Research on Engineering Structures & Materials
www.jresm.org
MIM Research Group

Research Article

Experimental study on the use of cement kiln dust to improve the CBR of granular sub-base soil

Omar K. Mohialdeen [1,a], Takwa Altaher [2,b], Mahdi Karkush [*,3,c]

[1]*Environmental Technology Department, University of Mosul, Mosul, Iraq*
[2]*Department of Mechanical Engineering, University of Sumer, Al-Rifai, Iraq*
[3]*Department of Reconstruction and Projects, University of Baghdad, Baghdad, Iraq*

Article Info

Article History:

Received 21 Jul 2026

Accepted 12 Oct 2026

Keywords:

Cement kiln;
Improvement;
CBR;
Sub-base soil;
Granular

Abstract

This study evaluates the potential of cement kiln dust (CKD) as a sustainable stabilizing agent for enhancing the engineering performance of weak granular sub-base soils. The investigation focused on assessing the influence of CKD addition on the compaction and strength characteristics of two commonly used granular sub-base materials, designated as type C and type D soils. Laboratory testing was conducted in accordance with relevant ASTM standards, including the determination of maximum dry density (MDD) from compaction tests and bearing capacity from the California bearing ratio (CBR) test. CKD was mixed with the soils at dosages of 2.5%, 5%, 7.5%, and 10% by dry weight of soil to identify the optimum stabilization content. The experimental results demonstrated a consistent improvement in both density and strength properties with increasing CKD content up to an optimum value of 5% to 7.5%. For type D soil, the MDD increased by approximately 10.5%, while the CBR value improved from 20% for the untreated soil to 31% at the optimum CKD content. Similarly, type C soil exhibited an increase in MDD of approximately 11.2%, accompanied by a substantial enhancement in CBR from 25% to 51%, indicating a significant improvement in load-bearing capacity.

© 2026 MIM Research Group. All rights reserved.

1. Introduction

Cement kiln dust (CKD) is a fine-grained by-product generated during the cement manufacturing process and collected from the exhaust gases of cement kilns. In recent years, CKD has received considerable attention as a potentially valuable construction material due to its engineering properties and its role in promoting sustainable development within the construction and geotechnical sectors [1]. The increasing emphasis on sustainable geotechnical engineering has encouraged researchers to explore the reuse of industrial by-products and waste materials as alternatives to conventional stabilizing agents for improving weak soils and pavement foundation layers [2]. The cement industry represents one of the most important industrial sectors worldwide and plays a fundamental role in infrastructure development. However, cement production is also associated with the generation of substantial quantities of industrial waste, particularly cement kiln dust. It is estimated that cement plants around the world produce approximately 30 million tons of CKD annually. Improper disposal of these materials can lead to significant environmental concerns, including air pollution, land contamination, and increased landfill requirements. Consequently, the beneficial utilization of CKD has become an important research topic aimed at reducing environmental impacts while simultaneously creating economic value from industrial waste.

*Corresponding author: mahdi_karkush@yahoo.com
[a]orcid.org/0009-0001-6412-1755; [b]orcid.org/0009-0001-2755-1772; [c]orcid.org/0000-0003-1304-0303
DOI: http://dx.doi.org/10.17515/resm2026-2005ic0721rs

CKD consists primarily of fine particles rich in calcium compounds, alkalis, and other cementitious constituents, which make it a promising material for soil stabilization applications. Previous studies have demonstrated that CKD can improve the engineering characteristics of weak soils through physical and chemical mechanisms, including particle bonding, void filling, and pozzolanic reactions. These processes contribute to enhanced soil strength, stiffness, and durability, making CKD an attractive and cost-effective alternative to traditional stabilizers such as lime and Portland cement. In particular, the use of CKD has been shown to significantly increase the CBR of weak soils, thereby improving their suitability for pavement and highway construction. In Iraq, where extensive road infrastructure projects are continuously being developed, several investigations have highlighted the potential benefits of utilizing CKD produced by both ordinary and white cement plants. Previous research has reported successful applications of CKD in soil stabilization, highway embankment improvement, and as a mineral filler in Hot Mix Asphalt (HMA) mixtures. These applications not only enhance the engineering performance of pavement materials but also contribute to reducing environmental burdens associated with industrial waste disposal. Furthermore, field and laboratory studies have demonstrated that CKD can provide sustainable improvements in the load-bearing capacity and performance of weak pavement subgrades, supporting its practical implementation in transportation infrastructure projects [2-5].

Among the various engineering properties used to evaluate stabilized soils, maximum dry density and California bearing ratio are considered key indicators of compaction efficiency and load-bearing capacity. MDD reflects the ability of soil particles to achieve dense packing under compaction effort, while CBR provides a direct measure of soil strength and resistance to penetration under loading conditions. The CBR test, originally developed by the California Division of Highways in the 1930s, remains one of the most widely adopted methods for assessing the suitability of subgrade, sub-base, and base materials in pavement design and construction worldwide. Therefore, the primary objective of this study is to investigate the effectiveness of cement kiln dust as a stabilizing agent for improving the engineering properties of weak granular sub-base soils. The research specifically evaluates the influence of different CKD contents on MDD and CBR values of two granular soil types commonly used in pavement construction. The findings are expected to provide valuable insights into the sustainable utilization of CKD in road engineering applications while contributing to the development of environmentally friendly and cost-effective ground improvement techniques. While extensive research has investigated CKD stabilization of fine-grained soils (such as expansive clays, gypsiferous, and lateritic soils) to alter plasticity and swelling, limited literature systematically evaluates the structural densification and load-bearing performance of standard coarse-grained granular sub-base materials (specifically types C and D according to local specification codes). Granular sub-base layers represent the primary stress-distributing layer in flexible pavements; thus, evaluating how varying CKD ratios affect their compaction energy, mechanical resistance (CBR), and mechanical optimal threshold provides practical engineering parameters directly applicable to road design, distinct from clay-bound mechanisms.

