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Two-Phase Stabilization of Black Cotton Soil in Kenya Using Sodium Chloride and Cement

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Abstract
This study explores the two-phase stabilization of Black Cotton Soil (BCS) in Kenya using sodium chloride and Portland cement to enhance strength and reduce swelling. A staged cement addition method—comprising primary and secondary dosages—was applied to improve soil structure and dimensional stability. Laboratory evaluations, including linear shrinkage, liquid limit, free swell, and Unconfined Compressive Strength (UCS), were conducted on specimens with cement additions of 50–150 kg/m³. Results indicate that the two-stage process significantly decreased shrinkage and increased UCS, particularly at higher cement levels. The method also proved environmentally safe, with hexavalent chromium levels below regulatory limits based on TCLP 1311 leaching tests. The findings demonstrate that staged cement addition provides a sustainable and cost-effective solution for stabilizing expansive soils. This study then aims to evaluate the effectiveness of a two-phase cement stabilization process using sodium chloride in improving the physical and mechanical properties of Black Cotton Soil in Kenya, and providing insights into sustainable utilization of expansive soils in construction.

Keywords: Black cotton soil, soil stabilization, sodium chloride, cement, expansive soils, construction, infrastructure resilience, Kenya

INTRODUCTION

Black Cotton Soil (BCS), which is widely distributed in many tropical and subtropical regions of the world, is also referred to as problematic soil due to its poor characteristics, such as high swelling when wet and significant shrinkage when dry. As a result, it is not suitable as a supporting natural foundation or a construction material for buildings and structures like roads, posing a challenge to the use of land where BCS is found. In the light of these factors, the modification of BCS holds significant engineering value, particularly if it can be enhanced using common and affordable materials such as sodium chloride or cement. This study investigates how staged cement addition influences shrinkage, strength, and environmental performance of BCS. The approach also provides useful insights into sustainable utilization of expansive soils in road and building construction.

THEORY

Expansive soils such as Black Cotton Soil (BCS) are well known for presenting significant challenges in engineering applications due to their pronounced swelling and shrinkage behavior. Collectively, BCS is widely recognized as a challenging construction material and numerous studies have sought to improve its properties, though its practical implementation remains limited. Previous studies carried out by Okita et al. (2014) and Mohan et al. (1978) have emphasized that untreated BCS is unsuitable for road and building foundations, often resulting in structural damage. Conversely, Clementine et al. (2024) reported that an optimal mixture of silica sand and lime can improve the mechanical properties of BCS, making it suitable for use as a road subgrade material. Similarly, Firoozi (2023) demonstrated that lime stabilization can significantly reduce plasticity and increase the CBR values of BCS.

Nevertheless, existing research often focuses on single-addition stabilization techniques, like lime treatment, where both the methods and additives

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may be costly, and environmental considerations receive little or no attention. Additionally, limited studies have explored the combined effect of such supplementary stabilizers like sodium chloride and staged cement addition, particularly under African soil and climatic conditions. This leaves a wide knowledge gap in understanding the synergistic benefits of chloride-assisted, two-phase cement stabilization for Kenya's Black Cotton Soils. This situation notably motivated such an investigation. Environmental considerations have also received attention, with leaching tests (EPA, 1993) ensuring that these chemical stabilizers do not exceed regulatory limits. Thus, effective utilization of BCS requires such a comprehensive approach that addresses both engineering performance and environmental sustainability. This study therefore addresses the existing knowledge gap by providing empirical evidence on issues of both engineering performance and environmental safety.

Mechanism and Rationale of the Staged Stabilizer Addition Method

The staged addition method (INVAX, 2022) consists of first adding and mixing a stabilizer into the soil as primary addition, then allowing it to undergo a preliminary curing period. After curing, the mixture is disaggregated, followed by a secondary addition of the stabilizer, mixing, and compaction to produce soil cement.

Even with the same total amount of stabilizer, staged addition usually gives higher strength, which means that less stabilizer is needed to reach the same strength when compared to single addition. Furthermore, in highly cohesive soils where mixing with stabilizers is difficult, adding water to make the soil fluid, then performing the primary addition, curing, disaggregating, and finally applying the secondary addition allows the stabilizer to be mixed more efficiently.

The effectiveness of the staged addition of stabilizers is attributed to two main factors: (a) improvement of soil properties through the primary addition, and (b) immobilization of hardening inhibitors such as humic acids. The primary addition visually decreases the apparent water content, while calcium ions from the stabilizer promote the aggregation and flocculation of soil particles. This process enhances the mixing efficiency and workability, thereby improving compaction. Furthermore, the primary addition immobilizes hardening inhibitors and other inhibitory substances that become fixed by reacting with calcium ions from the stabilizer. These combined effects are expected to accelerate the solidification reaction during the secondary addition, leading to an overall reduction in the total amount of stabilizer required.

Building on this theoretical framework, the present study investigates the combined effects of cement and sodium chloride on the mechanical properties of Black Cotton Soil, aiming to optimize stabilizer efficiency and enhance soil performance for potential engineering applications.

Conceptual Pathway from Expansive Soil Problems to Sustainable Stabilization Solutions

Figure 1 illustrates the conceptual framework for enhancing Black Cotton Soil (BCS) using chloride-assisted staged cement stabilization, showing the logical progression from soil-related challenges to process mechanisms and final outcomes. At the top of the framework, expansive Black Cotton Soil is identified as the core problem, characterized by high swelling and shrinkage, low load-bearing capacity, and unsuitability for roads and foundations in its natural state. The figure also highlights the limitations of conventional stabilizers such as lime and sand, which are often costly and inconsistently applied, particularly in African contexts.

