International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://theaspd.com/index.php

A Mineralogical and Microstructural analysis of bio enzyme stabilized soils.

Dr.Nandini D N[1], Vani A[2], Vidya Sagar J[1]
[1]REVA University, Bangalore, Karnataka, India
[2]Rajeev institute of Technology, Hassan, Karnataka, India
Email: nandini.dn@reva.edu.in, vania312@gmail.com, vidyasagar1996@gmail.com

Abstract
Bio enzyme application to stabilise subgrade soil is gaining importance in current trends due to increase in vehicular operation and rapid urbanization in developing countries. The analysis of stabilized soil through XRD and SEM indicates a decrease in void space and an improvement in the structural behaviour, validating the enhanced unconfined strength of stabilized soil in comparison to conventional soil. The increase in number of vehicles demands for a better highway having proper design, safety and economical. The overall road construction can be made economical by stabilizing the locally available subgrade soil. This study uses a methodical approach to examine the physical characteristics and strength behaviour of different subgrade soils, including red soil, black cotton soil, and lithomargic soil. The effect of bio enzyme curing at various dosages on the strength behaviour of various soils has been examined. The mineralogical behaviour of conventional and optimum dosage stabilized soil is analysed through XRD and SEM analysis. The analysis of stabilized soil through XRD and SEM indicates a decrease in void space and an improvement in the structural behaviour, validating the enhanced unconfined strength of stabilized soil in comparison to conventional soil
Keywords: *Bio enzyme, black cotton soil, lithomargic soil, Electronic Diffraction, X-ray diffraction, Scanning Electron Microscopy*

1.INTRODUCTION:

The increasing population demands better highways, but construction materials are depleting, raising costs. The Highway engineers face challenges meeting these demands. In order to address this, there's a shift towards soil stabilization, altering soil qualities for design needs [1]. The various stabilizers like lime, fly ash, GGBS, silica fumes, cement, and bio enzyme stabilizers are being explored as alternatives in the construction of road in various layers such as subgrade, sub base and base courses [2].
In countries like India, growing population necessitates efficient and cost-effective highway operations, emphasizing optimal design, pavement condition, and maintenance. In light of their cost-effectiveness, proper maintenance must be performed on roadways to ensure comfort, convenience, and safety [3]. The enhancement of soil particle bonding, resulting in a long-lasting structure resistant to water, weathering, and wear and tear, has been discovered through the use of Bio enzyme. The interaction of clay particles and water is the primary cause of pavement failures [4].
Both before and after stabilisation, the physical and mechanical characteristics of soil are examined using scanning electron microscopy (SEM) of soil particles. The primary purpose of conducting a soil SEM study is the evaluation of the microstructure of the soil at a high resolution [5]. To investigate how soil particles behave and how they bind with any additions, scanning electron microscopy (SEM), is used. In contrast the material crystalline structure is ascertained by X-ray diffraction (XRD) examination, which provides information on phase composition, particle size, and the existence of structural defects [6].
In this work, the investigation of the formation of interlocking bonding between soil particles and stabilizer is undertaken, and the observation of microstructure changes is accomplished through XRD and SEM analysis. The use of bio-enzymatic additives for the stabilization of subgrade soil is deemed apt for incorporation in pavement construction [7].
The behaviour, microstructure and bonding of soil particles are investigated using SEM. While the technique of X-ray diffraction analysis, determines material's crystallographic structure and provides information about particle size and defects [8]. Through SEM and XRD investigations, the microstructural alterations in the stabilised soil were previously noted, and The cause of the strength increase was identified. The previous research investigations of fly ash and lime on the strength of

locally available cohesive soil is explored. The micro-level analysis for stabilized soil is carried out using XRD and SEM, revealing that pozzolanic reaction dominates in the stabilization process over the cation exchange capacity [9].

To activate the stabiliser, the microstructural study of marine soft clay stabilised with bio enzymes and lime from the soil. XRD analysis revealed bio enzyme stabilized clay yield low porosity than un stabilized clay soil [10]. Mineralogy characters and microstructural behaviour through X-ray diffraction and SEM analysis showed that the formation of cementations compounds in the XRD image and established the development of dense matrix in SEM images.

