Laboratory Investigation of Weak Subgrade Soil Modified with Cement Kiln Dust and Quarry Stone Dust as Stabilizer

Abindra Basnet [1], Deepak Bahadur Kunwar [2*], Gopal Gautam [3]

[1] Postgraduate Student, MSc. in Transportation Engineering and Management, Nepal Engineering College (nec-CPS), Pokhara University, Nepal

[2] Life Member of Society of Transport Engineers Nepal (SOTEN), Nepal

[3] Assistant Prof., Nepal Engineering College (nec-CPS), Pokhara University, Nepal

* Corresponding Author: **Deepak Bahadur Kunwar**

Article Info

ISSN (online): 2582-7138
Volume: 06
Issue: 02
March-April 2025
Received: 29-01-2025
Accepted: 26-02-2025
Page No: 469-481

Abstract

The study deals with application of Cement Kiln Dust (CKD) and Quarry Stone Dust (QSD) as stabilizer to improve CBR of the weak subgrade soil. Laboratory experiments were conducted to determine the Particle size distribution, Atterberg's limit, Compaction Characteristics, CBR and Unconfined compression strength test and Permeability test of nine test specimens prepared by mixing different combination of CKD (5%, 10% and 15%) and QSD (10%, 15%, and 20%) with 5% increment by dry weight. It is observed that CBR value increases with increment of CKD and QSD dosage. Percentage increase in CBR was noticed 78.25% in least and 401.23% in maximum for S_1 (5% CKD & 10% QSD) and S_9 (15% CKD & 20% QSD) respectively. Hence, CKD and QSD could be considered as the effective stabilizer and S_9 can be considered as the best combination having maximum CBR value.

DOI: https://doi.org/10.54660/.IJMRGE.2025.6.2.469-481

Keywords: Cement Kiln Dust, Quarry Stone Dust, Unsoaked CBR, Subgrade Soil

1. Introduction

Subgrade soil serves as the foundational layer beneath pavement systems, extending up to 500 mm below the formation level. It comprises in-situ native material (cut road sections), selected localized soil, or stabilized soil that provides essential structural support to the pavement [1]. The effectiveness of subgrade soil is primarily determined by two fundamental properties: load bearing capacity and volume stability. To ensure long-term performance under varying climatic and traffic conditions, the subgrade must maintain adequate strength and stability. Subgrade strength plays a crucial role in determining pavement thickness, composition, and performance. The level of support provided by the subgrade depends on soil type, density, and moisture conditions during construction and throughout its service life [1]. In cases where weak subgrade soils are unavoidable, enhancement techniques must be employed to improve their engineering properties. Subgrade improvement techniques are classified into two main categories: mechanical stabilization, which strengthens soil through compaction and the addition of granular materials, and chemical stabilization, which utilizes stabilizers such as lime, cement, and industrial by-products to enhance soil strength and durability [2]. Among the various stabilizers available, Cement Kiln Dust (CKD) and Quarry Stone Dust (QSD) are cost-effective, readily available, and environmentally sustainable solutions. CKD is a by-product generated during cement manufacturing. It contains partially calcined and unreacted raw feed, clinker dust, and fuel ash, enriched with alkali sulfates, and other volatile compounds. Its primary components, such as calcium carbonate ($CaCO3$) and calcium oxide (CaO), contribute to its binding properties, pozzolanic reactions, moisture regulation, and chemical stabilization. Cement production is a key industry in Nepal, with a total investment exceeding NRS. 122.33 billion [3]. The country has approximately 1.25 billion metric tons of high-grade limestone deposits (DoMG, 2022). There are 114 registered cement industries, of which 65 are operational, with a total installed capacity of 14 million tons annually. On average, 0.6 to 0.7 tons of CKD is produced per ton of cement manufactured [4]. Utilizing CKD in subgrade stabilization is an efficient way to manage industrial waste while enhancing pavement performance. QSD is a by-product generated from aggregate crushing during screening and stockpiling. It is considered waste material, contributing to environmental pollution and storage issues in crushing plants [5]. However, QSD possesses valuable geotechnical properties, such as high shear strength, making it a suitable material for subgrade stabilization, and good permeability with minimal impact from variations in moisture content. QSD constitutes around 20-25% of the total output from rubble crusher units. While its physical and chemical properties vary based on aggregate type and source, they remain relatively consistent within individual quarries [6]. Incorporating QSD into subgrade stabilization presents an eco-friendly and cost-effective approach to improving soil performance.

2. Literature Review

2.1 Soil stabilization: Needs and advantage

Subgrade compaction must achieve at least 97% of laboratory dry density to mitigate rutting during pavement service life [7]. Roads with traffic exceeding 450 commercial vehicles per day require a minimum subgrade CBR of 8%, while those carrying more than 450 cvpd (two-way) at construction should have an effective CBR above 5% [8]. Stabilization alters or preserves subgrade properties by improving gradation or incorporating stabilizing additives to meet engineering requirements, enhancing strength, durability, and resistance to erosion and dust [9]. The structural design of pavements depends on subgrade quality, necessitating treatment of poor soils to meet construction standards, as in-situ materials often require modification for effective use [10]. The primary goal of subgrade stabilization is to enhance geotechnical properties, including bearing capacity, shear strength, slope stability, and resistance to volumetric changes and water infiltration. Additionally, stabilization optimizes cost, time, and energy, while using by-product additives promotes sustainable waste management.

2.2 Subgrade stabilization using cement kiln dust

Pre-Calciner-based Cement Kiln Dust (CKD) has effectively improved soil texture, strength, and reduce swelling when used as an additive. It was tested with eight different soil types (CH, CL, ML, SM, SP) and demonstrated significant improvements in soil strength, stiffness, plasticity, and swelling. Durability tests, including wet-dry, freeze-thaw, and leaching, revealed that CKD-treated soils performed well in wet-dry and leaching conditions and findings suggest that CKD is a promising stabilizer for subgrade soils, though a prior mix design is essential to determine the appropriate dosage for optimal performance (Robert & Justin, 2004). CBR tests on CKD-treated weak subgrade soils showed a notable increase in CBR from 3.4% to 48% with 20% CKD [10]. Generally, unconfined compressive strength (UCS) of. black cotton soil increases with increase in CKD content. This trend is observed due to chemical reaction between CKD and clay particles. The free calcium ion presents in CKD react with the lower valence metallic ions of the clay micro-structure, resulting cluster of the clay particles and increase UCS of the black cotton soil. Figure 1 shows the difference of UCS of black cotton soil with CKD content.

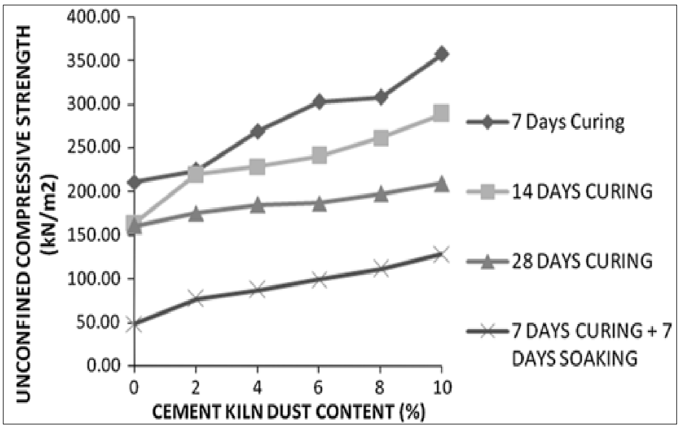

Fig 1: Difference of UCS of black cotton soil with CKD content.