2. Literature Review

The application of cement kiln dust as a soil stabilization material has attracted increasing attention in recent years due to its environmental and economic advantages. Numerous studies have demonstrated the effectiveness of CKD in improving the engineering properties of weak and problematic soils used in transportation and geotechnical infrastructure projects. Ogila [6] investigated the stabilization of highly expansive clay soils using fresh CKD and reported significant improvements in engineering performance. The study highlighted the chemical and physical stabilization mechanisms associated with CKD, including cation exchange, flocculation, and the formation of cementitious compounds that contribute to increased strength and reduced swelling potential [6]. Similarly, Sharifi Teshnizi et al. [7] evaluated the effects of CKD on loess soils and observed considerable improvements in compaction characteristics, shear strength, and soaking resistance. Their findings confirmed the suitability of CKD as an effective stabilizing agent for problematic soils subjected to moisture variations.

Almuaythir and Abbas [8] examined the influence of CKD on expansive soils and reported significant improvements in moisture-density relationships and strength characteristics. The study demonstrated that CKD treatment effectively reduced soil plasticity and enhanced its load-bearing capacity, making the stabilized soil more suitable for engineering applications. Likewise, Al-Gharrawi et al. [9] investigated the stabilization of gypsiferous subgrade soils and found that CKD substantially increased CBR values. The study concluded that the optimum CKD content and curing conditions play a crucial role in achieving maximum stabilization efficiency. Further evidence of the effectiveness of CKD was provided by Al-Homidy et al. [10], who evaluated the stabilization of dune sands for pavement support applications. Their results indicated significant improvements in strength and durability parameters under both soaked and unsoaked conditions. Although soaked specimens exhibited lower CBR values than unsoaked samples due to moisture-induced weakening of particle bonds, the treated soils still maintained enhanced performance compared with untreated materials. Similarly, Gul and Mir [11] investigated silty soils stabilized with a combination of CKD and glass fibers and reported considerable improvements in CBR values, strength characteristics, and soil microstructure, demonstrating the potential of CKD-based stabilization systems for subgrade applications.

Beyond soil stabilization, CKD has also been successfully utilized in asphalt pavement engineering. Fadhil et al. [12] investigated the feasibility of using white cement kiln dust (WCKD) from the Fallujah White Cement Factory as a mineral filler in Hot Mix Asphalt (HMA). Various filler combinations were examined, including 100% WCKD, 50% WCKD–50% cement, and 50% WCKD–50% limestone mixtures. The results showed that all mixtures satisfied the requirements of the American Association of State Highway and Transportation Officials (AASHTO) and Iraqi road specifications. Asphalt mixtures containing WCKD exhibited superior Marshall stability and stiffness values compared with conventional limestone filler mixtures, indicating that WCKD can serve as an effective and sustainable alternative filler material in asphalt production [12]. The growing interest in sustainable geotechnical engineering has further encouraged the utilization of CKD as an alternative binder. Zada et al. [13] reviewed recent developments in expansive soil stabilization and emphasized the increasing role of industrial by-products and waste-derived binders in achieving sustainable ground improvement solutions. Similarly, Jasim and Mohammed [14] evaluated the use of CKD for improving weak subgrade soils along the 150 m Ring Road in Erbil. CKD was incorporated at percentages ranging from 0.5% to 2.5%, resulting in significant improvements in CBR values and overall pavement support capacity. The study concluded that CKD stabilization offers substantial technical, environmental, and economic benefits for transportation infrastructure projects.

Salih et al. [15] investigated the combined use of CKD and waste plastic bottles (WPB) for stabilizing expansive soils. The research demonstrated that the optimum mixture, consisting of 12% CKD and 12% WPB with a curing period of 28 days, significantly improved soil properties. At this optimum condition, the liquid limit, plasticity index, and swelling potential decreased substantially, while the CBR value increased by approximately 98%. The study highlighted the potential of integrating industrial and plastic wastes into sustainable soil stabilization practices. More recently, Daimary et al. [16] examined the stabilization of lateritic subgrade soils using CKD and rice husk ash. Their findings confirmed that the combined use of industrial and agricultural waste materials can significantly enhance the geotechnical performance of weak soils while promoting sustainable construction practices. Furthermore, Donkor et al. [17] emphasized the importance of evaluating the long-term hydraulic performance of CKD-treated soils, noting that durability, permeability, and moisture susceptibility are critical factors that should be considered when assessing the long-term effectiveness of CKD stabilization techniques. Although previous studies have demonstrated the effectiveness of CKD in improving the engineering properties of cohesive, expansive, gypsiferous, and lateritic soils, limited research has focused on its application in weak granular sub-base materials commonly used in pavement construction. Therefore, the present study aims to investigate the influence of different CKD contents on the compaction and strength characteristics of weak granular soils by evaluating changes in MDD and CBR. The findings are expected to contribute to the development of sustainable and cost-effective stabilization methods for pavement foundation layers while promoting the beneficial reuse of cement industry by-products.

3. Materials

3.1 Granular Soil

Two granular sub-base materials, classified as type D and type C according to the relevant pavement specifications, were collected from the southern region of Mosul City and utilized in the experimental program. Prior to stabilization, the engineering and physical properties of both soils were thoroughly characterized through a series of laboratory tests. The investigated properties included particle-size distribution (gradation), California bearing ratio, gypsum content, total soluble salts (TSS), and organic matter content. All tests were conducted in accordance with the applicable ASTM and Iraqi Standard Specifications procedures. Table 1 summarizes the engineering properties, chemical characteristics, and testing procedures for the types C and D materials. These preliminary investigations were performed to establish the baseline properties of the untreated soils and to evaluate their suitability for subsequent stabilization with cement kiln dust.

