Key Words*:** Compaction test, CBR, UCS, Steel Fiber, CKD

1. INTRODUCTION

The construction of flexible pavements is significantly hindered by clayey soils, which exhibit low compressive strength, enhanced plasticity, high compressibility, and poor permeability. Such restrictions commonly cause substantial warping, cracking, and early pavement collapse. In most geotechnical initiatives, locating a site that entirely fulfills design criteria without any sort of ground alteration is infrequently achievable. In instances of insufficient soil carrying capacity, the predominant strategies often contemplated are redesigning to align with the prevailing site conditions, excavating and replacing the in-situ soil, or, as a last resort, abandoning the site. A multitude of areas has been forsaken chiefly because of insufficient bearing capacities, which has exacerbated land shortages and intensified the necessity for natural resources. The impacted zones include liquefaction areas, locales with soft clay, landslide-prone locations, and polluted terrains. As a result, this research has been carried out to modify and refine the engineering qualities of soft clayey soil to satisfy the requisite standards. The evolution of soil amelioration techniques enables the enhancement of soft clay to the necessary specifications for civil engineering applications. In addition, the rising costs of waste management and the environmental deterioration induced by these waste products have become a prominent problem. To alleviate environmental concerns and lessen degradation, the application of waste materials is a significant duty for civil engineers. Thus, strategies for soil stabilization that utilize industrial by-products and

metallic fibers have become increasingly important due to their affordability, ecological benefits, and enhancement of performance. Cement kiln dust (CKD), a by-product of cement manufacturing facilities, comprises reactive lime and silica that generate cementitious compounds when hydrated, enhancing the strength and rigidity of soft clay soils. The incorporation of CKD into soil diminishes flexibility, enhances strength, improves compaction, and modifies the soil's general behavior under stress. Moreover, Steel Fibers can enhance tensile strength, mitigate cracking, and influence post-peak performance.

In the current study, steel fibers are employed as reinforcement alongside cement kiln dust to enhance the geotechnical characteristics of clay soil. The CKD functions as a stabilizing agent, whereas steel fibers offer structural reinforcement in the soil composition. The amalgamation of their applications is anticipated to enhance compressive strength, penetration resistance, and general soil efficacy. The efficacy of this amalgamation is accessed via compaction, unconfined compressive strength (UCS), and California Bearing Ratio (CBR) evaluations.

2. Literature Review

Vinod Kumar et al. (2026)

The objective of the present research is to improve the engineering characteristics of intermediate-plasticity clay by the application of cement kilndust (CKD) and polypropylene fiber (PPF) as stabilizing and reinforcing materials. The research evaluates the influence of CKD, both independently and alongside PPF, on the compaction characteristics, strength, and load-bearing capability of intermediate-plasticity clay. Laboratory studies for the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) have been conducted to determine the optimal quantities of CKD and PPF. Soil stabilization utilizing CKD enhanced soil strength by pozzolanic processes. The incorporation of fibers enhances resistance to deformation by creating a robust interlocking network with the soil, so limiting the mobility of soil particles. Upon the incorporation of 5% CKD and 0.05% PPF, the soil's UCS and CBR escalated to 126% and 2027%, respectively. Microstructural examination by Scanning Electron Microscopy (SEM) demonstrates a distorted fiber morphology that enhances interlocking and adhesion strength between the fiber and soil–CKD matrix, together with a coating of cementitious hydration products on the fiber surface. The presence of calcium, oxygen, and silicon as the fundamental constituents for the production of C–S–H gel was confirmed by Energy Dispersive Spectroscopy (EDS). The refined CKD-PPF mixture significantly improved soil efficacy while reducing total construction expenses by 35%, as per a cost assessment based on pavement design standards followed in India. In summary, it was determined that the stabilization of intermediate-plasticity clay in pavement foundations through the appropriate use of CKD and PPF is both environmentally sustainable and cost-effective.

B. S. Pankaja et al. (2023) The study examines the prospective application of industrial byproducts, specifically fly ash (FA) and cement kiln dust (CKD), to enhance the stability of expansive soils such as black cotton (BC) soil for construction applications. Despite the availability of numerous soil stabilizing techniques, the implementation of columns made from industrial byproducts remains unexamined. Understanding the pozzolanic properties and interactions between the byproduct and the soil, this technique of utilizing industrial waste as a solution have to be tested. Consequently, this study suggests and examines the installation of FA-CKD columns into the soil through a variety of laboratory tests utilizing numerous mixtures and configurations for their placement. The influence of molding water content and curing duration on the consolidation and strength characteristics of BC soil was evaluated in this study. The experiments reveal that the ideal composition of FA-CKD for the columns is 90% to 10%, respectively. This column blend has been shown to substantially enhance the unconfined compressive strength of the soil, with its efficacy increasing throughout time of curing. The greatest enhancement in strength occurs at the optimal moisture content, succeeded by conditions that are wet and dry relative to the optimum, respectively. Positioning the columns in the ground with a spacing of 4.5D results in improved consolidation characteristics and less swelling potential of BC soil. The aforementioned findings indicate that the utilization of FA-CKD columns can enhance the engineering properties of BC soil, aiding in waste-to-wealth initiatives and sustainable soil stabilizing methods.