The framework then presents the rationale for enhanced BCS stabilization, positioning chloride-assisted staged cement addition as a cost-effective alternative that combines sodium chloride and cement to improve soil performance while meeting environmental safety requirements. This rationale links the soil problem to the proposed stabilization strategy.

The mechanisms of staged stabilization are shown next, emphasizing improvement of soil properties through particle aggregation and flocculation during the primary addition, as well as reduced cement usage and improved efficiency during the secondary addition. Environmental safety is addressed through compliance with leaching standards.

At the center of the framework, dual objectives are defined: improved engineering performance and environmental safety. The staged stabilization

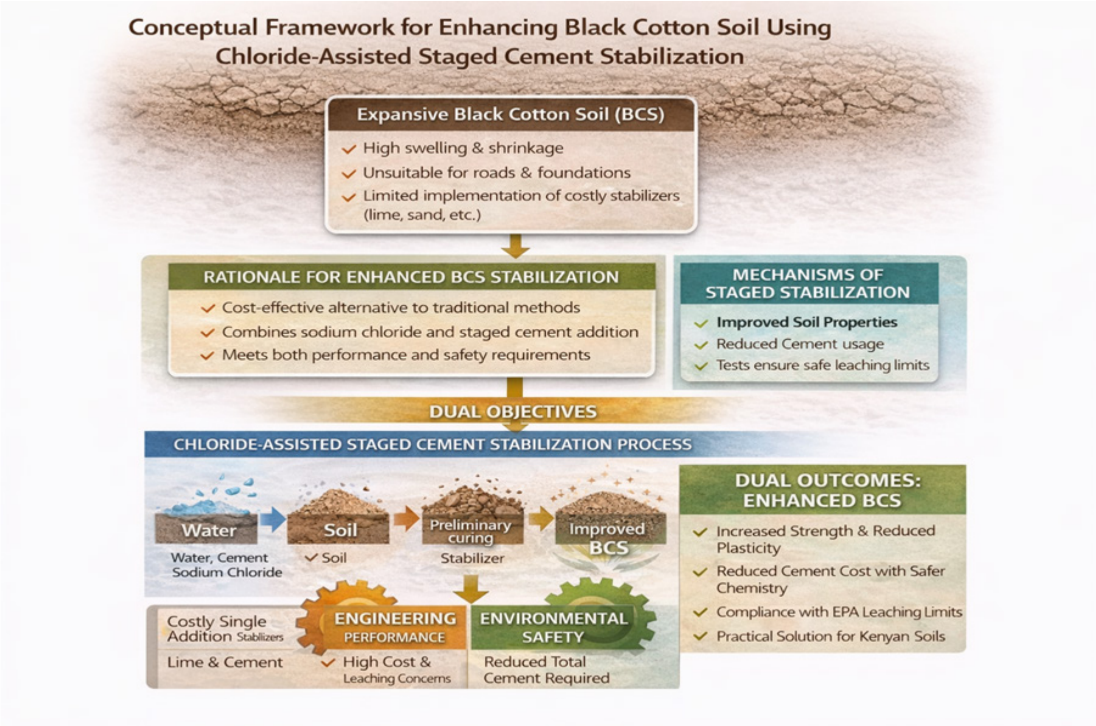

FIGURE 1
Conceptual framework for chloride-assisted staged cement soil stabilization
Source: Author's analysis adapted from geotechnical soil stabilization theory, 2026

process is illustrated as a sequence of primary addition, preliminary curing, and secondary addition, contrasting with single-addition methods that require higher cement content.

Finally, the framework presents dual outcomes, including increased strength, reduced plasticity, lower cement demand, and compliance with environmental regulations, demonstrating a practical and sustainable solution for Kenyan Black Cotton Soils.

RESEARCH METHODS

The study used a laboratory experimental design with staged cement additions. The entire flow chart is shown in **Figure 2**. Black Cotton Soil (BCS) samples from Jomo Kenyatta University of Agriculture and Technology (JKUAT) grounds were stabilized with 50 and 100 kg/m^3 cement (Cases A and B), followed by secondary dosages of 50–150 kg/m^3 after 105 days. Tests included liquid limit, shrinkage, free swell, and Unconfined Compressive Strength (UCS).

As shown in **Figure 2** procedure comprises a primary cement addition (50 and 100 kg/m^3) with saline water mixing and extended curing, followed by crushing, secondary cement addition (50–150 kg/m^3), re-compaction, and controlled curing of UCS specimens. Index properties and strength parameters were evaluated at multiple curing ages to assess the influence of staged cement addition on shrinkage behavior, plasticity, and unconfined compressive strength. Chromium leaching was tested using the United States Environmental Protection Agency (EPA) TCLP 1311 Method.

Data analysis identified correlations between moisture, shrinkage, and UCS. This approach provided a detailed evaluation of soil stabilization dynamics and its practical application.

Primary Addition

The formulation for the primary cement addition, as detailed in **Table 1**, was designed with two different levels distinguished by differing cement per unit volume. The amount of cement used in the primary addition was intentionally limited, as the primary objective at this stage was soil modification rather than strength development.

