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ENHANCING STRENGTH CHARACTERISTICS OF BLACK COTTON SOIL THROUGH COMBINED STABILISATION USING COAL TAILINGS AND CALCIUM LIGNOSULFONATE

The present study investigates the potency of stabilising a problematic Black Cotton (BC) soil using a combination of coal tailings and calcium lignosulphonate to address the subgrade problems of a part of the Narsapur- Aswaraopeta major highway. The BC soil creates problems in the construction and maintenance of road pavements in this region. An exhaustive experimental programme was performed on treated BC soil to evaluate the impact of distinct Coal Tailings of 0-20% and Calcium Lignosulfonate of 0-5% dosage. The results revealed that the optimal combination of 12% Coal Tailings and 4% Calcium Lignosulfonate yielded a rise in Maximum Dry Density, California Bearing Ratio and Unconfined Compressive Strength of the treated soil. These improvements are attributed to the development of Calcium Silicates and Calcite, as established through X-Ray Diffraction analysis and densification of the soil matrix observed through Field Emission Scanning Electron Microscopy. The Energy-Dispersive X-Ray Spectroscopy showed the alterations in primary composition, indicating the interaction between stabilisers and the BC soil. The analysis made on the optimum CBR value with corresponding pavement thicknesses revealed that the pavement thickness with the combinedly treated BC soil was greatly decreased to 290 mm. The combined stabilisers treatment proved significantly more effective than individual stabilisation methods, offering a promising approach for improving geotechnical characteristics of challenging BC soil for subgrade construction and other geotechnical applications.

Keywords: Black Cotton Soil; Calcium lignosulfonate; Coal Tailings; Geotechnical properties; Microstructural analysis; Stabilisation

Abbreviations: Al – Alumina; BC – Black Cotton; C – Calcite; Ca – Calcium; CBR – California bearing ratio; CLS – Calcium Lignosulfonate; CH – Clay of High Plasticity; CT – Coal tailings; CS – Calcium Silicates; EDAX – Energy-dispersive X-ray spectrometer analysis; FESEM analysis – Field emission

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scanning electron microscopy; IS – Indian standard; LL – Liquid Limit; MDD – Maximum dry density; OMC – Optimum moisture content; PL – Plastic Limit; Si – Silica; FESEM – Field Emission Scanning Electron Microscopy; UCS – Unconfined compressive strength; USCS – Unified Soil Classification System; XRD – X-ray diffraction analysis.

1. Introduction

In general, it is rare to come across soils with high bearing capacity and shear strength at construction sites around the world [1,2]. Among these challenging soils, Black Cotton (BC) soil is frequently encountered and poses significant challenges in providing economical and safe design for infrastructure development. Especially in road construction, they create challenges including undulations through heave and depression, causing cracking in the pavement layers. These are attributed to high swell-shrink potential and low bearing capacity of BC soil; thus, it is also known as an expansive soil [3,4]. These soils occupy nearly 20 percent of the total area of India [3], and many researchers have worked on these soils to make them suitable for engineering works [2-8]. Post mining soils also have similar problems as BC soil, such as poor structure, low strength and chemical instability. Thus, various studies conducted from coal belts in India, goldfields in South Africa and reclaimed mining lands in Australia and North America emphasised the need for sustainable stabilisation strategies to rehabilitate these degraded soils [9-12]. Studies have been conducted to stabilise the BC soil by using various stabilisers. These include the use of cement, recycled aggregate, ground-granulated blast-furnace slag, fly ash, lime [13], nano-calcium carbonate [14], rice husk ash, and calcium lignosulfonate [15]. Besides, the interest in utilising industrial by-products and bio-based additives is increasing for expansive soil stabilisation as a sustainable method. Thus, the current BC soil is stabilised using a combination of Coal Tailings (CT) and Calcium Lignosulfonate (CLS).