CSH and CAH are the major constituents responsible for increase the CBR values and strength of the black cotton soil with increases of CKD content and presented in Figure 2.

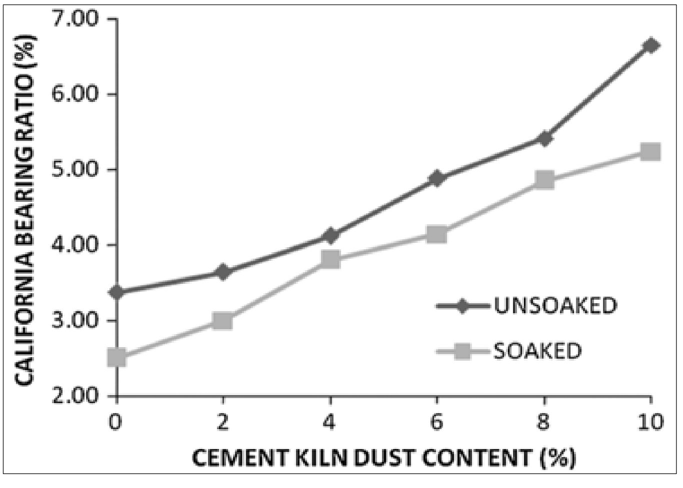

Fig 2: Difference of unsoaked and soaked CBR of black cotton soil with CKD

When CKD is used as soil stabilizing additive, soil particles become large-sized and change their texture. The enlarged particle size increases void ratio and decreases MDD, thus increase in moisture of soil-CKD mixture. Atterberg's indices shows that liquid limit and Plastic limit increases with increase in CKD content while Plasticity index decreases.

2.3 Subgrade stabilization using quarry stone dust

Quarry dust is cohesionless material, which mainly consists sand particles of specific gravity ranging over 2.74-2.8 and exhibits high shear strength [6]. With the addition of quarry dust, different engineering properties of soil substantially improved by reduction in liquid limit, plasticity and increase in maximum dry density, and CBR values [11]. CBR values gradually increase with an increase in the percentage of quarry dust. The improvement in CBR values significantly enhances the shearing resistance of the soil. Therefore, quarry stone dust is used as a subgrade stabilizer for weak soils under pavement layers [10].

2.4 Stabilization of subgrade using CKD and QSD

Cement and Lime are the predominantly used stabilizers for recapitalizing the problematic sub-grade soil. But, because of the conceivable increase in cost and ecological effects during their production, it is crucial to sort for a partial or all out substitution of Portland cement or Lime. Also, the use of single non- conventional stabilizers may not be efficient to rejuvenate the expected geotechnical properties of poor soils and this has invigorated the incorporation of multi-stabilizers or additives blended with imported stabilizers such as CKD-rice husk ash, hydrated lime-RHA, CKD-PSA, cement-PSA. The optimal blends obtained from their studies showed that the resultant effect of using multi-additives optimal blends in stabilization protocol of soft soil is greater than the effect either one of the stabilizers in the mixture could easily substitutes for the lack of efficacy of the other in treatment of a specific feature or properties of a given soil. Recent studies have recommended that cement kiln dust and quarry stone dust are viable stabilizer alternative in improving geotechnical properties of the soil. However, no such studies have been reported that compares or evaluate the differences in engineering behavior tied with other qualitative analysis of CKD and QSD treated subgrade soil. In this study, CKD and QSD are presumed to be advantageous and be an alternative to the costly traditional soil stabilizers. This will achieve two goals: improving the soil and disposing of waste in a healthy manner. Different scholars conducted the comprehensive research regarding the uses of different stabilizers either in combination or alone in different kind of soil type following different experimental methods for soil stabilization.

3. Methodology Framework

3.1 Research Approach

Research followed an experimental research technique. Different laboratory test was carried out to identify cause and effect of different percentages of CKD and QSD. Adopted research approach is shown in the Figure 3.