To the same amount of dry BCS samples, 1.85kg (Case A: 50 kg/m^3) and 3.70kg (Case B: 100 kg/m^3) of cement were added respectively and mixed using a shovel. Same amount of saline water was

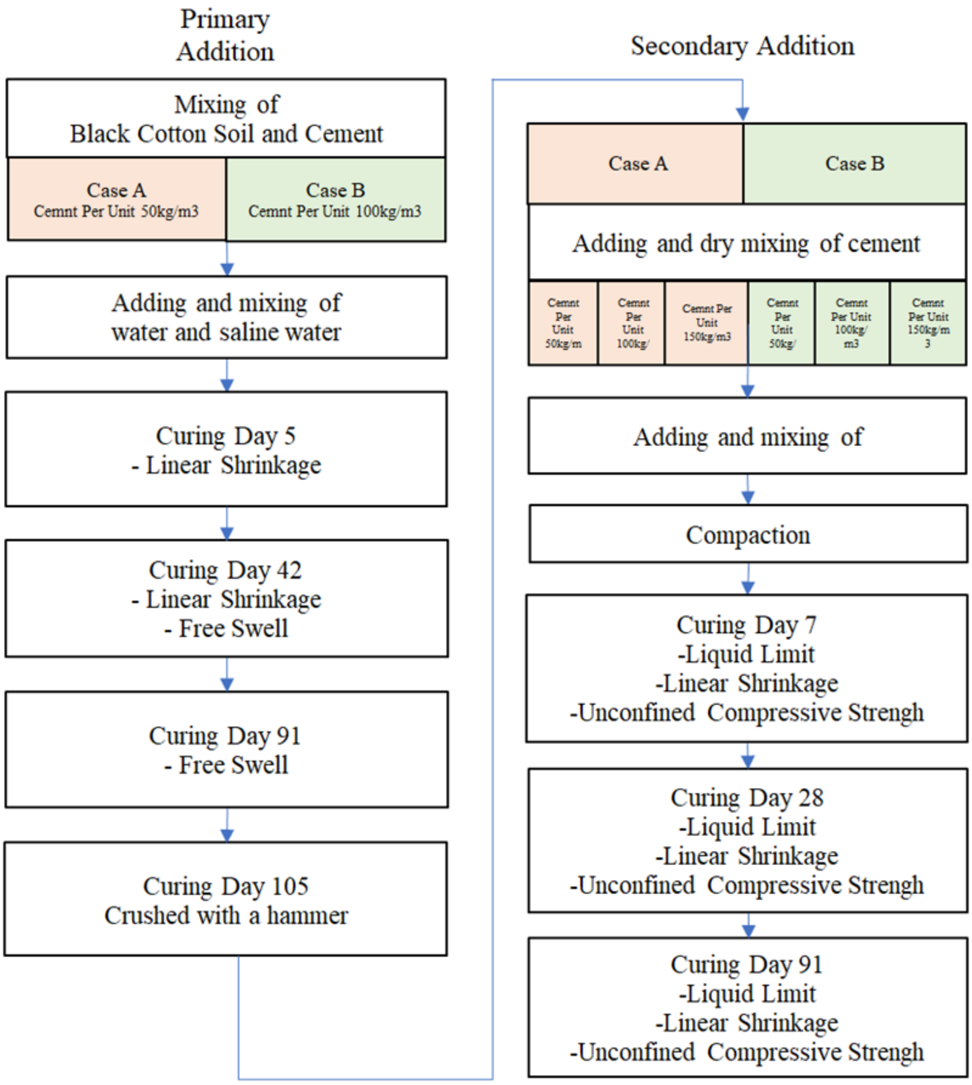

FIGURE 2
Flowchart of the experimental process for cement and saline water stabilization of black cotton soil
Source: Author's laboratory methodology, 2026

then added to both cases and further mixing was done using a paint mixer. The two soil samples for Cases A and B were stored indoors to cure. Linear shrinkage test was conducted at 5 days of curing age, followed by second linear shrinkage and free-swell at 42 days of curing age. Then another free-swell test was conducted at 91 days.

Secondary Addition

After the primary addition of mixing, the two soil samples for Cases A and B were stored indoors to cure for total of 105 days. Thereafter, each of the samples was crushed by striking with a hammer. Each sample was then divided into three portions, to which 50, 100, and 150 kg/m³ of cement were added respectively. After dry mixing of each portion with a shovel, 4% saline water was added and mixed further using a paint mixer.

Test specimens for the UCS were compacted in 100mm×50mmϕ cylindrical molds in three layers, with each layer receiving 5 blows from a special 1.5kg rammer. The test specimens were then sealed and stored indoors for curing. The UCS test was conducted on specimens from different portions after 7, 28, and 91 days of curing.

Liquid limit and linear shrinkage tests were then conducted on the recovered UCS test specimens from the various portions.