The dry mixing process of the natural fibers with the hot aggregate 145°C was performed for 45 seconds to achieve a homogeneous dispersion without fiber clumping. To prevent thermal degradation or burning, the mixing temperature (145°C) was maintained below the thermal decomposition threshold of the natural fibers (typically >200°C) Following the dry mixing, asphalt binder was immediately added and wet-mixed for an additional 60 seconds to fully coat the fiber-aggregate matrix.

Table 1. Test Results for sub-base types C and D

Sieve size (mm)	ASTM specifications	Requirements for gravel mixtures				Type C	Type D
		Class A	Class B	Class C	Class D		
75	ASTM C136/C136M-19	100	----	-----	----	-----	-----
50		100-95	100	-----	----	-----	-----
25		----	95-75	100	100	100	100
9.5		65-30	75-40	85-50	100-60	76	76
4.75		55-25	60-30	65-35	85-50	58	65
2.36		72-42	47-21	52-26	42-16	44	35
0.3		18-7	28-14	28-14	42-23	24	28
0.075		0-3	15-5	15-5	20-5	7	6
CBR%	ASTM D1883/24	55 Min.	35 Min.	25 Min.	20 Min.	25	20
L.L (%)	ASTM D4318-17e1	25% Max.				7	9
P.I (%)		6 % Max.				2	2
MDD (g/cm^3)	AASHTO T 180-21	----				2.05	2
Optimum moisture content (OMC) (%)	AASHTO T 180-21	----				8	8
SO_3 (%)	B.S1377-3/1990 test No.5	5% Max.				3.7	3.5
$CaSO_4.2H_2O$ (%)	Diagnosis and improvement of saline and alkali soils	10.75% Max.				6.8	6.8
Organic materials (%)	ASTM D2974 - 20e1	2% Max.				0.87	0.87

3.2 Cement Kiln Dust

Cement kiln dust is a hazardous industrial by-product that poses significant environmental and public health risks if improperly managed. Recognizing these threats, the Environmental Protection Agency (EPA) issued a regulatory finding in 2001, mandating stricter management controls to mitigate potential contamination [18]. Chief among these concerns is the degradation of groundwater and potable water resources due to inadequate disposal practices, as well as health hazards arising from airborne particulates and bioaccumulation within the food chain. The CKD evaluated in this study was sourced from the Fallujah White Cement Factory, and its chemical composition is detailed in Table 2.

Table 2. Oxide composition and physical properties of used CKD

Oxide	Percentage (%)	Oxide	Percentage (%)	Property	Value
SiO_2	14.2	Na_2O	0.18	Specific gravity	2.60-2.85
Al_2O_3	3.80	K_2O	2.40	pH	>12
Fe_2O_3	1.48	LOI	23.74		
CaO	48.8	SO_3	3.20	Appearance	Fine, light-colored particulate powder
MgO	2.20	-	-		

4. Results of Experimental Work

4.1 Maximum Dry Density

Beyond baseline material characterization, modified Proctor compaction tests were conducted in accordance with the AASHTO T180 standard to determine the dry density-moisture content relationships of the soil. Evaluating these compaction characteristics is vital because the introduction of a fine-grained, chemical by-product like cement kiln dust substantially alters the internal structure, void ratio, and matrix packing efficiency of the granular soil. Test specimens were prepared by blending type D granular sub-base soil with CKD at dosages of 2.5%, 5.0%, 7.5%, and 10.0% by dry weight of the soil. To ensure reproducibility and minimize experimental uncertainty, all tests were performed in triplicate, and mean values were reported. Outliers deviating significantly from the mean were identified and excluded in accordance with standard data validation protocols. Each mixture was systematically compacted under controlled laboratory conditions to establish its unique moisture-density curve, as illustrated in Figure 1 and summarized in Table 3.

Table 3. Relation between MDD and moisture content for different ratios of CKD added to sub-base type D

Moisture content (%)	MDD (g/cm³)				
	0% CKD	2.5% CKD	5% CKD	7.5% CKD	10% CKD
4	1.866	2.070	2.098	2.155	2.064
6	1.888	2.090	2.131	2.190	2.105
8	2.000	2.100	2.142	2.210	2.150
10	1.866	2.060	2.090	2.138	2.084

From these experimental relationships, the maximum dry density and corresponding optimum moisture content (OMC) were derived for each additive increment. This step is critical to observe how the highly porous, fine particulates of CKD, which typically possess a lower specific gravity than raw aggregate influence the compaction energy needed to eliminate air voids. Furthermore, the high surface area of CKD increases the immediate water demand necessary to lubricate the soil particles during compaction. Finally, to establish the definitive stabilization threshold, the correlation between increasing CKD content and the achieved MDD values was evaluated (Table 4 and Figure 2). This analysis identifies the optimum stabilizer dosage required to achieve the

absolute maximum dry density, defining the precise point where particle-packing optimization balances with the physical properties of the additive to stabilize the type D granular sub-base.

