Performance Evaluation Of Black Cotton Soil Stabilised With Fibres And Industrial By-Products For Low-Volume Roads

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Abstract: Black cotton soil, a widely occurring expansive clay in India, poses serious challenges for road construction due to its high swelling and shrinkage potential, low bearing capacity, and poor stability under varying moisture conditions. Such problematic soil conditions lead to premature pavement failures, particularly in low-volume rural roads where economical solutions are essential. This study focuses on improving the engineering properties of black cotton soil by stabilizing it with a combination of **fibres (polypropylene and coir)** and **industrial by-products (RBI Grade-81 and ground granulated blast furnace slag – GGBS)**. A comprehensive experimental program was undertaken to evaluate **index properties, compaction characteristics, unconfined compressive strength (UCS), California Bearing Ratio (CBR), and static and cyclic plate load behaviour** of the untreated and treated soils. The results revealed that the combined use of **RBI Grade-81 with polypropylene fibre** significantly enhanced strength, ductility, and stiffness modulus compared to other stabilizers, while GGBS showed progressive strength improvement with curing. Overall, the treated soil exhibited substantial gains in CBR values, enabling a **reduction of pavement thickness by up to 50%** for low-volume road applications. The findings highlight that blending fibres with chemical and industrial stabilizers offers a cost-effective and sustainable solution for enhancing the performance of black cotton soil in rural infrastructure development.

***Index Terms* -** Black Cotton Soil; Soil Stabilization, Polypropylene Fibre, Coir Fibre, RBI Grade-81; Ground Granulated Blast Furnace Slag (GGBS); Low-Volume Roads; Pavement Performance.

I. INTRODUCTION

Expansive soils, particularly black cotton soil, pose significant challenges in geotechnical and pavement engineering. Black cotton soil, which covers nearly 20% of India's land area, is predominantly composed of montmorillonite clay minerals that exhibit extreme swelling when wet and shrinkage during dry seasons. These volume changes cause differential settlements, cracks, and pavement distortions, making such soils highly problematic as a subgrade material. The soil is further characterized by a high plasticity index, low bearing capacity, and poor drainage properties, all of which contribute to premature pavement failures when used in untreated form.

Low-volume rural roads form the backbone of India's transportation network, connecting villages to markets, healthcare, and education. However, due to budget constraints and the use of locally available soils like black cotton soil, these pavements often experience rapid deterioration. The Indian Roads Congress (IRC) specifies that subgrade soil must meet minimum California Bearing Ratio (CBR) requirements, but black cotton soil typically falls below these thresholds. This necessitates soil improvement strategies to make rural road construction both feasible and durable.

Traditional stabilization techniques include the use of lime, cement, and fly ash. While effective, these approaches have drawbacks such as high cost, susceptibility to sulphate attack, environmental concerns, and brittle behaviour of the treated soil. In recent years, alternative methods have gained attention, particularly the use of natural and synthetic fibres and industrial by-products. Fibres such as polypropylene and coir can enhance ductility and residual strength, while industrial stabilizers like RBI Grade-81 and ground granulated blast furnace slag (GGBS) contribute to improved stiffness and long-term strength. The combined use of these materials offers the potential for sustainable, economical, and performance-driven solutions for rural infrastructure.

The objective of the present study is to evaluate the **engineering properties of black cotton soil stabilized with fibres and industrial by-products** for low-volume road applications. Specifically, the study investigates the effect of polypropylene fibre, coir fibre, RBI Grade-81, and GGBS, both individually and in combination, on index properties, compaction behaviour, unconfined compressive strength (UCS), California Bearing Ratio (CBR), and load-deformation characteristics. The outcomes are expected to identify optimum stabilizer combinations that enhance subgrade performance and reduce pavement thickness requirements, thereby providing a cost-effective solution for rural road construction.

II. LITRATURE REVIW

2.1 Studies on expansive soils and stabilization methods

Expansive soils such as black cotton soil (rich in montmorillonite) exhibit large seasonal volume changes (swelling when wet and shrinkage when dry), high plasticity, low bearing capacity and low CBR in saturated condition — characteristics that make them problematic for subgrades and pavements. Ground improvement for such soils has been widely studied; conventional stabilization approaches include mechanical stabilization (grading, compaction) and chemical stabilization using lime, cement and fly ash. While these traditional additives improve strength and reduce plasticity, they can be costly and in some cases susceptible to durability issues (e.g., sulphate reactions, leaching), and may impart brittle behaviour to the treated soil. Therefore, alternative or blended approaches that combine physical reinforcement with pozzolanic/chemical binders are increasingly recommended for economical and durable low-volume road works.

2.2 Use of fibres in soil improvement

Randomly distributed short fibres (both natural — e.g., coir, jute — and synthetic — e.g., polypropylene) have been shown to alter soil behaviour by improving toughness, post-peak ductility and residual strength. Laboratory studies report that fiber inclusion can increase shear strength, reduce brittleness, and improve resistance to permanent deformation; the effectiveness depends on fibre type, length (aspect ratio), content and interaction with soil gradation and density. Natural fibres (coir) are inexpensive and biodegradable (coir is relatively durable compared to other natural fibres), while polypropylene fibres provide long-term stability and higher tensile strength. Several investigators also report that fibres alone sometimes yield limited strength increase and perform best when combined with cementitious stabilizers to achieve both strength and ductility.

