

Enhancement of Soft Soil Subgrades Using Sustainable Waste-Based Stabilization Materials for Flexible Pavement Applications

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Abstract - The increasing demand for road infrastructure has intensified the consumption of natural construction materials, while the disposal of industrial and agricultural wastes has become a major environmental concern. Sustainable stabilization of weak subgrade soils using waste-based materials provides an effective approach to enhance pavement performance and promote resource conservation. This study investigates the feasibility of utilizing Kota Stone Mining Waste (KSMW) in combination with Lime and Rice Husk Ash (RHA) for improving the engineering properties of soft subgrade soils used in flexible pavement applications. Laboratory investigations include Index Property tests, Standard Proctor Compaction, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and durability evaluation under different curing conditions. Microstructural characterization using X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) is performed to examine the mineralogical changes responsible for strength enhancement, while regression analysis is employed to establish relationships between engineering parameters. The stabilized soil is expected to exhibit significant improvements in strength, load-bearing capacity, and durability compared to untreated soil. The combined use of KSMW, Lime, and RHA offers a sustainable and economical alternative for subgrade stabilization by reducing dependence on natural materials, minimizing waste disposal issues, and improving the long-term performance of flexible pavements.

Keywords— Soft Subgrade Soil, Flexible Pavement, Kota Stone Mining Waste (KSMW), Rice Husk Ash (RHA), Lime Stabilization, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), Sustainable Pavement Materials, Soil Stabilization.

1.INTRODUCTION

The rapid expansion of transportation infrastructure has substantially increased the demand for durable and sustainable pavement construction materials. Flexible pavements constitute the majority of highway networks due to their economic advantages and ease of construction. The long-term

performance of these pavements largely depends on the engineering characteristics of the subgrade soil, which serves as the foundation supporting the pavement structure. Weak or expansive subgrade soils generally exhibit low bearing capacity, high compressibility, excessive plasticity, and significant volume changes under moisture fluctuations, resulting in pavement distresses such as rutting, cracking, differential settlement, and reduced service life. Consequently, improving the engineering properties of soft subgrade soils has become an important aspect of pavement engineering.

Conventional soil stabilization techniques primarily employ cement and lime to enhance the strength and durability of weak soils. Although these stabilizers provide satisfactory engineering performance, their large-scale production is associated with high energy consumption, depletion of natural resources, and considerable carbon dioxide emissions. Growing environmental concerns and the increasing emphasis on sustainable infrastructure have encouraged researchers to investigate alternative stabilization materials derived from industrial and agricultural wastes. The utilization of such waste materials not only minimizes environmental pollution but also contributes to resource conservation and the development of cost-effective pavement systems.

Among the various industrial by-products, Kota Stone Mining Waste (KSMW) is generated in substantial quantities during quarrying, cutting, and polishing operations. Large volumes of this waste are dumped near mining sites and processing industries, occupying valuable land and creating serious environmental problems, including dust pollution, contamination of nearby water resources, and degradation of surrounding ecosystems. Simultaneously, agricultural residues such as Rice Husk Ash (RHA), produced from the controlled burning of rice husk, are rich in amorphous silica and possess excellent pozzolanic characteristics. When combined with lime, RHA participates in secondary cementitious reactions that form calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels, thereby improving soil strength, stiffness, and durability. The incorporation of mineral-rich stone waste together with lime and RHA offers an environmentally sustainable alternative for soil stabilization while reducing dependence on conventional construction materials.

Numerous researchers have demonstrated that waste materials such as quarry dust, marble dust, granite waste, fly ash, and rice husk ash can significantly improve the compaction characteristics, California Bearing Ratio (CBR), and unconfined compressive strength (UCS) of weak soils. However, relatively limited research has focused on the combined utilization of Kota Stone Mining Waste, lime, and rice husk ash for stabilizing soft subgrade soils, particularly

with comprehensive evaluation of strength development, durability, and microstructural characteristics. Existing studies have largely emphasized individual waste materials or isolated engineering properties, indicating the need for further investigation into synergistic stabilization mechanisms and optimized mix proportions.