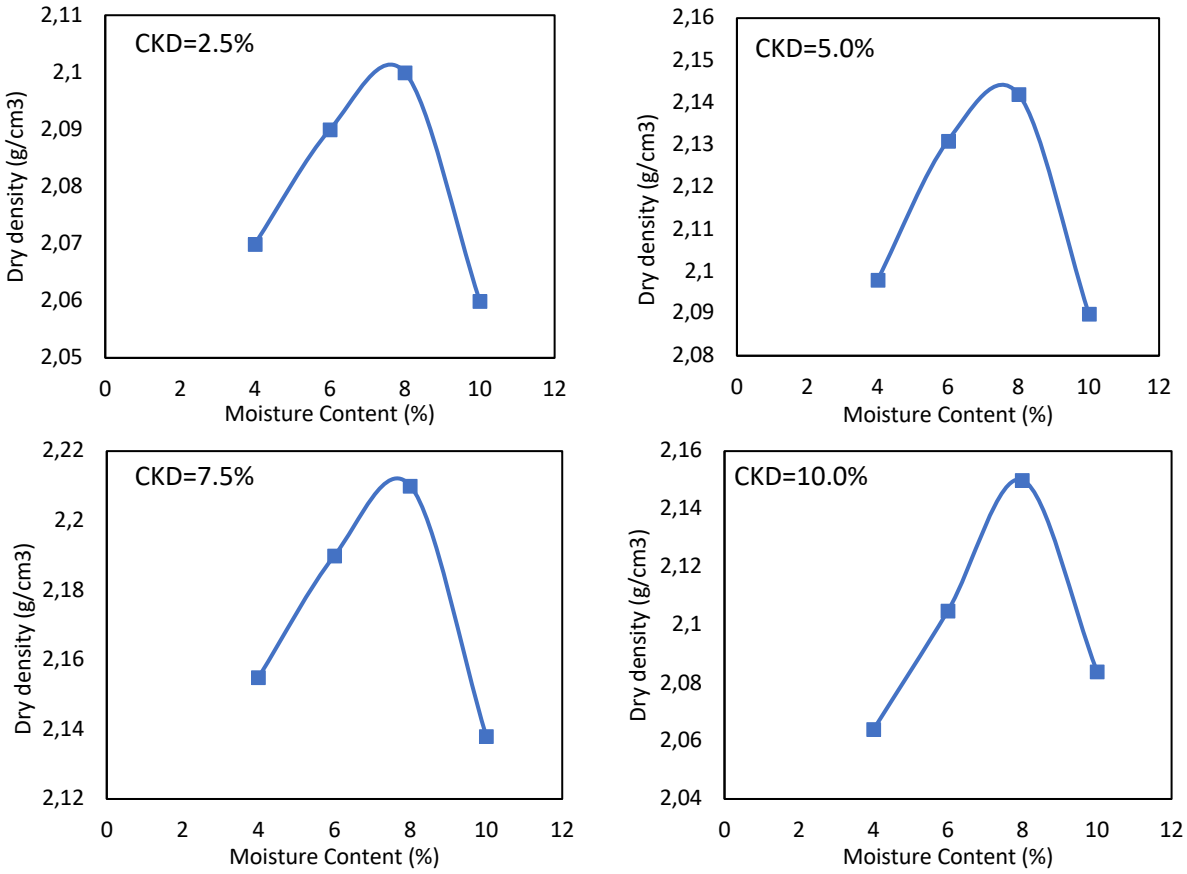


Fig. 1. Variation of dry density with moisture content for sub-base type D treated with CKD (2.5%, 5%, 7.5%, and 10%)

Table 4. Relation between MDD and CKD increments for sub-base type D

CKD (%)	MDD (g/cm^3)	Improving (%)
0	2.000	0.00
2.5	2.154	7.70
5	2.174	8.75
7.5	2.210	10.50
10	2.150	7.50

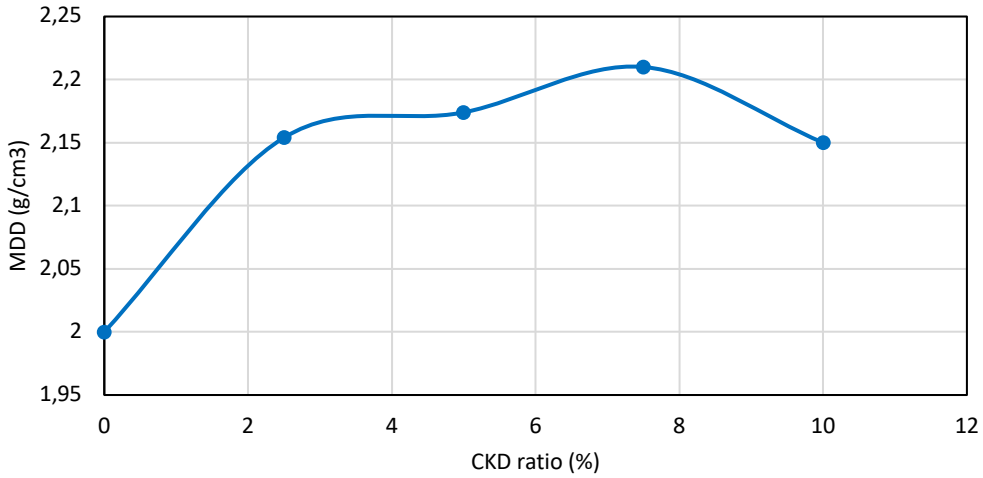


Fig. 2. Variation of maximum dry density with different CKD ratios for sub-base type D

An identical experimental program was executed to evaluate the compaction characteristics of the type C granular sub-base soil. Modified Proctor compaction tests were conducted in accordance with the AASHTO T180 standard to establish the dry density-moisture content relationships of the soil under varying stabilizer content. Understanding these relationships is essential since the integration of cement kiln dust introduces highly active, fine-grained components into the coarser type C aggregate matrix, altering the internal friction, void distribution, and overall packing efficiency of the compacted mass. The test specimens were prepared by blending the type C soil with CKD at corresponding ratios of 2.5%, 5%, 7.5%, and 10% by dry weight of the soil. Each blended mixture was systematically compacted under standardized laboratory conditions to generate the respective moisture-density curves, with the experimental findings thoroughly detailed in Table 5 and illustrated in Figure 3.