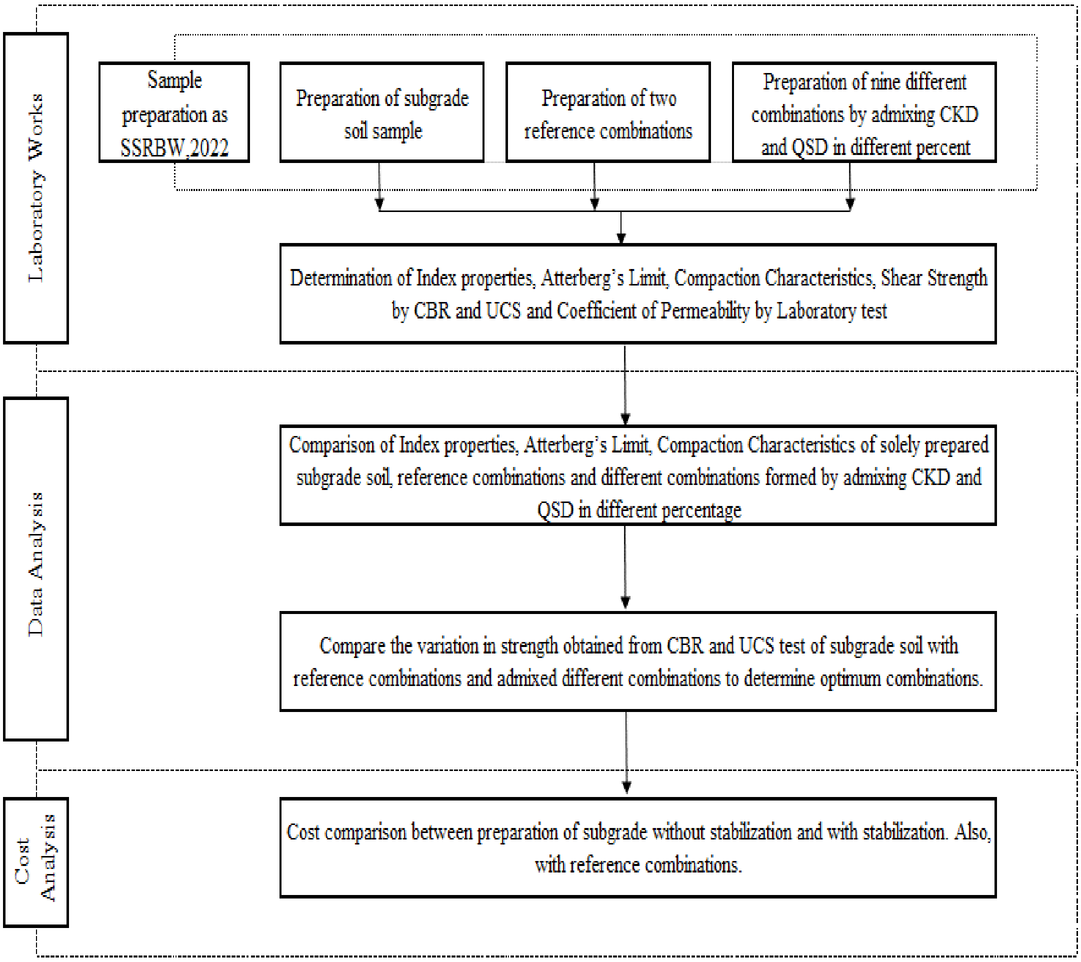

Fig 3: Flow chart of research approach

3.2 Study Location

The Pusphalal Midhill Highway (H18), an ongoing 1879 KM long national pride road project from easternmost hill at Chiyo Bhanjyang to westernmost hill at Jhulaghat in Nepal, was realigned through Ramechhap district viewing the consequences after the construction of the proposed Sunkoshi Marin Diversion Multipurpose Project. The new alignment section passes through the virgin land where fresh cutting was accomplished three years ago but tarred is yet to be done where in about 1300 m of the road alignment passes through land slide deposit of slit and clay from the adjoining active landslide. For the research purpose new aligned section, Ramechhap section of the Highway is considered, where subgrade soil consists of clay and silt with high lime contents deposited by the rivulet from the adjoining active landslide. The climatic factors in combination with the very steep slopes and inherently weak geologic conditions, make highly susceptible to landslides [12]. Figure 4 represent the study location map of the study area.

Source: Google earth

Fig 4: Midhill (Pusphalal) Highway Ramechhap section from Khurkot to Dolalghat

3.3 Primary data collection

Different subgrade soil samples were collected from the vicinity of the selected road alignment and different nine test specimens were prepared by admixing different percentage of CKD and QSD. Those nine different specimens were tested in laboratory to identify their physical properties. Following are different tests performed in laboratory as recommended by SSRBW 2nd amendment, [13].

a) Determination of Index properties
1. Determination of Atterberg's Limit
2. Modified Proctor Compaction Test
3. Determination of Shear strength
   - California Bearing Ratio
   - Unconfined Compression Strength Test
4. Determination of Coefficient of Permeability by Falling Head Method

3.4 Stabilizer Selection

CKD and QSD were two stabilizers considered in the study. CKD from Arghakhanchi Cement Industries Pvt. Ltd., Siyari Rural Municipality-02, Rupandehi, Lumbini Province and QSD from the crushing plant collected from Mahadev Crusher Industry Pvt. Ltd., Nepalthok, Kavrepalanchowk were used. Theconstituents of CKD vary from manufacturer to manufacturer [14].

Table 2 show the summary of composition of the CKD used in this study.

Table 2: Summary of physical properties of Cement Kiln Dust

Constituent	Weight, %	Constituent	Weight, %
CaO	49.3	SO_3	3.56
$Si0_2$	17.1	BaO	7.82
Chloride	6.90	Cr_2O_3	0.011
Al_2O_3	15.8	CuO	0.029
Fe_2O_3	4.24	NiO	0.012
K_2O	2.89	SrO	0.37
MgO	2.18	TiO_2	0.34
Na_2O	1.14	V_2O_5	0.013
P_2O_5	3.84	ZnO	65.8

Source: Arghakhanchi Cement Industries Pvt. Ltd.

3.5 Sample preparation and method of analysis

Representative subgrade soil samples were prepared and the relevant laboratory tests were carried out following the test procedures prescribed in the SSRBW (2nd amendment), 2022 and Manual of Standard Test, 2016. Two reference combinations were prepared and named as R1 and R2. R1 was prepared by blending 10% CKD and 90% subgrade soil by dry weight [15] and R2 was prepared by blending of 15% QSD and 85% subgrade soil by dry weight [6]. Other nine combinations were prepared by mixing, 5% to 15% CKD and 10% to 20% QSD, in which mix proportion were increased in step increment of 5% by dry weight. The details of test samples and method of testing are presented in
Table 3.

Table 3: No of samples and method of analysis

SNo.	Test	Description of samples	No of sample	Test method	Sample size	Output
1	Sieve Analysis	subgrade soil sample	1	IS 2720 (Part 4)-1985	3	Soil Type Identification
		sample with 10% CKD (R_1)	1		3	
		sample with 15% QSD (R_2)	1		3	
		C_1 (CKD 5% & QSD 10%)	9		27	
		C2(CKD 5% & QSD 15%)				
		C3(CKD 5% & QSD 20%)				
		C4(CKD 10% & QSD 10%)				
		C5(CKD 10% & QSD 15%)				
		C6(CKD 10% & QSD 20%)				
		C7(CKD 15% & QSD 10%)				
		C8(CKD 10% & QSD 15%)				
		C9(CKD 10% & QSD 20%)				
2	Atterberg's Limit	subgrade soil sample	1	IS: 2720 (Part V)	3	LL, PL, PI
		sample with 10% CKD (R_1)	1		3	
		sample with 15% QSD (R_2)	1		3	
		C_1 (CKD 5% & QSD 10%)	9		27	
		C2(CKD 5% & QSD 15%)				
		C3(CKD 5% & QSD 20%)				
		C4(CKD 10% & QSD 10%)				
		C5(CKD 10% & QSD 15%)				
		C6(CKD 10% & QSD 20%)				
		C7(CKD 15% & QSD 10%)				
		C8(CKD 10% & QSD 15%)				
		C9(CKD 10% & QSD 20%)				
3	Proctor Compaction Test	subgrade soil sample	1	IS:2720 (Part II)	3	OMC, MDD
		sample with 10% CKD (R_1)	1		3	
		sample with 15% QSD (R_2)	1		3	
		C_1 (CKD 5% & QSD 10%)	9		27	
		C2(CKD 5% & QSD 15%)				
		C3(CKD 5% & QSD 20%)				
		C4(CKD 10% & QSD 10%)				
		C5(CKD 10% & QSD 15%)				
		C6(CKD 10% & QSD 20%)				
		C7(CKD 15% & QSD 10%)				
		C8(CKD 10% & QSD 15%)				
		C9(CKD 10% & QSD 20%)				
4	California Bearing Ratio (CBR) Test	subgrade soil sample	1	IRC: 2720 (Part 16)	3	CBR value
		sample with 10% CKD (R_1)	1		3	
		sample with 15% QSD (R_2)	1		3	
		C_1 (CKD 5% & QSD 10%)	9		27	
		C2(CKD 5% & QSD 15%)				
		C3(CKD 5% & QSD 20%)				
		C4(CKD 10% & QSD 10%)				
		C5(CKD 10% & QSD 15%)				
		C6(CKD 10% & QSD 20%)				
		C7(CKD 15% & QSD 10%)				
		C8(CKD 10% & QSD 15%)				
		C9(CKD 10% & QSD 20%)				
5	Unconfined Compression Strength Test (UCS)	subgrade soil sample	1	IRC: 2720 (Part 10)	6	Compressive strength
		sample with 10% CKD (R_1)	1		6	
		sample with 15% QSD (R_2)	1		6	
		C_1 (CKD 5% & QSD 10%)	9		36	
		C2(CKD 5% & QSD 15%)				
		C3(CKD 5% & QSD 20%)				
		C4(CKD 10% & QSD 10%)				
		C5(CKD 10% & QSD 15%)				
		C6(CKD 10% & QSD 20%)				
		C7(CKD 15% & QSD 10%)				
		C8(CKD 10% & QSD 15%)				
		C9(CKD 10% & QSD 20%)				
6	Falling Head Permeability Test	subgrade soil sample	1	IRC: 2720 (Part 17)	3	Coefficient of Permeability
		sample with 10% CKD (R_1)	1		3	
		sample with 15% QSD (R_2)	1		3	
		C_1 (CKD 5% & QSD 10%)	9		27	
		C2(CKD 5% & QSD 15%)				
		C3(CKD 5% & QSD 20%)				
		C4(CKD 10% & QSD 10%)				
		C5(CKD 10% & QSD 15%)				
		C6(CKD 10% & QSD 20%)				
		C7(CKD 15% & QSD 10%)				
		C8(CKD 10% & QSD 15%)				
		C9(CKD 10% & QSD 20%)				