The CT is a byproduct of coal mining. Disposing of it is difficult, leading to various environmental problems [16], and CLS is a cost-effective and environmentally friendly by-product of the pulping industry [17]. This composite is hypothesised to enhance BC soil's strength characteristics through its binding and dispersive properties. Compared to CLS, traditional stabilisers like cement, lime, and fly ash have some drawbacks. During manufacture, cement stabilisation frequently results in increased brittleness, shrinkage cracks, and increased carbon emissions. In sulfate-rich soils, expansive ettringite minerals occur, which can cause delayed swelling and reduce the effectiveness of lime stabilisation. Although fly ash enhances soil qualities, strength growth necessitates a sufficient supply of pozzolanic activity and longer curing periods. A similar study conducted with CLS and granite sand (GS) on cohesive soil strength observed an increase in UCS and a reduction in hydraulic conductivity. Also identified formation of a denser soil matrix due to CLS-induced flocculation with effective curing periods of 7 to 90 days [18]. Therefore, the present study aims to investigate the potency of stabilising problematic BC soil with CLS and CT to address the subgrade problems due to the perennial irrigation canal running alongside the Tadepalligudem-Bhimavaram highway, a part of the Narsapur-Aswaraopeta major highway in Andhra Pradesh, India. The road is frequently damaged by subgrade problems due to the effect of canal water.

In this study, the impact of different CT and CLS doses on the treated BC soil is methodically assessed with Atterberg's limits, maximum dry density (MDD), California bearing ratio (CBR) and unconfined compressive strength (UCS). The detailed investigation of the micro-level interactions in treated soil and the optimisation of the combined treatment dosage distinguish this research from earlier studies [8,16,19-25]. Most of those studies were focused on individual stabilisers or their combination with traditional stabilisers such as cement or lime. Furthermore, the underlying mechanisms of soil improvement are observed through advanced microstructural and compositional techniques like Field Emission Scanning Electron Microscopy (FESEM), Energy-Dispersive X-Ray Spectroscopy (EDAX), and X-Ray Diffraction (XRD), which have not been thoroughly explored in the context of combined CT and CLS stabilised soils [19,26]. This lack of widespread understanding impedes the expansion of optimised and sustainable stabilisation approaches for problematic expansive soils. By addressing these research gaps and subgrade soil problems with pavements in BC soil, the current study contributes to the development of sustainable and operational stabilisation strategies using mining and industrial by-products (CT and CLS) by providing valuable insights into the optimised additive dosages and the fundamental mechanisms governing for the enhancement of BC soil.

2. Methodology

2.1. Materials

2.1.1. Black cotton soil

The BC soil was collected from a deep open pit located more than 1.5 m below the ground surface near the study area, which is situated on agricultural land in Yendagandi village (Fig. 1) located at coordinates (16.64, 81.53), which lies midway between Tadepalligudem and Bhimavaram of Andhra Pradesh. The soil was collected in air-tight bags and packed to prevent contamination. The bags were transported to the geotechnical laboratory for testing.

Fig. 1. Soil sample location map

2.1.2. Coal tailings

The coal mines produce the CT as a by-product of the coal extraction process. Usually, coal mines produce 10% to 30% of Coal Tailings as a byproduct in the coal washing process during the extraction of coal in coal mines. Coal mines manage the waste through backfill in opencast mines [16] and this practice can lead to groundwater contamination, degradation of soil, etc.

2.1.3. Calcium lignosulfonate

The CLS is an industrial by-product, low-cost, environmentally sustainable and renewable material which is derived from the abundant plant and descendant of the pulping industry [17,20]. Along with other colloidal characteristics, the hydrophilic and anionic surfactant CLS exhibits good dispersive ability, absorptivity and wettability [21], which makes it feasible to use as a stabiliser to treat BC soil to improve properties by more easily adsorbing onto soil particles.

2.2. Methods

The procedure for soil sampling and the laboratory tests for untreated, CT and CLS-treated BC soil in separate and combined form were conducted in accordance with Indian standards in the following stages:

2.2.1. Soil sampling procedure

The BC soil sample was collected from an agricultural land well-known for typical BC soil characteristics near the study site. The top surface of the sampling location was cleared to ensure the collection of a pure soil sample, excluding roots of plants or any other foreign material. Soil samples were collected from an open pit excavation to a depth of 1.5 m to avoid surface disturbances and ensure consistency in engineering properties. A total of five bulk samples, each weighing approximately 25 kg, were collected from different spatially variable spots within the same pit. The collected BC soil samples were transported to the laboratory for the preparation of soil samples according to IS: 2720-1 (1983), depending on the test to be conducted. To ensure representativeness, the samples were homogeneously mixed before laboratory testing.