Yusef Ahmed Fiener (2023)

Roadway engineers frequently encounter the difficulty of creating a robust foundation on Sabkha soil, characterized by elevated salinity, minimal load-bearing capacity, and a reduction in strength when exposed to moisture. Roads built on this soil type mostly encounter

issues of subsidence due to vehicular loads and the exceedingly poor load-bearing capability of Sabkha soft soil. This category of soil requires stabilization by one of the available treatments. The objective of this research is to investigate and assess the sabkha soil issue located in the Northwest region of Libya, where the principal road from Libya to Tunisia traverses. This study demonstrates the outcomes of employing Cement Kiln Dust (CKD) for the stabilization of Sabkha soil. The findings indicate a significant enhancement in the characteristics of sabkha soil as evidenced by testing, particularly the CBR values.

Dr. Suhail A. Khattab et al. (2021) Recently, numerous efforts have been undertaken to utilize steel fiber reinforcement to enhance various soil characteristics. This study examined the influence of steel fibers on the compaction and mechanical characteristics of cement-stabilized silty soil. Factors including the content of stabilizer (cement) and the quantity and variety of steel fibers were examined. Findings suggest that including fibers results in an elevation of the maximum dry unit weight. Conversely, the highest levels of unconfined and tensile strength were achieved with the incorporation of 0.5% short fiber (FS) and 1.5% long fiber (FL), respectively.

Bharat Singh Chauhan et al. (2021) Soil stabilization is a recognized method employed to enhance soil characteristics, augmenting shear strength and regulating swell and shrink qualities, hence minimizing soil settlement. The utilization of steel products in our daily lives is progressively rising, thus leading to an increase in steel product manufacturing. The steel manufacturing sector generates substantial trash, which becomes unusable since recycling it necessitates melting, a process that is economically unfeasible. This research suggests a partial remedy to this issue by utilizing steel fiber (waste) as a soil stabilizer. This research aims to determine the ideal length of steel fiber to provide the highest soil strength. The literature study indicates that the utilization of steel fiber for soil stabilization remains under-researched and warrants further focus from scholars. The testing is undertaken for steel fibers having three distinct ratios of length to diameter (L/D). The locally sourced black cotton soil in the area was utilized for experiments, and the results revealed discrepancies in soil properties corresponding to various L/D ratios of steel fiber depicted in X–Y plots. The examinations were conducted in compliance with the Indian Standard Codes of Practice. The influence of steel fiber on the shear strength of the soil is considerable. The impact of steel fibers on enhancing the characteristics of black cotton soil is examined, and the viability of steel fibers for soil applications is assessed.

Sadegh Ghavami et al. (2020)

An experimental investigation was carried out to assess the influence of cement kiln dust (CKD) and fly ash (FA) on the compaction and strength properties of high-plasticity clay sourced from a forest road in northern Iran. Consequently, the soil was blended with 15% CKD based on dry weight, and a partial substitution of the CKD with 10%, 20%, and 30% FA was implemented to create mixes. Unconfined compressive strength assessments were conducted on specimens following curing durations of 7 and 28 days. The microstructures of both untreated and treated samples were analyzed utilizing a scanning electron microscope (SEM). The integration of CKD and FA results in a reduction of pore volume within the soil matrix, attributed to the development of calcium silicate hydrates and calcium aluminate hydrates gels. The cementitious substances inside the combinations were believed to be the primary element enhancing strength.

Mohamed Sakr et al. (2020) Collapsible soils are metastable substrates distinguished by internal voids, with particle sizes varying from silt to fine sand. Upon saturation, they implode, resulting in deformations that could lead to structural failure. In this research, a fake collapsible soil was created with identical characteristics to the original collapsible soil sourced from the deposit to prevent alteration during transportation. Subsequently, both the natural and synthetic soil specimens were fortified with fly ash and cement kiln dust at various proportions. Kaolin particles were utilized to create artificial samples with reduced density to simulate the metastable soil structure. The fly ash and cement kiln dust were utilized in varying proportions of 5%, 10%, and 15% to illustrate the impact of these stabilizing substances on the Odometer test. The incorporation of fly ash (up to 15%) into natural or synthetic soil led to a reduction in collapse potential (CP) from 15.4% to 4.4% and from 13.8% to 2.6%, respectively. The findings indicated that the application of CKD on failing soils (both natural and artificial) decreased the collapse potential from 15.4% to 0.72% and from 13.8% to 0.95%, respectively. The findings indicated a notable enhancement in the stabilized collapsible soil compared to the non-stabilized variant,

regardless of whether it was treated with fly ash or CKD. Furthermore, CKD shown superior efficacy compared to fly ash in all conducted assessments.