4. Results and Discussion

4.1 Properties of subgrade soil samples

Subgrade soil sample consists of major portion of sand i.e. about 98% while only nominal constituent i.e. about 1% of gravel and fines each. The Atterberg's limit test could not be conducted for the subgrade soil sample due to non-plastic behaviour of the soil and thus its attribute LL, PL and PI could not be determined. The maximum dry density and the optimum moisture content was 2.16 gm/cc^3 and 9.04% respectively. The coefficient of Uniformity (C_u) and coefficient of Curvature (C_c) of the subgrade soil was 2.03 and 0.90 respectively. On classifying the subgrade soil sample viewing its physical attribute, the subgrade soil is classified as A-3 Fine Sand as per AASHTO classification system.

Table 4 depicts the summary of physical properties of the subgrade soil.

Table 4: Summary of physical properties of subgrade soil sample

S.No.	Properties	Description
1	Color	Grey
2	Liquid Limit/Plastic Limit Plasticity Index	NA non-plastic
3	6.3 mm sieve passing % 475 mm sieve passing % 2.36 mm sieve passing % 1.18 mm sieve passing % 0.6 mm sieve passing % 0.425 mm sieve passing % 0.3 mm sieve passing % 0.15 mm sieve passing % 0.075 mm sieve passing %	100 % 98.77% 94.89 % 87.80 % 79.39 % 71.93 % 52.08 % 2.52 % 0.92 %
4	Percentage of Gravel Percentage of Sand Percentage of Fines	1 % 98% 1%
5	D_{60} (mm) D_{30} (mm) D_{10} (mm) C_u C_c	0.35 0.23 0.17 2.03 0.90
6	Soil Classification	A-3 as per AASHTO

The loose untreated materials for use as subgrade material shall not contain particles larger than 60 mm and an organic matter content less than 3% as per SSRBW (2nd amendment), 2022. Based on this, a particle size distribution test was performed, and the corresponding particle size distribution curve is shown in **Fig 5**.

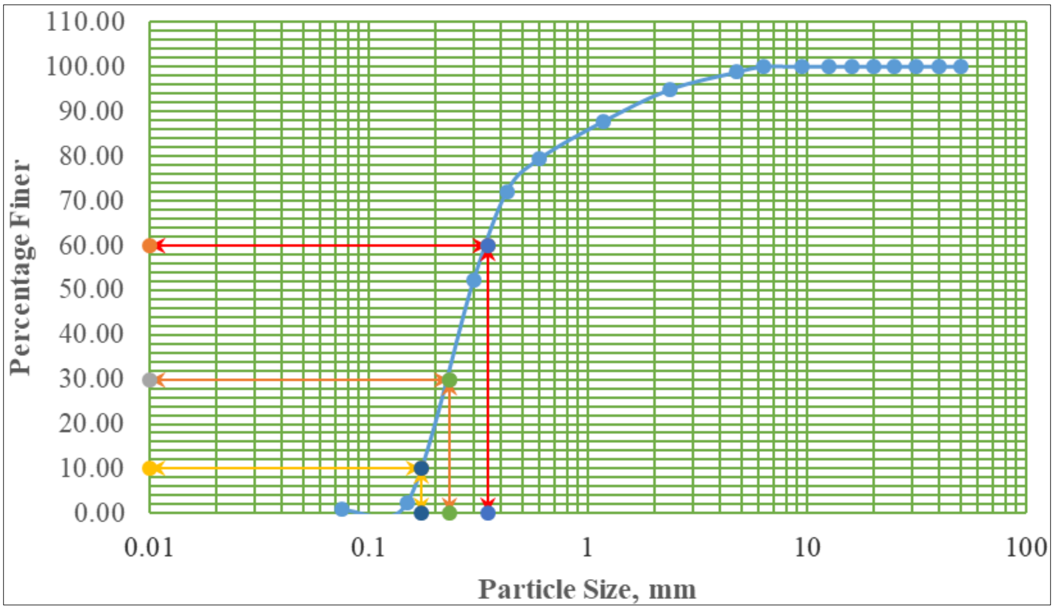

Fig 5: Particle size distribution curve of subgrade soil sample

4.2 Physical properties of reference combination

Subgrade soil sample combined with 10% CKD was considered as R_1 reference combination whereas combined with 15% QSD was considered as R_2 reference combination. **Table 5** below depicts the physical properties for R_1 and R_2

Table 5: Summary of physical properties of reference combination

	R₁ (10% CKD)	**R₂ (15% QSD)**
Gravel Percentage	3.57	14.65
Sand Percentage	95.62	85.17
Fines Percentage	0.81	0.18
D_{60} (mm)	0.42	1.15
D_{30} (mm)	0.34	0.37
D_{10} (mm)	0.25	0.29
Coefficient of Uniformity (C_u)	1.72	3.90
Coefficient of Curvature (C_c)	1.13	0.41
Maximum Dry Density Optimum moisture	2.06 gm/cc^3 9.2%	2.17 gm/cc^3 6.3%
Liquid Limit/Plastic Limit Plasticity Index	NA non-plastic	NA non-plastic

The Particle size distribution curve of the R_1 and R_2 combination is shown in **Fig 6**.