Using a calcite precipitation approach to induce bioenzymes to stop silty sandy soil erosion. The SEM studies have shown that top 2.45 cm specimen layer had calcite precipitation which helped in reducing soil erosion. Based on above literature review the current work focus on the mineralogical characteristics of bio enzyme stabilized soil and to compare the same with conventional soil. For this XRD, SEM and EDS analysis is done for conventional and optimum dosage and curing period of stabilized soils.

Black cotton soil - Conventional soil and optimum dosage stabilized soil (200ml/2m3 of soil cured for 15 days)

Lithomargic soil- Conventional soil and optimum dosage stabilized soil (200ml/2m3 of soil cured for 07 days)

Red soil- Conventional soil and optimum dosage stabilized soil (200ml/2m3 of soil cured for 07 days)

The black soil, formed from volcanic rocks and lava, is characterized by being rich in calcium carbonate, lime, potash, and magnesium carbonates. It contains frequent smectite group minerals and undergoes significant expansion when absorbed by water. The cause of extreme swell-shrink in Black Cotton (BC) soils is seasonal variation. In India, around 20% of land is covered by this soil[11] These soils are capable of experiencing volume variations, which are considered harmful to residential buildings, pavements, linings, etc.[12]In general, a soil is considered weak for subgrade due to their low strength, substantial expansion in moist conditions and California Bearing Ratio (CBR) of less than 2% is considered weak for subgrade due to their low strength and substantial expansion in moist conditions [13][14]. A volume expansion of 150–300% can be exhibited by high plasticity clay, and a swell pressure of 8–10 kg/cm2 can be generated by this soil upon expansion [15]16]

The primary constituents of lithomargic soil are hydrated alumina and kaolinite powder. This soil is considered to be problematic as it contains silt sized particles which loses its strength upon saturation. After stabilizing with bio enzyme there is an improvement in strength by filling voids between soil particles established through XRD and SEM analysis.

The locally available red soil is siliceous and aluminous in nature chemically with free quartz as sand. Loamy soil being majority varying from sand to clay. The top layer of soil is permeable and sandy leads to soil erosion, acidification and pollution which has become major environmental concern. This paper worked on stabilization of red soil with Bio enzyme resulted in good compaction and strength properties with optimum dosage and curing period.

2. MATERIALS

Black cotton soil

The study's black cotton soil collected from Chitra Durga, Karnataka.

Lithomargic soil

Lithomargic soil was collected from Bhadravathi, Karnataka.

Red soil

The red soil used in this study was collected from Kattigenahalli, Yelahanka, using the open excavation method.

Bio enzyme- Terra zyme

Terra zyme, a bioenzyme, was obtained from Avijeet Agency in Chennai, India. It is a dark, aqueous liquid with a pH of 3.1 and a specific gravity of 1.05.It is completely soluble in water and has high thermal stability. Its composition includes more than 50% of water, less than 30% of alcohol and 20% of vegetable extract.

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://theaspd.com/index.php

Figure 1: Preparation of soil sample for testing.

Physical properties		Black cotton soil	Lithomargicsoil	Red soil
Color		Grey	Brown	Red
Specific Gravity		2.65	2.30	2.57
Grain Sizedistribution (%)	Gravel	-	37.85	30.2
	Sand (%)	10.23	59.7	68.1
	Silt &Clay (%)	89.77	2.45	1.7
ConsistencyLimits (%)	Liquid Limit (%)	64.5	55	23.5
	Plastic Limit (%)	26.2	20	17
	Plasticity Index	38.3	35	6.5
	Free swell Index	60%	-	-
Compaction Characteristics (%)	MDD (kN/m3)	1.62	1.68	1.94
	OMC (%)	21.7	18.2	13.5
Unconfined compressive strength (kN/m^2)		67.45	124.26	135.32
California Bearing Ratio (%)	Soaked condition	2.01	4.5	6.86
	Unsoaked condition	2.96	6.75	9.8

Table 1: Physical properties of soils

3.RESULT AND DISCUSSION:

Strength characteristics of bio enzyme stabilized soils.

UCS results of various soils treated with or without bio enzyme at different dosages for varied curing periods and optimum bio enzyme percentage for each soil is determined. The improvement in soil strength in the presence of bio enzyme is time dependent [17], so to study the curing period effect for various soils, For both conventional and stabilised soils, UCS tests were conducted with varying dosages of Bio enzyme for cure times of 0, 7, 15, and 30 days. The results have been recorded.