2.3 Use of industrial by-products

Industrial by-products and proprietary stabilizers have been extensively researched as sustainable binders. Ground Granulated Blast Furnace Slag (GGBS) and fly ash act as supplementary cementitious materials — they participate in pozzolanic reactions (often activated by lime or ambient alkalinity) to form C–S–H and increase strength with curing time; several studies report optimum GGBS/fly ash mixes that substantially improve UCS and CBR. RBI Grade-81 (a powdered inorganic stabilizer) has been reported to reduce voids and reduce moisture absorption, significantly improving both soaked and unsoaked CBR for different soils. Use of these by-products is attractive due to lower embodied CO_2 and cost compared to pure cement, and they are especially suitable for rural/low-volume roads when properly proportioned and cured.

2.4 Research gaps identified

Although numerous studies document the individual benefits of fibres and industrial by-products, gaps remain in: (a) systematic comparison of **combined** fibre + industrial-byproduct stabilisation for black cotton soils under the same laboratory programme, (b) assessment of cyclic (repeated) loading and permanent deformation behaviour of fibre-reinforced and chemically stabilized black cotton soil (most studies focus on UCS/CBR but not cyclic plate load behaviour), (c) optimisation of combined dosage (fibre content × binder %) to minimize additive usage while achieving target CBR/E values for low-volume roads, and (d) long-term durability (effects of leaching/seasonal moisture) of such combined treatments. The present study addresses these gaps by evaluating polypropylene and coir fibres, RBI-81 and GGBS — individually and in combination

— with tests including index properties, compaction, UCS, CBR and **static/cyclic plate load tests** to determine stiffness (E) and modulus of subgrade reaction (K) relevant to pavement design.

III. MATERIALS & METHODS

3.1 Source and Properties of Black Cotton Soil

The black cotton soil used in this study was collected from **Davanagere, Karnataka, India**, at a depth of 1.5 m below the natural ground surface near a tank bed. The soil was manually pulverized and sieved through a 425 µm IS sieve before testing. It is classified as **expansive clay**, with montmorillonite as the predominant clay mineral. Laboratory characterisation showed a **liquid limit of 50–100%, plasticity index of 20–60%, and fine content (>70% passing 0.075 mm sieve)**, confirming its high swelling potential and low suitability as a subgrade material without treatment.

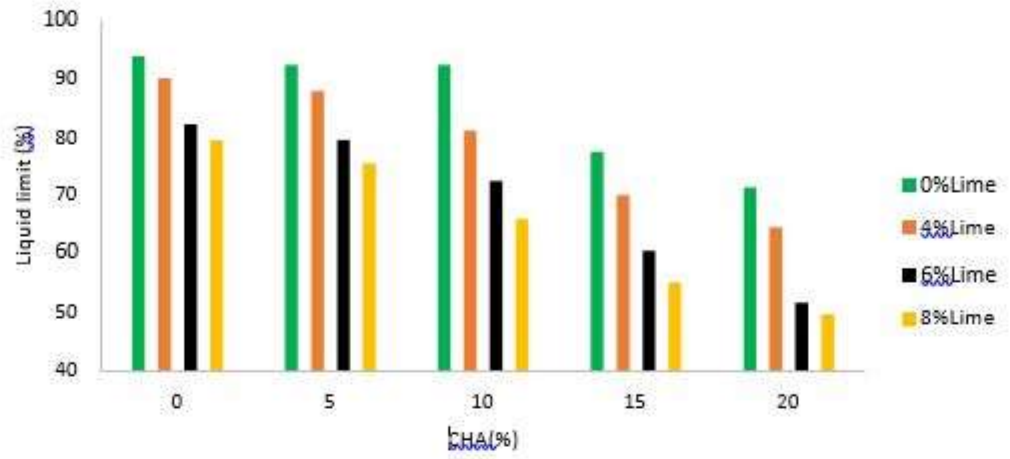
3.2 Stabilizers Used

- **Polypropylene Fibre (PPF):** Synthetic fibre with 10 mm length, aspect ratio of 300, specific gravity 0.91, and melting point 165 °C. It improves tensile strength, ductility, and post-peak behaviour of soil.
- **Coir Fibre (CF):** Natural fibre obtained as loose fibrous coir waste from local markets. Average length 30 mm, diameter 0.3 mm, specific gravity 0.7, and aspect ratio 100. Known for its eco-friendliness and moderate durability, coir fibre increases ductility and reduces plasticity.
- **RBI Grade-81:** A patented, inorganic, environment-friendly stabilizer in powdered form. It modifies engineering properties of soil by reducing plasticity and enhancing stiffness. Widely used for pavement construction due to its compatibility with different soil types.
- **Ground Granulated Blast Furnace Slag (GGBS):** By-product from iron and steel industries, obtained from Hubli Steel Plant. It is produced by quenching molten iron slag in water, followed by drying and grinding into fine powder. GGBS exhibits latent hydraulic properties, improving long-term strength of soil.

