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Performance Assessment of Sand–Clay Blends: Practical Applications In Sustainable Pavement Design

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ABSTRACT *: A vital role is played by Subgrade soils in the overall performance of low-volume pavements. In areas underlain by weak clays, this often leads to early pavement distress, and modification of the soil is often required to achieve economical and durable designs. Although lime is commonly used for chemical stabilization, these methods may not always be effective or sustainable. Alternatively Mechanical modification using granular inclusions serves as a simple and practical alternative. This research examines the influence of sand addition on the overall strength, compaction, and pavement design implications of clay subgrades. Clay–sand mixtures were prepared with sand contents varying between the ranges of 0% to 50% by dry weight. Standard and Modified Proctor compaction tests were performed to determine the effect of sand on optimum moisture content and maximum dry density. In other to evaluate strength and bearing capacity the unconfined compressive strength (UCS) and California Bearing Ratio (CBR) tests were carried out. These test results were incorporated into the analysis of pavement thickness design following AASHTO, USACE, CBR, and Caltrans methodologies. Compaction results shows that sand inclusion consistently increased maximum dry density and lowered optimum moisture content, leading to improved workability. However, strength parameters declined as sand content increased. The 50% sand blend exhibited revealed more than a 50% loss in strength compared with natural clay, requiring an increase of 37% to 47% in pavement thickness depending on the design method. An optimum range of 10% to 20% sand was identified, providing a balance between compaction benefits and acceptable strength (UCS values 752–516 kPa; CBR values 19%–18%). Beyond this value, the decrease in structural strength outweighed compaction advantages. For rural areas with low traffic, controlled sand–clay blending may be used as a modification technique to improve workability characteristics, provided adequate drainage and maintenance are ensured.*

KEYWORDS: *Sa*nd–clay optimisation: Soil modification; CBR-UCS characteristics; Subgrade performance: Low-volume roads

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I. INTRODUCTION

Sand is one of the most abundant natural materials globally and is widely used for infrastructure due to low cost and availability as well as limited availability higher-quality aggregates. It has attracted attention as an alternative for low-volume pavement especially in areas where conventional aggregate are scares (Li et al., 2024). A Sand–clay blends increases strength and stiffness, with sand proportion have significant (Pedarla et al., 2015). In Southern Africa, neat sand bases have shown satisfactory performance, with aluminum and iron contents supplementing behaviour (Paige-Green et al., 2015; Netterberg & Elsmere, 2015). Field studies have confirm that drainage and construction quality are the main determinants of success in sealed low-volume roads, enabling relaxed material standards while conserving resources. Well-graded sands, due to their frictional resistance, drainage capacity, and granular interlock, are suitable for subgrades, capping, and bases (Otto et al., 2020; Toole et al., 2018; Pinard et al., 2015). Sands that are sourced locally can further reduce costs and hauling distances while meeting structural requirements and standards if properly graded and compacted (Paige-Green et al., 2024).

Nevertheless, granular shoulders and unstabilized sands are often likely to rutt, erosion, and edge drop-offs, with about 67% of roads exhibiting drops >38 mm (Mekkawy et al., 2010). Proper compaction, drainage, and protective sealing can hanle these issues, as demonstrated in a 50-year road carrying 1.0M E80 load repetitions (Netterberg & Elsmere, 2015). In expansive soil regions, uncontrolled moisture remains critical; clay–sand liners and sloped shoulders effectively control infiltration (Dafalla et al., 2022). Particle gradation also controls liquefaction resistance, enhancing cyclic strength at low densities but potentially reducing it at high densities. Fine sands may retain capillary moisture, lowering bearing capacity where drainage is poor. In seismic regions, loose saturated sands are vulnerable to liquefaction (Guo et al., 2013; Russell, 2015). Thus, gradation control, densification, moisture management, and partial stabilization are pertinent.

Compacted clay liners complement sand by controlling seepage. Studies show ~74% of 85 liners achieve conductivities $\leq 1\times10^{-7}$ cm/s, with values as low as 1×10^{-9} m/s under proper compaction (Benson et al., 1999; Okonkwo et al., 2018; Arinze & Davie, 2025). Locally available clays, tills, and bentonite–sand mixtures can also function effectively as hydraulic barriers (Michette et al., 2017; Widomski et al., 2018). When compacted wet-of-optimum, clays not only restrict permeability but also provide cohesive strength, contributing to stable working platforms. Their sustainable use potentially reduces costs and embodied energy, while supporting mechanistic–empirical pavement system (Usanga et al., 2025; Ares et al., 2021).

One of the downside of clay subgrades is due to moisture sensitivity, weakness and shrink–swell cycles despite their availability (Amakye et al., 2022; Arinze et al., 2018), depending on the type stabilization with lime, cement, fly ash, or industrial by-products can improve modulus, CBR, and durability (Solanki et al., 2010; Amakye et al., 2022). Lime and cement act via cation exchange and pozzolanic reactions, reducing plasticity and increasing stiffness, though durability under wetting–drying requires higher mixes (Sandoval et al., 2020). Waste-based stabilizers further reduces costs and carbon footprint.

