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TECHNICAL PAPER

Strength characteristics of modified black clay subgrade stabilized with cement kiln dust

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Abstract
This paper presents the results of a laboratory study in which the strength properties of black cotton soil (BC soil) subgrade modified with quarry fines (QF) were stabilized with cement kiln dust (CKD). The experimental program included Atterberg limits, compaction and unconfined compression testing of BC soil treated with QF at a constant dosage of 10% stabilized with CKD for dosages in the range 0–16% on dry weight basis. Soil mixtures were compacted with British Standard Light energy, and specimens for unconfined compression testing were prepared at predetermined optimum moistures and cured for 28 days. Test results showed that the studied soil which classify as A-7-6 (20) group in American Association of State Highway and Transportation Officials classification system has liquid limit and plasticity index of approximately 85.0 and 50.5%, respectively, as well as a free swell of 65.0%. The application of QF together with the varying percentages of CKD lowered these parameters to values compatible with specification for subgrade layers prescribed by Nigerian General Specification for Roads and Bridges. While the addition of QF caused an increase in the maximum dry unit weight of the soil, the introduction of CKD resulted in the reduction of the maximum dry unit weight of soil mixtures. On the other hand, optimum moisture contents increased slightly following the treatments. Furthermore, both the unconfined compressive strength (UCS) and the stiffness moduli (initial tangent, E_i, and secant, E_{sec}, evaluated from the experimental stress–strain responses) of soil mixtures increased significantly as a consequence of the joint effects of quarry fines and CKD treatment producing soil mixtures with desired values for performance in road pavement subgrades.

Keywords Black cotton soils · Cement kiln dust · Quarry fines · Soil stabilization · Strength characteristics

Introduction

Black cotton soils are frequently encountered in foundation engineering designs for highways, embankments, retaining walls, backfills, etc., particularly in tropical latitudes. Design and construction of engineering infrastructures on weak and expansive soil deposits is quite challenging and problematic. They have low resilient modulus as well as low shear strength and tend to lose strength further upon wetting or other physical disturbances [1–4]. For these reasons, BC soils are generally considered as poor materials for foundations and therefore unsuitable for use as subgrade or foundation soil in their natural state.

In most areas where black cotton soils deposits occur, they are especially troublesome as pavement subgrade and create considerable instability to lightly loaded engineering structures. Roads constructed on BC soils subgrade develop undulations at the road surface due to loss of strength of the subgrade through softening during rainy season, while features such as cracks in masonry fences, grade beams and members of reinforced concrete are observed on lightly loaded structures [1, 5–7].

In Nigeria, black cotton clays constitute a major soil group. In terms of extent of deposit, they are widespread throughout the northeastern region of the country [2, 4, 8, 9]. Specifically, they are formed from altered products of

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weathered basic volcanic rocks (e.g., basalts) in arid regions with low rainfall and limited leaching and have a high percentage of clay (60–90%) which is predominantly montmorillonite. Structurally, montmorillonite clays have 2:1 layers (consisting of two tetrahedral sheets with an octahedral sheet between them), which allow for various substitutions in the sheets, hence the affinity for water and large interlayer swelling of the structure [8, 10–13].

The use of this soil for providing platform for placement of pavement layers can result in unstable subgrade, inadequate pavement support and reduced pavement life but may nonetheless be improved and upgraded through the addition of chemicals or cementitious additives. Extensive research efforts have been made to improve the strength characteristics of the soils with new additives/technologies [4, 6, 14–19]. These additives are used to enhance their engineering properties, particularly properties relevant to pavement construction. The use of traditional stabilizing agents such as lime and cement always resulted in high cost of construction. For sustainable and cost effective improvement, a combined treatment involving cement kiln dust (CKD), a waste material created from cement manufacturing process and quarry fines (QF), a supplementary stabilizer is being proposed. Soil stabilization using CKD presents a cheaper alternative as compared to lime, when encountering problematic soils that are collapsible, expansive and frost susceptible [5, 13, 20–22]. Furthermore, since the stabilization mechanism of fine-grained soils requires calcium (in the form of lime), it is possible that CKDs, especially those high in free lime, would be effective in stabilizing clay soils.