3.3 Tests Conducted

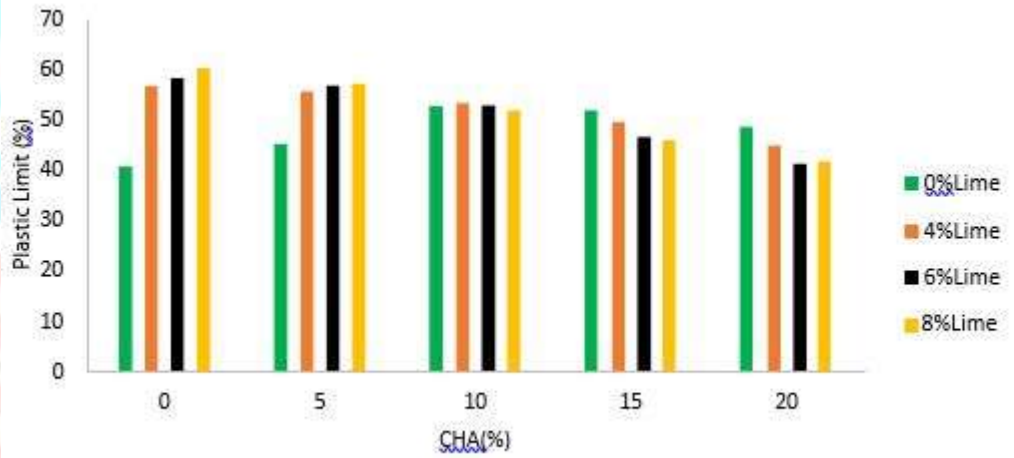
To evaluate the improvement in engineering properties of black cotton soil, the following laboratory and model tests were performed in accordance with **IS codes** and **IRC guidelines**:

- **Index Properties:** Determination of liquid limit (LL), plastic limit (PL), and plasticity index (PI) to assess changes in plasticity due to stabilisation.
- **Compaction Characteristics:** Standard Proctor compaction tests to determine **maximum dry density (MDD)** and **optimum moisture content (OMC)** for untreated and treated soils.
- **Unconfined Compressive Strength (UCS):** Carried out on specimens with varying percentages of fibres and stabilisers to evaluate strength gain and brittle/ductile behaviour.
- **California Bearing Ratio (CBR):** Both soaked and unsoaked CBR tests were conducted to measure load-bearing capacity and to reconfirm optimum stabilizer content for pavement design.
- **Static and Cyclic Plate Load Tests:** Conducted in a model test box (1.2 m × 1.2 m × 2.0 m) with compacted soil layers of 100 mm thickness. These tests provided load-deformation characteristics, modulus of subgrade reaction (K), and modulus of elasticity (E), essential for evaluating pavement performance under repeated traffic loading.



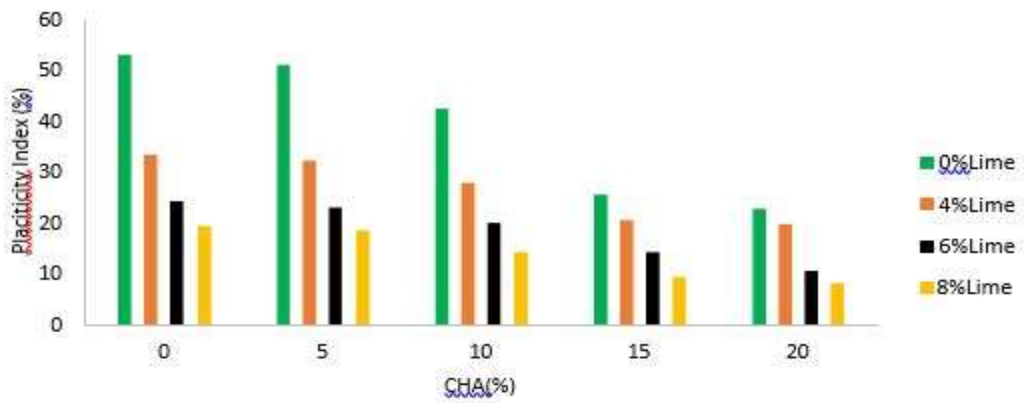
(a)

Fig 1 (a) shows liquid limit (LL)



(b)

Fig 2 (b) shows plastic limit (PL)



(c)

Fig 3 (c) shows Plasticity Index

IV. RESULTS AND DISCUSSION

4.1 Effect of Individual Stabilisers

- **Polypropylene Fibre (PPF):**
  The addition of PPF increased the liquid limit of black cotton soil due to replacement of soil particles with low surface area fibres. UCS values showed consistent improvement with curing, and the CBR increased by nearly **40–50%** at an optimum dosage of 2% PPF by dry weight. The stress–strain behaviour indicated improved ductility and post-peak strength retention compared to untreated soil.
- **Coir Fibre (CF):**
  Inclusion of coir fibre reduced plasticity and marginally improved compaction characteristics. UCS and CBR values increased with fibre addition, although the improvement was lower than PPF. Coir fibre contributed to enhanced ductility, but long-term durability under wet conditions remains a limitation.
- **RBI Grade-81:**
  RBI-81 significantly reduced plasticity index, increased compaction density, and enhanced strength. The UCS values improved with curing, and CBR values increased up to three times compared to untreated soil. RBI-81 also reduced volumetric changes, making the soil more stable under moisture variations.
- **Ground Granulated Blast Furnace Slag (GGBS):**
  The addition of GGBS produced moderate improvements in UCS and CBR at early curing ages, with significant strength gains after **28 days** due to pozzolanic reactions. At optimum dosage (~25%), soaked CBR values increased substantially, making it a suitable sustainable alternative stabilizer.