dr inż. Tomasz Zdeb et al. (2020) The document reveals the findings of experiments about the chemical makeup and pH of the pore solution in soil-cements, derived from leaching and pressure extraction methods. The research focused on two soil-cements with varying compositions: varieties of loose and cohesive native soil, together with the water-to-cement ratio of the cement paste incorporated into the soil, which were 0.8 and 2.0 respectively. The test outcomes related to pore solution composition and pH levels, derived from ion chromatography, were utilized to evaluate the protective characteristics of soil-cements for reinforcing steel. The outcomes of the experiments performed demonstrate the complete capacity of the examined soil-cements to safeguard steel against corrosion, along with the possibly significant durability of the soil-cements themselves.

Joshi et al. (2018) The incorporation of steel slag enhances the load-bearing capacity and strength of black cotton soil, hence indirectly reducing construction expenses. Various proportions of 5%, 10%, 15%, and 20% steel slag have been employed to enhance the stability of black cotton soil and to assess its viability as a construction material for roadways. The steel slag obtained from Kalika Steel in Jalna and the black cotton soil sourced from Himayatbaugh in Aurangabad. The entire software was executed in two stages. In the initial stage, essential tests including Atterberg limit, C.B.R, and conventional proctor compaction tests on unadulterated soil were conducted to evaluate the maximum dry density and optimum moisture content. In the second phase, the black cotton soil was combined with 5%, 10%, 15%, and 20% of steel slag.

Dhyanendra Singh Rajput et al. (2018)
Swift advancements in engineering have significantly impacted human lifestyles. However, the daily actions of humanity are increasing environmental threats correspondingly. The utilization of steel goods across several sectors is escalating daily, resulting in numerous environmental issues. Consequently, the elimination of steel waste without inducing ecological risks has emerged as a significant task. Steel waste has emerged as a significant global issue. In recent years, scholars from other disciplines have endeavored to address environmental issues and the substantial waste generated by the manufacture of non-biodegradable materials such as steel. From a geotechnical perspective, this research offers a partial remedy to a significant issue with the accumulation of garbage, specifically steel waste. The main aim of this research is to investigate the feasibility of utilizing discarded steel fiber for soil stabilization. A range of assessments, including Standard Proctor and CBR, were conducted using diverse samples to evaluate the influence of steel fibers in silty clay. The preliminary findings were encouraging and corroborated the attainment of soil stability. The benefits of this research manifest in three aspects: the use of natural resources (silty clay), economic gains, and waste management. The incorporation of steel waste fibers into expansive soil aids in reducing the volumetric fluctuations of the soil.

Anil kumar et al. (2017) Currently, the management of industrial waste has become a worldwide issue. The disposal of these items is expensive and detrimental to the environment. Due to these issues, certain studies are being undertaken to employ these waste materials in soil construction and enhancement. Cement kiln dust (CKD) is an industrial waste product that results from the production of Portland cement. Cement is an extensively utilized building material, leading to a substantial accumulation of cement kiln dust from manufacturing facilities. Cement kiln dust can be effectively employed in applications such as soil stability, waste product stabilization, agriculture, and cement manufacturing. Subpar soil conditions may lead to insufficient strength and load-bearing capacity of the soil. Soil stabilization can be generally described as the modification or maintenance of specific soil attributes to enhance the engineering qualities and functionality of the soil. In this project, soil stabilization is achieved through the incorporation of CKD, varying from 0% to 30% of the soil's dry weight. Initially, the inherent parameters of the native soil, including compaction characteristics, Atterberg's limits, compressive strength, CBR, and permeability, were assessed and subsequently compared following the incorporation of CKD ranging from 0% to 30%.

Shalabi et al. (2017) Elevated moisture levels in these soils will result in significant expansion and a decrease in shear strength and foundation carrying capability. The engineering characteristics of various soil types can be enhanced through the application of additives and chemical stabilizers. In this study, steel slag as a by-product was utilized to enhance the engineering characteristics of clay soils. Laboratory and field

experimental initiatives were established to examine the impact of incorporating varying proportions of steel slag on the plasticity, swelling, compressibility, shear strength, compaction, and California bearing ratio (CBR) of the modified materials. The findings from the examinations of the clay soil indicated that with an increase in steel slag content, the dry density, plasticity, swelling potential, and cohesion intercept of the soil diminished, while the angle of internal friction augmented. The test outcomes indicated that the CBR value rose with the augmentation of slag content.