Similarly, studies on the effect of quarry fines on the geotechnical properties of soils concluded that the plasticity and strength together with the dry density increased on addition of quarry fines with associated decrease in the optimum moisture content and that the quarry fines proved to be a promising substitute for sand [23–26]. The improvement in strength values can be attributed to the significant improvement in angle of shearing resistance.

The objective of this study therefore was to investigate the effect of a constant dosage of quarry fines and different percentages of CKD on strength and stiffness parameters of subgrades dominated by weak and expansive tropical black cotton clay deposit.

Materials and test procedures

Black cotton soil

The black cotton soil (BC soil) sample used for this research work was collected from the savannah area of Adamawa state (Latitude 10° 91′ N and longitude 11° 30′ E), Nigeria, at a depth of between 1.0 and 1.5 m using the method of disturbed sampling.

Quarry fines

The quarry fines (QF) used in this study was obtained from Dantata and Sawoe Quarry in Abuja, Nigeria. Only fraction passing through BS sieve No. 4 (4.76 mm) was used throughout the study without additional treatment.

Cement kiln dust

The cement kiln dust (CKD) used for this research work was obtained from Benue Cement Company, Benue State, Nigeria. The CKD sample was stored in airtight containers to avoid pre-hydration before usage.

Soil mixtures and specimen preparation

Air-dried and pulverized soil samples were mixed with 10% QF and treated with 0, 4, 8, 12 and 16% CKD by dry weight of soil. The laboratory tests carried out on the soil and mixtures included particle size distribution, Atterberg limits, compaction and unconfined compressive strength (UCS) following procedures outlined in BS 1377 [27, 28]. Atterberg tests were carried out using specimens passing through British Standard No. 40 sieve (425 μm aperture), while compaction test was carried out on specimens passing through British Standard No. 4 sieve (4.76 mm aperture). Soil mixtures were compacted with British Standard Light (BSL) compactive effort. Specimens for unconfined compression test were prepared at the predetermined optimum moisture contents (OMC) and cured for 28 days. A 28-day curing period was adopted to allow sufficient pozzolanic reaction.

Results and discussion

Materials characterization

According to the AASHTO classification system, the soil is classified as A-7-6 (20) soil with liquid limit of 85% and plasticity index of 50.5%, respectively. Particle size analysis showed the percentage passing No. 200 sieve as 88%. A summary of the index properties of the BC soil is presented in Table 1, while the oxide compositions of BC soil and CKD are reported in Table 2.

In general, the plasticity characteristics of the soil were substantially modified by the addition of QF and CKD. Atterberg limits test results showed that the addition of QF and CKD altered the consistency of the natural soil. The liquid limit (LL) and plasticity index (PI) decreased from

Table 1 Properties of black cotton soil used in the study

Properties	Percent
Natural moisture content (%)	8
Percent passing BS No. 200 sieve (%)	88
Liquid limit (%)	85
Plastic limit (%)	34.5
Plasticity index (%)	50.5
Linear shrinkage (%)	35
Free swell (%)	65
Specific gravity	2.26
Group index	20
AASHTO classification	A-7-6
Color	Grayish black
Dominant clay mineral	Montmorillonite
Max. dry unit weight (kN/m^3)	13.6
OMC (%)	28.4

Table 2 Chemical composition of black cotton and cement kiln dust used in the study

Oxide	%	
	Black cotton Soil	Cement kiln dust[a]
CaO	0.9	43.69
SiO_2	48.70	12.18
Al_2O_3	18.70	2.17
Fe_2O_3	2.40	2.40
MgO	2.22	0.89
SO_3	ND	0.78
Mn_2O_3	ND	0.12
K_2O	0.7	0.4
TiO_2	ND	0.35
Ag_2O	ND	1.55
CaO/SiO_2	–	0.21
Silica:sesquioxide ratio	1.48	–
Loss on ignition	10.20	37.54

[a]*Source*: Benue Cement Factory, Benue State—Nigeria

ND not determine

85 to 70.5 and 50.5 to 35.4%, respectively, on introduction of QF. Further reduction occurred when CKD was incorporated. At the highest CKD content of 16% for example, the LL and PI were lowered to values (LL = 40.62%, PI = 10.6%) that are generally rated as good pavement subgrade and compatible with specification for subgrade construction. Acceptable requirements for subgrade materials include: percentage fines ≤ 35%; liquid limit (LL) ≤ 50%; PI ≤ 30% [29]. The variation of Atterberg limits with the admixture percent is shown in Fig. 1.