Table 5. Relation between MDD and moisture content for different ratios of CKD added to sub-base type C

Moisture content (%)	MDD (g/cm³)				
	0% CKD	2.5% CKD	5% CKD	7.5% CKD	10% CKD
4	1.900	1.900	2.060	2.028	1.994
6	1.987	2.000	2.150	2.090	2.087
8	2.050	2.060	2.280	2.244	2.221
10	1.878	1.900	2.044	2.010	2.000

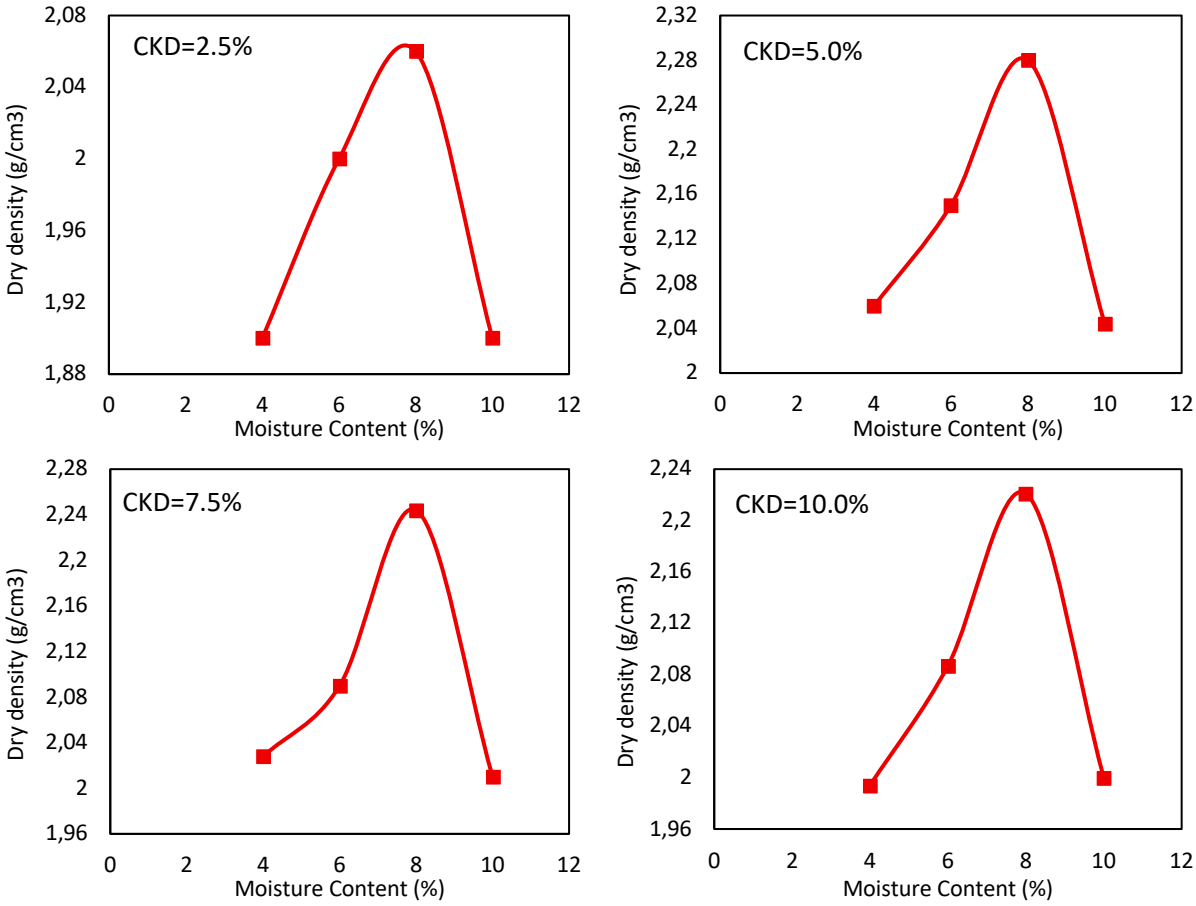


Fig. 3. Variation of dry density with moisture content for sub-base type C treated with CKD (2.5%, 5%, 7.5%, and 10%)

From these individual compaction curves, the maximum dry density and the corresponding optimum moisture content (OMC) were calculated for each distinct CKD increment. Tracking these parameters is crucial because the high specific surface area of the CKD typically heightens the matrix's water absorption, shifting the lubrication threshold required for optimal grain

realignment under a given compaction energy. Finally, to determine the precise stabilization efficiency of the additive, the correlation between the varying CKD percentages and the resulting MDD values was evaluated. As demonstrated in Table 6 and Figure 4, this analytical relationship successfully identifies the optimum ratio of CKD necessary to yield the absolute maximum dry density for the type C granular sub-base soil.

Table 6. Relation between MDD and CKD increments for sub-base type C

CKD (%)	MDD (g/cm^3)	Improving (%)
0	2.050	0.00
2.5	2.060	0.48
5	2.280	11.22
7.5	2.244	9.46
10	2.221	8.34

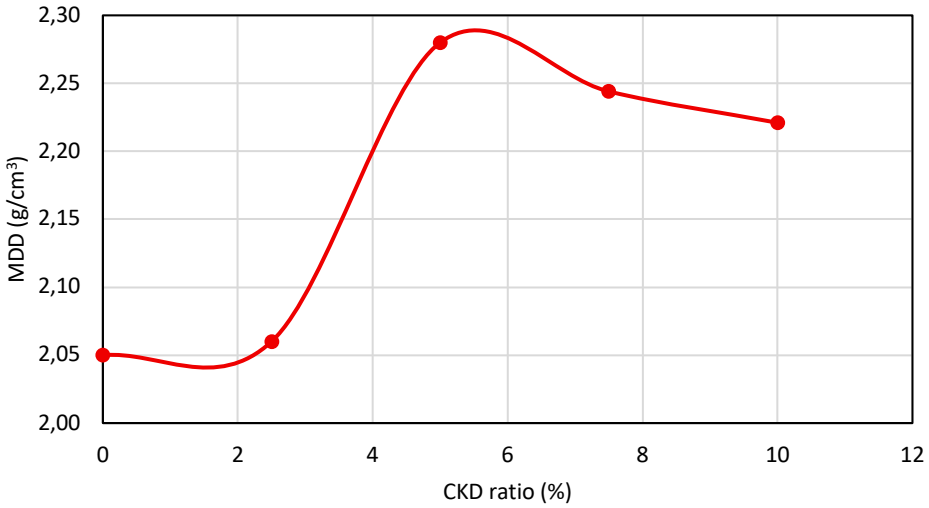


Fig. 4. Variation of maximum dry density with different CKD ratios for sub-base type C