4.2 Combined Effect of Fibres and Chemical Stabilisers

The combination of RBI-81 with PPF exhibited the best performance among all treatments.

- Plasticity index decreased, indicating reduced swelling potential.
- UCS and CBR values increased more than with individual stabilisers.
- The stress–strain curves showed improved ductility, combining the stiffness imparted by RBI-81 and the toughness imparted by PPF.
  Similarly, RBI-81 combined with coir fibre improved CBR values, though the performance was lower compared to PPF combinations.

4.3 Strength and Compaction Improvements

- Addition of RBI-81 increased maximum dry density (MDD) and reduced optimum moisture content (OMC), improving compaction efficiency.
- Fibre inclusion alone slightly reduced MDD due to lighter material replacing soil particles but increased OMC.
- UCS values showed peak improvements with **RBI + PPF**, followed by **RBI + Coir** and GGBS.
- CBR improvements followed the same trend, with maximum soaked CBR observed for **RBI + PPF stabilized soil**.

4.4 Modulus of Elasticity and Subgrade Reaction

Static and cyclic plate load tests revealed that stabilisation significantly improved load–deformation characteristics:

- The **modulus of subgrade reaction (K)** and **modulus of elasticity (E)** increased considerably for RBI + PPF treated soil compared to untreated black cotton soil.
- RBI + Coir fibre also showed improvement, though less pronounced.
- GGBS stabilisation exhibited progressive increase in modulus values with curing, making it a sustainable option for long-term performance.

4.5 Comparative Analysis of Stabilisers

- **Best Performer:** RBI-81 + PPF combination, due to superior improvement in UCS, CBR, ductility, and modulus values.
- **Eco-friendly Option:** Coir fibre stabilisation offers moderate improvement and sustainability but requires protection against biodegradation.
- **Sustainable Industrial By-Product:** GGBS provides strength gains with curing and is suitable where long-term durability is a priority.
- **Overall Observation:** Fibre reinforcement alone enhances ductility, but maximum geotechnical improvement is achieved when fibres are combined with chemical stabilisers such as RBI-81.

4.6 Grain Size Analysis

Atahu et al., 2017 performed grain size analysis on the BC soil and CHA used for this study, the result shows that the soil contains 85% silt and clay. As the clay fraction (finer than 0.002 mm in soil diameter) increases, the swelling potential increases (Emarah and Seleem, 2018). The soil used in this study is fine-grained with high plasticity (PI=52%). Lime stabilization is suggested for soils if more than 25% passes through a 0.075mm sieve and the PI is greater than 20% (ERA, 2013). According to ASTM C977-10, hydrated lime used for soil stabilization shall not have more than 3% retained on a 590µm sieve and not more than 25% retained on a 75µm sieve. As shown in Fig.4, the hydrated lime used for this study met the grain size requirement for soil stabilization. The grain size of CHA depends on the degree of the burning process. For this study, CHA with 57.1% sand and 42.9% silt and clay size were used. Fig.5 shows micrographs of the BC soil, lime and CHA.

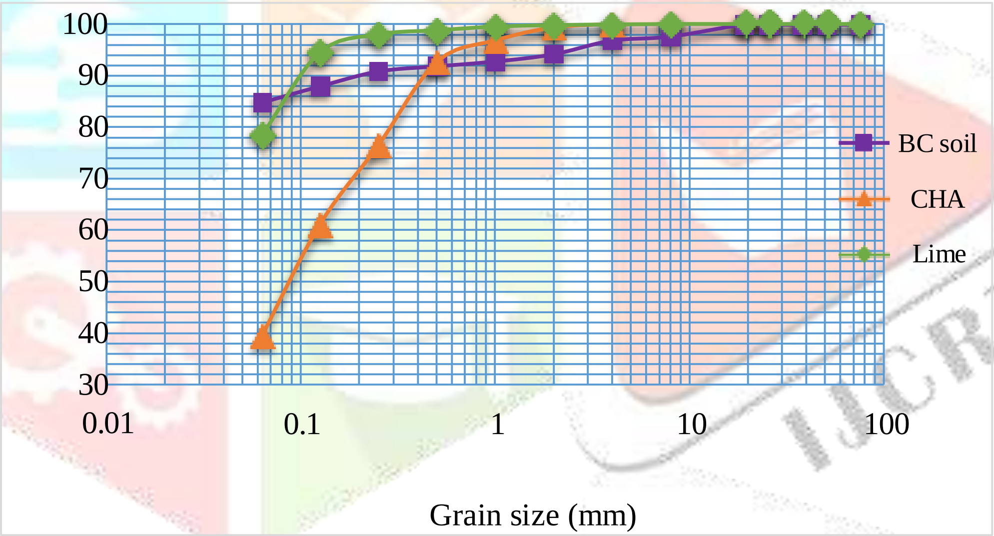


Fig. 4 Grain size distribution of soil, CHA and lime.