Compaction characteristics

The maximum dry unit weight of the studied soil achieved was 13.6 kN/m^3 which increased on addition of quarry fines to 14.9 kN/m^3. Dry unit weights were thereafter generally lowered when CKD was introduced by 0.5–1.5 kN/m^3. The optimum moisture content on the other hand increased from 28.4% for the natural soil to 32.4% when QF was added. Further increase was recorded when soil mixture was treated with varying CKD contents. The effect of CKD treatment on dry unit weight and OMC is reported in Fig. 2a, b. These variations are the result of flocculation of clay particles due to cation exchange and short-term pozzolanic reactions initiated by CKD application [6, 7, 12].

Unconfined compression strength (UCS)

The effectiveness of the combined treatment on the strength development was evaluated using the UCS tests. In Fig. 3, it can be observed that the addition of QF together with CKD to the BC soil and subsequent compaction increased the UCS almost linearly with increases in the CKD content, thus improving its structural properties [3]. UCS of BC soil + QF mixture increased from 118 kN/m^2 at 0% CKD to 820 kN/m^2 at 16% CKD, an increase of about 7 times that of unstabilized mixture after 28 days of curing. It was however observed that the increases for CKD treated specimens are lower than that attained by cement stabilized BC soils [6, 30, 31]. Nevertheless, Miller and Zaman [20] reported that UCS increased with CKD treatment at least to a level equivalent to lime stabilization.

The relationship between the UCS and CKD content can be approximated by the following expression:

$$\text{UCS} = -\,2.97\text{CKD}_{\text{content}}^2 + 88.75\text{CKD}_{\text{content}} + 145.0 \quad (R^2 = 0.98) \tag{1}$$

Stabilized materials are often categorized differently by various researchers. For example, AUSTROADS [32] classified materials with UCS between 0.7 and 1.5 MN/m^2 as 'modified materials' and those having UCS greater than 1.5 MN/m^2 as bound materials. Das [33] on the other hand merely rated the quality of subgrade soils used in pavement application as a function of their UCS. When the UCS of soil mixtures were interpreted based on the definitions by Das [33], the quality (consistency) of soil mixtures was upgraded to superior class of subgrades ranging from medium to hard (Table 3).

Strength improvement in soil mixtures was achieved through direct cementation, flocculation/agglomeration of the soil particles, ion exchange and pozzolanic reaction initiated by the presence of CKD.

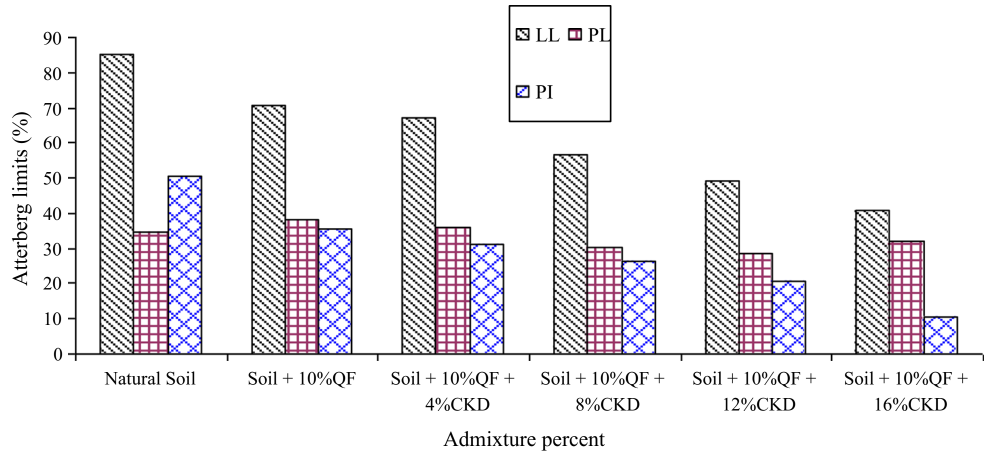

Fig. 1 Variation of Atterberg limits of black cotton soil—quarry fines mixtures with cement kiln dust