4.2 CBR Results

To evaluate the strength characteristics of the granular sub-base materials, a series of CBR tests were conducted in accordance with AASHTO T193 and ASTM D1883 standards. Test specimens were prepared at their respective optimum moisture content (OMC) and maximum dry density, as previously determined from standard compaction tests. The soil mixtures were formulated with varying proportions of cement kiln dust specifically, 2.5%, 5%, 7.5%, and 10% by weight of the selected granular soil to investigate its stabilizing effect on bearing capacity. Following specimen preparation and compaction, CBR tests were performed to assess the influence of CKD content on soil strength. The resulting CBR values for sub-base type D are presented in Table 7 and Figure 5, which clearly illustrate a notable variation in bearing capacity with increasing CKD percentages. Similarly, the corresponding results for sub-base type C soils are compiled in Table 8 and depicted in Figure 6. Collectively, these findings demonstrate that CKD addition consistently enhances the bearing capacity of the granular sub-base materials, underscoring its potential as an effective stabilization agent.

The experimental results reveal a consistent and progressive enhancement in CBR values with increasing CKD content across both sub-base material types, underscoring the efficacy of CKD as a soil stabilizer. This improvement can be attributed to several interrelated physicochemical mechanisms. Firstly, the pozzolanic reactivity of CKD rich in silica, alumina, and calcium oxides facilitates the formation of calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) gels upon hydration. These cementitious products bind the granular particles together, thereby increasing interparticle cohesion and frictional resistance, which directly translates to higher bearing capacity. Secondly, the hygroscopic nature of CKD promotes moisture absorption and facilitates more efficient compaction, potentially leading to denser particle packing and reduced

void ratios. Thirdly, the presence of free lime in CKD may induce mild flocculation of fine particles, further contributing to the structural integrity of the soil matrix.

Table 7. Relation between CBR and dry density for different CKD increments for sub-base type D

CKD (%)	0	2.5	5	7.5	10
CBR	20	22	27	31	24
Improving (%)	0	10	35	55	20

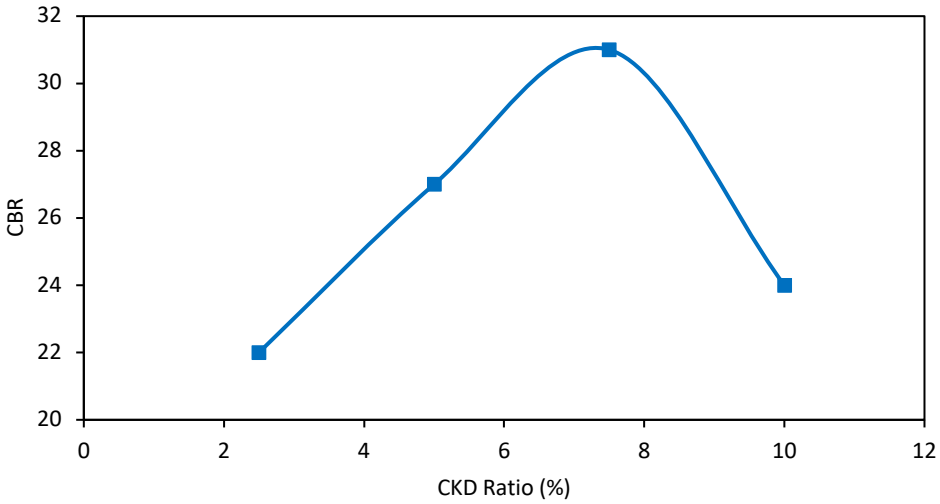


Fig. 5. Variation of CBR with different CKD ratios for sub-base type D

Table 8. Relation between CBR and dry density for different CKD increments for sub-base type C

CKD (%)	0	2.5	5	7.5	10
CBR	25	30	41	51	30
Improving (%)	0	20	64	104	20

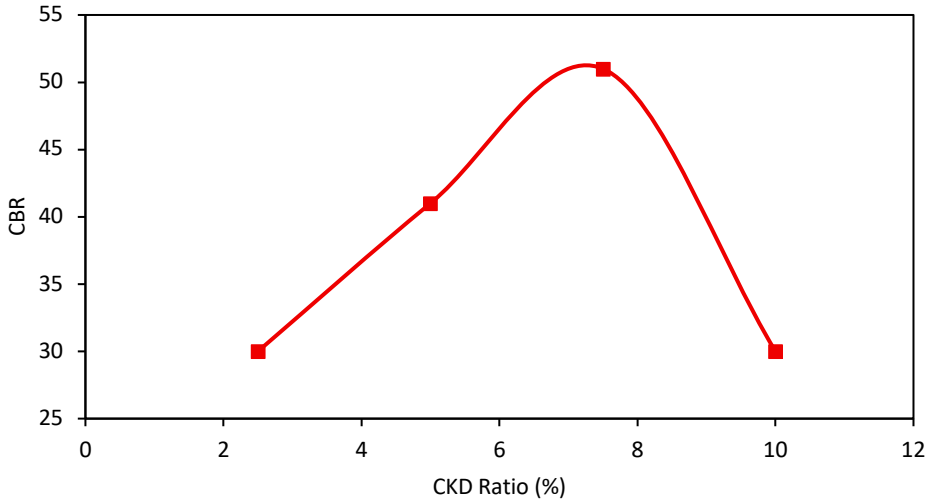


Fig. 6. Variation of CBR with different CKD ratios for sub-base type C

A comparative analysis between sub-base type D and type C soils reveal notable differences in their response to CKD treatment. Type D exhibits a more pronounced relative increase in CBR at lower CKD dosages (up to 5%), suggesting that its gradation and fines content may be more conducive to early-stage cementitious reactions. In contrast, type C shows a more gradual yet steady improvement, with the maximum gain observed between 7.5% and 10% CKD. This disparity likely stems from differences in particle size distribution, plasticity characteristics, or the inherent mineralogical composition of the two soil types. Such findings highlight that the optimal CKD