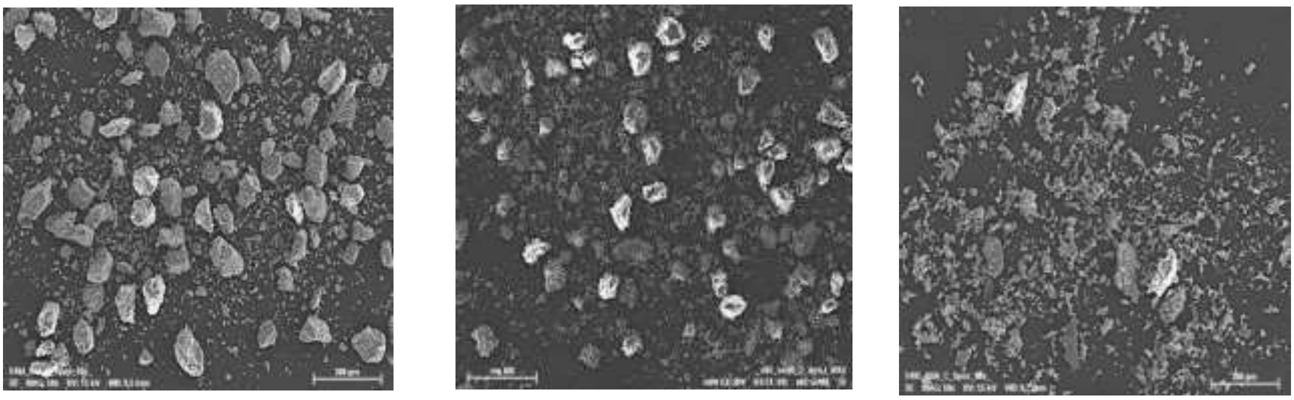


Fig.5. Micrographs of BC soil (a), lime (b) and CHA (c).

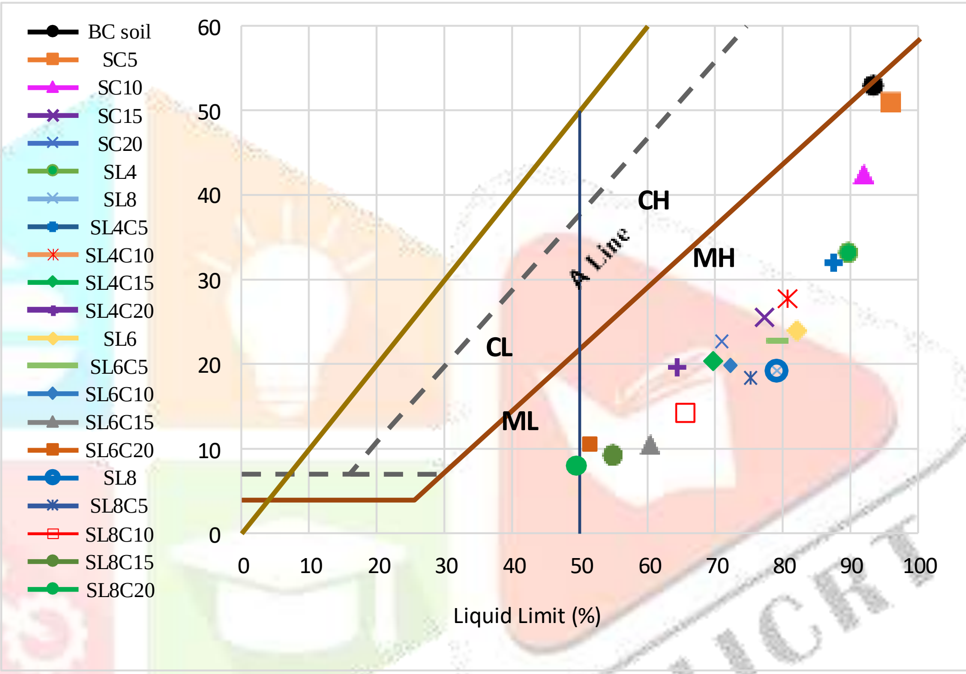


Fig 6 Plasticity index versus liquid limit for untreated and treated samples (USCS chart)

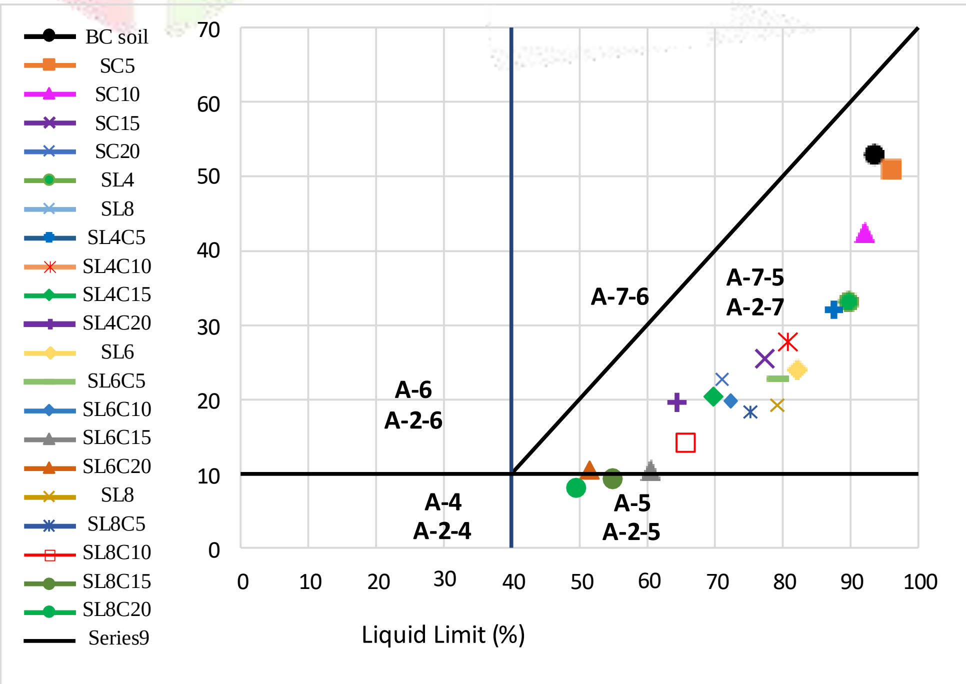


Fig. 7 Plasticity index versus liquid limit for untreated and treated samples (AASHTO chart).