The blending of sand with clay also has several benefits. Studies have revealed that CBR raises up to 224% and leads to reductions in plasticity index to non-plastic levels, thgis is because of enhanced inter-particle friction and gradation (Pedarla et al., 2015; Gadzama et al., 2023; Gupta et al., 2024). For expansive soils, sand addition reduces swell and chemical stabilizer demand. Yet excessive sand reduces density and CBR, emphasizing the need for optimized proportions (Hosna & Sagor, 2025). These texture-modified subgrades reliably achieve ~10% CBR, enabling thinner aggregate layers in rural designs (Gadzama et al., 2023).

Optimization-based approaches show promise; Fuller's gradation model improved mechanical performance over arbitrary specifications (Cheng Li et al., 2018). Still, most times design practices depend on heuristic CBR-based methods, while overlooking mechanistic parameters such as resilient modulus (Zapata, 2017; Yang et al., 2015). There is need for a cost-effective and durable stabilization due to the Inconsistencies across different soil types which suggest the need for systematic models, integrating sand fraction, gradation, compaction, and minimal binders are necessary (Almeida et al., 2024; de Lima et al., 2020).

Previous literatures on sand–clay mixtures mainly focused on chemically stabilized composites and/or empirical determination of strength without detailed assessment of their implications for pavement design. Therefore, there remains limited understanding of how constituent modification using sand alone affects the combined compaction–strength behaviour and corresponding pavement thickness requirements for sustainable low-volume roads.

This study fills that gap by studying the engineering properties of sand–clay blends without any chemical stabilizer, integrating laboratory compaction and strength properties (UCS, CBR) directly with pavement design outcomes using multiple design models (AASHTO, USACE, CBR, and Caltrans). The main contribution of this paper is the identification of an optimum sand range (10–20%) at which improved workability and adequate bearing capacity is achieved, providing a low-cost, environmentally friendly modification strategy for weak clay subgrades in rural pavement construction in tropical soils. Though sand-clay composite has been stabilized with cement in the past (Xu et al., 2021; Yamashita et al., 2021; Qian et al., 2021), this study involve the Performance Assessment of Sand–Clay Blends for potential use as a highway construction material without traditional stabilizer or additives.

II. MATERIALS AND METHODOLOGY

2.1 Materials

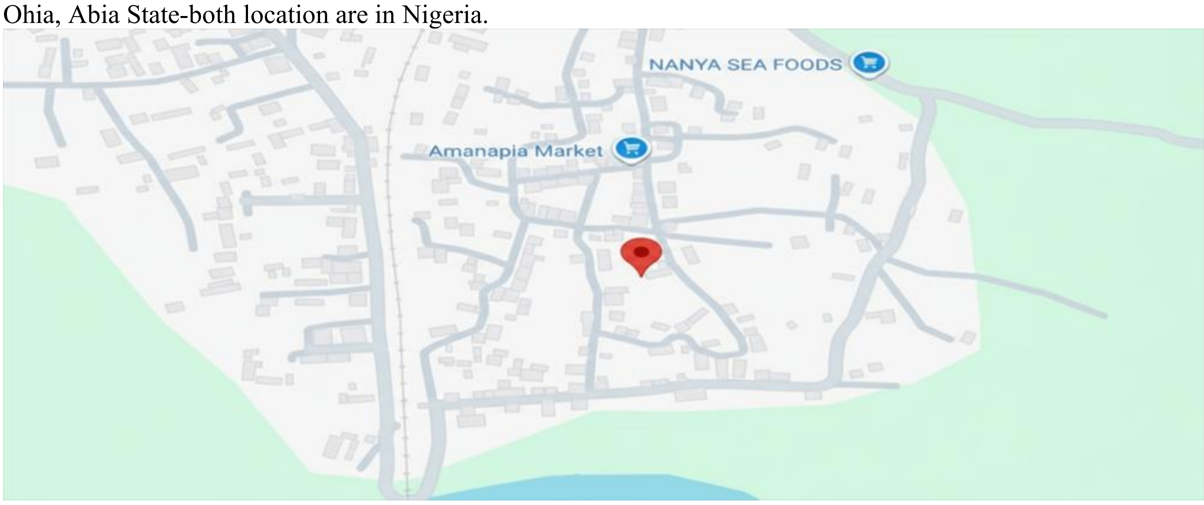
2.1.1 Soil

Two different soil types were employed: a stiff clay and a clean sand, both chosen to represent locally available construction materials. The clay was sourced from the Onuimo River at the Imo–Abia State boundary, while the sand was obtained from Ohia, Abia State-both location are in Nigeria.