2.2.2. Soil pH

The pH of BC soil is determined by the electrometric method as per IS: 2720 (Part 26) – 1987. A representative soil sample was mixed with distilled water to prepare a suspension, which was allowed to equilibrate before testing. Measurements were taken using a calibrated pH meter with a glass and calomel reference electrodes, standardised against buffer solutions of pH 4.0 and 9.2. Readings were recorded once stable within ±0.05 units, and the final pH value was reported to the nearest 0.1 unit.

2.2.3. Grain Size Analysis

The grain size distribution of BC soil is determined by wet sieving as per IS: 2720 (Part 4) – 1985. The fraction passing the 4.75 mm sieve was oven-dried, soaked with dispersing agent, and washed through a nest of sieves (2 mm, 425 µm, 75 µm). Each retained fraction was dried, weighed, and expressed as a percentage, from which cumulative passing values were used for the analysis.

2.2.4. Atterberg Limits

The air-dried, untreated and 28-day-cured treated BC soil samples of this study were sieved through a 0.09 mm size sieve and weighed to 200 g and then water was added to it. The plasticity characteristics- namely, the plastic and liquid limits of the BC soil sample, treated with 12% CT and CLS contents of 1%, 2%, 3%, 4% and 5% [19,27] were determined as per IS: 2720-5 (1985) using Cassagrande's apparatus.

2.2.5. Free swell index

The free swell index (FSI) is conducted by following IS: 2720-40 (1977) method of testing soil samples used to measure swelling potential caused by the occurrence of expansive clay mineral (montmorillonite) in soil by submerging under water. It is determined by allowing the BC soil sample to swell freely underwater by submerging it for 24 hours and comparing the variation in its initial and final volumes with the soil sample submerged under kerosene. The FSI is a quick and economical way to assess the impact of CLS and CT on swelling potential.

2.2.6. Standard proctor test

This test was conducted as per IS: 2720-7 (1980), which is exploited to make soil specimens for testing of engineering properties conducted in the following stages by establishing MDD and optimum moisture content (OMC). The BC soil was individually stabilised with various CLS dosages as mentioned above, CT dosages of 1.0%, 2.0%, 4.0%, 8.0%, 12.0%, 16.0% and 20.0%, and treated in combination with 12% optimum dosage of CT with varying dosages of CLS. The MDD and OMC of these mixtures were then determined. The stabiliser CT/ CLS is directly added to the 3 kg of soil sample and tested with gradually added water content in each repetition of the test until the soil and CLS/CT mixture obtains OMC and MDD as mentioned in the standard procedure.

2.2.7. California bearing ratio test

The CBR is a basic strength test for assessing the suitability of the soil for the subgrade of road pavement and embankment according to the IS: 2720-16 (1987). The stabilising agent CLS/CT was individually added in various percentages and also in combinations to the 5 kg of BC soil sample, and the test specimen was prepared as per the IS standard procedure. All the CBR samples prepared in this process were tested after 96 hrs. of soaking, and the result at the penetration of 2.5 mm was considered if it achieved a greater CBR value than the penetration at 5.0 mm.

2.2.8. Unconfined compression strength test

The UCS test was conducted using strain-controlled UCS equipment of model no. AIM 074-1 at 1 mm/min constant strain for untreated, CLS-treated, CT-treated and combinedly treated BC soil to ascertain the maximum compressive strength according to IS: 2720-10 (1991). The BC soil samples treated with CLS/CT were prepared with the obtained OMC and MDD, cured up to 7 and 28 days in a desiccator, and tested to understand the time-dependent variation in strength characteristics and compared with the 0^{th} day UCS results of untreated BC soil.

2.2.9. Microstructural and Compositional Analysis

The FESEM analysis gives the size, shape, composition and crystallography of soil in the form of magnified images. The mechanism of strength improvement for CT and CLS-treated BC soil was visually evaluated with the help of the acquired micrographs. The acquired micrographs were analysed for the improvements in soil morphology due to the reactions that take place with CLS and CT. The high-resolution imaging of the surface morphology and microstructures of BC soil was executed using Carl Zeiss microscopy equipment up to 25.0 KX magnifications. Furthermore, the elemental composition of BC soil was quantitatively identified using the EDAX component, which is responsible for the soil's gradual stabilisation and improvement. The test was executed using the Quantax 200 equipment. For a better picture of the shift in mineralogical stages in the treated BC soil, the analysis using XRD was executed at a wavelength of C-Kα, 40 mA of current, along with 40 kV of input voltage. An uninterrupted scan mode with Bragg's angle from 3° to 70° in the laboratory was used. After completion of the UCS test, the samples of 28 days cured were oven-dried and crushed into a fine powder, which was used for FESEM, EDAX and XRD tests to determine their microstructural properties.