Hattamleh et al. (2017) This research aimed to investigate the efficacy of fine steel slag aggregate (FSSA) in enhancing the geotechnical characteristics of high plasticity subgrade soil. The mechanical and engineering characteristics of initial soil and fine steel slag were assessed. Subsequently, fine steel slag (FSSA) was incorporated into the prepared soil samples at concentrations of 0%, 5%, 10%, 15%, 20%, and 25% dry weight. The efficacy of the FSSA was evaluated based on enhancements in consistency limits, compaction, free swell, unconfined compressive strength, and California bearing ratio (CBR). The test findings indicate that 20% FSSA additions will decrease the plasticity index and free swell by 26.3% and 58.3%, respectively. Moreover, the incorporation of 20% FSSA additives will enhance the unconfined compressive strength, maximum dry density, and CBR value by 100%, 6.9%, and 154%, respectively. In conclusion, FSSA positively influenced the geotechnical properties of the soil and can serve as an admixture to enhance the geotechnical features of subgrade soil, addressing the waste disposal issue as well.

Anil Kumar Sharma et al., (2016) A binder was created through the amalgamation of fly ash with Ground Granulated Blast Furnace slag. Initially, the primary strength assessment was conducted on various proportions of fly ash and GGBS blend. A 70:30 blend of fly ash and GGBS demonstrated superior strength compared to either fly ash or GGBS alone, even without the presence of chemical activators. The amalgamation of binder devoid of lime shown a reduction in both liquid limit and plasticity index. As the binder content rises, the OMC diminishes while the MDD climbs. To ascertain the strength properties of each amalgamation of soil binder specimens, experiments were conducted during varying curing durations of 7, 14, and 28 days. It may be observed that strength escalates until 20% of the binder content, after which it diminishes.

Mahesh et al. (2016) Soil stabilization is employed to diminish the permeability and compressibility of the soil mass in terrestrial structures and to enhance its shear strength. Soil stabilization is necessary to enhance the load-bearing capability of foundational soils. The primary application of stabilization is to enhance natural soils for the development of roadways and airstrips. The CBR value is elevated at 10% lime and 1.5% fiber in comparison to the other ratios. The CBR value for both (soil +10% lime) and (soil +40% lime) is identical. CBR progressively rises with the addition of fibers up to 2% (soil plus 5% lime).

Ashima J Catherine et al. (2015) Numerous researchers have explored reinforced soil as a comparable homogeneous substance to comprehend its behavior and ascertain its strength properties. Reinforced soil is appropriate for the construction of geotechnical constructions as it enhances the tensile and shear strength of the soil. A range of materials such as prestressed concrete panels, geotextiles, geogrids, plastics, glass-reinforced polymers, and lumber can be utilized for this objective. The integration of reinforcement inside the soil mass by galvanized steel mesh provides significant tensile rigidity in the direction of tension. Synthetic rubber serves as an additional substance for soil reinforcement. It is cost-effective and provides stability when integrated into the ground. This research work involves the comparative evaluation of strength parameters of subgrade soil reinforced with galvanized steel mesh and synthetic rubber. The soil's strength properties, enhanced with galvanized steel mesh and synthetic rubber, are assessed through laboratory evaluations including sieve analysis, water content determination, specific gravity assessment, Modified Proctor compaction test, Atterberg limits evaluation, and CBR testing. An examination of soil augmented with galvanized steel mesh and synthetic rubber has been conducted, and the findings are juxtaposed to recommend an appropriate material.

Alaa M. Rashad et al., (2015) The recycling of waste materials constitutes an effective resolution to the issue of their disposal. Fly ash (FA) and phosphogypsum (PG) necessitate extensive disposal sites and cause significant environmental pollution, including leaching and dust emissions. Utilizing these wastes as construction materials is crucial to prevent environmental damage. This study examined the potential of utilizing calcined PG (CPG) as a partial replacement for FA in alkali-activated FA (AAFA) paste. FA was partially substituted with CPG at concentrations of 0%, 5%, 10%,

and 15% by weight. The compressive strength was assessed at 3, 7, and 28 days. The efficacy of the examined mixes, following exposure to temperatures of 400, 600, 800, and 1000 °C for 2 hours, was assessed by quantifying the remaining compressive strength.