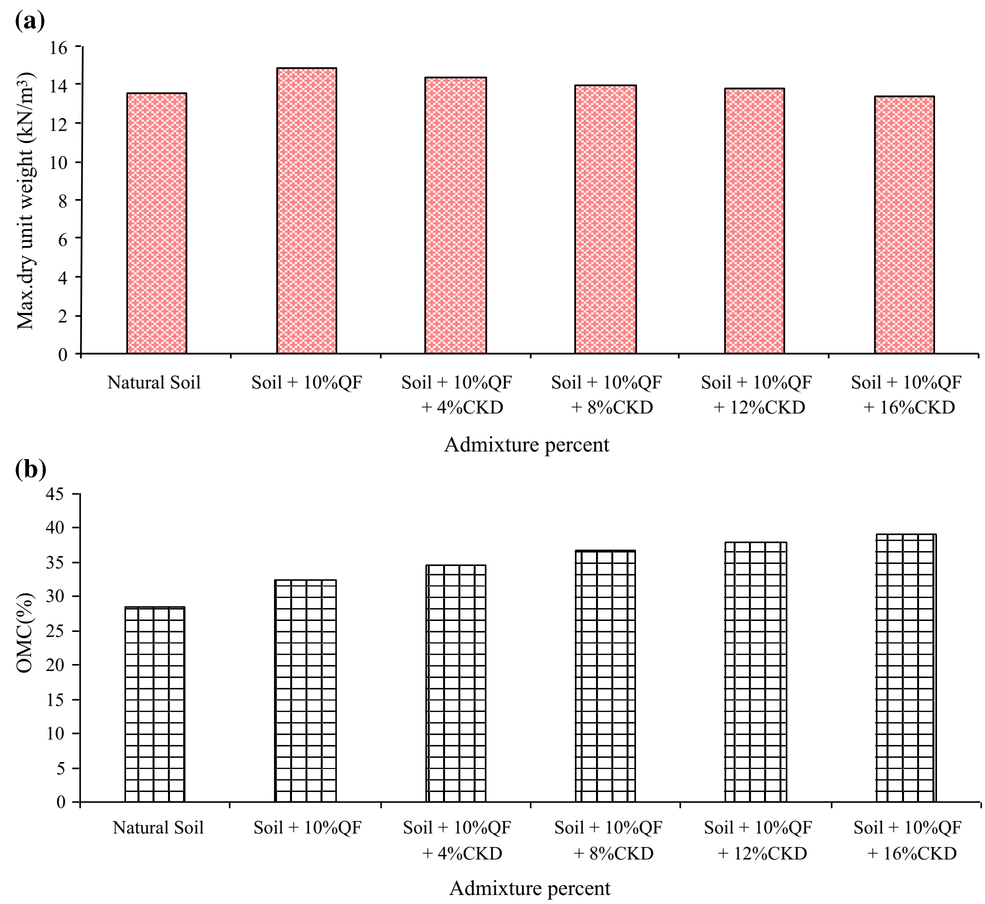

Fig. 2 **a** Variation of maximum dry unit weight of black cotton soil—quarry fines mixtures with cement kiln dust content. **b** Variation of optimum moisture content of black cotton soil—quarry fines mixtures with cement kiln dust content

Stiffness (modulus) characteristics of soil mixtures

In pavement design, road materials, particularly stabilized materials, are usually characterized in terms of their mechanical properties such as stiffness and strength. The accurate determination of the stiffness parameters in pavement is therefore necessary not only to ascertain the amount of movement that will result from the application of load and decide whether this movement is permissible but for a consistent design and quality control of the pavement.

Two types of stiffness (modulus), namely initial tangent and secant moduli, were considered in this study. Initial stiffness (initial tangent modulus, E_i) was defined as the slope of tangent at origin, while the secant stiffness (secant modulus, E_{sec}) was defined by the slope between the initial point of zero stress and strain to the failure point of maximum stress