3. Results and Discussions

The BC soil is characterised as inorganic clay of high plasticity (CH) with an expansive nature, and the detailed characterisation is depicted in TABLE 1. The effects of the CLS and CT on various indices, strength and microstructural parameters of stabilised BC soil are discussed in the following sections.

TABLE 1

Characteristics of BC Soil

Property	Quantity
Color	Brownish black
Specific Gravity (G)	2.65
Free swell index (%)	56
pH	7.46
Liquid Limit (%)	68
Plastic Limit (%)	24.81
Plasticity Index (%)	43.19
Dry density (g/cm^3)	1.49
OMC (%)	22.25
CBR-Soaked (%)	1.71
Dominant clay minerals	Montmorillonite, Kaolinite
Soil Classification (USCS)	CH
Grain Size Distribution	
Clay	62.91
Silt	35.19
Sand	1.90

3.1. Effect of CLS and CT on the Plasticity Characteristics and Free Swell Index

The plasticity characteristics and FSI of BC soil based on varying percentages of CLS mixed with 12% of CT were determined. The stabilisation dropped the Liquid Limit (LL), slightly raised the Plastic Limit (PL) and led to a noticeable drop in the soil Plasticity Index. The swelling potential of the CT-treated soil was reduced up to 35%, CLS was reduced up to 34% and it results in up to 34% when treated in combination with CLS and CT (TABLE 2). The swell potential reduced to medium range from the high range with stabilisation. The changes in plasticity characteristics and FSI are ascribed to the genesis of agglomeration in stabilised soil and cation exchange reaction due to Ca^{+2} in the CLS. This property altered the BC soil particle into a siltier form by increasing the average particle size [22,28], which in turn improved the plasticity characteristics. The cation exchange plays a decisive role in altering soil plasticity and FSI, particularly in clay-rich soils like BC soil. Introducing the Ca^{2+} ions through CLS replaces the weaker monovalent cations (e.g., Na^{+}, K^{+}) within the clay structure, leading to a drop in the DDL thickness. This cation exchange mechanism helps in reducing plasticity and improving workability, soil flocculation and aggregation as confirmed by FESEM results [23,24] and promoted by the reduction in the DDL, which reduces the specific surface area available for water absorption. The occurrence of Ca^{2+} ions boosts the formation of stable particle bonding, which contributes to a more rigid soil matrix with decreased swelling potential. By filling in the voids between soil particles, CT acts as a filler. It reduces the space available for water absorption and decreases the free swell index. As confirmed by EDAX analysis, the increased calcium content in the combined stabilised soil indicates the occurrence of such exchange reactions, leading to improved compaction characteristics and enhanced strength.

TABLE 2

Properties of BC soil treated with CT and CLS

12% CT + CLS (%)	LL	PL	PI	FSI	MDD (kN/m^3)	OMC (%)	UCS (kPa)/ Curing Periods (Days)			Soaked CBR (%)	Pavement Thickness (mm)
							0	7	28		
0	68	24.8	43.2	39	17.8	19.6	69.1	69.1	69.1	1.7	700
1	53	25.5	27.5	38	18.3	18.8	196.9	212.1	245.9	7.7	370
2	51.5	25.7	25.8	37	19.1	18.6	212.6	234.3	286.6	8.9	330
3	50	26.1	23.9	36	19.4	18.4	240.6	265.4	296.2	9.4	320
4	49	26.3	22.7	34	20.3	17.9	257.7	282.7	318.9	11.1	290
5	47	26.8	20.3	33	19.4	18.2	238.2	255.7	290.4	10.3	305

3.2. Strength characteristics

The MDD of BC soil treated with 12% CT is 17.80 kN/m^3, which is a 21.6% improvement on the MDD of untreated BC soil, and further dosage of CT caused a drop in MDD. The phenomenon of a decline in the OMC of BC soil with 12% CT dosage from 22.25% of untreated BC soil to 19.55% could be understood as the lower specific surface area of CT decreased the average specific surface area of the mix. The addition of varying dosages of CLS to the 12%