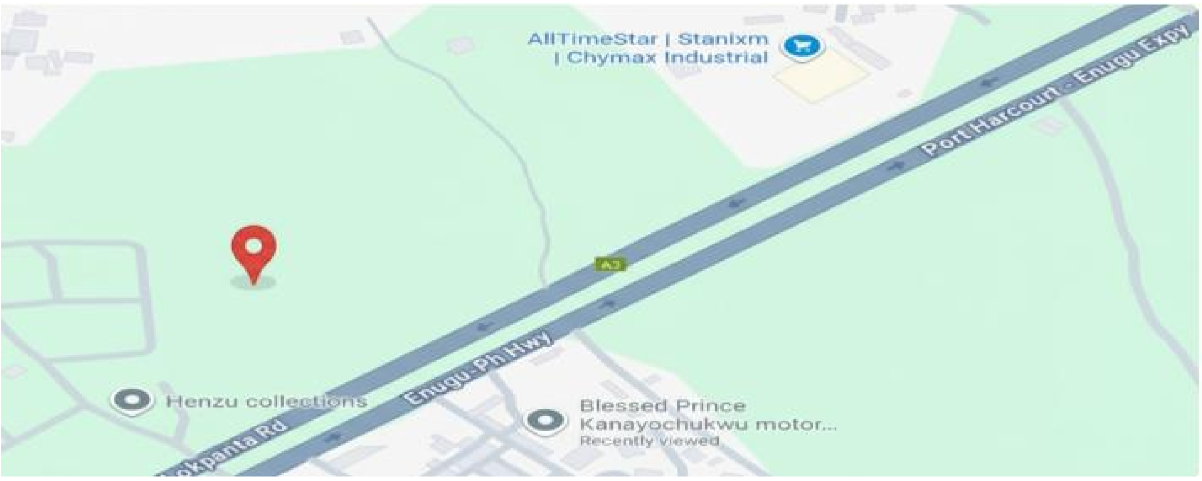
The geographical coordinates of the sampling locations are as follows:

Onuimo River (Imo–Abia State boundary): Latitude 4°53′04″ N (≈ 4.88444° N), Longitude 7°10′24″ E (≈ 7.17333° E). Ohia, Umuahia (Abia State): Latitude 5.51546° N, Longitude 7.44928° E.

These locations are illustrated in Fig.s 1(a) and 1(b). The geotechnical properties of the samples were subsequently determined through standard laboratory characterization.



(a)



(b)

Fig. 1: Google Maps of Sample collection maps

2.2. Sample Preparation

Clay–sand mixtures were prepared with sand contents of 0–50% (by dry weight). The soils were oven-dried at 105 ± 5 °C for 24 h, pulverized, and sieved through a No. 4 (4.75 mm) sieve. Proportions were thoroughly mixed to homogeneity before de-aired water was added to achieve target moisture conditions following ASTM D2216.

2.3. Laboratory Testing Program

Laboratory tests were conducted to evaluate compaction, strength, and bearing capacity. Assessment of Compaction was conducted using the Standard and Modified Proctor tests (ASTM D698, ASTM D1557) to establish the Maximum Dry Unit Weight (MDUW) and Optimum Moisture Content (OMC). The Unconfined Compressive Strength (UCS) test was conducted on cylindrical specimens measuring 38 mm × 76 mm, which were compacted to Modified Proctor density and tested at OMC and OMC ± 4% under a loading rate of 1.0 mm/min (ASTM D2166/D2166M). The California Bearing Ratio (CBR) test involved specimens compacted with Modified Proctor energy in CBR moulds of 152 mm diameter, soaked for 96 hours under surcharge loads, and then subjected to penetration testing at a rate of 1.25 mm/min (ASTM D1883). The higher value at either 2.54 or 5.08 mm penetration was reported.

2.4. Pavement Design Analysis

CBR results informed pavement design using four methods: the AASHTO (1993) guide (MR ≈ 1500 × CBR), USACE design charts (EM 1110-3-137), classical CBR charts, and Caltrans Local Vicinity Criteria (LVC) for lean concrete base thickness determination.

2.5. Data Analysis

Test data were analyzed to investigate and establish a correlations between sand content and engineering properties (MDD, OMC, UCS, CBR). Graphical trends were identified, and the implications for pavement design were evaluated to guide practical recommendations.

III. RESULTS AND DISCUSSION

Table 1: Properties of soil samples used

Property	Stiff Clay	Clean Sand
C (kPa)	88	0
Φ (°)	0	41
LL	72	Non Plastic
PL	39	Non Plastic
PI	33	Non Plastic
Gs	2.67	2.58
w (%)	33	5
AASHTO Classification	**A-7-5 (43)**	**A-3 (0)**

Table 1 summarizes the key geotechnical properties of the two base materials, stiff clay and clean sand, which were mixed in various proportions for the research study. In terms of shear strength, the soils represent two distinct models. The stiff clay derives its strength entirely from cohesion (C = 88 kPa) with no internal friction (φ = 0°), which is typical of undrained conditions. In contrast, the clean sand derives its strength entirely from internal friction (φ = 41°) with no cohesion (C = 0 kPa). With respect to plasticity and composition, the clay is highly plastic, as indicated by its high liquid limit (LL = 72) and plasticity index (PI = 33), classifying it as a fat clay, while the sand is non-plastic, confirming its clean, coarse-grained nature. The basic physical properties show similar specific gravity values for both soils (clay: 2.67, sand: 2.58), which is typical of soils composed of silicate minerals. However, their natural moisture content differs significantly, with the clay at 33% (a moist state) and the sand at 5% (a dry state). These properties establish the endpoints for the sand–clay mixtures. The experiments were designed to investigate how engineering behaviour, such as strength and compaction, transitions from a cohesive, plastic clay-dominated matrix to a frictional, non-plastic sand-dominated matrix as the sand content increases from 0% to 50%. In essence, the table defines the contrasting properties of the two soils that formed the basis of the laboratory testing program.