4.7 Compaction Characteristics

The effect of CHA on the compaction characteristics of the lime-treated BC soil was evaluated by conducting a standard proctor test. It can be seen that the maximum dry density (MDD) of untreated and CHA-treated soils

Decreases as the lime content increases (Fig. 9). Conversely, the optimum moisture content (OMC) increases as the lime content increases (Fig. 10). Similar behaviour in MDD and OMC was observed when lime was added to expansive soils (Seco et al., 2011; Al-Taie et al., 2016; Etim et al., 2017). The MDD of lime-treated samples decreased slightly and the OMC increased from 37% to 44% when the amount of lime added was increased from 0% to 8%. These changes in compaction behaviour due to lime treatment could be the result of a pozzolanic reaction between the soil and the lime, which is responsible for the increase in OMC (Harichane et al., 2011). The aggregation of the particles to occupy larger spaces due to the addition of lime and the lower specific gravity of the lime could be responsible for the decrease in MDD (Harichane et al., 2011).

On the contrary, the addition of CHA to the lime-stabilized soil slightly increases the MDD and decreases the OMC, as shown in Fig. 9 and Fig. 10. The OMC decreases as the percentage of CHA increases for all lime content. The reduction in the OMC of CHA-stabilized samples could be attributed to the amount of water needed to reach an optimum state is lower for CHA-stabilized samples compared to untreated samples; this is because of the lower affinity of CHA particles for water.

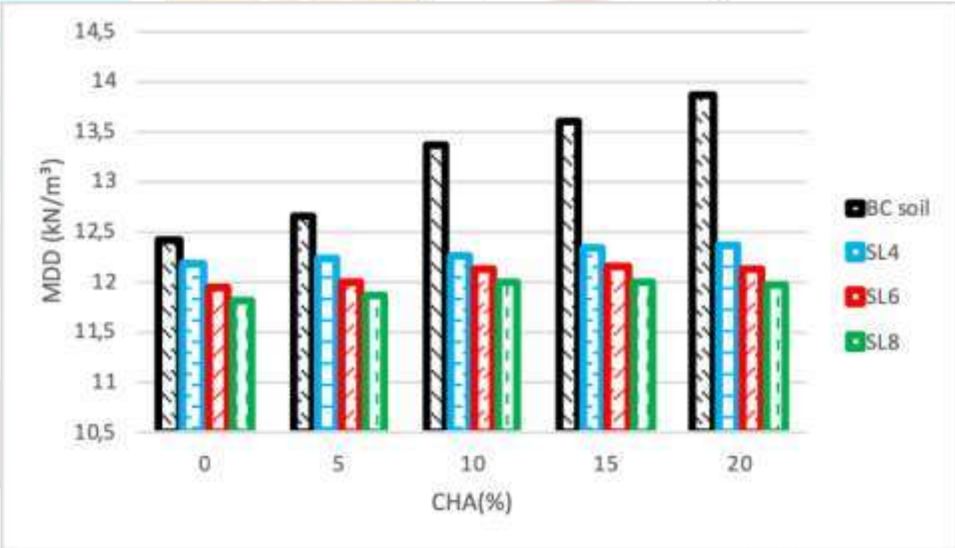


Fig. 8 Variation of MDD with additive content.

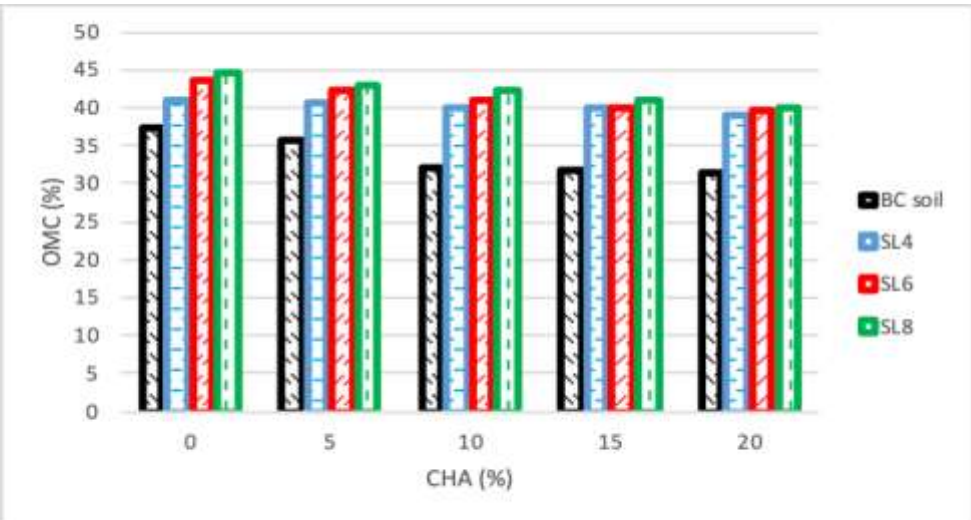


Fig.9 Variation of OMC with additive content.