The present study aims to investigate the effectiveness of stabilizing soft subgrade soil using a combination of Kota Stone Mining Waste, lime, and Rice Husk Ash for flexible pavement applications. Laboratory investigations include the determination of index properties, compaction characteristics, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and durability performance under various curing conditions. In addition, X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) analyses are employed to examine the mineralogical and chemical changes responsible for strength enhancement. Regression analysis is also performed to establish relationships among important engineering properties and strength parameters.

The findings of this research are expected to demonstrate that the combined utilization of Kota Stone Mining Waste, lime, and Rice Husk Ash significantly enhances the engineering performance of soft subgrade soils while promoting sustainable waste management. The proposed stabilization approach offers an economical and environmentally friendly alternative for flexible pavement construction by reducing the consumption of virgin materials, minimizing waste disposal problems, lowering construction costs, and supporting circular economy principles in transportation infrastructure.

2. LITERATURE REVIEW

2.1 General

The performance of flexible pavements is primarily governed by the engineering behavior of the subgrade soil. Weak subgrade soils possessing high plasticity, low bearing capacity, excessive compressibility, and high moisture susceptibility often result in premature pavement failures such as rutting, cracking, differential settlement, and reduced service life. Traditionally, soil stabilization has been achieved using cement and lime. However, increasing environmental concerns, depletion of natural resources, and high carbon emissions associated with cement production have encouraged researchers to investigate sustainable waste-based stabilizers. Recent studies have demonstrated that industrial and agricultural wastes containing silica, alumina, and calcium compounds can effectively improve the engineering characteristics of problematic soils while simultaneously addressing waste disposal issues.

2.2 Soil Stabilization Using Lime

Lime is one of the oldest and most effective chemical stabilizers for clayey soils. Hydrated lime reacts with clay minerals through cation exchange, flocculation, and pozzolanic reactions, producing cementitious compounds such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). These reactions reduce plasticity, improve workability, increase strength, and enhance durability. Numerous

investigations have shown that lime stabilization significantly increases California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS), particularly after adequate curing periods. However, excessive lime content may become uneconomical and may not provide proportional strength improvement. Therefore, lime is often combined with silica-rich waste materials to improve stabilization efficiency.

2.3 Rice Husk Ash as a Sustainable Pozzolan Material

Rice Husk Ash (RHA) is an agricultural by-product rich in amorphous silica. Because of its high pozzolanic activity, RHA reacts with calcium hydroxide released from lime to form additional cementitious products, thereby improving soil strength and durability. Researchers have consistently reported reductions in liquid limit, plasticity index, and swelling characteristics, accompanied by improvements in Maximum Dry Density (MDD), CBR, and UCS. The combination of lime and RHA has been identified as an economical and environmentally sustainable alternative to conventional stabilization techniques, especially for expansive and soft clay soils. Recent review studies also conclude that optimum RHA contents generally range between 10% and 20% depending on soil type and lime dosage.

2.4 Utilization of Stone Mining Waste in Pavement Construction

Stone processing industries generate enormous quantities of quarry waste, crusher dust, granite dust, marble dust, and polishing sludge. Disposal of these materials creates serious environmental and land-use problems. Consequently, researchers have investigated their reuse in pavement engineering. Stone wastes generally act as granular fillers that improve particle packing and reduce soil plasticity. Several studies reported considerable improvements in compaction characteristics, CBR, UCS, shear strength, and resilient modulus following the incorporation of stone waste into weak soils. The reuse of stone waste also reduces dependence on natural aggregates while promoting sustainable construction practices.

2.5 Kota Stone Mining Waste (KSMW)

Kota Stone Mining Waste is generated during quarrying, cutting, polishing, and finishing operations. Large quantities of this waste are dumped in open areas, causing dust pollution, water contamination, and land degradation. Due to its limestone-rich composition, KSMW possesses significant potential as a stabilizing material for pavement applications. Previous investigations have demonstrated that Kota stone waste improves compaction properties, reduces plasticity, and enhances the load-bearing capacity of weak soils. Nevertheless, studies involving the combined use of KSMW with lime and Rice Husk Ash remain limited, indicating considerable scope for further investigation.