This study investigated the effect of sand content on the stabilization of clay soil, with a specific focus on engineering properties critical for pavement subgrade applications. The key parameters evaluated include Unconfined Compressive Strength (UCS), moisture content (W%), Dry Unit Weight (DUW), California Bearing Ratio (CBR), and the resulting pavement layer thicknesses considering various design methods. The results, summarized in Table 1, demonstrate a clear and significant trend: the addition of sand, while improving compaction characteristics, leads to a progressive reduction in strength and bearing capacity of the clay soil.

Table 2: Results of Sand-Clay Stabilization

Sample	UCS (kPa)	W (%)	DUW (kN/m³)	CBR (%)	Capping Layer (mm)	AASHTO Method (mm)	USAGE Method (mm)	CBR Design Method (mm)	Caltrans LVC (mm)
Clay (Control)	880.5	21.5	15.7	21.5	150	160	66	80	150
Clay +10% Sand	752.4	20.2	16.1	19.2	150	170	71	87	150
Clay +20% Sand	516.1	18.4	16.6	18.4	150	190	85	105	200
Clay +30% Sand	431.6	18.6	17.4	17.9	150	210	93	114	250
Clay +40% Sand	407.9	17.8	18.6	16.9	150	215	96	117	250
Clay +50% Sand	389.1	15.4	18.9	15.5	150	220	97	118	250

3.1. Effect on Strength and Compaction Characteristics

The Unconfined Compressive Strength (UCS) of the soil decreased markedly with increasing sand content (Fig. 2). This is in keeping with Pedarla et al. (2015) and in contrast with the findings of Cabalar and Mustapha (2017) which is most likely to be occasioned by the used of laterite by the later instead of using soil very rich in clay content. The control pure clay sample exhibited the highest UCS value of 880.5 kPa**.** With the introduction of 10% sand, the UCS dropped to 752.4 kPa, and this declining trend continued consistently, reaching a minimum of 389.1 kPa at 50% sand content. This represents a strength reduction of approximately 56% compared to the control. This phenomenon can be attributed to the dilution of the clay's natural cohesion.

Similar reductions in UCS with increasing sand content have been witnessed by Cabalar and Mustafa (2017) and Pedarla et al. (2015), who attributed this to the replacement of cohesive clay bonds with frictional sand contacts thereby providing limited tensile resistance. The reduction in cohesion overshadows any gain in internal friction at high sand contents, leading to a weaker composite.

The trend is also in keeping with the findings of Almeida et al. (2024), who noted that excessive sand in lateritic soils decreased the active clay fraction that contributes to bonding and particle interlock. However, the moderate sand inclusion (10–20%) identified in this research appears to balance these opposing effects, confirming that controlled sand introduction can optimize both unit weight and strength — an outcome also reported by Gadzama et al. (2023) for stabilized sandy clays.

Clay particles possess inherent electrochemical bonds that provide cohesive strength. The introduction of non-cohesive sand particles disrupts this cohesive matrix, replacing strong clay-clay interactions with weaker clay-sand and sand-sand contacts, ultimately leading to a less cohesive and weaker composite material.

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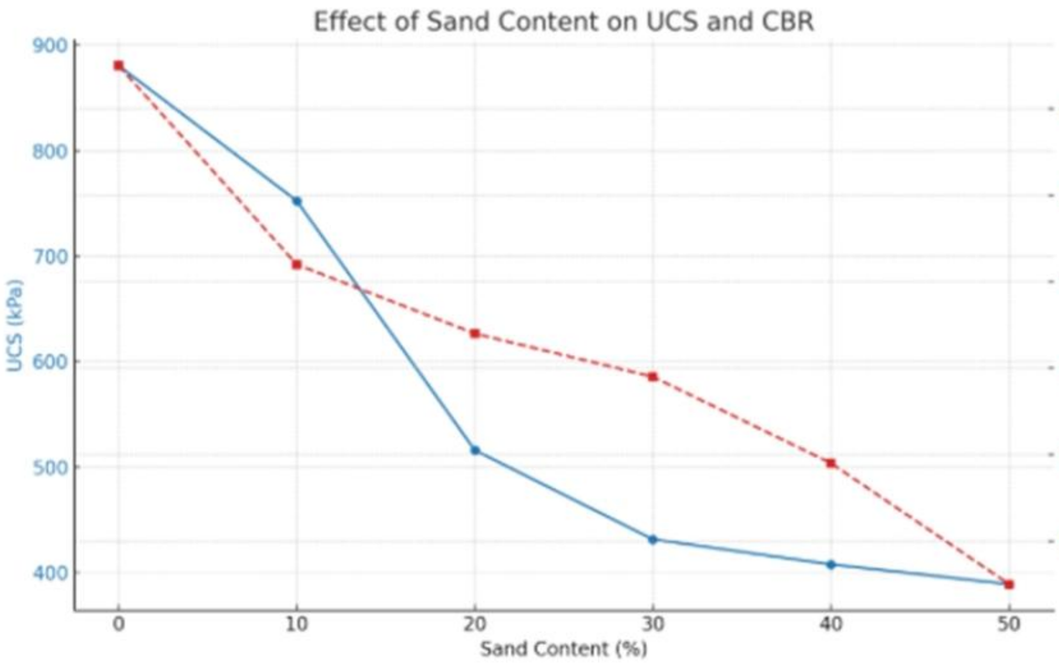