Brijesh kumar et al. (2013) Clays are widely recognized for causing swelling issues and challenges in building because of significant settling and insufficient strength. Consequently, many soil types require stabilization prior to construction to enhance their engineering characteristics. In soil stabilization, cement is frequently employed as a stabilizing ingredient to enhance both the strength and rigidity of the initially weak, pliable material. Nonetheless, cement is comparatively costly and may pose environmental risks when mixed with soils. The necessity for substitute stabilizing chemicals that could diminish cement consumption is thus evident. The aim of the current research is to examine the shear strength properties and mechanical resilience of Kaolinite clay soil modified with 5, 10, 15, 20, and 25 percent by weight of cement kiln dust. This has been executed to render the soil appropriate for constructing pavements above it. Standard Proctor tests have been performed to ascertain the ideal moisture content and peak dry density of Kaolinite clay, as well as Kaolinite clay modified with 5, 10, 15, 20, and 25% of CKD that has passed through a 425 micron IS filter. It has been noted that when the proportion of cement kiln dust rises, the optimum moisture content diminishes while the maximum dry density escalates. The reduction in OMC with the rise in cement kiln dust content may be ascribed to the incorporation of a material categorized as silty sand into the base material.

3. Materials

The present experimental investigation focuses on assessing the performance of cement kiln dust (CKD) stabilized clayey soil reinforced with steel fibers. The study aims to evaluate the changes in the engineering properties of clayey soil resulting from the addition of CKD and steel fibers. CKD is used as a stabilizing agent, whereas steel fibers are incorporated to improve the mechanical response of the soil and resist the development of cracks.

The experimental programme consists of collecting and characterizing the constituent materials, preparing soil mixtures with different CKD contents, identifying a suitable CKD percentage, and subsequently incorporating steel fibers into the selected mixture.

Laboratory tests are conducted to determine the compaction characteristics, swelling behavior, compressive strength and bearing capacity of untreated and treated soil. The experimental results are compared to assess the effectiveness of the proposed stabilization technique.

3.1 SOIL

S.No.	Properties	Result
1.	Liquid limit (%)	40
2.	Plastic limit (%)	26
3.	Plasticity Index (%)	14
4.	Specific Gravity	2.62
5.	Free Swell Index (%)	31
6.	Maximum Dry Density (KN/m³)	15.18
7.	Optimum Moisture Content (%)	13.28
8.	Soil Classification	CI (Intermediate Compressive Clay)
9.	CBR (%) (soaked)	2.8
10.	CBR (%) (Unsoaked)	4.6
11.	UCS (7days) (kPa)	168
12.	UCS (14days) (kPa)	220
13.	UCS (28days) (kPa)	268

Table no. 1 Properties of soil used in the study

Source of soil

Clayey soil is used as the base material for the investigation. Its engineering behavior depends on particle-size distribution, clay mineral composition, moisture content and plasticity characteristics. The soil is collected from a suitable location and transported to the laboratory for sample preparation.

Before testing, the soil is air-dried, pulverized gently to break down soil lumps without crushing individual particles, and passed through the appropriate sieve for each laboratory test. Representative samples are used to determine the physical and index properties of the untreated soil. These properties provide a reference for evaluating the effects of CKD and steel-fiber additions. The characterization of soil includes specific gravity, particle-size distribution, Atterberg limits, free swell index and compaction characteristics. The initial strength and bearing capacity are also determined wherever required for comparison with the treated mixtures.

The soil required for the project is taken from an empty field in Local Area. The soil is alluvial in nature and contains high amounts of clay.

2 CEMENT KILN DUST

Cement kiln dust is a fine particulate by-product harvested from the gas filtration apparatus of cement producing establishments. It consists of different amounts of calcium-based compounds, silica, alumina, iron oxides, sulfates, and alkalis. Its makeup is determined by the fabrication technique and the source of procurement.

This experiment involves the incorporation of CKD into clayey soil at varied quantities to evaluate its impact on the engineering qualities of the composite. The tiny particles can change the soil structure, whereas calcium-rich reactive chemicals could facilitate chemical stabilization when conditions are favorable. The CKD is preserved in a dry, sealed receptacle before application to limit contamination and modifications resulting from moisture exposure. In locations where facilities exist, the chemical makeup and quality are evaluated to aid in the interpretation of the experimental outcomes. The physical and chemical attributes of CKD fluctuate based on the source, the kind of raw materials utilized, the operational processes of the plant, the fuel type, and the disposal methods. Table 2 presents the chemical attributes of CKD. In general, CKD presents a grayish coloration.

Table 2: Chemical Properties of CKD

CONTENT	CKD (%)
Silicon dioxide (SiO_2)	17.62
Aluminum Oxide (Al_2O_3)	4.90
Iron Oxide (Fe_2O_3)	2.58
Calcium Oxide (CaO)	62.09
Magnesium Oxide (MgO)	1.93
Potassium Oxide (K_2O)	3.76
Sodium Oxide (Na_2O)	0.56
Sulphur Oxide (SO_3)	5.79
Titanium oxide (TiO_2)	-

3.3 STEEL FIBER

Metallic reinforcement components, known as steel fibers, are included into the chosen CKD-treated soil blend. Steel fibers, based on their shape, can enhance the tensile deformation resistance, crack propagation, and post-peak failure of compacted soil.