TABLE 1
Formulation of materials for primary cement addition in two-phase stabilization

Material	Case A	Case B	Unit
Cement content per unit volume	50	100	kg/m³
Black Cotton Soil (dry mass)	54.76	54.76	kg
Cement added	1.85	3.70	kg
Added water	24.34	24.34	kg
4% saline water (NaCl solution)	1.01	1.01	kg

Source: Author's laboratory formulation , 2026

Three specimens were tested for each condition. Including specimens tested at curing ages of 7, 28, and 91 days, as well as those prepared at 40% moisture content, a total of 180 specimens were tested across various conditions, ensuring data reliability for statistical comparison. The cement range of 50–150 kg/m³ was selected based on preliminary trials, representing practical dosages suitable for field implementation. The staged addition technique follows the patented INVAX (2022) process, which enhances particle aggregation and accelerates hydration reactions through immobilization of humic acids, resulting in improved soil strength and stability.

Hexavalent Chromium ($CR6^+$) Leaching Test

Hexavalent Chromium ($CR6^+$) Leaching Test was conducted on the solidified specimen at a curing age of 7 days according to TCLP 1311. A test utilizing lime which was not employed in the previously mentioned tests, was conducted for reference purposes. A leaching test according to the Environmental Agency Notification No. 46 of Japan was also conducted. However, no air-drying was applied in TCLP 1311 whereas Environmental Agency Notification No. 46 included air-drying as part of the testing conditions.

RESULTS

Materials

Black Cotton Soil

Black Cotton Soil (BCS) sample was collected from within the Jomo Kenyatta University of Agriculture and Technology (JKUAT) grounds. The physical properties of the soil sample are shown in **Table 2**. Approximately 90% of its particles pass through 75-micron sieve, indicating a fine-grained soil with a high degree of plasticity.

Table 3 summarizes the results of preliminary tests conducted on the collected soil sample after the addition of sodium chloride in form of saline water. Both results of free-swell and liquid limit were found to decrease significantly with sodium chloride, indicating clear improvement in the soil properties.

Sodium Chloride and Portland Cement

The sodium chloride used was of the commercial grade made by Kensalt Limited. The cement used was Portland cement (type Power Plus 42.5N)

TABLE 2
Physical and Index Properties of Black Cotton Soil (BCS)

Property	Value	Unit
Natural moisture content	14.9	%
Wet density	1.48	Mg/m³
Soil particle density (specific gravity)	2.56	Mg/m³
Particle size distribution		
Clay fraction	62	%
Silt fraction	28	%
Sand fraction	8	%
Gravel fraction	2	%

Source: Authors' analysis, 2026

manufactured by Bamburi Cement Limited.

Primary Addition

The results of linear shrinkage at 5 and 42 days, and free-swell at 42 and 91 days for both Cases A and B after completion of their mixing are shown in **Table 4**. The comparison of linear shrinkage of both cases is shown in **Figure 3**.

Linear shrinkage was lower in Case B, which had a higher cement content. This is thought to be the result of a higher cement content, which promotes a decrease in free water through hydration and enhances shrinkage resistance through strength development. This trend was particularly strong at the early curing age of day 5. Similarly, the increase in shrinkage ratio from 5 to 42 days was smaller in Case A and larger in Case B. This is considered to be due to the difference in cement content, with Case A exhibiting a faster rate of shrinkage.

On the other hand, free-swell showed a change only at day 91 in Case B. It was found that the swelling was almost completely suppressed after

TABLE 3

Effect of sodium chloride addition on the index properties of black cotton soil

Parameter	0% NaCl	4% NaCl	8% NaCl	Unit
Black Cotton Soil mass	66.9	66.9	66.9	g
Added water	31.0	31.0	31.0	g
Sodium chloride content	0	4	8	%
Free swell	53	48	43	%
Liquid limit	67.8	62.7	56.1	%

Source: Authors' analysis, 2026

TABLE 4

Linear shrinkage and free swell of black cotton soil after primary cement addition

Property	Curing Age	Case A	Case B	Unit
Linear shrinkage	Day 5	24	9	%
	Day 42	30	21	%
Free swell	Day 42	0	0	%
	Day 91	0	8	%

Source: Author’s laboratory analysis , 2026

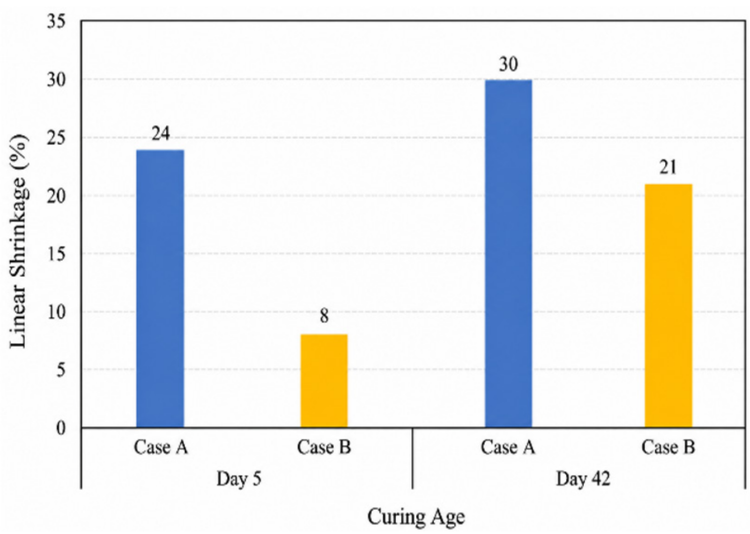

FIGURE 3

Linear Shrinkage Comparison of Cases A and B

Source: Author’s analysis, 2026

the primary addition of cement. Therefore, free-swell was not considered after the secondary addition of cement.