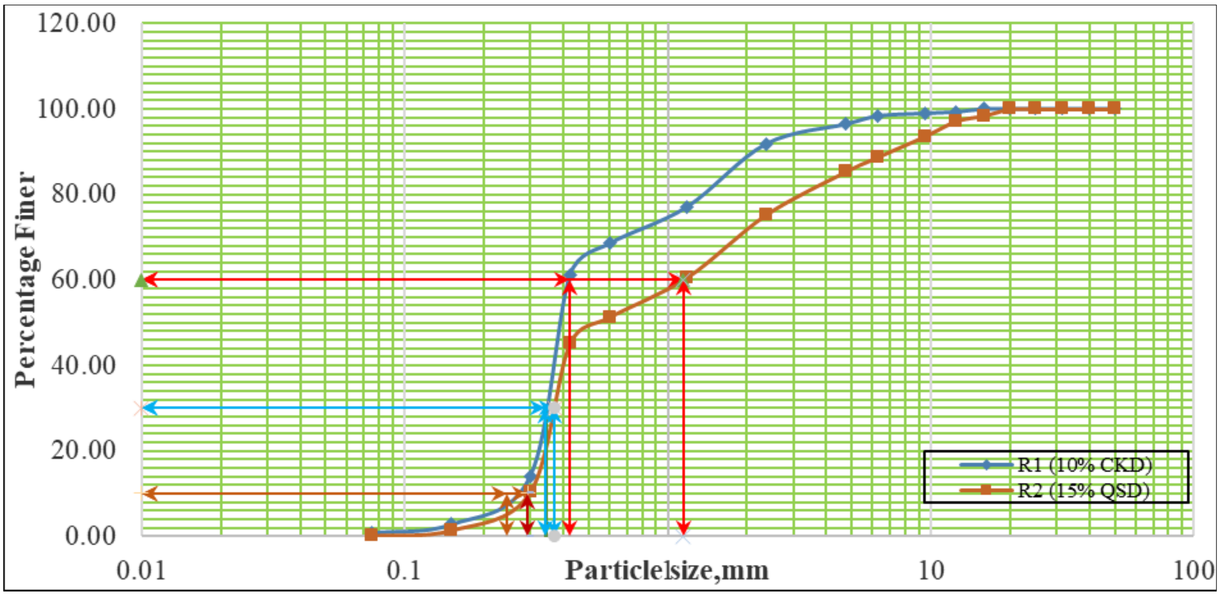

Fig 6: Particle size distribution curve of R_1 and R_2 combination

With the agglomeration of CKD in the subgrade soil sample, physically percentage of gravel and fine increases from 1% to 3.57% and 0.81% to 1% respectively whereas the sand percentage decrease from 98% to 95.62% which impart decrease of coefficient of uniformity (C_u) and increase of coefficient of curvature (C_c).

The test result reveals that the gravel percentage increase from 1% to 14.65% while the sand and fine percentage decrease from 98% to 85.17% and 1% to 0.81% respectively when the subgrade soil is admixed with QSD which cause increase in coefficient of curvature (Cc) from 2.03 to 3.90 and decrease in coefficient of uniformity (Cu) from 0.90 to 0.41.

4.3 Physical properties of different combination

The subgrade soil sample agglomerated with 5% to 10% CKD and 10% to 20% QSD both in increment of 5% by dry weight forming nine different combinations were prepared comply with the procedures set by IRC 2720-Part 1.

Table 6 summarize the physical properties of each sample prepared by admixing the CKD and QSD as concluded after different tests recommended on Manual of Standard Test, 2016.

Table 6: Summary of physical properties of different combinations

	Composition							
	Gravel %	**Sand %**	**Fines %**	**D_{60} (mm)**	**D_{30} (mm)**	**D_{10} (mm)**	**C_u**	**C_c**
Combination S_1	25	74	2	1.60	0.44	0.32	4.98	0.39
Combination S_2	32	67	1	2.94	0.67	0.40	7.36	0.38
Combination S_3	30	68	2	2.27	0.39	0.29	7.82	0.24
Combination S_4	9	87	4	0.56	0.32	0.18	3.18	1.02
Combination S_5	7	92	1	0.89	0.37	0.28	3.23	0.55
Combination S_6	11	88	1	0.58	0.45	0.25	2.30	1.40
Combination S_7	27	72	1	1.85	0.39	0.22	8.30	0.37
Combination S_8	10	89	1	0.50	0.31	0.19	2.66	1.02
Combination S_9	15	85	1	0.53	0.32	0.20	2.66	0.98

For different combinations, the major constituents were sand and their proportion vary from 67% for combination S_2 to 92% for combination S_5 and gravel constituents ranges from 32% in greatest for S_2 combination and least to 7% for S_5 combination whereas fines were nominal constituents with its weightage about 1%. Comparing the admixed combination formed by combining CKD and QSD with the subgrade soil sample, the percentage of sand decrease at greatest 31.63% to least 6.12% whereas the gravel portion increase significantly. C_u was found to be more than that of subgrade soil sample for every combination varying to maximum 8.30 for combination S_7 and least to 2.30 for combination S_6 whereas the Cc vary from 0.24 for combination S_3 to 1.40 for combination S_6.

4.4 Compaction Characteristics

Modified Proctor Compaction Test was conducted to determine the compaction characteristics which include determination of optimum moisture content (OMC) and maximum dry density (MDD) following Manual of Standard Tests, 2016 comply with comply with IS:2720 (Part 8).

4.4.1 Compaction characteristics of subgrade soil sample

The OMC of the subgrade soil sample is 9.04% whereas the MDD of the subgrade soil sample is 2.16 gm/cc. **Fig 7** shows the moisture content (%) vs Dry density (gm/cc) curve.

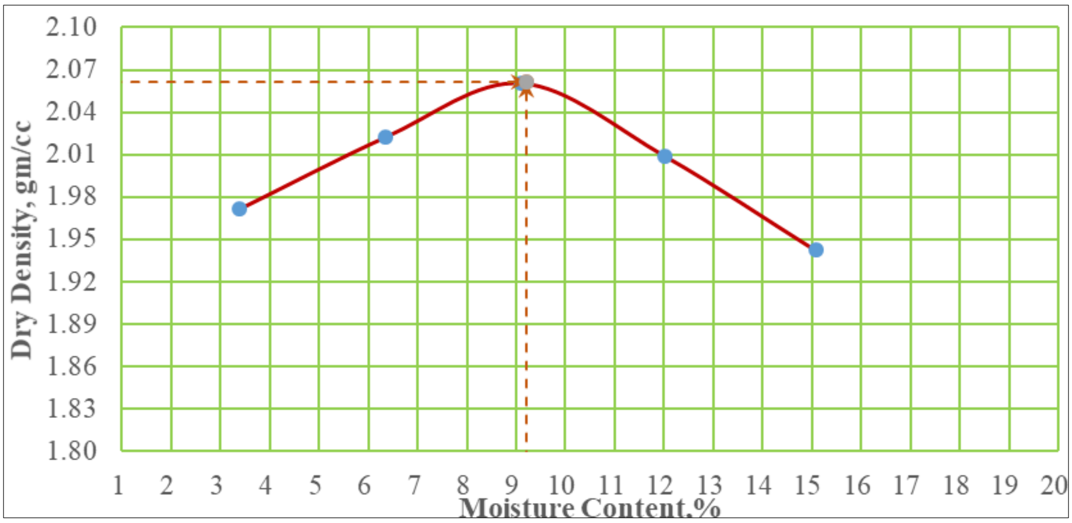

Fig 7: Dry density Vs moisture content

4.4.2 Compaction characteristics of reference combination

The OMC and MDD for R_1 combination were found to be 9.2% and 2.06 gm/cc respectively whereas for R_2 combination is 6.3% and 2.17 gm/cc respectively. **Fig 8** reflects the curve between Moisture Content vs Dry Density for the reference combinations R_1 and R_2. For R_1 combination, the MDD reduces from 2.16 gm/cc^3 to 2.06 gm/cc^3 compared with that of subgrade soil sample i.e. reduces by 4.63% and the optimum moisture content (OMC) increases from 9.04% to 9.2% compared with that of subgrade soil i.e. increase by 1.77%. When CKD is used as soil additive, soil particles become large-sized clusters, resulting in texture change. This flocculation-agglomeration process results in flock formation. The enlarged particle size causes the void ratio to increase. This increase in void ratio reflects the decrease in MDD and increase of moisture content for the soil-CKD mixture [14].