dosage is not universal but rather soil-specific, necessitating preliminary compatibility assessments before field-scale implementation.

From a practical engineering standpoint, the observed improvements carry significant implications for pavement design and construction. Enhanced CBR values directly correlate with increased sub-base layer stiffness, which can reduce the required thickness of overlying pavement layers, yielding substantial material cost savings and shorter construction timelines. Moreover, the utilization of CKD, an industrial by-product that would otherwise require costly disposal, offers a dual environmental benefit: it diverts waste from landfills while reducing the dependence on traditional stabilizers like Portland cement or lime, whose production entails high energy consumption and carbon emissions. However, it is essential to consider potential limitations, including the risk of sulfate-induced heaving in sulfate-bearing soils, the possible leachability of heavy metals from CKD, and the long-term durability under freeze-thaw or wet-dry cycling conditions. These factors warrant further investigation through durability testing and environmental impact assessments prior to recommending CKD stabilization for large-scale infrastructure projects.

In summary, the present findings conclusively demonstrate that CKD addition significantly enhances the bearing capacity of both sub-base type D and type C granular materials. The observed improvements are dose-dependent and soil-type-specific, with CKD contents in the range of 5–7.5% appearing to offer an optimal balance between strength gain and economic feasibility. Nevertheless, the selection of the most effective CKD proportion should be guided by project-specific requirements, cost-benefit analyses, and a thorough evaluation of long-term performance and environmental compatibility. Future research should focus on microstructural characterization (e.g., SEM, XRD) to further elucidate the underlying mechanisms, as well as field-scale trials to validate these laboratory findings under realistic traffic and climatic conditions.

5. Discussion

Increasing the fiber content to 0.7% resulted in excessive absorption of free binder and fiber agglomeration (clumping). This disruption in the aggregate matrix created interconnected macro-voids, sharply increasing the Air Voids (AV) and destabilizing the Marshall Flow beyond the SCRB specification limits. Although intermediate contents (e.g., 6% or 8%) were not experimentally included as standard testing protocols utilize 2.5% step-increments to identify broad performance trends, 7.5% effectively defines the practical optimal stabilization limit for engineering application. To translate the experimental CBR findings into practical pavement engineering, the results were evaluated within the context of structural pavement design (AASHTO 1993 Framework) and local specification standards:

- In flexible pavement design, the California Bearing Ratio (CBR) can be used to estimate the resilient modulus (Mr) and the subbase layer coefficient (a_3) through empirical correlations. For the Type C subbase material, treatment with 7.5% cement kiln dust (CKD) increased the CBR from approximately 20% to 51%. Where the design correlation assigns a higher (a_3) to the treated material, the treatment increases the subbase contribution to the pavement's structural number (SN) at the same layer thickness. According to the AASHTO structural number design equation, this mechanical gain allows for a reduction in the required sub-base layer thickness (or equivalent asphalt overlay thickness) while maintaining identical load-carrying performance under heavy traffic loads.
- A reduced sub-base thickness directly lowers raw material extraction, transportation, and compaction energy requirements. Utilizing cement kiln dust, a low-cost industrial by-product not only significantly lowers initial construction costs per square meter of road, but also aligns with sustainable construction practices by diverting industrial waste from landfills.
- The improved CBR values fully comply with and exceed the minimum strength requirements specified by local standards (such as the Iraqi General Specification for Roads and Bridges, SCRB Section R6, which mandates CBR ≥ 35% - 45% for sub-base materials) and AASHTO M 147 standards. This validates that 7.5% CKD-stabilized granular soil can be safely incorporated as a high-quality structural sub-base layer in field applications.

The observed improvements can be attributed to the filler effect and the pozzolanic and cementitious reactions induced by CKD, which enhance particle interlocking, reduce void spaces, and increase the stiffness of the soil matrix. However, when the CKD content exceeded the optimum level, a decline in performance was recorded, likely due to the presence of excess fines that adversely affected soil structure and compaction efficiency. Overall, the findings confirm that CKD is an effective and economic stabilization material for upgrading weak granular sub-base soils and improving their suitability for use in pavement construction. Furthermore, the beneficial reuse of CKD contributes to sustainable waste management practices by reducing the environmental burden associated with cement industry by-products and promoting the circular utilization of industrial waste materials in geotechnical engineering applications.

6. Conclusions

This study investigated the mechanical stabilization of standard granular sub-base soils (types C and D) using CKD as a sustainable industrial by-product binder. Based on the experimental findings and structural analysis, the following core conclusions are drawn:

- Incorporating CKD substantially enhances both the compaction characteristics (MDD) and load-bearing capacity (CBR) of granular sub-base materials. An optimum CKD dosage of 7.5% by dry weight was identified for both soil types, beyond which higher replacement ratios (10%) lead to performance degradation due to fines-induced disruption of aggregate interlocking and elevated water demand.
- The density improvements are primarily driven by the physical filler effect of fine CKD particles filling aggregate voids. Concurrently, the marked increase in CBR strength is governed by pozzolanic and hydration reactions between the free lime in CKD and soil moisture, creating permanent interparticle cementitious bonding and elevating stiffness.
- Stabilizing weak granular sub-bases with 7.5% CKD provides a high-quality structural layer that fully satisfies and exceeds standard highway requirements (e.g., SCRB Section R6 and AASHTO M 147). Economically and structurally, this strength gain translates to an increased structural layer coefficient, allowing for a reduction in required design pavement thickness, lower raw aggregate consumption, and cost-effective road construction.
- While these short-term laboratory findings are highly promising, the study is limited to unconfined short-term curing conditions and index compaction properties. Future research should evaluate the long-term durability under severe environmental cycles (freeze-thaw and wet-dry), leaching behavior of industrial salts, dynamic Mr, and field-scale pilot test sections.