These results confirm that increasing primary cement content enhances dimensional stability and reduces shrinkage, indicating that early hydration contributes to improved workability and resistance to volume change.

Secondary Addition
Test results were obtained for specimens with different formulations and curing periods. The specimens were tested for liquid limit, linear shrinkage and Unconfined Compressive Strength (UCS) at curing day 7, 28, 91 of which the results are shown in **Table 5**. They were analyzed for consistency and for correlation with moisture content. The trends and relationships so obtained are discussed under each of Cases A and B for secondary addition of cement.

All results presented correspond to 7-day curing. Additional curing ages (28 and 91 days) are analysed in subsequent sections.

Secondary Addition - Case A (Primary Addition of 50kg/m3Cement)
Liquid limit was observed to have no consistent trend in relation to the moisture content. It is possible that there was an issue with test accuracy. However, only for the secondary addition of 50 kg/m^3 cement did the result of liquid limit increase as the moisture content increased.

The correlations of the moisture content with linear shrinkage and UCS, for Case A at curing day 28 are shown in **Figures 4** and **5**. Linear shrinkage (**Figure 3**) tends to increase with higher moisture content. However, a peak was observed at 50 and 100 kg/m^3 of secondary addition and the value decreased in the high moisture content range. This is considered to be due to the fact that, as described in the earlier section, specimens with lower secondary cement addition exhibited a faster rate of shrinkage.

Compressive strength (**Figure 5**) tends to increase with the rise in moisture content regardless of the different amount in secondary addition. However, for the secondary addition of 50 kg/m^3, it slightly decreased in the high moisture content range. Basically, the higher the moisture content and the greater the amount of secondary cement addition, the higher the compressive strength. However, in the cases where the secondary addition amount is small, the amount of hydration water is also small. Therefore, it is necessary to set the moisture content slightly lower.

Regarding linear shrinkage, as mentioned in the result of primary addition section, in addition to the difference in strength development due to the amount of secondary addition, a lower moisture content contributes to a reduction in linear shrinkage.

Thus, incremental cement additions further reduce shrinkage and increase compressive strength, demonstrating the efficiency of sequential stabilization compared to single-stage treatment.

Secondary Addition - Case B (Primary Addition of 100kg/m3Cement)
The correlations of the moisture content with linear shrinkage and UCS, for Case B are shown in **Figures 6** and **7**. Although the overall behavior was generally consistent with that of Case A, certain deviations were observed in liquid limit and linear shrinkage. Notably, at a secondary additive dosage of 100 kg/m^3, liquid limit decreased at intermediate moisture contents. In contrast, within the same moisture range, but at a secondary additive dosage of 50 kg/m^3, linear shrinkage exhibited a pronounced increase. On the other hand, in the case of the secondary addition of 150 kg/m^3, a remarkable increase in strength was observed under the highest water content condition, suggesting that the cement hydration reaction was significantly activated.

Despite differences in curing ages for each test value, the observed trends remained generally consistent for both cases. As the amount of secondary addition increased, liquid limit and linear shrinkage tended to decrease, whereas UCS exhibited a tendency to increase.

The observed trends validate that higher secondary cement dosages at elevated moisture levels enhance UCS while mitigating shrinkage, confirming that moisture control and staged cement ratios are key to optimal performance.