Figure 2: UCS samples for Curing and Testing

As the proportion of bioenzymes rose, the UCS of black cotton soil improved, with the strength being determined to be maximum for all curing periods and varied level dosages as compared to the untreated soil sample. The effect of cat ion exchange and flocculation increases the UCS strength of stabilized soil without any curing period[18], and high for all the levels of doses after 15 days of curing for a dosage of 200 ml /2 m^3 of soil compared to other curing periods. If the curing period is extended beyond 15 days, the strength will steadily decrease. This is because black cotton soil loses its affinity for calcium ions found in bio enzyme, which is the basis for stabilized soil's pozzolanic reaction[19].

As the amount of bio enzyme increase Lithomargic soil's unconfined compressive strength increased as well and it was discovered that maximum strength is attained for dosage 200 ml /2 m^3 after 7 days of curing, after which continued curing resulted in a drop in strength forall dosages. The results shows that the soil sample treated with for a dosage of 200 ml /2 m^3 has a considerable improvement in strength during all curing durations.

The bio enzyme addition to red soil sample results in a strength increase as compared to un treated soil at all dosage levels and for all curing periods. In comparison to other curing times, the maximum strength is shown during 7 days of curing for locally accessible soil at all dosage levels. When the curing period exceeds 7 days, it is observedthat the strength decreases drastically, and in some circumstances, the strength approaches that of virgin soil. It was discovered that maximum strength is attained for dosage 200 ml /2 m^3 after 7 days of curing.

A comprehensive investigation was conducted into the impact of bio-enzyme stabilization on the unconfined compressive strength (UCS) of different types of soil. The results showed that, in comparison to untreated control specimens, the application of bio-enzyme at a dosage level of 200 ml per 2.0 m^3 of soil increased UCS values over the course of the curing period.

For lithomargic and red soils, the most significant increases in UCS were observed within the initial 7 days of curing. In contrast, black cotton (BC) soil exhibited its peak UCS at 15 days of curing, with subsequent curing durations producing only marginal improvements. These findings suggest that the efficacy of bio-enzyme stabilization is dependent on both time and soil type, with early-stage curing playing a critical role in strength development, particularly for non-expansive soils[20][21].

Study of mineralogical characteristics of treated and untreated samples through XRD and SEM analysis. XRD provides information on texture, phases and other structural parameters. Whereas SEM and EDS analysis evaluates changes in micro structure and morphology of tested specimen [5].

3.1 Black cotton soil

3.11 SEM results of conventional and stabilized Black cotton soil

The SEM results of Black cotton soil treated with the optimum concentration of bio enzyme and cured for 15 days are shown in Figures 1 and 2.

Figure shows conventional soil surface is plane and discontinuous where voids are more visible due to lack of inter bonding property.

The soil structure treated with bio-enzyme exhibits the formation of particle clusters due to aggregation, wherein discrete soil particles are bound together, resulting in a more cohesive and integrated structural framework.