of CT-treated BC soil increased the MDD up to a dosage of 4% at 31.63 % of increment with a value of 19.27 kN/m^3 due to the combined effect of CLS and CT (TABLE 2). An interaction between the CLS, CT and soil during the water addition in the proctor compaction test makes the soil matrix harder, which raises the weight of the soil, CLS and CT matrix. The soaked CBR of individual CT-treated soil increased progressively to a peak strength of 6.20%, with the balance between BC soil and CT is optimal for densification and load resistance, with a further decrease beyond 12% of CT (TABLE 2). Beyond this percentage, CT introduces a higher fraction of non-plastic material, which may lower the cohesion properties and decrease the MDD of the BC soil-CT matrix, thus the soaked CBR. The increased water retention capacity of excess CLS can hinder effective compaction, leading to lower dry density and CBR values. The soaked CBR of an optimum CT and CLS-treated BC soil increased to a peak strength of 15.61%, with a further decrease by increasing the CLS. The CLS acts as a binding agent, coating the CT and soil particles, also enhancing the additional cohesion and interparticle bonding required between soil particles. Additionally, the mixed CT fills the voids within the soil particles, both creating a denser matrix. The UCS of untreated BC soil is recorded as 69.09 kPa. As the Coal Tailings are chemically inactive, the strength improvement with optimum dosage over the period of 28 days of curing was not shown to be a significant change. The UCS of CT and CLS-treated BC soil was recorded as 318.95 kPa at 28 days of curing. The curing duration has a great impact on the UCS of CLS-treated soil compared to CT-treated soil due to the distinct stabilisation mechanisms involved.

As CLS is a water-soluble lignin-based polymer, it undergoes time-dependent chemical reactions in the curing period [29]. As the curing progresses, the CLS gel formed within the soil matrix creates a dense and interconnected network, as observed in FESEM micrographs, that significantly enhances the soil's UCS. When the CLS content exceeds 4%, it develops thick, viscous coatings around the soil particles and restricts the development of proper interparticle friction and interlocking of soil particles. As a consequence, the soil's capacity to resist compressive stresses is reduced, leading to a decrease in UCS values.

3.3. Microstructural analysis

3.3.1. FESEM Micrographs and EDAX of 28-day cured specimens

The FESEM micrograph of untreated BC soil, as depicted in Fig. 2a, shows an undulating, filmy microstructure and rough surface with a well-established crack network. It exhibits intergrain porosity brought on by significant surface voids and cracks. Significant morphological alterations, dense and smooth surface, agglomeration of particles along with a few large voids (Fig. 2b), resulted from the CT and CLS. The packed multiple parallel stacked flaky sheets in the treated soil confirm the genesis of Calcium Silicates [25], which contributes to the improvement of strength characteristics [30].

As the CT is a chemically inert material, individual BC soil treatment hasn't shown any spike in Carbon or any other compounds like combined treatment. A spike in Calcium compound is observed in the EDAX of the individual treatment with 4% CLS. An increase in elemental Carbon (C) and Calcium (Ca), and a reduction in Silicon (Si), Aluminium (Al) and Titanium (Ti) were observed (TABLE 3), likely reflecting compound transformations involving carbonates, aluminium-bearing silicates and TiO_2 in the optimum CLS and CT treated BC soil.

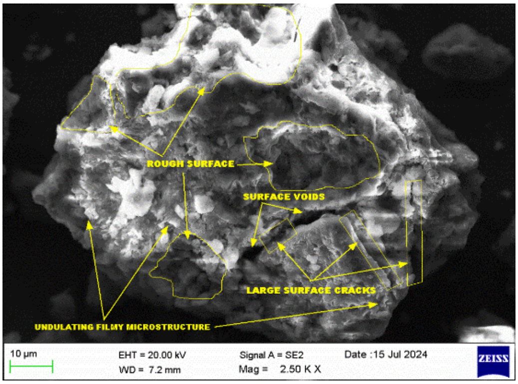

Fig. 2a. FESEM micrograph of BC soil

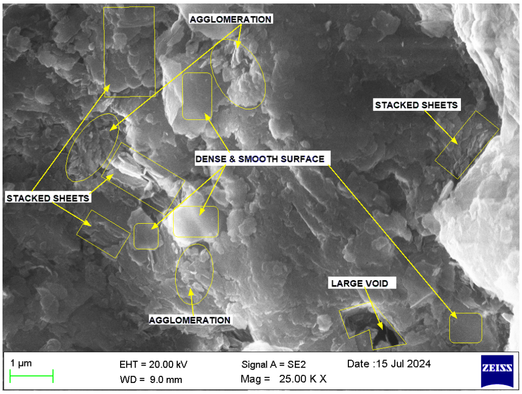

Fig. 2b. FESEM micrograph of treated BC soil

It is hypothesised that during curing, atmospheric CO_2 dissolves in soil moisture to form carbonic acid (H_2CO_3), which subsequently reacts with calcium hydroxide ($Ca(OH)_2$) released from CLS hydration. This interaction may generate Ca^{2+} and CO_3^{2-} ions that precipitate as calcite ($CaCO_3$), accompanied by water formation:

$$H_2CO_3 + Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^- + 2H^+ + CO_3^{2-} \rightarrow CaCO_{3\,(s)} + 2H_2O$$

The development of calcium silicate hydrate (C-S-H) [31] in the treated BC soil is hypothesised to occur through the interaction of Ca^{2+} ions from CLS with reactive silica released from clay minerals under alkaline conditions. Although traditional cementitious compounds are absent, the elevated pH and presence of silicates enable the development of amorphous C-S-H (non-stoichiometric, gel-like phase), contributing to the matrix densification and strength enhancement.

$$2Ca_3SiO_5 + 9H_2O \rightarrow CaO \cdot 2SiO_2 \cdot 4H_2O + 5Ca(OH)_2$$

The increase in carbon percentage and variation in other elements contribute to the change in chemical reactions of the soil matrix, confirming the efficiency of the combined CT and CLS.

TABLE 3

Elemental Distribution through EDAX

Element	Weight %			
	Untreated	12% CT	4% CLS	12% CT &4% CLS
O	55.40	47.49	53.48	47.91
Si	14.42	19.58	17.82	10.45
C	12.86	13.78	8.09	29.22
Al	9.53	10.55	9.62	6.61
Fe	4.97	4.40	6.47	4.32
Mg	1.20	0.87	1.16	0.65
Ca	0.66	0.95	2.17	0.83
K	0.60	1.52	0.64	—
Ti	0.36	0.86	0.55	—

3.3.2. X-Ray Diffraction Analysis

The untreated and 28-day cured, treated BC soil XRD diffractograms are stacked in Fig. 3. According to the investigative findings, the leading minerals found in BC soil are quartz, montmorillonite, kaolinite and trace amounts of Illite. The montmorillonite clay mineral peak is sited at a Bragg's angle of 35.08°. The two new spikes formed in the combinedly treated soil are ascribed to the development of a comparatively new crystalline compound at Bragg's angles of 28.28° and 28.35°, which is identified as Calcite [32]. As observed from the EDAX spectra analysis, the increased percentage of Carbon (C) and Calcium (Ca) in the combinedly treated BC soil may be related to the development of these compounds. There is a reduction in the relative peak intensity of minerals is also observed in treated soil. As the positively charged CT and CLS can also interact electrostatically with negatively charged clay minerals, resulting in CLS adsorption to the clay mineral surface, this may cause the reduction in the relative peak intensity [26]. The reduced spike of Quartz in the diffractogram of treated BC soil at 21.09°, 26.84°, and 50.350 of Bragg's angle can witness the phenomenon of reduction in the relative peak intensity.

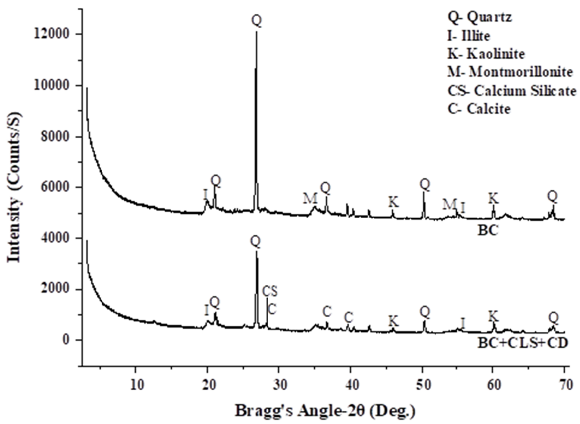

Fig. 3. X-ray diffractograms

3.4. Variation in CBR and pavement thickness with different soil conditions

The service life of the pavement will be adversely affected when its subgrade contains BC soil. The present study tried to overcome these adverse effects by transforming the BC soil through combined stabilisation with CT and CLS. Weak soils with low soaked CBR need thicker subgrades, making construction difficult. Stronger soils with higher CBR reduce pavement thickness and cost. As per IRC: SP-72 (2007), 7 to 9% soaked CBR is suitable for subgrade layers. The variation in soaked CBR and pavement thickness for BC soil under different stabilisation conditions is shown in Fig. 4. The combined treatment with 12% CT and 4% CLS significantly reduced pavement thickness compared to individual treatments. This highlights the potential of using industrial waste combinations in soil stabilisation. The treated soil achieved a soaked CBR of 11.12%, meeting IRC guidelines, and an optimum subgrade thickness of 290 mm suitable for a two-lane bypass carrying 310 commercial vehicles per day.