Two-phase stabilization
Figure 8 illustrates the effect of the additive ratio

TABLE 5
Summary of secondary formulations and test results

Primary Addition of cement	Composition					7 days of age				28 days of age				91 days of age			
	Secondary Addition of cement (kg/m³)	Mois-ture Content (%)	Soil (kg)	Cement (kg)	4% Saline Water (kg)	Liquid Limit (%)	Linear Shrinkage (%)	Volume Per Unit (kN/m³)	Compressive Strength (N/mM2)	Liquid Limit (%)	Linear Shrinkage (%)	Volume Per Unit (kN/m³)	Compressive Strength (N/mM2)	Liquid Limit (%)	Linear Shrinkage (%)	Volume Per Unit (kN/m³)	Compressive Strength (N/mM2)
A Cement 50kg/m³ Moisture content 20.7%	50	22,8	3,16	0,110	0,053	62,3	4,4	15,11	0,367	55,2	6,6	15,02	0,423	51,3	5,0	14,73	0,719
		27,8	3,16	0,110	0,184	63,2	12,6	15,58	0,681	66,1	11,4	15,68	0,675	61,3	9,6	15,30	1,18
		32,9	3,16	0,110	0,312	72,7	15,5	16,68	0,975	69,3	12,8	16,65	1,07	66,5	11,5	16,50	1,64
		40,0	1,87	0,065	0,298	No data				71,0	11,7	16,29	0,967	67,8	9,6	16,01	1,3
	100	23,3	3,16	0,220	0,066	62,3	5,3	15,25	0,681	64,8	3,3	15,21	0,479	62,9	3,3	14,85	0,683
		28,3	3,16	0,220	0,197	59,5	8,5	15,85	1,06	65,3	6,5	15,72	0,958	60,9	6,4	15,50	1,08
		33,3	3,16	0,220	0,328	61,8	8,4	16,76	1,11	68,1	9,3	16,36	1,01	63,4	7,1	15,89	1,47
		40,0	2,01	0,140	0,321	No data				65,2	7,1	16,42	1,67	62,9	6,9	15,96	2,05
	150	23,9	3,16	0,330	0,082	61,4	4,2	15,38	0,809	65,0	2,9	15,30	0,777	63,7	2,1	15,06	1,03
		28,9	3,16	0,330	0,213	57,3	5,1	15,74	1,58	60,8	3,3	15,70	1,42	59,6	3,2	15,45	1,62
		33,9	3,16	0,330	0,344	61,2	6,5	17	2,16	64,5	5,1	16,74	1,85	64,1	5,1	16,57	2,96
		40,0	2,01	0,210	0,321	No data				66,3	8,3	16,97	1,98	62,8	6,4	16,34	2,67
B Cement 100kg/m3 Moisture content 32.0%	50	40,0	3,33	0,110	0,202	74,8	12,3	14,77	0,399	74,9	10,5	14,69	0,657	73,2	7,9	14,36	0,743
		46,0	3,33	0,110	0,353	72,5	14,3	15,48	0,515	72,1	14,1	15,56	0,671	69,5	10,7	15,36	1,04
		52,0	3,33	0,110	0,505	73,1	14,4	16,82	0,785	74,1	12,3	15,94	1,04	69,9	7,9	14,71	1,95
	100	40,6	3,33	0,220	0,217	71,7	5,1	14,76	0,707	71,6	6,1	14,66	0,729	70,4	3,7	14,37	0,924
		46,6	3,33	0,220	0,368	70,4	8,9	16,08	1,48	66,5	8,4	16,01	1,32	62,2	7,1	15,72	1,94
		52,6	3,33	0,220	0,520	74,7	8,0	16,8	1,68	72,0	11,3	16,81	1,27	68,4	10,1	16,53	2,33
	150	41,2	3,33	0,330	0,232	72,8	4,4	14,77	1,02	68,9	4,4	14,75	0,83	67,7	2,4	14,38	1,4
		47,2	3,33	0,330	0,384	68,5	8,6	15,7	1,69	66,5	5,5	15,67	1,57	65,7	5,4	15,43	2,15
			3,33	0,330	0,535	69,2	9,4	16,97	2,09	70,6	6,8	16,78	2,74	67,3	6,7	16,66	3,69

Source: Author’s laboratory analysis , 2026

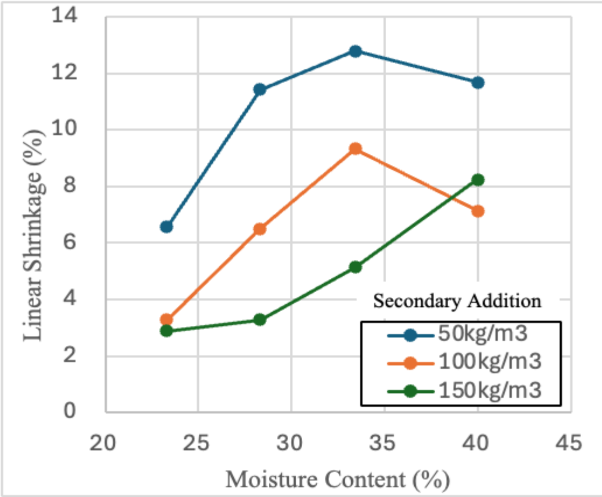

FIGURE 4
Moisture Content and Linear Shrinkage (Case A)
Source: Author's analysis, 2026

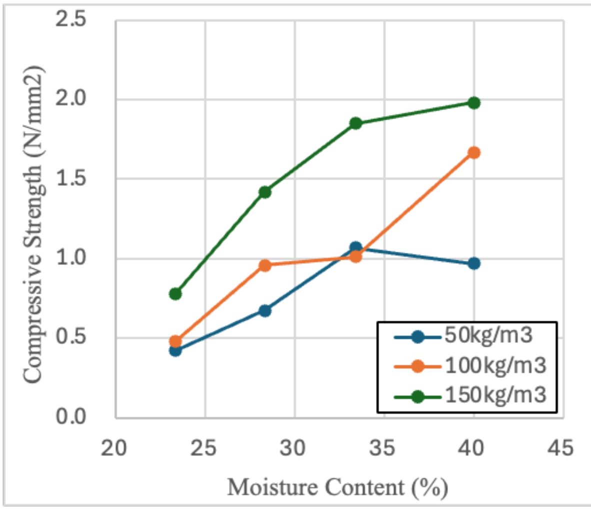

FIGURE 5
Moisture Content and UCS (Case A)
Source: Author's analysis, 2026

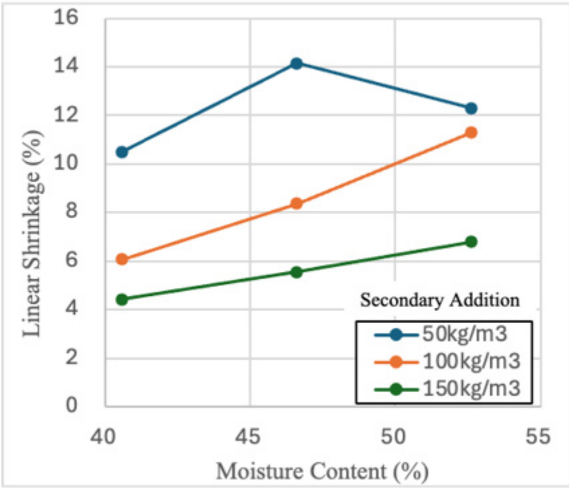

FIGURE 6
Moisture Content and Linear Shrinkage (Case B)
Source: Author's analysis, 2026