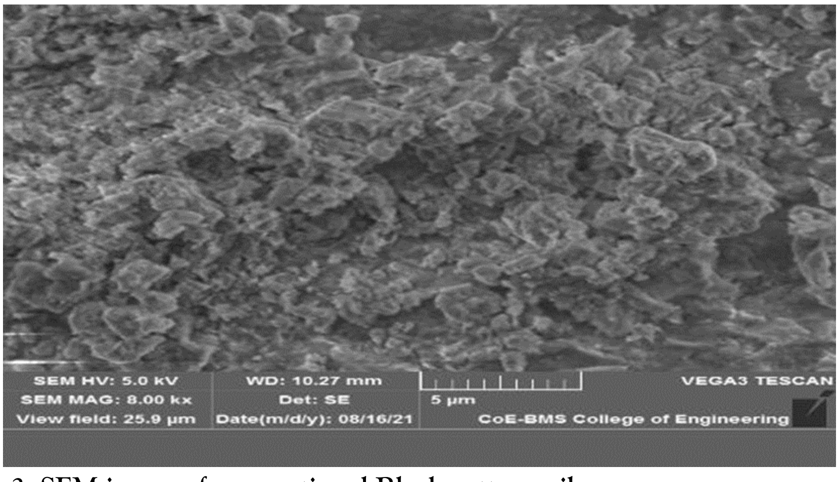

Figure 3: SEM image of conventional Black cotton soil

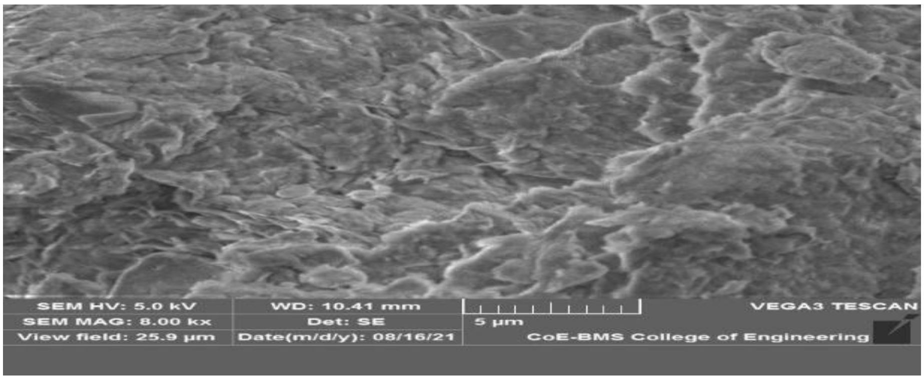

Figure 4: SEM image of stabilized Black cotton soil

3.1.2 XRD results of conventional and stabilized Black cotton soil

The XRD patterns of Black cotton soil treated with bioenzyme and untreated soil are shown in Figures 4 and 3 respectively.

The presence of montmorillonite, a high-swelling mineral, and quartz is observed in both graphs. The peaks of montmorillonite alone at 2θ of 19.0°, 29.50°, and 62.0°, and the quartz peaks at 2θ of 21.0°, 27.0°, and 43.0° were noted in both sets of data.

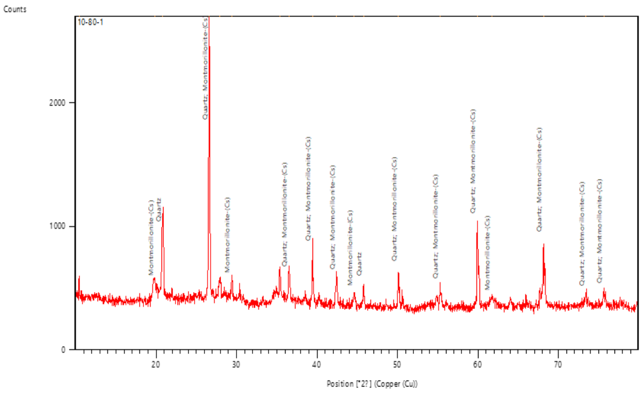

Figure 5: XRD image of conventional Black cotton soil

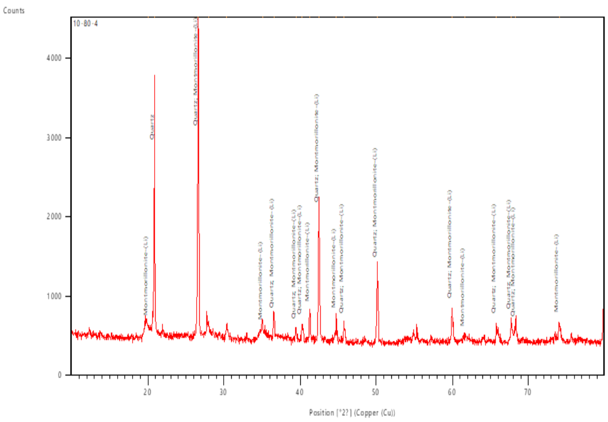

Figure 6: XRD image of stabilized Black cotton soil

he chemical composition of the stabilized soil shows an increased accumulation of silica, alumina, and metal oxides, which are critical in facilitating pozzolanic reactions that lead to the formation of cementitious compounds [15][16]. Table 3.1 presents the elemental composition of both conventional Black Cotton (BC) soil and bio-enzyme stabilized BC soil, highlighting the weight percentages of key elements.