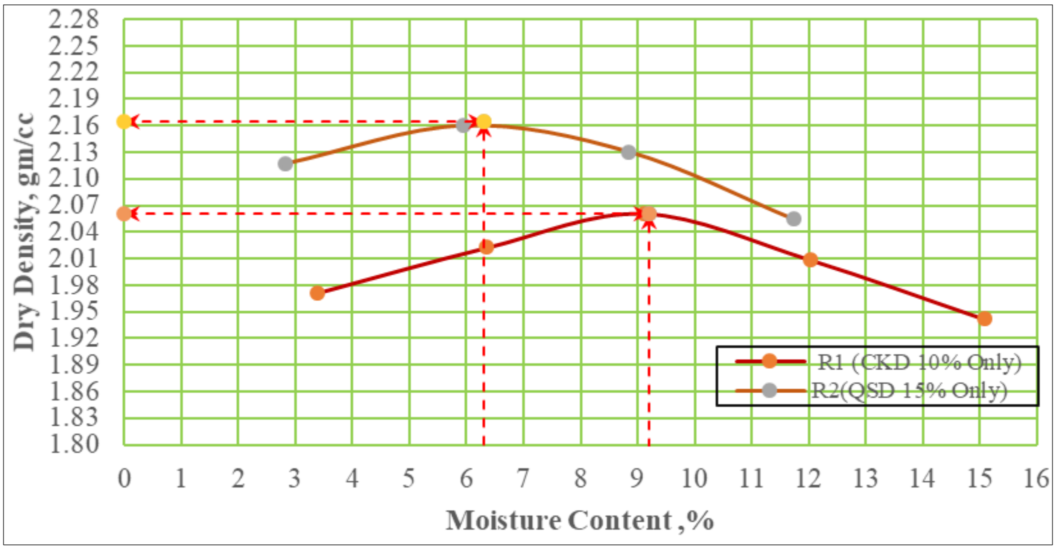

Fig 8: Dry density Vs moisture content

Similarly, for R_2 combination slide increase in MDD was noticed whereas tremendous decrease in OMC i.e. about 30.31% compared with that of subgrade soil sample. The improvements of the engineering properties of soils with the addition of the QSD in the form of reduction of liquid limit, reduction of plasticity, increase in MDD, decrease in OMC and increase in soaked and unsoaked CBR values [6]. Compaction studies on soil-quarry dust mixes showed considerable increase in maximum dry density and decrease in OMC which is attributed to the grain size distribution being better graded. The probable reason for increase in maximum dry density of soil by addition of quarry stone dust is due to proper rearrangement of soil particles and addition of non-plastic material which improves the binding capacity [16].

4.4.3 Compaction characteristics of different combination

Table 7 below summarize the compaction characteristics of nine combinations prepared by admixing the CKD and QSD with subgrade soil sample in varying portion after concluding Modified Proctor Compaction Test following the procedure as recommended on Manual of Standard Test, 2016.

Table 7: Summary of combination characteristics of different combinations

	Optimum Moisture content (%)	Maximum Dry Density gm/cc
Combination S_1	9.10	2.11
Combination S_2	8.50	2.13
Combination S_3	8.50	2.15
Combination S_4	8.80	2.11
Combination S_5	9.00	2.09
Combination S_6	9.60	2.10
Combination S_7	9.80	2.17
Combination S_8	6.70	2.09
Combination S_9	9.20	2.06

The result reveals that with the agglomeration of CKD and QSD with the subgrade soil sample, the MDD decrease while the OMC do not show any consistency but in majority of the combination the OMC was noticed to be decreased with the incremental of CKD and QSD. Comparing with the subgrade soil sample, the maximum dry density decreases to maximum 4.63% for S_9 combination and minimum to 0.46% for S_3 combination whereas comparing the subgrade soil sample with the reference combination, the maximum dry density decreases by 4.63% for R_1 combination and it increase by 0.46% for R_2 combination. Similarly, OMC decrease to maximum 25.88% for S_8 combination and increase to maximum of 8.41% for S_7 combination showing non-consistency whereas OMC increase by 1.77% for R_1 combination and decrease by 30.31% for R_2 combination.

4.5 California bearing ratio test (CBR)

California Bearing Ratio Test was performed on the remoulded samples for 96 hours-soaked condition following the procedure mentioned in Manual Standard Test, 2016 from ASTM D 1883 comply with the IRC 2720-Part 16 of all nine combinations, two reference combination and a subgrade soil sample.

4.5.1 California bearing ratio test of subgrade soil sample

Table 8 depicts the California Bearing Ratio of the remoulded subgrade soil sample after soaking for 96 hours.

Table 8: CBR of subgrade soil sample

	Moisture content at compaction %	Dry Density at compaction gm/cc	% of Water absorbed %	Soaked CBR %
Subgrade soil sample	9.06	2.149	0.07	1.71

Referring to SSRBW (2nd amendment), 2022, materials for use in the subgrade should have CBR not less than 5% measured after a 4-day soak on a laboratory mix compacted to 95% MDD (heavy compaction), a swell of less than 1%. Also, in-situ material in the subgrade in cutting that does not meet these requirements shall be either spoiled or, if suitable, placed in the embankment. The spoiled material shall be replaced with material meeting the requirement for loose material in the subgrade. The subgrade soil sample don't comply with the requirements set forth by SSRBW (2nd amendment), 2022 as the CBR value was only 1.71% and thus the only option remain was to spoiled and be replaced with the superior quality meeting the requirements set by SSRBW (2nd amendment), 2022.

4.5.2 California bearing ratio test of reference combination

Table 9: reflect the CBR value for reference combinations R_1 and R_2.

	Moisture content at compaction %	Dry Density at compaction gm/cc	% of Water absorbed %	Soaked CBR %
R_1	9.20	1.86	0.64	5.905
R2	6.37	2.18	0.58	4.286

The soaked CBR value of R_1 and R_2 combinations compared with subgrade soil sample reflect tremendous increase in the CBR value i.e. 245.32 % for R_1 combination and 150.64% for R_2 combination. The increase in the CBR value can be assumed by the cementing behaviour of the CKD [10] which more or less cannot be anticipated much in QSD. Thus, using only, the R_2 combination could not fulfil the requirement of SSRBW (2nd amendment), 2022 as the strength achieved thereby do not comply and thus either admixed with other stabilizers or increase the proportion of QSD to achieve the satisfactory results.

4.5.3 California bearing ratio test of different combination

Table 10 depicts the CBR of the remoulded sample prepared by agglomerating 5% to 15% CKD and 10% to 20% QSD forming nine combinations and soaking for 96 hours and commencing the test procedure following the procedures complied with IRC: 2720 Part 16.