The fibers employed in the research must be defined by their length, diameter, aspect ratio, morphology, and surface texture. The aspect ratio is determined by the proportion of fiber length to its corresponding diameter. These traits affect fiber dispersion, engagement with soil particles, and the strengthening impact. Steel fibers are incrementally introduced during the mixing process to ensure consistent dispersion within the soil blend. Efforts are made to reduce fiber aggregation, since uneven distribution may influence compaction and strength assessments.

Table 3:- Properties of Steel fiber

S. No	Property	Value
1	Material	Carbon steel
2	Appearance	Silver-grey
3	Shape	Straight
2	Specific Gravity	7.8

3	Water Absorption (%)	Generally Negligible
4	Length of fiber (mm)	06
5	Diameter of Diameter fibre (mm)	0.2
6	Tensile Strength(MPa)	600-2000
7	Modulus of elasticity (GPa)	200
8	Density (Kg/m^3)	7800-7900

4. EXPERIMENTAL RESULTS

4.1 STANDARD PROCTOR TEST

The Standard Proctor compaction test is performed to ascertain the maximum dry density (MDD) and optimum moisture content (OMC) of unprocessed clayey soil and blends with varying ratios of CKD and steel fibers. Variations in MDD and OMC are contingent upon the characteristics of the initial soil, the granularity and formulation of CKD, and the quantity of additive included. Steel fibers can affect compaction due to their density, configuration, and dispersion within the soil matrix.

Table no. 4: Results of OMC and MDD for mix proportions of Soil, CKD and SF

CS:CKD:SF	MDD (kN/m³)	OMC (%)
100:00:00	15.18	13.28
84.5:15:0.5	16.90	12.80
84.25:15:0.75	16.50	13.30
84.0:15:1.0	16.10	13.70

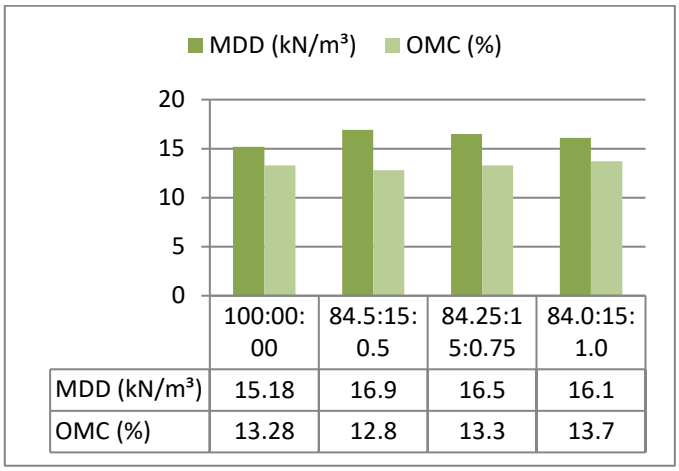


Fig:-1 variations b/w MDD and OMC of CKD, Steel Fiber & soil with different proportions

- When the CKD content was maintained at 15% and the steel fiber content was varied from 0.5% to 0.75% and 1.0%, the maximum dry density (MDD) increased from 15.18 kN/m³ for untreated soil to 16.90 kN/m³ after the addition of the admixtures, reaching 16.10 kN/m³ at the final mixture.
- The initial increase in MDD may be attributed to improved particle packing due to CKD addition, which helps fill the voids between soil particles. However, the subsequent reduction in MDD with increasing steel fiber content may result from the fibers disrupting the uniform arrangement of soil particles and creating additional void spaces.
- The optimum moisture content (OMC) increased from 13.28% to 13.70%, indicating a slight increase in the water required to achieve effective compaction. These findings suggest that the combined effects of CKD and steel fibers influence the compaction characteristics of clayey soil.

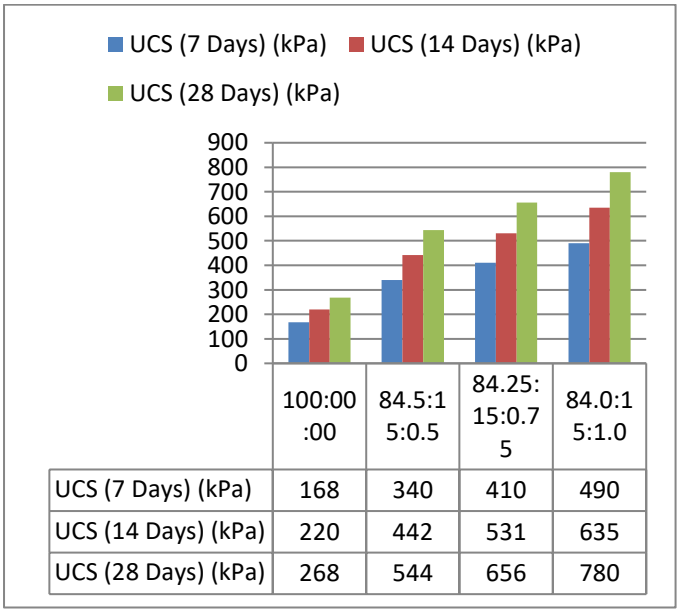
4.2 UNCONFINED COMPRESSION STRENGTH TEST