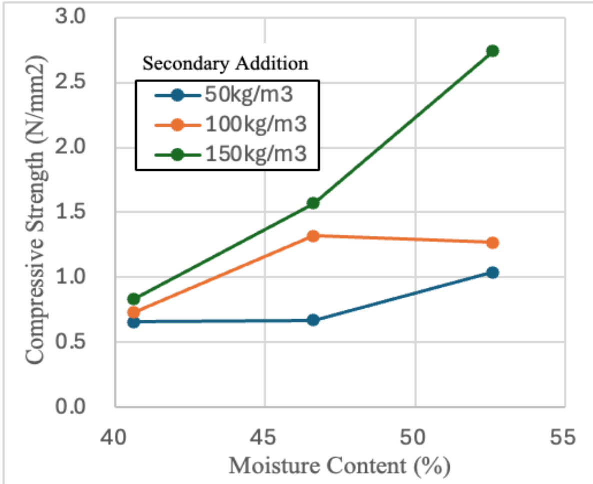

FIGURE 7
Moisture Content and UCS (Case B)
Source: Author's analysis, 2026

(primary and secondary) on strength development in split addition. The moisture content was kept constant at 40% for all comparisons.

For both total cement amounts of 150 and 200 kg/m^3, a lower ratio of the primary and secondary additives resulted in two to three times higher strength. This suggests that modifying with a small amount of primary addition and using the secondary addition for strength enhancement is desirable. As explained in the theory section, the staged addition of stabilizers resulted in improved strength compared to the single addition.

Overall, the two-phase method produced superior results to single-stage mixing, confirming that sequential hydration and particle restructuring improve mechanical strength and environmental stability.

Hexavalent Chromium (CR6+) Leaching Test
Table 6 shows the results of the hexavalent chromium leaching test conducted on the solidified specimen at a curing age of 7 days according to TCLP 1311.

The leaching amount according to TCLP 1311

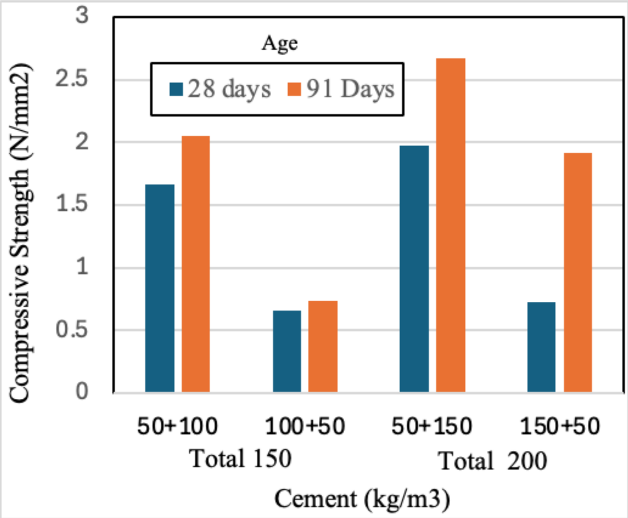

FIGURE 8
Correlation of Primary and Secondary Additive Ratios with UCS
Source: Author's analysis, 2026

was consistently 0.008 mg/L, which does not exceed the Japanese standard, but the result of the Environmental Agency Notification No. 46 test exceeded the Japanese standard. This discrepancy is believed to be due to differences in the sample soil, solidified body strength, and testing methods. Nevertheless, the yielded results indicated that use of Portland cement and hydrated lime poses no danger to the environment.

DISCUSSION

The results of this study demonstrate that the two-phase stabilization approach using sodium chloride and staged cement addition provides a marked improvement in the engineering performance of Black Cotton Soil (BCS) compared to conventional single-stage stabilization techniques. Across all test regimes, staged treatment resulted in significant increases in Unconfined Compressive Strength (UCS) and substantial reductions in linear shrinkage and free swell, confirming the effectiveness of sequential modification and strength development.

The observed reduction in shrinkage and improvement in strength are consistent with earlier findings on chemical stabilization of expansive soils. Studies by Firoozi (2023) and Clementine et al. (2024) showed that lime-based stabilization can reduce plasticity and enhance bearing capacity of BCS. However, the present study demonstrates that comparable or superior performance can be achieved through a chloride-assisted, two-phase cement process. Unlike lime treatment, which often requires higher dosages and longer curing periods, the sodium chloride–cement combination facilitated faster strength gain and improved workability, suggesting a more efficient stabilization pathway.

From a mechanistic perspective, the effectiveness of the staged addition process can be explained by the physicochemical interactions occurring in two distinct phases. As proposed by Kaname et al. (2002), the primary addition initiates soil particle aggregation and flocculation through calcium ion exchange, reducing apparent water content and improving soil fabric. This early modification stage enhances soil workability and compaction efficiency while immobilizing hardening inhibitors such as humic acids. The secondary addition then benefits from this improved soil structure, allowing more efficient cement hydration and bonding, which translates into higher UCS and reduced volumetric instability.