4.8 California Bearing Ratio

The California bearing ratio test is performed to evaluate the bearing capacity of the BC soil treated with CHA, lime and lime-CHA mixture. The results obtained from CBR tests conducted on the BC soil treated with CHA, lime and with the mixture of lime and CHA are shown as load-penetration curves in Fig. 11. The results show that the CBR value increased from 1% to 3% when the amount of CHA added increased from 0% to 20% (Fig. 12). From these results, the CBR value of the CHA-treated soil at OMC and MDD is three times greater than the natural BC soil. The addition of 4% lime alone increased the CBR value to 16% from 1% for the untreated BC soil. The mixture of lime and CHA treatment showed more enhancements on the bearing capacity of the BC soil compared to both lime and CHA treatment. As shown in Fig. 12, the CBR values of the samples are almost inversely proportional to their plasticity index. The highest CBR values were found at 20% for CHA treatment, at 8% for lime treatment and at 6% lime and 15% CHA for the mixture, respectively. The improvement in the bearing capacity could be attributed to the formation of cementitious compounds due to the reaction between the soil and the additives (Al-Swaidani et al., 2016).

According to Hossain et al., 2007, the minimum CBR value usually required by many specifications for pavement subgrade is 15%. Thus, the minimum CBR value was attained for all samples treated with lime alone and with the mixture of lime-CHA (Fig. 12).

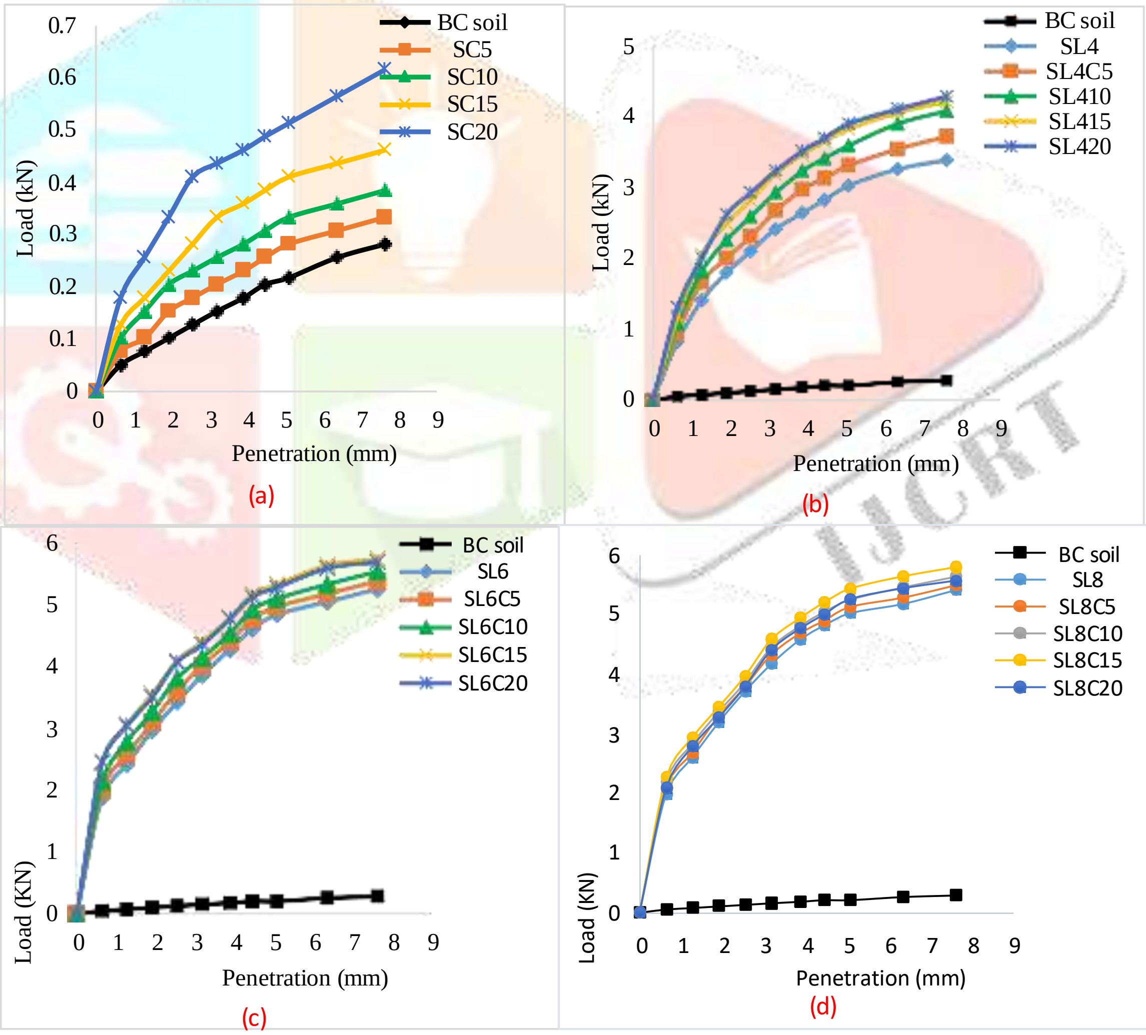


Fig. 10 Load versus penetration curves for 0% lime (a),4% lime (b) 6% lime (c) and 8% lime (d).