The unconfined compressive strength evaluation is carried out to analyze the capacity of untreated and treated soil to withstand axial compression. The UCS values are ascertained for the given CKD materials and steel-fiber ratios under particular specimen preparation and curing circumstances.CKD can aid in the formation of strength by changing the soil structure and encouraging cementitious processes when its chemical properties are favorable. Steel fibers have the potential to augment the mechanical behavior by spanning fissures and countering deformation. The joint effect is contingent upon the quantity of each addition, fiber dispersion, and curing conditions.

Table 5: Results of UCS of CKD and Steel Fiber Mix with Soil

CS:CKD:SF	UCS (7 Days) (kPa)	UCS (14 Days) (kPa)	UCS (28 Days) (kPa)
100:00:00	168	220	268
84.5:15:0.5	340	442	544
84.25:15:0.75	410	531	656
84.0:15:1.0	490	635	780

Fig:-2 Variations b/w UCS Values of CKD, Steel Fiber & soil with different proportions and different days of curing period



- The unconfined compressive strength (UCS) of clayey soil stabilized with 15% cement kiln dust (CKD) and reinforced with steel fibers increased as the fiber content varied from 0.5% to 0.75% and 1.0%. At 7 days of curing, the UCS values were 340, 410 and 490 kPa, respectively. After 14 days, the corresponding values increased to 442, 531 and 635 kPa, while at 28 days, they reached 544, 656 and 780 kPa.
- The increase in UCS with increasing steel fiber content may be attributed to the reinforcing effect of the fibers, which helps distribute applied stresses, restrict crack development and improve resistance to compressive deformation. The presence of 15% CKD may further contribute to strength development by improving interactions between soil particles and, depending on its chemical composition, promoting cementitious reactions.
- The continuous increase in UCS with curing time indicates progressive strength development within the treated soil matrix. Among the tested combinations, 15% CKD with 1.0% steel fiber achieved the highest UCS of 490 kPa, 635 kPa and 780 kPa after 7, 14 and 28 days, respectively. These results indicate that combining CKD stabilization with steel fiber reinforcement can improve the compressive strength of clayey soil under the tested conditions.

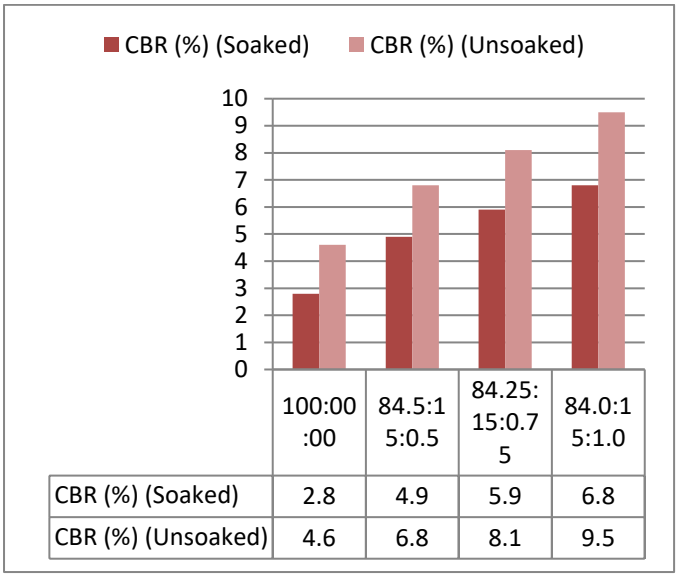
4.3 CALIFORNIA BEARING RATIO TEST

The California bearing ratio test is performed to assess the ability of compacted soil to withstand penetration. The findings aid in evaluating the prospective efficacy of the treated soil as a subgrade material for roads. Both saturated and unsaturated CBR values are documented as these assessments constitute a segment of the experimental protocol. The incorporation of CKD may enhance the load-bearing properties of clayey soil by altering its structure and, when certain reactions take place, augmenting interparticle cohesion. Steel fibers might provide supplementary resistance to distortion by mechanical engagement with the adjacent earth. The degree of enhancement is contingent upon the ratios of materials, compaction circumstances, and water exposure.