Table 10: CBR of different combinations

	Moisture content at compaction (%)	Dry Density at compaction (gm/cc)	% of Water absorbed (%)	Soaked CBR (%)
Combination S_1	8.24	2.14	0.11	3.048
Combination S_2	8.02	2.13	0.23	4.870
Combination S_3	9.75	2.13	0.17	5.230
Combination S_4	8.71	2.12	1.07	6.280
Combination S_5	9.00	2.07	0.55	6.476
Combination S_6	9.64	2.10	0.47	6.892
Combination S_7	9.86	2.17	0.41	6.905
Combination S_8	6.80	2.08	1.54	7.810
Combination S_9	9.27	2.05	0.64	8.571

With the addition of CKD and QSD in different proportion with the subgrade soil sample, the CBR value was noticed to be increased for every incremental of CKD and QSD portion in the subgrade soil sample. Maximum CBR value of 8.571% was event for S_9 combination and least CBR value of 3.048% was noticed for S_1 combination. But the significant increase can be accomplished only after the addition of more than 10% CKD. Percentage increase in CBR was noticed 78.25% in least and 401.23% in maximum for S_1 and S_9 respectively.
The use of CKD on weak soil would reduce the plasticity, increase in OMC and MDD as a result of filler effects and CBR increase due to formation of hydration products [17]. When CKD is used as soil stabilizing additive, soil particles become large-sized clusters, resulting in texture change. The enlarged particle size causes the void ration to increase which reflects the decrease in MDD and increase of moisture content and also the Plasticity index decrease may be attributed by chemical and cementation effect on structural composition of the soil which ultimately cause CBR to increase [14]. While with the addition of QSD, CBR values increased steadily with increase in percentage of quarry dust which can be attributed due to significant improvement in angle of shearing resistance [6].

The rise in CBR value might be called from the collective improvement measures of CKD and QSD which include i) Binding properties ii) pozzolanic reaction iii) Chemical stabilization iv) moisture control due to addition of CKD and i) filler effect due to addition of QSD.

4.6 Unconfined Compression Test (UCS)

Unconfined compression test is carried out to determine the strength of bound materials and is typically a strength parameter used to verify whether the subgrade soil is suitable for applications with satisfactory performance by researchers and engineers. Unconfined compression strength is the basis for determining other material properties such as resilient modulus through empirical relationships developed, essential for pavement design [18]. UCS test was performed on the remoulded samples for soaked condition following the procedure mentioned in DoR Manual for standard test comply with the IRC 2720-Part 10 of all nine combinations, two reference combination and a subgrade soil sample.

4.6.1 Unconfined compression test of subgrade soil sample

Table 11 depicts the UCS of the remoulded subgrade soil sample prepared following the procedure mentioned by IRC after soaking for 7 days.

Table 11: UCS of subgrade soil

	Unconfined Compression Strength (KN/m^2)
Subgrade Soil	81.00

The required unconfined compression strength for subgrade soil can vary depending on the specific project and design requirements. However, as a general guideline for low-volume roads UCS should be greater than 50 KN/m^2 (7.3 psi) and for heavy-duty roads UCS shall be greater than 100KN/m^2 (14.5 psi) [19].

4.6.2 Unconfined compression test of reference combination

Table 12 shows the Unconfined Compression Strength reference combinations with subgrade sample

Table 12: UCS of reference combination

	Unconfined Compression Strength (KN/m^2)
R_1 combination	89.00
R_2 combination	85.00

With the addition of 10% CKD in the subgrade soil, the UCS increases by around 10%. Similarly, for R_2 combination, on addition of 15% QSD, UCS increases by 4.94%. It is evident that with the addition of CKD, the pozzolanic activity as the result of significant amount of silica and alumina which ultimately form C-S-H may exhibit [10] whereas with the addition of QSD filler effect may exhibit that fill the voids between the soil particles and reduces the porosity and form denser microstructure that enhance the strength of the subgrade soil.

4.6.3 Unconfined compression test of different combination

Table 13 shows the UCS for different combinations with subgrade soil sample. UCS increase with the incremental of the percent of stabilizers. Increase in UCS might be of collective action of i) binding action of CKD with subgrade soil, ii) pozzolanic reaction and iii) Chemical stabilization in addition of filler action of QSD.

Table 13: UCS of different combination

	Unconfined Compression Strength (KN/m^2)
Combination S_1	82.00
Combination S_2	86.50
Combination S_3	88.20
Combination S_4	90.00
Combination S_5	93.00
Combination S_6	95.50
Combination S_7	100.80
Combination S_8	102.50
Combination S_9	106.75

4.7 Permeability Test

Falling Head Permeability Test was conducted to determine the hydraulic conductivity of the subgrade soil and the different combination following the procedure mentioned on IRC 2720.

Table 14 shows results of Falling Head Permeability test conducted on the combination.

Table 14: Details of coefficient of permeability

	Coefficient of Permeability (cm/sec)
Soil sample	9.483E-05
R_1 combination	9.790E-05
R_2 combination	9.600E-05
Combination S_1	9.874E-05
Combination S_2	1.087E-04
Combination S_3	1.117E-04
Combination S_4	1.317E-04
Combination S_5	1.866E-04
Combination S_6	2.054E-04
Combination S_7	2.354E-04
Combination S_8	2.452E-04
Combination S_9	2.754E-04

Coefficient of Permeability increase with the incremental of dosage of stabilizers. The subgrade soil sample possess the coefficient of permeability 9.483E-05 cm/sec whereas on adding the CKD and QSD the coefficient permeability goes on increasing. Least value of coefficient of Permeability noticed was 9.874E-05 cm/sec for S_1 combination whereas the maximum value of coefficient of permeability was for S_9 combination 2.754E-04 cm/sec. For good drainage, the pavement foundation design requires the value of permeability coefficient of the subgrade material. Therefore, it is necessary to improve the hydraulic conductivity of soil in order to achieve a good drainage function in the subgrade.

4.8 Determination of the best combination from the prospect of strength parameter

Table 15 presents the physical characteristics of subgrade soil stabilized with varying percentages of Cement Kiln Dust (CKD) and Quarry Stone Dust (QSD), along with the properties of the untreated subgrade soil and reference combinations. The results indicate that the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) values increase progressively with higher percentages of CKD and QSD. The subgrade soil, classified as A-3 fine-graded sand according to the AASHTO classification system, exhibits poor quality in terms of strength. Its compaction characteristics include a Maximum Dry Density (MDD) of 21.18 kN/m³ and an Optimum Moisture Content (OMC) of 9.04%. The strength parameters of the untreated soil include a CBR value of 1.71% and a UCS value of 81.00 kN/m². Additionally, the coefficient of hydraulic conductivity (permeability) was determined to be 9.48× 10^{-5} m/s, indicating low drainage capacity. Based on the subgrade strength classes outlined in the Guideline for the Design of Flexible Pavement, 2014 (Second Edition, 2021), the soil falls under the S1 category, signifying very poor subgrade strength. Among the tested combinations, the S9 mixture demonstrated the highest improvement in strength parameters, with a CBR value of 8.571%, a UCS value of 106.75 kN/m², the lowest MDD, and the highest coefficient of permeability. In contrast, the S1 combination exhibited the lowest CBR and UCS values, at 3.048% and 82.00 kN/m², respectively. The addition of CKD and QSD in varying proportions by dry weight significantly enhanced the strength characteristics of the subgrade soil. However, combinations S1 and S2 failed to meet the strength requirements specified by the SSRBW, 2022 (2nd Amendment), which mandates a CBR value of not less than 5% (measured after 4 days of soaking) and physical particles smaller than 60 mm for laboratory mixes compacted to 95% MDD. Consequently, these combinations were excluded from further consideration for optimal dosage selection. The remaining combinations (S3 through S9) complied with the specified requirements, demonstrating viable potential for subgrade soil stabilization. The continuous increase in CBR and UCS values with higher percentages of CKD and QSD can be attributed to the synergistic effects of both materials. Among these, the S9 combination emerged as the most effective, based on its superior physical and strength characteristics.