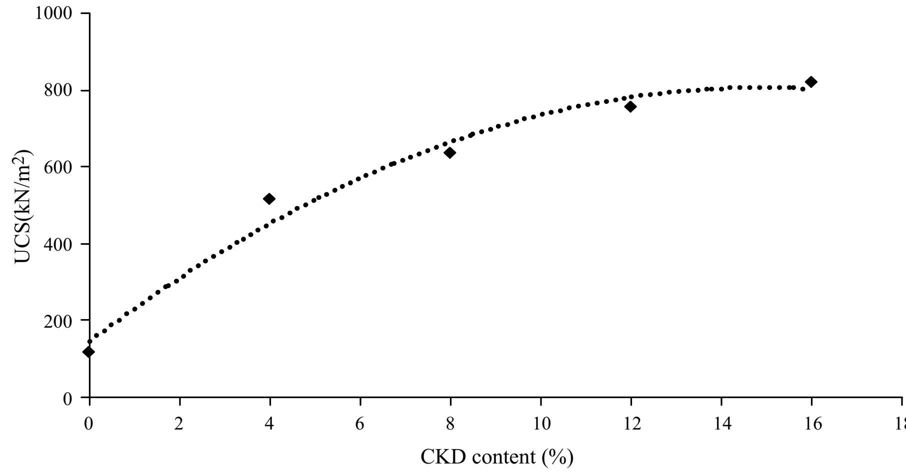

Fig. 3 Variation of UCS of soil mixtures with CKD content

Table 3 Rating of soil mixtures strength as a function of UCS values (as per [33])

Admixture percent	UCS (kN/m^2)	Rating of subgrade
Natural BC soil	38	Soft
Soil + 10%QF	118	Medium
Soil + 10QF + 4%CKD	515.96	Hard
Soil + 10QF + 8%CKD	635.81	Hard
Soil + 10QF + 12%CKD	755.65	Hard
Soil + 10QF + 16%CKD	820	Hard

and its corresponding strain at failure. A summary of the initial tangent and secant moduli evaluated from the nonlinear stress–strain curves of UC tests (Fig. 4) is provided in a comparison bar chart (Fig. 5).

Typical of clay soils, the modulus of the natural soil was low but increased as a consequence of the joint effects of quarry fines and CKD treatment. The initial tangent and secant moduli values of the natural compacted BC soil are 4.57 and 4.04 MN/m^2, respectively. Upon treatment with QF, more than threefold increase in E_i and E_{sec} was recorded which increased further by 15 and 12 folds, respectively, on introduction of 4% CKD. When CKD content was increased to 16%, E_i and E_{sec} values increased significantly to about 40 folds the value of the natural soil at the end of 28-day curing period. Expectedly, it can be observed that the E_i was higher than the E_{sec} at all CKD contents.

Variation of stiffness modulus with UCS

The correlations between initial tangent modulus, E_i, and the secant modulus, E_{sec}, of soil mixtures and UCS are also plotted in Fig. 6 and shown in Eqs. (2) and (3).

$$E_i = 13.99e^{0.003UCS} \quad R^2 = 0.989 \tag{2}$$

$$E_{sec} = 10.41e^{0.003UCS} \quad R^2 0.985 \tag{3}$$

An exponential relationship exists between both E_i and E_{sec} and the UC strength increasing with higher UCS. Therefore, those samples with higher compressive strengths were stiffer and had greater modulus, making them better candidates as

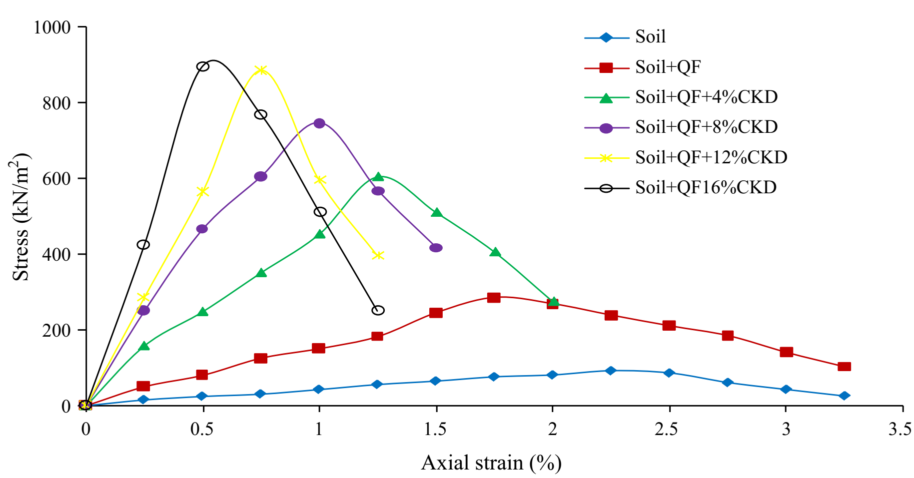

Fig. 4 28-day stress–strain curves for BC soil treated with 10% QF and varying CKD content