Comparative analysis with studies conducted in similar expansive soil environments further supports these findings. Investigations in Ethiopia by Okita et al. (2014) and earlier work in India by Mohan and Bhandari (1978) reported that conventional cement stabilization of expansive soils often requires high cement contents to achieve acceptable strength levels. In contrast, the present study shows that staged cement addition

TABLE 6
Results of Hexavalent Chromium (Cr^{6+}) Leaching Tests for Cement- and Lime-Stabilized Black Cotton Soil

Parameter	Portland Cement (50 kg/m³)	Portland Cement (100 kg/m³)	Lime (50 kg/m³)	Lime (100 kg/m³)	Unit
Stabilizer content per unit volume	50	100	50	100	kg/m³
Initial moisture content	10	10	10	10	%
Moisture content after water addition*	68.0	68.0	68.0	68.0	%
Cr^{6+} concentration in leachate	0.16	0.16	0.16	0.16	mg/kg
Calculated Cr^{6+} leached amount**	0.008	0.008	0.008	0.008	mg/L

***4% Saline Water.**
****According to TCLP 1311, the calculation value was based on the extraction of 100g with 2000ml.**

Source: Author's laboratory analysis, 2026

achieves equivalent or higher UCS at lower total cement dosages. This reduction in cement demand not only improves cost efficiency but also reduces the environmental footprint associated with cement production.

The role of sodium chloride in the stabilization process is particularly noteworthy. The preliminary reduction in free swell and liquid limit following saline water addition confirms its effectiveness in suppressing clay mineral expansion. By promoting flocculation and reducing diffuse double-layer thickness, sodium chloride improves particle contact and enhances the efficiency of subsequent cement reactions. This synergistic effect between sodium chloride and cement has received limited attention in previous African studies, highlighting the novelty and relevance of the present findings.
Environmental performance is another critical aspect addressed in this study. Leaching test results indicated that hexavalent chromium (Cr^{6+}) concentrations remained below regulatory limits under TCLP 1311 testing conditions, aligning with environmental safety considerations highlighted in EPA (1993) guidelines. This confirms that the use of Portland cement and sodium chloride within the tested dosages does not pose significant environmental risks, supporting the method's suitability for large-scale application.

Overall, the findings validate the theoretical premise that staged stabilization enhances both mechanical performance and environmental compliance. By separating soil modification and strength development into two controlled phases, the method optimizes stabilizer efficiency, improves dimensional stability, and reduces material consumption. In the context of Kenya's widespread Black Cotton Soils, this approach offers a technically robust, economically viable, and environmentally responsible solution for road construction and foundation engineering.

CONCLUSION

This study evaluated chloride-assisted, two-phase stabilization of Kenyan Black Cotton Soil (BCS) using sodium chloride and staged Portland cement addition. The findings confirm that sequential cement treatment significantly improves soil performance by reducing swelling and shrinkage while increasing Unconfined Compressive Strength (UCS). Preliminary saline-water conditioning lowered free swell and liquid limit, indicating reduced expansivity and improved workability before cement hydration. The staged cement process—primary modification followed by secondary strength development—produced higher strength at lower total cement demand than conventional single-addition approaches, supporting the mechanism proposed by Kaname et al. (2002) and the staged treatment rationale in INVAX (2022). Environmental assessment using TCLP 1311 showed hexavalent chromium (Cr^{6+}) levels below regulatory limits, consistent with EPA (1993) leaching compliance expectations. Overall, the method offers a technically effective and environmentally responsible option for stabilizing expansive BCS in Kenya, with clear potential for application in road subgrades and foundation works where conventional lime or single-stage stabilization may be less efficient or costlier (Clementine et al., 2024; Firoozi, 2023; Okita et al., 2014; Mohan & Bhandari, 1978).

RECOMMENDATIONS

1) Practice and Engineering Application

- Adopt staged cement addition as a standard procedure for BCS stabilization in roadworks and shallow foundations, using a low primary dosage for modification followed by a targeted secondary dosage for strength gain, as outlined in the staged method framework.
- Use sodium chloride conditioning (saline water) as a pre-treatment to suppress expansivity and improve mixing efficiency, especially where BCS has high clay fraction and plasticity.
- Control moisture content during mixing and compaction as a key quality parameter, since strength and shrinkage responses are moisture-sensitive and staged hydration relies on achieving workable yet reactable water conditions.
- Include environmental screening as part of acceptance testing, particularly Cr^{6+} leaching checks where cementitious stabilizers are used, consistent with leaching-test guidance.

2) Policy and Standards

- Integrate staged stabilization protocols into national geotechnical and road design guidance, expanding beyond single-stage lime/cement approaches where performance or cost constraints exist.
- Develop specification clauses for chloride-assisted staged cement treatment, including allowable cement ranges, curing controls, and minimum performance thresholds (UCS, shrinkage), supported by documented laboratory verification.
- Require environmental compliance reporting for chemical stabilization projects using standard leaching methods to strengthen public and regulatory confidence.

3) Further Research

- Conduct long-term field trials in Kenyan BCS corridors to validate laboratory trends under real traffic loading, wet–dry cycling, and seasonal moisture fluctuation, benchmarking against conventional lime-based stabilization outcomes.
- Optimize dosage design using performance-based criteria, identifying the minimum primary cement needed for modification and the most efficient secondary cement for UCS targets, consistent with the staged strength rationale.

Extend environmental evaluation beyond short-term leaching, including sensitivity to curing regime differences (e.g., air-drying vs no air-drying) as highlighted by the discrepancy between TCLP 1311 and alternative notification methods.

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