In the stabilized BC soil, there is a decrease in sodium (Na) content from 1.4% to 0.89%, phosphorus (P) from 0.69% to 0.48%, sulfur (S) from 0.46% to 0.35%, potassium (K) content from

0.32% to 0.1%, calcium (Ca) from 1.74% to 1.54%, and a notable decrease in iron (Fe) content from 4.09% to 2.46% while a slight increase in magnesium (Mg) from 3.38% to 3.6%, aluminum (Al) content from 22.82% to 23.44%, and silicon (Si) content from 65.1% to 67.14%, in the stabilized BC soil. These changes in elemental composition reflect alterations induced by the stabilization process, illustrating shifts in the concentration of key elements within the soil.

Table 2: Chemical composition of conventional and stabilized BC soil

Element	Weight (%)	
	Conventional BC Soil	Stabilized BC Soil
Na	1.4	0.89
Mg	3.38	3.6
Al	22.82	23.44
Si	65.1	67.14
P	0.69	0.48
S	0.46	0.35
K	0.32	0.1
Ca	1.74	1.54
Fe	4.09	2.46

EDAX results that increase in accumulation of Silica, Alumina and oxide in stabilized BC soil which leads in forming cementitious compound by filling voids.

3.2 Lithomargic soil

3.2.1 SEM Results of Conventional and Stabilized Lithomargic Soil.

Following seven days of curing, the above figure displays the SEM images of both regular lithomargic soil and soil treated with the ideal dosage of bio-enzyme.The morphological differences are evident, with the bio-enzyme treated soil exhibiting a more compact and aggregated structure compared to the untreated sample. The treated soil shows enhanced interlocking between particles, which contributes to an increase in Unconfined Compressive Strength (UCS).

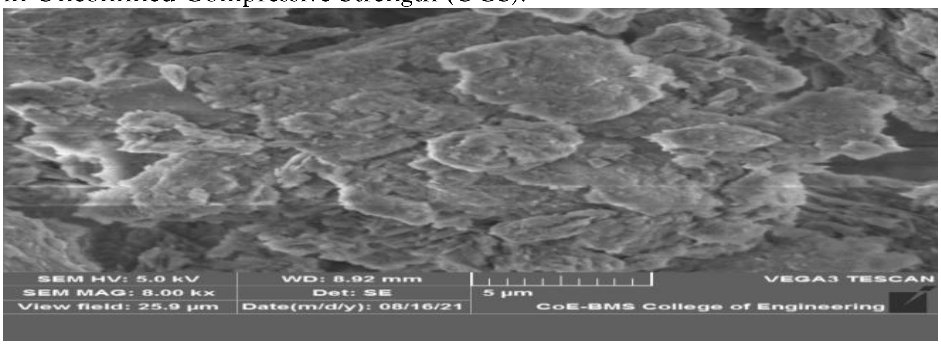

Figure 7: SEM image of conventional Lithomargic soil

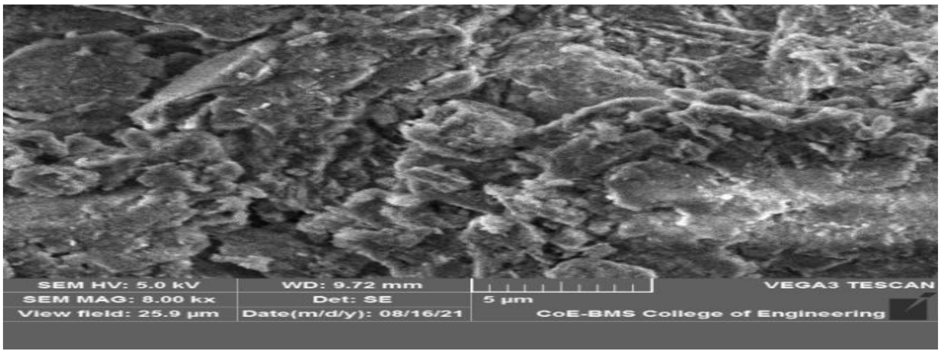

Figure 8: SEM image of stabilized Lithomargic soil

The SEM pictures of typical lithomargic soil and soil treated with the optimum amount of bio-enzyme after seven days of curing are shown in Figures 5 and 6.A comparative analysis reveals that the bio-enzyme treated soil (Figure 6) exhibits a distinct change in morphology compared to the untreated soil (Figure 5).