2.6 Previous Research on Waste-Based Soil Stabilization

Several researchers have investigated different waste materials for improving subgrade performance.

- Okagbue and Onyeobi (1999) reported that marble dust significantly improved compaction characteristics and CBR of tropical soils.
- Soosan et al. (2005) observed that quarry dust enhanced bearing capacity while reducing plasticity.
- Sridharan et al. (2006) concluded that quarry dust increased Maximum Dry Density and shear strength.
- Eze-Uzomaka et al. (2010) demonstrated that quarry dust combined with cement considerably improved durability and strength.
- Ogbonnaya and Illobachie (2011) recommended granite dust for pavement subgrades and embankments.
- Gupta and Sharma (2013) reported that marble dust and fly ash effectively stabilized expansive soils.
- Mishra et al. (2014) found that granite slurry significantly reduced swelling and improved UCS.
- Khader et al. (2017) concluded that granite dust combined with lime substantially increased CBR and reduced expansive behavior.
- Zorluer and Gucek (2017) demonstrated that granite waste and fly ash considerably improved long-term durability.
- Salam et al. (2018) emphasized the importance of limestone fines in improving compaction and bearing characteristics of pavement layers.

2.7 Microstructural Investigations

Recent research has increasingly incorporated microstructural characterization techniques such as X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) to understand stabilization mechanisms. XRD identifies newly formed cementitious minerals, while XRF determines the chemical composition of stabilizing materials. These techniques confirm the formation of calcium silicate hydrate and calcium aluminate hydrate gels responsible for long-term strength development. Microstructural analysis provides scientific evidence supporting improvements observed in engineering properties such as CBR and UCS.

2.8 Research Gap

Based on the literature reviewed, the following research gaps are identified:

1. Most previous studies investigated individual waste materials such as quarry dust, marble dust, granite waste, or Rice Husk Ash independently.
2. Very limited research has been conducted on the combined utilization of **Kota Stone Mining Waste, Lime, and Rice Husk Ash** for stabilizing soft subgrade soils.

3. Comprehensive evaluation involving Index Properties, Standard Proctor Compaction, CBR, UCS, durability, and microstructural characterization has not been adequately reported.
4. Few studies have established regression relationships between engineering properties and strength parameters.
5. There remains a need for developing sustainable and economical stabilization techniques suitable for flexible pavement construction using locally available industrial and agricultural wastes.

2.9 Summary

The reviewed literature demonstrates that waste-based stabilization materials significantly improve the engineering properties of weak subgrade soils while reducing environmental impacts associated with waste disposal and excessive consumption of natural resources. Although considerable research has been carried out on quarry dust, marble dust, granite waste, and Rice Husk Ash, comprehensive studies combining **Kota Stone Mining Waste, Lime, and Rice Husk Ash** remain scarce. The present study addresses this gap by evaluating the combined effect of these sustainable materials on the strength, durability, and microstructural characteristics of soft subgrade soils for flexible pavement applications.

3. OBJECTIVES

1. To determine the physical and engineering properties of the natural soft subgrade soil.
2. To investigate the influence of varying proportions of Kota Stone Mining Waste (KSMW), Lime, and Rice Husk Ash (RHA) on the stabilization of soft subgrade soil.
3. To evaluate the compaction characteristics of stabilized soil through Standard Proctor Compaction tests.
4. To assess the strength improvement of stabilized soil using California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests under different curing conditions.
5. To investigate the mineralogical and chemical characteristics of the stabilizing materials and stabilized soil using X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) analyses.
6. To develop regression relationships between engineering properties and strength parameters of stabilized soil.
7. To identify the optimum combination of KSMW, Lime, and RHA for enhancing subgrade performance while promoting sustainable waste utilization in flexible pavement construction.

4. METHODOLOGY

The methodology adopted in this study consists of laboratory investigations to evaluate the effectiveness of **Kota Stone Mining Waste (KSMW), Lime, and Rice Husk Ash (RHA)** as sustainable stabilizing materials for improving the engineering properties of soft subgrade soil used in flexible pavement applications. The overall experimental procedure is illustrated in Fig. 1.