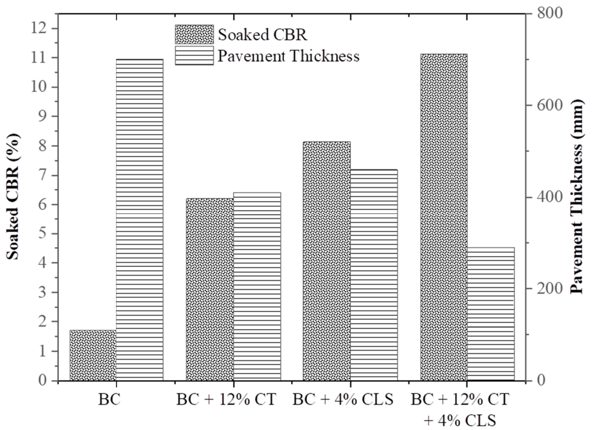

Fig. 4. Variation in CBR and pavement thickness

3.5. Combined Mechanism of CLS and CT in BC Soil Stabilisation

When a lignin-based polymer, CLS, is introduced to the BC soil, it works as a binder as well as a dispersing agent. The CLS molecules adsorbed onto the clay particle surface decrease the thickness of the DDL [25], indicating that the repulsive forces decreased between clay particles in addition to promoting flocculation and aggregation. The cation exchange between CLS and BC soil leads to a reduction in interlayer spacing, which results in stable and compact soil structure [33]. By filling the voids among soil particles and enhancing packing density in the combinedly treated soil, CT serves as a filler material. As well as the fine CT particles provide extra surface area for the CLS molecules adsorption, further promoting the formation of an interconnected dense soil matrix. The calcium ions presented by CLS and the alkaline nature influenced by CT generate a favourable environment for the cementitious compounds, such as calcium silicate hydrate (CSH) and calcite. The formation of both CSH and Calcite contributes to a strong interconnected network of cementitious bonds development in the soil matrix, as evidenced by the formation of stacked flaky sheets in FESEM micrograph, resulting in a more substantial increase in UCS [34].

3.6. Environmental concern

Using the CLS extensively causes organic compounds, heavy metals and chemical traces to leach into the adjacent soil and groundwater, which can limit the effect if it is used at an acceptable limit [36]. Similarly, if CT is not properly handled, it may potentially release heavy metals like lead, mercury, and arsenic into the environment, endangering human health. Therefore, the encapsulation of CT and CLS within the stabilised soil matrix and the cementitious compounds formed through stabilisation may help to immobilise and reduce the risk of leaching harmful contaminants. By using these industrial by-products, we can also lower the demand for virgin soil, minimise the effect of produced waste materials, decrease the carbon footprint of the construction industry and address environmental concerns in association with waste disposal.

4. Conclusions

The effects of coal tailings (CT) and calcium lignosulfonate (CLS) as combined stabilisers with problematic BC soil were investigated in the present study. The major findings and their implications with combined CT and CLS stabilisation over the individual are presented as follows:

- The transformed plasticity characteristics indicate the development in workability and a decrease in water sensitivity of the soil.
- The achieved densification of soil leads to enhanced compaction properties, with an indication of increased MDD and decreased OMC.
- The development of CSH, a calcite, strongly interconnected and dense soil matrix, along with the formation of stacked flaky sheets revealed by XRD and FESEM analyses, contributes to the increased soaked CBR and UCS.
- The rise in carbon content revealed by EDAX analysis is an indication of the successful incorporation of CLS and CT into the treated soil.
- These observed phenomena support waste management principles and demonstrate the potential use of organic additives and industrial by-products in combination for sustainable soil stabilising techniques.
- In order to maximise its practical uses, future study will focus on the extended performance, durability, and environmental effects of CT and CLS.

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