Fig. 2: Effect of Sand Content on UCS and CBR

Conversely, the Dry Unit Weight (DUW) showed a positive correlation with sand content, increasing from 15.7 kN/m³ for pure clay to 18.9 kN/m³ for the 50% sand mixture **(**Fig. 3). This is expected, as sand grains are typically denser and have a higher specific gravity than clay minerals. The sand particles help to fill the voids between larger clay aggregates, leading to a denser packing and a higher overall weight per unit volume upon compaction. Accordingly, the optimum moisture content (W%) required for compaction decreased from 21.5% **to** 15.4% **(**Fig. 2**)**, further supporting the finding that the sand-clay mixtures achieve maximum density at lower water contents, which is a characteristic of less plastic, coarser-grained materials. The moisture-density relationship in this study is in conformity with the findings of Cabalar and Mustafa (2017) as well as Pedarla et al. (2015).

The observed increase in maximum dry density (MDD) with sand addition depicts the higher specific gravity and improved packing structure of coarse grains, consistent with the mechanisms described by Li et al. (2018) and Xu et al. (2021)**.** The concurrent reduction in optimum moisture content (OMC) emanates from the lower surface area of sand relative to clay, which reduces water adsorption during compaction. This explains why sand–clay mixtures are easier to compact and more workable than pure clays.

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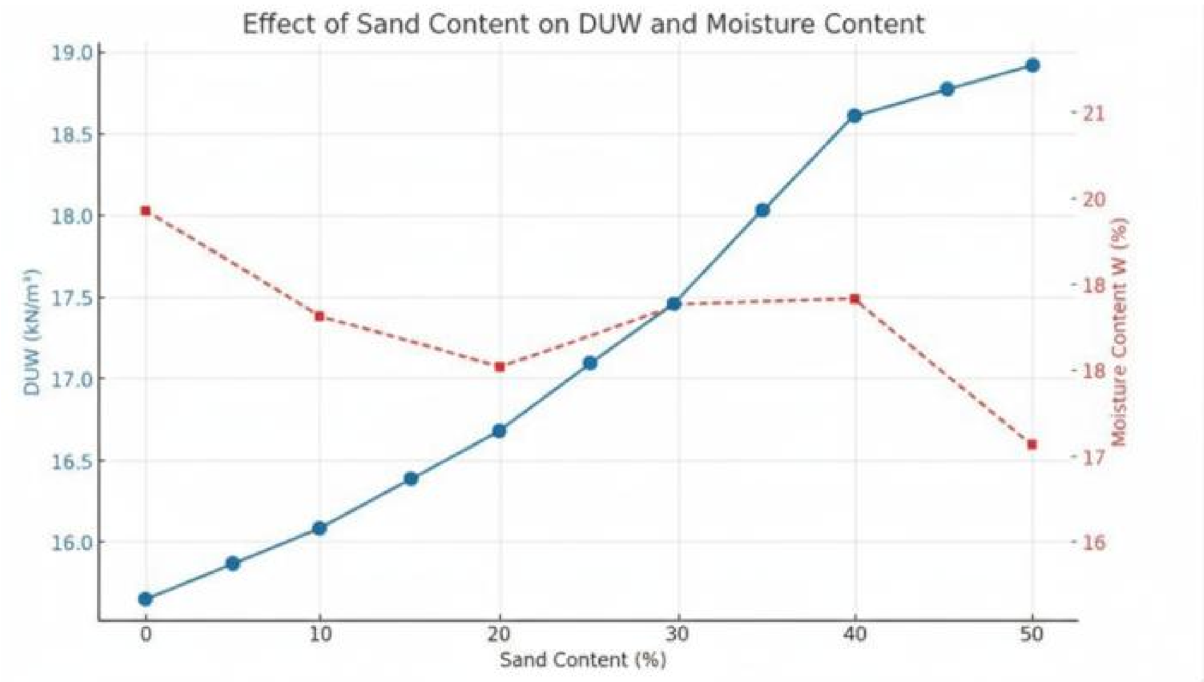

Fig. 3: Effect of Sand Content on DUW and moisture content

3.2. Effect on Bearing Capacity and Implications for Pavement Design

The California Bearing Ratio (CBR), a critical indicator of a soil's strength and suitability for subgrade support, mirrored the trend observed in UCS results (see Fig. 4). The CBR value decreased from 21.5% for the control clay to 15.5% for the 50% sand mix. This reduction in subgrade strength has a direct and substantial impact on pavement design, as a weaker subgrade necessitates a thicker pavement structure to distribute loads and prevent failure.