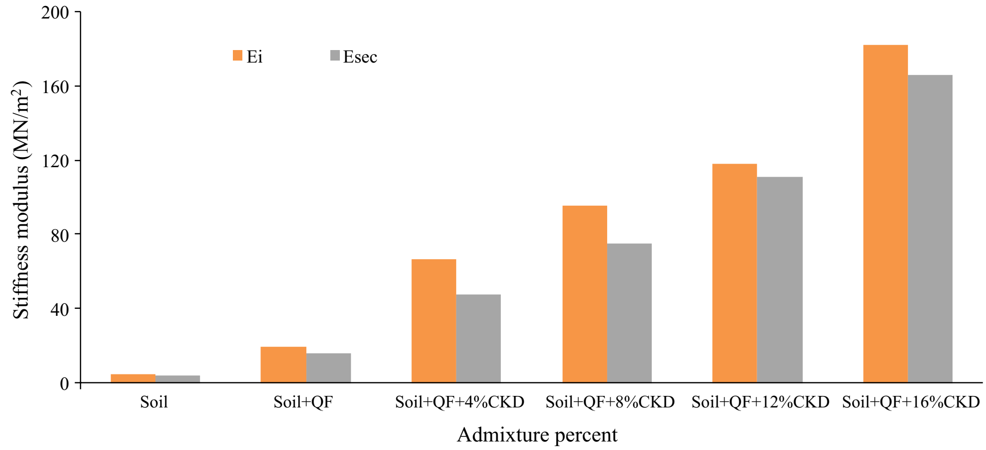

Fig. 5 Comparison bar chart for E_i and E_{sec}

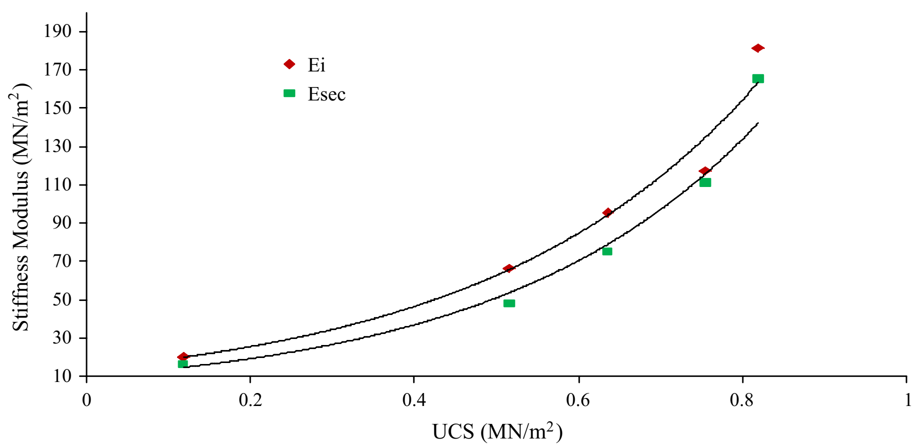

Fig. 6 Variation of secant and tangent moduli with UCS

subgrade for pavement structures. It is however important to note that higher modulus may be sometimes more susceptible to cracking.

The very high R^2 values obtained from these equations indicate that the moduli of the specimens with different CKD contents could be consistently and reliably determined from their UCS values.

Conclusion

A laboratory study was undertaken to evaluate the strength characteristics of quarry fines-modified black cotton soil stabilized with cement kiln dust, and the conclusions of the study are as follows:

The application of QF and CKD was efficient in reducing the plasticity, producing soil mixtures that conformed to the established values for performance in road pavement structures in accordance with the Nigeria General Specification [28]. The highest alterations occurred at 16% CKD.

The combined treatment also resulted in significant improvement in compaction parameters. The maximum dry unit weight decreased from 14.9 kN/m^3 for soil + QF only to 13.4 kN/m^3 at 16% CKD.

The treatment promoted increase in the strength and stiffness of soil mixtures measured by UCS and stiffness modulus (i.e., tangent and secant modulus) recording the highest alterations on addition of 16% CKD.

These results support the use of combined QF and CKD treatment as an efficient stabilization technique for subgrades dominated by black cotton soils.

Compliance with ethical standards

Conflict of interest The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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