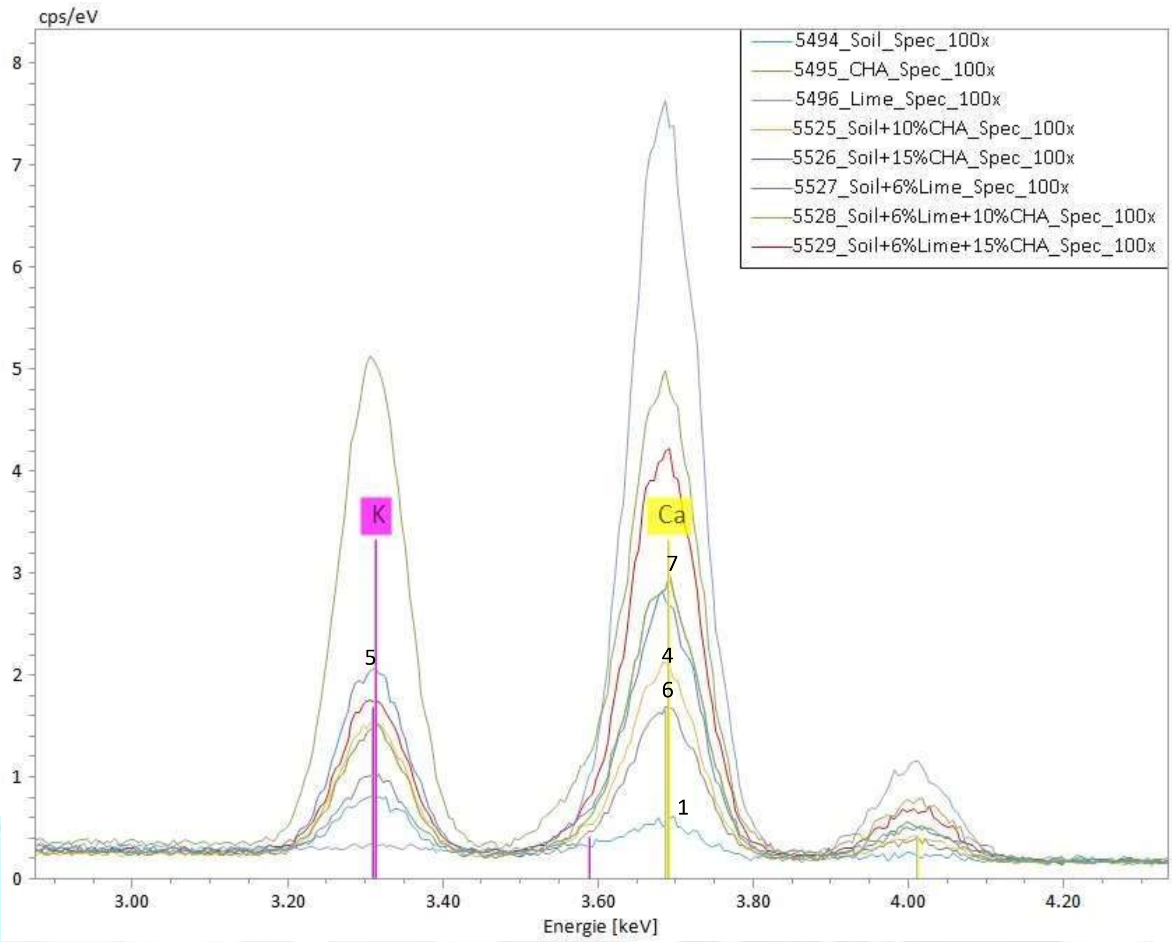


Fig.11 EDX spectrum of K and Ca for untreated and treated samples.

CONCLUSIONS

This study presents the characteristics of the BC soil treated with CHA, lime and a mixture of lime and CHA. Based on the test results obtained from the Atterberg limits, compaction, CBR, microstructural and mineralogical tests, the following conclusion can be drawn.

The BC soil used in this study was classified as high plasticity clay (CH) according to USCS. As the content of the additives increased, both LL and PI decreased, shifting the classification of the BC soil to high plasticity silt and low plasticity silt. These changes in the plasticity behaviour indicate that the treated samples became more workable and stable.

From the compaction test results, it was observed that the maximum dry density (MDD) of the lime-treated samples slightly decreased and the optimum moisture content (OMC) increased as the lime content increased. In contrast, the addition of CHA on lime stabilized the soil, slightly increases the MDD and decreases the OMC. The lime and lime-CHA-treated samples resulted in a considerably higher CBR than the untreated BC soil.

The micrograph of the BC soil indicated discontinuity in its structure and more visible voids. The SEM images of the treated samples showed that the addition of CHA, lime, and lime-CHA has a marked change on the microstructure of the BC soil. EDX results showed a decrement in Si and Al and an increment in Ca content, as the amount of the additives increased. In addition, the XRD results confirmed the formation of cementitious compounds, which is responsible for the improvement in geotechnical properties of the investigated soil.

This investigation reveals the potential use of CHA for road sub-grade construction. It is not limited to the socio- economic advantages in infrastructure developments, but could also play a significant role in reducing the environmental impact arising from the storage of the waste.

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