A denser microstructure as a result, a higher Unconfined Compressive Strength (UCS) of the soil are caused by the treated sample's increased interlocking and enhanced particle bonding between soil particles.

3.2.2 XRD results of conventional and stabilized Lithomargic soil The XRD pattern of untreated lithomargic soil and treated with Bio enzyme are shown in figure respectively. Both the graphs shows that the kaolinite and quartz are present. The peaks of kaolinite at 2θ of 21^0, 27^0 can be observed in both the figure 7 and 8. From both the figures it is clear that significant amount of quartz and kaolinite is present in both conventional and stabilized soil. Since the soil treated with Bio enzyme, there is no change in mineralogical characteristics of stabilized soil as displayed in figure 10.

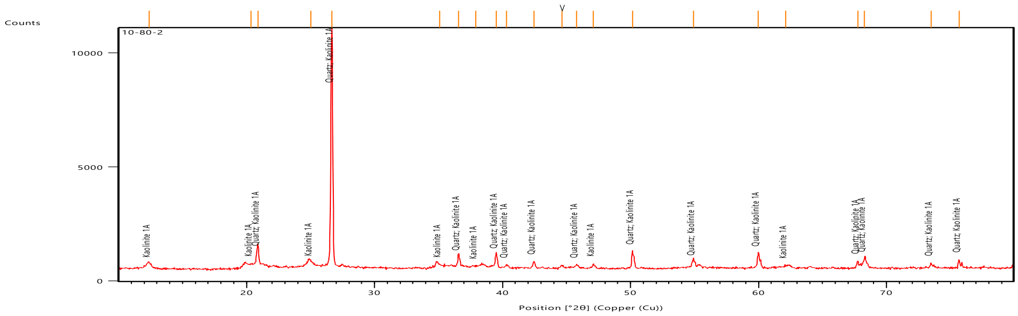

Figure 9: XRD image of conventional Lithomargic soil

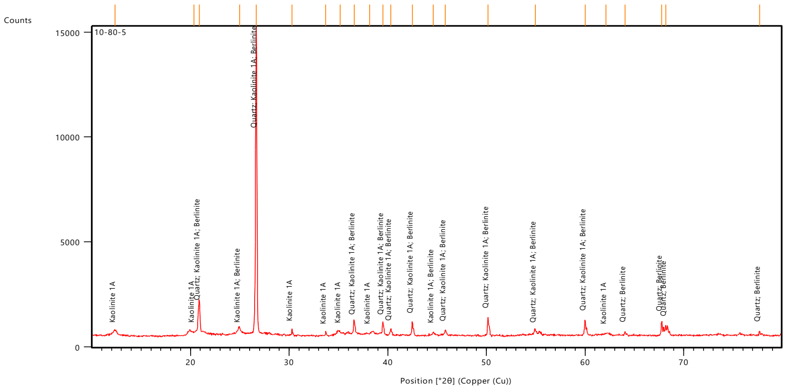

Figure 10: XRD image of stabilized Lithomargic soil

The chemical composition of conventional and treated soil obtained through EDAX analysis are seen in table 2. The composition of chemical of stabilized soil cured for 7 days shows increase in accumulation of iron content along with presence of calcium silicate hydrate interaction between soil particles and results in denser inter assembling of voids.

In the stabilized Lithomargic soil, there is a increase in sodium(Na) content from 0.90% to 1.73%, magnesium (Mg) from 1.12% to 1.23%, Potassium (k) from 0.58% to 1.29% and iron (Fe) from 3.78% to 8.29%, and a notable decrease in content sulphur (S) from 0.45% to 0.33%, Phosphorous (P) content from 0.39% to 0.26% potassium (K) content from 0.39% to 0.26, silicon (Si) content from 61.18% to 57.71%, in the stabilized lithomargic soil. These changes in elemental composition indicates changes induced by the stabilization process resulted in increase in shear strength of stabilized lithomargic soil.