A. Material Collection and Characterization

Soft subgrade soil was collected from a representative site and air-dried before testing. Kota Stone Mining Waste (KSMW) was obtained from a local stone processing industry, while commercially available hydrated lime and Rice Husk Ash (RHA) were used as stabilizing materials. The chemical and mineralogical compositions of the materials were determined using **X-ray Fluorescence (XRF)** and **X-ray Diffraction (XRD)** analyses.

B. Preparation of Stabilized Soil Mixes

The natural soil was mixed with varying proportions of KSMW, Lime, and RHA to prepare different stabilization combinations. The mixtures were thoroughly blended to achieve uniform distribution of stabilizing materials. The optimum mix proportion was identified based on the engineering performance obtained from laboratory tests.

C. Laboratory Testing

The engineering properties of untreated and stabilized soils were evaluated through laboratory testing. Index Property tests, including specific gravity, grain size distribution, Atterberg limits, and free swell index, were conducted to determine the basic characteristics of the soil. Standard Proctor Compaction tests were performed to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of each mix.

The strength characteristics were assessed using **California Bearing Ratio (CBR)** and **Unconfined Compressive Strength (UCS)** tests. UCS specimens were tested after different curing periods to evaluate strength development resulting from pozzolanic reactions. Soaked and unsoaked CBR tests were performed to assess the suitability of stabilized soil for flexible pavement subgrades.

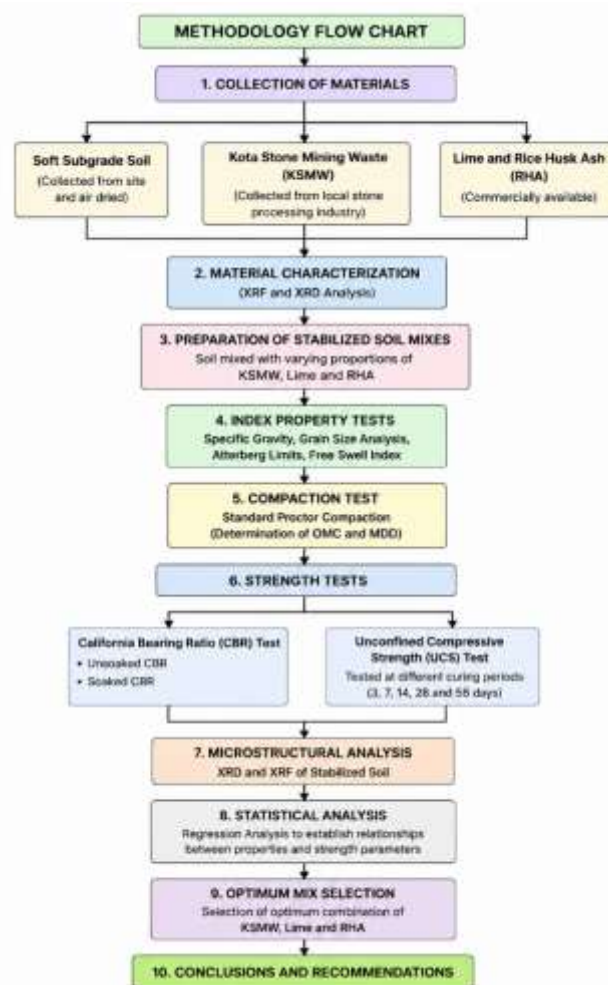
D. Microstructural Analysis

Microstructural investigations were carried out using **XRD** and **XRF** techniques to identify the mineralogical phases and chemical composition of the stabilizing materials and stabilized soil. The formation of cementitious compounds responsible for strength enhancement was examined through these analyses.

E. Statistical Analysis

Regression analysis was performed to establish relationships between compaction characteristics, CBR, UCS, and other engineering parameters. The developed regression models were used to evaluate the effectiveness of the stabilization technique and identify the optimum mix for pavement applications.