Comparable reductions in CBR with sand enrichment have been reported by Hosna and Sagor (2025) and Pedarla et al. (2015), indicating that while sand improves drainage and compaction, it affects the clay matrix that provides structural stability. Conversely, Gupta et al. (2024) reported that moderate sand addition, when combined with slight binder content, can achieve a more sustainable strength-to-cost ratio.

The strong correlation between UCS and CBR trends in this study confirms the mechanistic relationship between shear strength and bearing capacity (de Lima et al., 2020). The increase in required pavement thickness predicted by multiple design methods shows the importance of the model equilibrium between improved constructability and reduced stiffness — a balance that is often overlooked in empirical pavement designs.

The calculated pavement thicknesses obtained using different design methodologies confirm this conclusion, as illustrated in Fig. 5. According to the AASHTO method, the required thickness increased from 160 mm for pure clay to 220 mm for the 50% sand mixture. Using the USACE method, the thickness increased from 66 mm to 97 mm. Similarly, the CBR design method indicated an increase from 80 mm to 118 mm.

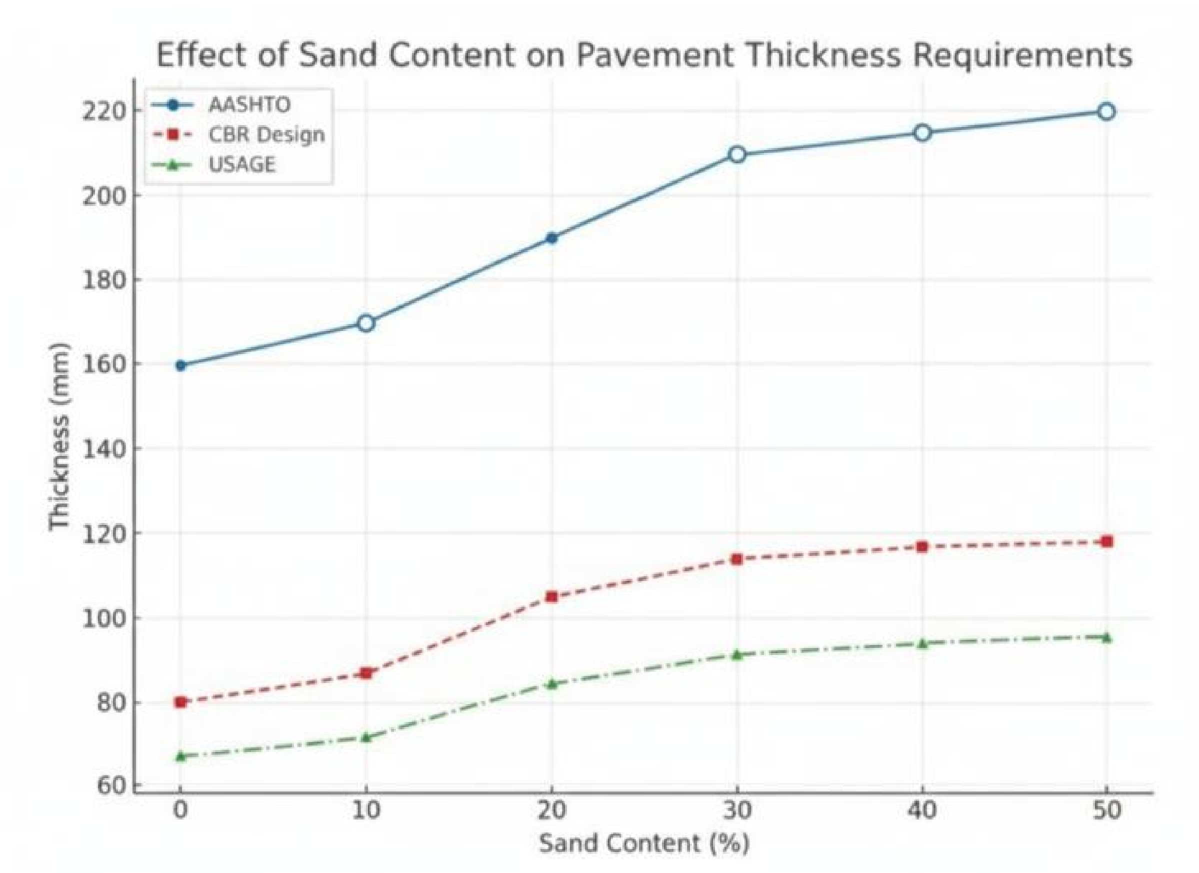

Fig. 4: Effect of Sand Content on Pavement Thickness Requirement

These increases in design thickness, ranging from 37% to 47% across the different methods, highlight the significant economic disadvantage of simply adding sand to clay without a chemical stabilizer. While the sand improves workability and reduces moisture sensitivity, the consequent loss of strength translates into a need for more expensive, thicker pavement sections.