Table 3: Chemical composition of conventional and stabilized BC soil

Element	Conventional lithomargic soil	Stabilized lithomargic soil
	Weight (%)	
Na	0.90	1.73
Mg	1.12	1.23
Al	31.60	28.48

Si	61.18	57.71
P	0.39	0.26
S	0.45	0.33
Ca	0.0	0.68
K	0.58	1.29
Fe	3.78	8.29

EDAX results shows that increase in accumulation of iron content with the presence of calcium silicate hydrate interaction between soil particles and results in denser inter assembly of voids.

3.3 Lithomargic soil

3.3.1 SEM Results of Conventional and Stabilized Red Soil.

Figures 9 and 10 display the SEM images of locally accessible soil and soil that has been treated with the ideal concentration of bio enzymes and allowed to cure for seven days. From the figure 10 it is evident that locally available red soil stabilized with optimum dosage soil shows change in morphology compared with conventional soil. The structure of soil treated with Bio enzyme shows reduction in pores forming more integrated structure of soil particles thus improving the interlocking property and the strength of stabilized soil.

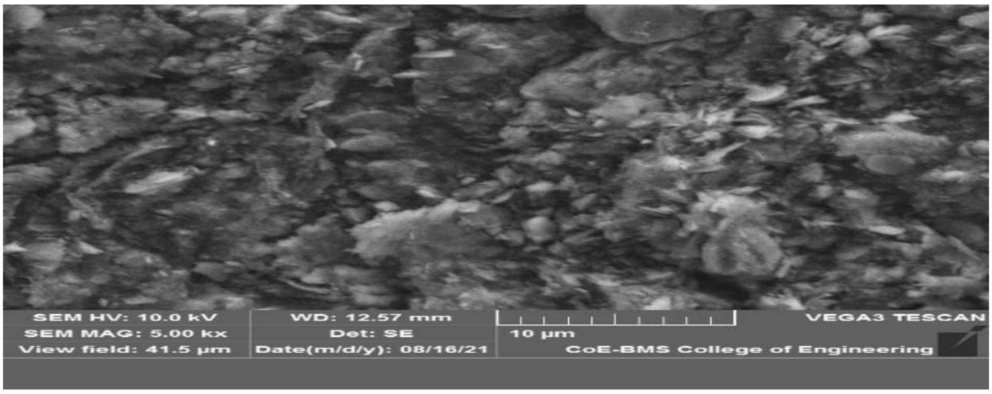

Figure 11: SEM image of conventional Red soil

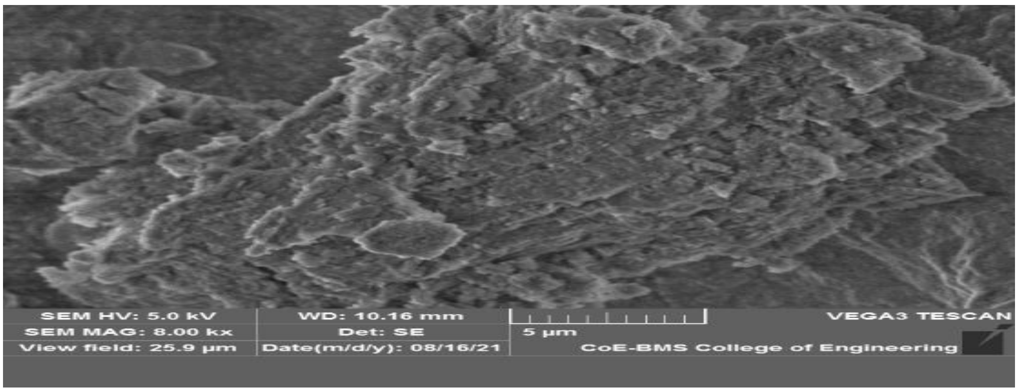

Figure 12: SEM image of stabilized Red soil

3.3.2 XRD results of conventional and stabilized Red soil

The XRD pattern of untreated locally available red soil and treated with Bio enzyme are shown in figure 6.15 and 6.16 respectively. Both the graphs shows that kaolinite and quartz are present. The peaks of kaolinite and quartz are similar in both the cases. It is observed from both the figures the peaks are at 2θ of 21^0, 27^0.From both the figures it is clear that significant amount of quartz and kaolinite is present in both conventional and stabilized soil. Since the soil treated with Bio enzyme, there is no change in mineralogical characteristics of stabilized soil as displayed in figure12