Table 15: Detail of strength characteristics of different combinations

	Compaction Characteristics		Permeability Test	Califorina Bearing Test				Unconfined Compression Test
	Optimum Moisture content (%)	Maximum Dry Density gm/cc	Coefficient of Permeability, k cm/sec	Moisture content at compaction %	Dry Density at compaction gm/cc	% of Water absorbed %	96 hour soaked CBR %	Unconfined Compression Strength KN/m²
Soil sample	9.04	2.16	9.48E-05	9.06	2.15	0.07	1.71	81.00
R1 combination	9.20	2.06	9.79E-05	9.20	1.86	0.64	5.905	89.00
Combination S3	8.50	2.15	1.12E-04	9.75	2.13	0.17	5.230	88.20
Combination S4	8.80	2.11	1.32E-04	8.71	2.12	1.07	6.280	90.00
Combination S5	9.00	2.09	1.87E-04	9.00	2.07	0.55	6.476	93.00
Combination S6	9.60	2.10	2.05E-04	9.64	2.10	0.47	6.892	95.50
Combination S7	9.80	2.17	2.35E-04	9.86	2.17	0.41	6.905	100.80
Combination S8	6.70	2.09	2.45E-04	6.80	2.08	1.54	7.810	102.50
Combination S9	9.20	2.06	2.75E-04	9.27	2.05	0.64	8.571	106.75

5. Conclusion

The subgrade soil, classified as A-3 fine sand (AASHTO), exhibited weak geotechnical properties with an OMC of 9.04%, an MDD of 2.16 g/cm³, a CBR of 1.71%, and a UCS of 81.00 kN/m², falling below the SSRBW (2022) standards. Stabilization with CKD (5%–15%) and QSD (10%–20%) in 5% increments significantly improved its strength characteristics. The soaked CBR increased fivefold, and UCS rose by 30.86%, with the S9 combination (15% CKD and 20% QSD) achieving the highest CBR (8.571%) and UCS (106.75 kN/m²) and the lowest MDD (20.20 kN/m³). While MDD and OMC did not follow a linear trend, the S9 mix emerged as the optimal combination for enhancing strength. This study demonstrates that CKD and QSD can effectively stabilize weak subgrade soil, making it suitable for highway construction in a cost-effective manner.

6. Recommendation for Further Study

This study demonstrates the effectiveness of Cement Kiln Dust (CKD) and Quarry Stone Dust (QSD) as stabilizers for weak subgrade soils, meeting the physical and strength requirements outlined in the *SSRBW (2nd Amendment), 2022*. For practical applications, the S3 combination (5% CKD and 20% QSD) is recommended as a cost-effective solution. However, for scenarios requiring maximum strength and enhanced physical properties, the S9 combination (15% CKD and 20% QSD) is preferred, as it achieved the highest CBR, UCS, and hydraulic conductivity values. To further validate and expand these findings, it is recommended that governmental agencies, such as the Department of Roads (DoR), Department of Local Infrastructure (DoLI), and municipal authorities, conduct extensive field studies to explore the broader applicability of CKD and QSD in diverse road construction projects. Future research should also focus on larger road sections with a wider variety of weak subgrade soils, employ advanced geotechnical testing methods (e.g., R-value, K-value, resilient modulus, and mineralogical analyses), and incorporate microstructural investigations to better understand the mechanisms underlying the improvement in soil properties.

7. References

1. Department of Roads (DoR). Guidelines for the Design of Flexible Pavements-2014. 2nd ed. Kathmandu: Ministry of Physical Infrastructure and Transport, Government of Nepal; 2021.
2. Shubber KHH, Saad AA. Subgrade stabilization strategies effect on pavement thickness according to AASHTO pavement design method (Review). In: IOP Publishing Ltd, editor. 2020.
3. Nepal Rastra Bank (NRB). Foreign Direct Investment in Cement Industry in Nepal: A Study on Socio-economic Impact. Kathmandu: Economic Research Department, Economic Development Division; 2021.
4. Okafora FO, Egbe EA. Potentials of cement kiln dust in sub-grade stabilization. Nigerian Journal of Technology. 2013;32(1):109-116.
5. Paribesh P, Kumar DB. Effect of Stone Dust on Geotechnical Parameter of Fine Grained Soil. In: 10th IOE Graduate Conference. Kathmandu; 2021.
6. Soosan TJ, Sridharan A, Abraham BM. Utilization of quarry dust to improve the geotechnical properties of soils in highway construction. Geotechnical Testing Journal. 2005;28(4):334.
7. Bureau of Indian Standards. IS 2720 (Part 8): Methods of Test for Soils - Part 8: Determination of Water Content-Dry Density Relation Using Heavy Compaction. New Delhi; 1983.
8. Indian Road Congress. IRC 37: Guidelines for the Design of Flexible Pavements. 4th revision. New Delhi; 2018.
9. Hussen HM, Baligh FA, Hamed MM. Proceedings of the 17th African Regional Conference on Soil Mechanics and Geotechnical Engineering. Cape Town, South Africa; 2019.
10. Ahmed MM, Amer TH, Layth AJA. Improvement of poor subgrade soils using cement kiln dust. Elsevier. 2017;7:138-143.

11. Roland EK, David EU, Imoh AC, Kennedy OC. Effect of micro-sized quarry dust particle on the compaction and strength properties of cement stabilized lateritic soil. Elsevier. 2021;2.
12. Gurung SB. Soil Distribution in Nepal. NUTA Journal. 2020;7(1&2):79-89.
13. Government of Nepal, Ministry of Physical Infrastructure and Transport, Department of Roads. Standard Specifications for Road and Bridge Works (SSRBW). Kathmandu; 2022.
14. Anil K, A.K. S. Stabilization of Soil using Cement Kiln Dust. International Journal of Innovative Research in Science. 2017;6(6).
15. Salahudeen AB, Eberemu AO, Osinubi KJ. Assessment of Cement Kiln Dust-Treated Expansive Soils. Geotechnical and Geological Engineering. 2014;32(10).
16. Paribesh P, Kumar DB. Effect of Stone Dust on Geotechnical Parameter of Fine Grained Soil. In: 10th IOE Graduate Conference. Kathmandu; 2021.
17. Adeyanju EA, Okeke CA. Clay soil stabilization using cement kiln dust. IOP Conf Series: Materials Science and Engineering. 2019;640:1-10.
18. Yinning Z, Leena TKK, Mari B. Assessment for Sustainable Use of Quarry Fines as Pavement Construction Materials: Part II - Stabilization and Characterization of Quarry Fine Materials. MDPI. 2019;12(2450):1-18.
19. Chief of Engineers. Annual Report, Volume I, of the Chief of Engineers on Civil Works Activities, Fiscal Year 1984, 1 October 1983—30 September 1984. 1984.