References

[1] Al-Bakri AY, Ahmed HM, Dust MH. Potential beneficial applications and eco-sustainable solutions. Sustainability. 2022;14(12):7022. https://doi.org/10.3390/su14127022
[2] Jastrzębska M. Use of alternative materials in sustainable geotechnics: state of world knowledge and some examples from Poland. Appl Sci. 2025;15(6):3352. https://doi.org/10.3390/app15063352
[3] Karkush MO, Yassin SA. Using sustainable material in improvement the geotechnical properties of soft clayey soil. J Eng Sci Technol. 2020;15(4):2208-22.
[4] Karkush MO, Kareem MS, Jawad SI, Babu S. Sustainability analysis of improvement of contaminated clayey soil using lime piles technique. AIP Conf Proc. 2024;2864(1):030035. https://doi.org/10.1063/5.0186092
[5] Bandara N, Hettiarachchi H, Jensen E, Binoy TH, Perera R. Using kiln dust to improve weak subgrades for pavement construction: a field verification in Michigan, USA. Geotechnics. 2023;3(2):179-92. https://doi.org/10.3390/geotechnics3020011
[6] Ogila WAM. Effectiveness of fresh cement kiln dust as a soil stabilizer and stabilization mechanism of high swelling clays. Environ Earth Sci. 2021;80(7):283. https://doi.org/10.1007/s12665-021-09589-4
[7] Sharifi Teshnizi E, O'Kelly BC, Karimiazar J, Moosazadeh S, Arjmandzadeh R, Pani A. Effects of cement kiln dust on physicochemical and geomechanical properties of loess soil, Semnan Province, Iran. Arab J Geosci. 2022;15(18):1482. https://doi.org/10.1007/s12517-022-10751-w

[8] Almuaythir S, Abbas MF. Expansive soil remediation using cement kiln dust as stabilizer. Case Stud Constr Mater. 2023;18:e01983. https://doi.org/10.1016/j.cscm.2023.e01983
[9] Al-Gharrawi AM, Sheer Ali T, Alzerjawi AK, Fakhraldin MK, Abdul-Husain HA. Improvement of CBR of gypsum subgrade soil by cement kiln dust and granulated blast-furnace slag. Open Eng. 2023;13(1):20220397. https://doi.org/10.1515/eng-2022-0397
[10] Al-Homidy AA, Abd El Aal AK, Nabawy BS, Radwan AE. Effect of adding cement kiln dust on the effective geotechnical properties of sand dunes in Najran–Sharourah, Kingdom of Saudi Arabia: a laboratory study. J Mater Cycles Waste Manag. 2024;26(1):373-91. https://doi.org/10.1007/s10163-023-01831-4
[11] Gul N, Mir BA. Performance evaluation of silty soil reinforced with glass fiber and cement kiln dust for subgrade applications. Constr Build Mater. 2023;392:131943. https://doi.org/10.1016/j.conbuildmat.2023.131943
[12] Fadhil TH, Jasim SS, Aziz KE, Ahmed AS. Influence of using white cement kiln dust as mineral filler on hot asphalt concrete mixture properties. Anbar J Eng Sci. 2017;8(1):148-57. https://doi.org/10.37649/aengs.2017.130885
[13] Zada U, Jamal A, Iqbal M, Eldin SM, Almoshaogeh M, Bekkouche SR, et al. Recent advances in expansive soil stabilization using admixtures: current challenges and opportunities. Case Stud Constr Mater. 2023;18:e01985. https://doi.org/10.1016/j.cscm.2023.e01985
[14] Jasim FM, Mohammed T. Cement Kiln Dust Soil Stabilization for Subgrade Layer of Erbil Ring Highway (150m). Eurasian J Sci Eng. 2019;4(4):99-109. https://doi.org/10.23918/eajse.v4i4p99
[15] Salih NB, Rashed KA, Abdulwahab K. Experimental study on using cement kiln dust and plastic bottle waste to improve the geotechnical characteristics of expansive soils in Sulaimani City, Northern Iraq. J Eng. 2022;28(4):20-38. https://doi.org/10.31026/j.eng.2022.04.02
[16] Daimary N, Sarmah D, Bhattacharjee A, Barman U, Saikia MJ. Geotechnical performance of lateritic soil subgrades stabilized with agro-industrial waste: an experimental assessment and ANN-based predictive modelling. Geotechnics. 2025;5(3):65. https://doi.org/10.3390/geotechnics5030065
[17] Donkor SA, Razavi M, Wilson CM, Abankwa B, Otoo R, Armah A. Long-term effects of cement kiln dust (CKD) on the permeability of a treated soil slope. Geotechnics. 2025;5(4):87. https://doi.org/10.3390/geotechnics5040087
[18] U.S. Environmental Protection Agency. Regulatory and non-regulatory approaches to pollution control. Chapter four. In: Guidelines for preparing economic analyses [Internet]. Washington (DC): U.S. Environmental Protection Agency; 2010 [cited 2026 Nov 17]. Available from: https://www.epa.gov/sites/default/files/2017-09/documents/ee-0568-04.pdf