Fig. 1. Methodology Flow Chart



5. MATERIAL CHARACTERIZATION

The materials used in this investigation include soft subgrade soil, Kota Stone Mining Waste (KSMW), hydrated lime, and Rice Husk Ash (RHA). The soft subgrade soil was collected from the selected project site, air-dried, pulverized, and sieved through a 4.75 mm IS sieve before testing. Kota Stone Mining Waste was obtained from a nearby stone processing industry and processed to achieve the required particle size for stabilization. Commercially available hydrated lime and Rice Husk Ash were used as chemical stabilizers. The engineering properties of the natural soil were determined through laboratory tests, including specific gravity, particle size distribution, Atterberg limits, and

free swell index, in accordance with relevant Indian Standard (IS) codes.

The chemical composition of KSMW, lime, and RHA was determined using X-ray Fluorescence (XRF) analysis, while X-ray Diffraction (XRD) analysis was carried out to identify the mineralogical phases present in the materials. These analyses were performed to evaluate the pozzolanic potential and the formation of cementitious compounds responsible for strength enhancement in the stabilized soil.

The collected characterization data served as the basis for selecting suitable mix proportions and interpreting the improvement in compaction, strength, and durability characteristics of the stabilized subgrade soil.

Table-I Materials Used

Material	Purpose
Soft Subgrade Soil	Base soil for stabilization
Kota Stone Mining Waste (KSMW)	Sustainable mineral filler and strength enhancer
Hydrated Lime	Chemical stabilizer promoting pozzolanic reactions
Rice Husk Ash (RHA)	Silica-rich pozzolanic material for secondary cementation

Table-II Characterization Tests

Material	Characterization Test	Standard
Soft Soil	Specific Gravity	IS 2720 (Part 3)
Soft Soil	Grain Size Analysis	IS 2720 (Part 4)
Soft Soil	Atterberg Limits	IS 2720 (Part 5)
Soft Soil	Free Swell Index	IS 2720 (Part 40)
KSMW	XRF Analysis	ASTM/Instrument Standard
KSMW	XRD Analysis	ASTM/Instrument Standard
Lime	XRF Analysis	ASTM/Instrument Standard
RHA	XRF Analysis	ASTM/Instrument Standard

6. MIX PROPORTIONING

The natural soft subgrade soil was stabilized using **Kota Stone Mining Waste (KSMW)**, **hydrated lime**, and **Rice Husk Ash (RHA)** to evaluate their combined influence on the engineering properties of the soil. Initially, the untreated soil was tested as the control specimen. Different combinations of KSMW, lime, and RHA were then prepared by replacing the natural soil with predetermined percentages of stabilizing materials. The dry materials were thoroughly blended to achieve a uniform mixture before the addition of water corresponding to the Optimum Moisture Content (OMC).

The prepared mixtures were compacted according to the Standard Proctor method for determining compaction characteristics and for preparing specimens for California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests. UCS specimens were cured for **7, 14, and 28 days** to evaluate the development of strength due to pozzolanic reactions between lime, RHA, and the calcium-rich constituents of KSMW. The optimum mix was selected based on improvements in compaction characteristics, CBR, UCS, and durability performance.

Table-III Mix Proportions Adopted in the Study

Mix ID	Soil (%)	KSMW (%)	Lime (%)	RHA (%)
S0	100	0	0	0
M1	90	5	3	2
M2	85	10	3	2
M3	80	15	3	2
M4	75	20	3	2
M5	70	25	3	2

Mix Preparation Procedure

1. Air-dry and pulverize the natural soil.
2. Sieve all materials through a 4.75 mm IS sieve.
3. Weigh soil, KSMW, lime, and RHA according to the selected mix proportions.
4. Dry-mix all constituents until a homogeneous blend is obtained.
5. Add water gradually to achieve the Optimum Moisture Content (OMC).
6. Compact the mixtures using the Standard Proctor method.
7. Prepare specimens for CBR and UCS testing.
8. Cure UCS specimens for the specified periods before testing

7. TEST RESULTS AND DISCUSSION

A. Index Properties

The index properties of the untreated soft subgrade soil were determined to establish the baseline engineering characteristics. The results indicated that the natural soil exhibited relatively high plasticity and poor engineering properties, making it unsuitable for direct use as a pavement subgrade. The incorporation of Kota Stone Mining Waste (KSMW), Lime, and Rice Husk Ash (RHA) reduced the liquid limit and plasticity index, while improving the workability of the soil. These improvements are attributed to flocculation and pozzolanic reactions occurring between the stabilizing materials and the clay particles.