The results for the capping layer and Caltrans LVC thickness further illustrate this point (Fig. 4). The capping layer requirement remained at 150 mm for sand contents up to 20%, but for mixtures with 30% sand or more, the design codes (as interpreted for Caltrans) dictated a thicker layer of 200-250 mm. This indicates that beyond a certain threshold (around 20-30% sand in this case), the mixture is classified as having sufficiently low strength to warrant a thicker working platform or subbase.

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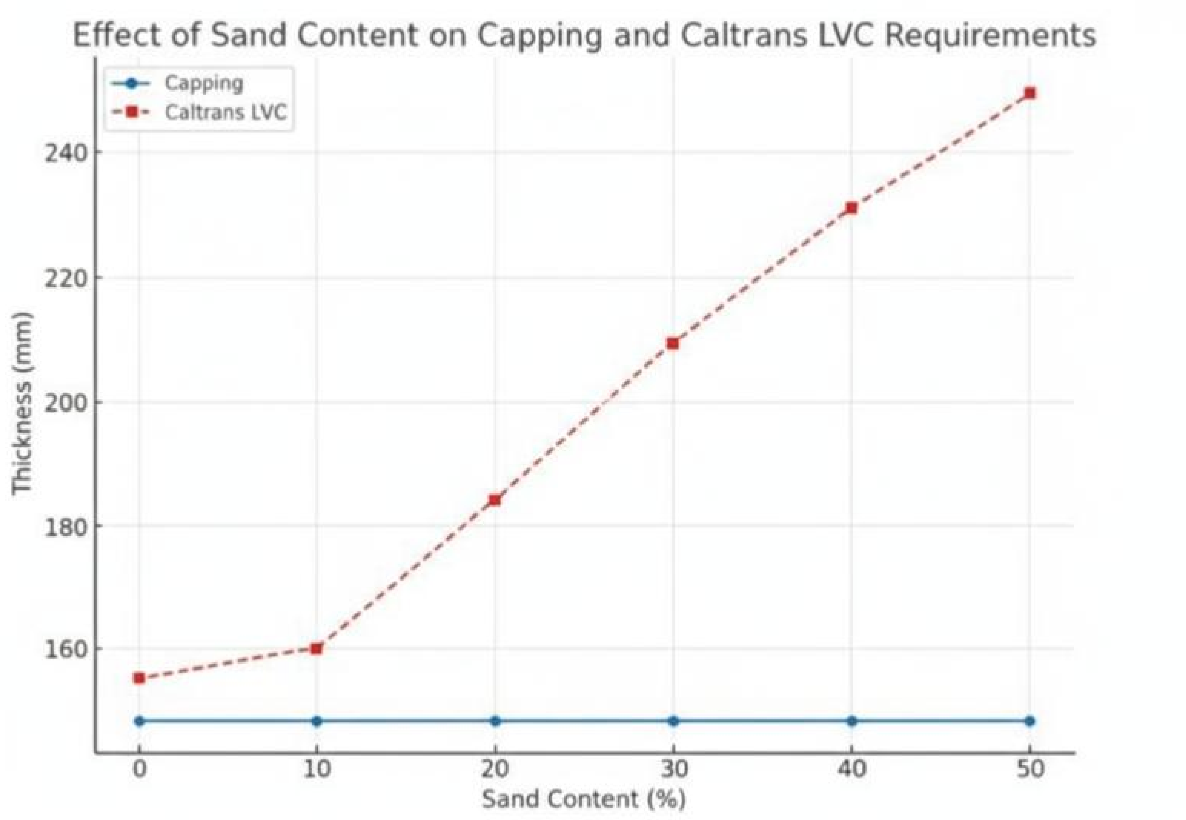

Fig. 5:Effect of Sand Content on Capping and Caltrans LVC Requirements

3.3. Practical Implications and Recommendations

The results confirm that sand addition enhances clay's compaction by lowering moisture demand and increasing density, which improves handling during excavation and placement. However, this modification comes at the expense of mechanical strength, indicating that sand should be regarded as a workability aid rather than a stabilization method. For applications requiring higher strength, chemical binders such as lime, cement, or fly ash remain more suitable options.

The findings is in keeping with Dafalla et al. (2022), who discovered that drainage and controlled gradation are critical for maintaining performance of sandy or partially stabilized layers in expansive soil environments. Furthermore, the optimum 10–20% sand content determined in this research supports the proposals of Paige-Green et al. (2015) for low-volume roads, where limited modifications can deliver satisfactory performance under light traffic conditions.

Overall, the results provide new experimental evidence on the structural limitations of sand addition without chemical binders, contributing to the current body of knowledge on natural-material modification for sustainable rural road design.

An optimum sand content of 10–20% offers a balanced compromise: strength and bearing capacity (UCS 752–516 kPa; CBR ~19–18%) remain acceptable, while density and moisture control improve. At contents above 30%, strength reductions dominate, as reflected in increased pavement thickness requirements and subgrade reclassification.