Table 6: Results of CBR of CKD and Steel Fiber Mix with Soil

CS:CKD:SF	CBR (%) (Soaked)	CBR (%) (Unsoaked)
100:00:00	2.8	4.6
84.5:15:0.5	4.9	6.8
84.25:15:0.75	5.9	8.1
84.0:15:1.0	6.8	9.5

Fig:-3 CBR value variations of soil-Steel Fiber and CKD mixtures under soaked and unsoaked conditions with varying proportions



	100:00 :00	84.5:1 5:0.5	84.25: 15:0.7 5	84.0:1 5:1.0
CBR (%) (Soaked)	2.8	4.9	5.9	6.8
CBR (%) (Unsoaked)	4.6	6.8	8.1	9.5

- The California Bearing Ratio (CBR) test results demonstrate the combined influence of 15% cement kiln dust (CKD) and varying steel fiber contents on the penetration resistance of clayey soil. Under soaked conditions, the CBR value increased from 2.8% for virgin soil to 4.9%, 5.9% and 6.8% with the addition of 0.5%, 0.75% and 1.0% steel fibers, respectively. This improvement indicates that the combined stabilization and reinforcement approach enhanced the soil's resistance to penetration under soaked conditions.
- Under unsoaked conditions, the CBR value increased from 4.6% for untreated soil to 6.8%, 8.1% and 9.5% for the corresponding fiber contents. The improvement may be attributed to the combined effects of CKD and steel fibers. CKD may improve the bonding and arrangement of soil particles, depending on its chemical composition, while steel fibers can help transfer stresses and resist deformation through interaction with the surrounding soil matrix.
- Among the tested mixtures, 15% CKD with 1.0% steel fiber achieved the highest CBR values of 6.8% under soaked conditions and 9.5% under unsoaked conditions. The results suggest that combining CKD with steel fiber reinforcement can improve the load-bearing capacity of clayey soil and may enhance its suitability for subgrade applications, subject to the relevant pavement design requirements.

5. CONCLUSIONS

Based on the experimental investigation of clayey soil stabilized with cement kiln dust (CKD) and reinforced with steel fibers, the following conclusions are drawn in accordance with the research objectives.

1. The addition of CKD improved the compaction characteristics of clayey soil. The maximum dry density (MDD) increased from 15.18 to 17.82 kN/m³, while the optimum moisture content (OMC) decreased from 13.28% to 11.83%. This indicates an improvement in the compaction behavior of the treated soil. The addition of steel fibers at contents of 0.5%, 1.0% and 1.5% reduced the MDD from 15.18 to13.90 kN/m³, while the OMC increased from 13.28% to 14.40%. These changes indicate that steel fiber reinforcement influenced the packing arrangement and moisture requirements of the soil.
2. The UCS results showed a progressive increase with increasing CKD content and curing period. At 15% CKD, the UCS reached 471 kPa after 7 days, 612 kPa after 14 days and 753 kPa after 28 days, compared with 168, 220 and 268 kPa, respectively, for virgin soil.Steel fiber reinforcement improved the UCS of clayey soil. Among the tested fiber contents of 0.5%, 1.0% and 1.5%, the highest UCS was obtained at 1.5% steel fiber, reaching 290 kPa, 377 kPa and 464 kPa after 7, 14 and 28 days of curing, respectively. The combined use of 15% CKD and steel fibers produced a further improvement in UCS. With 1.0% steel fiber, the UCS reached 490 kPa after 7 days, 635 kPa after 14 days and 780 kPa after 28 days. This combination exhibited the highest compressive strength among the tested CKD–fiber mixtures.
3. The CBR results indicated that CKD improved the penetration resistance of the soil under both soaked and unsoaked conditions. At 15% CKD, the soaked and unsoaked CBR values increased from 2.8% and 4.6% for virgin soil to 6.5% and 9.1%, respectively. Steel fiber reinforcement alone increased the soaked CBR from 2.8% to 3.9% and the unsoaked CBR from 4.6% to 5.4% at 1.5% fiber content. The initial reduction in unsoaked CBR at 0.5% fiber indicates that the response to fiber addition was not uniformly

positive at every dosage. The combined addition of 15% CKD and steel fibers further enhanced CBR performance. At 1.0% steel fiber, the soaked CBR reached 6.8%, while the unsoaked CBR increased to 9.5%. These were the highest values recorded among the tested combined mixtures.

4. The compaction results for the combined mixtures showed that, with CKD fixed at 15% and steel fiber content varied from 0.5% to 1.0%, the reported MDD values ranged from 16.10 to 16.90kN/m³, while the OMC increased from 13.28% to 13.70%. These results suggest that the combined additives influenced the compaction behavior of the soil. The individual values should be checked against the laboratory records before final submission.
5. Overall, the experimental results identify 15% CKD combined with 1.0% steel fiber as the best-performing tested combination for UCS and CBR. This mixture demonstrated improved strength and penetration resistance compared with virgin soil and may have potential for road subgrade applications, subject to applicable design criteria and further durability assessment.

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