B. Compaction Characteristics

The Standard Proctor Compaction test was conducted to determine the **Optimum Moisture Content (OMC)** and **Maximum Dry Density (MDD)** of untreated and stabilized soil mixtures. The addition of KSMW improved particle packing, resulting in an increase in MDD, while lime and RHA influenced moisture demand due to hydration and pozzolanic reactions. The optimum stabilization mix exhibited the highest dry density and satisfactory moisture content suitable for field compaction.

C. California Bearing Ratio (CBR)

The CBR test results demonstrated a significant improvement in the load-bearing capacity of the stabilized soil compared with the untreated soil. Both soaked and unsoaked CBR values increased with the addition of KSMW, lime, and RHA up to the optimum dosage. The increase is attributed to improved particle interlocking and the formation of cementitious compounds that enhanced the stiffness of the stabilized matrix.

D. Unconfined Compressive Strength (UCS)

The UCS results indicated a continuous increase in compressive strength with curing time. The pozzolanic reaction between lime and RHA, together with the filler effect of KSMW, produced a denser soil matrix, thereby enhancing strength. The highest UCS value was obtained for the optimum mix after 28 days of curing, demonstrating the effectiveness of the proposed stabilization technique.

E. XRD and XRF Analysis

XRF analysis confirmed that KSMW contained significant amounts of calcium-bearing minerals, while RHA was rich in reactive silica. XRD analysis revealed the formation of cementitious phases, such as calcium silicate hydrate (C-S-H), after stabilization. These mineralogical changes explain the observed improvements in CBR and UCS values by producing a denser and stronger soil matrix.

F. Regression Analysis

Regression analysis showed a strong correlation between compaction characteristics and strength parameters. The coefficient of determination (R^2) indicated that CBR and UCS could be reliably predicted from MDD and OMC, confirming the effectiveness of the stabilization process.

Table-IV Properties of Black Cotton Soil and Kota Stone Slurry

Parameters	BCS	KSS	Code
Soil Type	CI	-	IS: 1498 (1970)
Liquid limit (%)	49.2	23.90	IS:2720 Part V (1985)
Plastic limit (%)	20.1	Non-Plastic	
Optimum moisture content (%)	20.5	21.9	IS: 2720 Part VII (1980)
Maximum Dry density (gm/cc)	1.524	1.604	
Specific Gravity	2.62	2.87	IS: 2720 Part III (1980)
Fineness Modulus	5.17	2.16	IS: 383 (1970)

Table-V Chemical Composition of Black Cotton Soil and Kota Stone

Chemical composition (in %)	CaO	SiO ₂	MgO	Fe ₂ O ₃	Al ₂ O ₃	LOI
Black cotton soil	6.15	65.45	2.01	4.98	Trace s	Nil
Kota Stone	37.15	23.14	7.02	Traces	Nil	31.89