These findings suggest a cautious but context-specific use of sand–clay blends.

IV. CONCLUSION

4.1 Conclusions

This research studied the effect of sand inclusion on the engineering behaviour and pavement design implications of clay subgrades used in low-volume roads. Based on the experimental results and analyses, the following conclusions were drawn:

i. Optimized Sand–Clay Ratio:
Sand introduction meaningfully changed the compaction and strength properties of clay soils. An optimum range of 10–20% sand content was identified as providing equilibrium between improved workability and acceptable mechanical strength (UCS: 752–516 kPa; CBR: 19–18%).

ii. Strength and Density Relationship:
The duo of Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) reduces progressively with increasing sand percentages, basically due to the reduction in cohesive bonds between clay particles. Again, maximum dry density increased, and optimum moisture content decreased, indicating improved packing and reduced moisture content.

iii. Pavement Design Implications:
The reduced strength at higher sand resulted to thicker pavement requirements—37–47% higher according to AASHTO, USACE, and Caltrans design models. This indicates that uncontrolled sand addition is uneconomical despite improved compaction properties.

iv. Sustainability and Practical Relevance:
The findings demonstrate that mechanical modification without cement or lime can be a cost-effective and environmentally sustainable technique for improving workability of weak clays in rural road construction, especially in areas where traditional stabilizers are costly or unavailable.

v. Novel Contribution:
Unlike most previous studies that focused on chemically stabilized sand–clay mixtures, this work provides concept of how sand alone influences strength, density, and pavement performance. The study thus fills a key gap in understanding the structural limits of natural sand–clay modification for sustainable pavement design in addition to being the first time tropical soils were used in the study.

4.2 Recommendations for Rural Roads

i. **Adopt Controlled Sand Content (10–20%):** This range maintains subgrade adequacy while improving workability and reducing moisture sensitivity.

ii. **Apply in Capping or Subbase Layers:** Blended sand–clay materials can serve as intermediate layers over weak subgrades, capped with thin bituminous surfacing for rural pavements.

iii. **Prioritize Drainage and Maintenance:** Proper cross-falls, side drains, and periodic regrading are essential to maintain the performance of sand–clay subgrades.

iv. **Future Research:** Further studies are recommended to evaluate long-term durability, resilient modulus, and field performance of sand–clay systems under varying climatic and traffic conditions.

Finally, sand addition modifies clay beneficially for handling but weakens its structural role. At controlled low proportions, however, it can provide a viable, low-cost solution for sustainable rural road construction when combined with good drainage and maintenance practices.

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4.1 Conclusions

This research studied the effect of sand inclusion on the engineering behaviour and pavement design implications of clay subgrades used in low-volume roads. Based on the experimental results and analyses, the following conclusions were drawn:

vi. Optimized Sand–Clay Ratio:
Sand introduction meaningfully changed the compaction and strength properties of clay soils. An optimum range of 10–20% sand content was identified as providing equilibrium between improved workability and acceptable mechanical strength (UCS: 752–516 kPa; CBR: 19–18%).

vii. Strength and Density Relationship:
The duo of Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) reduces progressively with increasing sand percentages, basically due to the reduction in cohesive bonds between clay particles. Again, maximum dry density increased, and optimum moisture content decreased, indicating improved packing and reduced moisture content.

viii. Pavement Design Implications:
The reduced strength at higher sand resulted to thicker pavement requirements—37–47% higher according to AASHTO, USACE, and Caltrans design models. This indicates that uncontrolled sand addition is uneconomical despite improved compaction properties.

ix. Sustainability and Practical Relevance:
The findings demonstrate that mechanical modification without cement or lime can be a cost-effective and environmentally sustainable technique for improving workability of weak clays in rural road construction, especially in areas where traditional stabilizers are costly or unavailable.

x. Novel Contribution:
Unlike most previous studies that focused on chemically stabilized sand–clay mixtures, this work provides concept of how sand alone influences strength, density, and pavement performance. The study thus fills a key gap in understanding the structural limits of natural sand–clay modification for sustainable pavement design in addition to being the first time tropical soils were used in the study.

4.2 Recommendations for Rural Roads

v. **Adopt Controlled Sand Content (10–20%):** This range maintains subgrade adequacy while improving workability and reducing moisture sensitivity.

vi. **Apply in Capping or Subbase Layers:** Blended sand–clay materials can serve as intermediate layers over weak subgrades, capped with thin bituminous surfacing for rural pavements.

vii. **Prioritize Drainage and Maintenance:** Proper cross-falls, side drains, and periodic regrading are essential to maintain the performance of sand–clay subgrades.

viii. **Future Research:** Further studies are recommended to evaluate long-term durability, resilient modulus, and field performance of sand–clay systems under varying climatic and traffic conditions.

Finally**,** sand addition modifies clay beneficially for handling but weakens its structural role. At controlled low proportions, however, it can provide a viable, low-cost solution for sustainable rural road construction when combined with good drainage and maintenance practices.

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