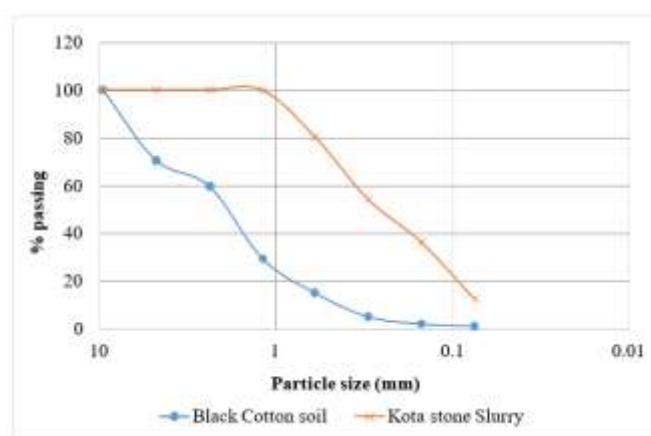


Figure 1: Gradation of Soil and Slurry Particles

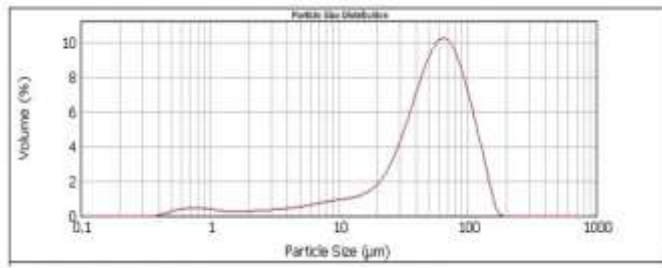


Figure 2: Particle Size Distribution (finer than 75 microns) of Black Cotton Soil

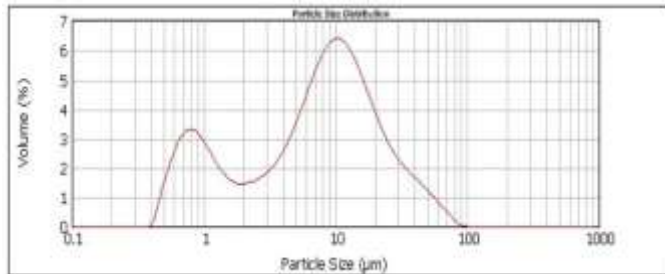


Figure 3: Particle Size Distribution (finer than 75 microns) of Kota Stone Slurry

Property	KSA	Convention al aggregate	Permissibl e Value	Test Metho d
Los Angeles test (500 revolution)	25.34%	14.26%	35% max.	IS:2386 Part IV (1963)
Impact test	18.41%	13.53%	27% max.	IS:2386 Part IV (1963)
Water Absorptio n Test	0.23%	0.18%	2% max.	IS:2386 Part III (1963)
Combined Flakiness and Elongatio n indices	33%	28.24%	35% max	IS: 2386 Part I (1963)
Bulk Specific Gravity of Coarse Aggregate (gm/cc)	2.87	2.75	-	IS :2386 Part III (1963)
Stripping value	100%	99%	Minimum retained coating 95%	IS:6241 (1971)

8. CONCLUSIONS

This study investigated the effectiveness of **Kota Stone Mining Waste (KSMW)**, **Lime**, and **Rice Husk Ash (RHA)** as sustainable stabilizing materials for improving the engineering properties of soft subgrade soil for flexible pavement applications. Based on the experimental investigation, the following conclusions are drawn:

1. The incorporation of KSMW, Lime, and RHA significantly improved the engineering characteristics of the soft subgrade soil by reducing plasticity and enhancing overall soil stability.
2. The stabilized soil exhibited improved compaction characteristics, with an increase in **Maximum Dry Density (MDD)** and an optimum **Optimum Moisture Content (OMC)** suitable for field compaction.
3. Significant improvements were observed in the **California Bearing Ratio (CBR)** and **Unconfined Compressive Strength (UCS)** compared with the untreated soil, indicating enhanced load-bearing capacity and strength suitable for flexible pavement subgrades.
4. Strength development increased with curing time due to pozzolanic reactions between lime, Rice Husk Ash, and the calcium-bearing minerals present in Kota Stone Mining Waste, resulting in the formation of cementitious compounds that improved the soil structure.
5. **XRD** and **XRF** analyses confirmed the mineralogical and chemical changes responsible for strength enhancement, supporting the laboratory observations of improved engineering performance.
6. Regression analysis demonstrated a strong correlation between compaction characteristics and strength parameters, indicating that stabilized soil performance can be effectively predicted using statistical models.
7. The combined utilization of **KSMW**, **Lime**, and **RHA** provides a sustainable and economical alternative to conventional stabilizers by reducing the consumption of natural construction materials, minimizing industrial and agricultural waste disposal, and lowering the environmental impact of pavement construction.

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