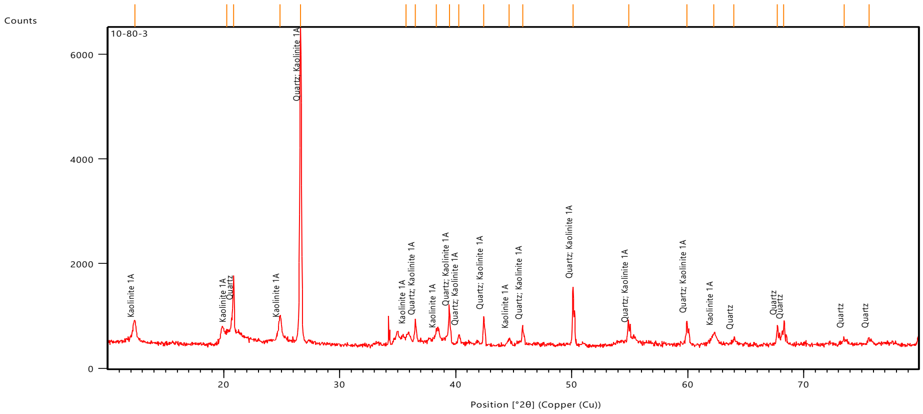

Figure 13: XRD image of conventional Red soil

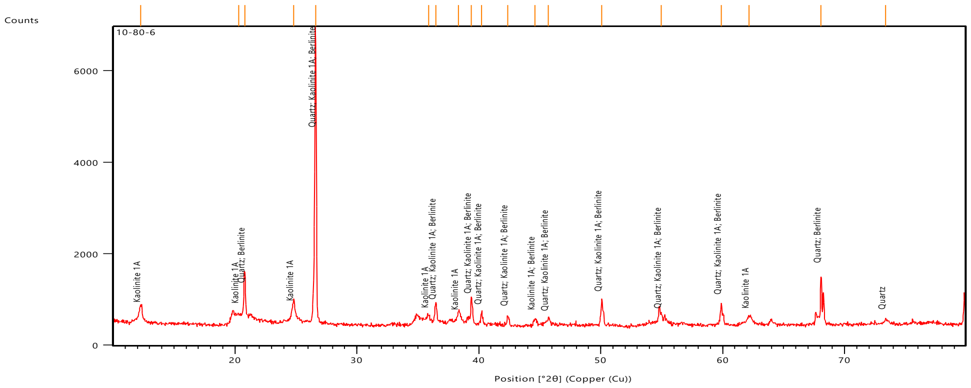

Figure 14: XRD image of stabilized Red soil

The chemical composition of conventional and treated soil obtained through EDAX analysis are shown in table 6.3. The chemical composition of stabilized soil cured for 7 days shows increase in accumulation of silica and iron content which plays a very important role in pozzolanic reaction which is primary source for forming cementitious compounds thus resulting in interfacial bonding between particles.

Table 4: Chemical composition of conventional and stabilized Red soil

Element	Conventional soil	Stabilized soil
	Weight (%)	
Na	1.79	1.20
Mg	1.04	1.94
Al	34.53	32.14
Si	58.70	60.77
P	0.44	0.36
S	0.21	0.01
K	0.32	0.05
Fe	2.97	3.53

In the stabilized red soil, there is a increase in magnesium (Mg) from 1.04% to 1.94%, silicon (Si) content from 58.70% to 60.77% and iron (Fe) from 2.97% to 3.53%., Potassium(k) from 0.58% to 1.29%, and a notable decrease in sodium(Na) content from 1.79% to 1.20%, sulphur (S) from 0.21% to 0.01%, Phosphorous (P) content from 0.44% to 0.36% potassium (K) content from 0.32% to 0.05, in the stabilized red soil. These changes in elemental composition indicates changes induced by the stabilization process resulted in increase in shear strength of stabilized red soil.

4.CONCLUSIONS

- In case of black cotton soil, Micro graph has shown that soil structure treated with bio enzyme shows formation of clusters as a result which transfers the individual soil particles in to integrated structure form.Black cotton soil contains quartz and montmorillonite, a high swelling mineral, according to the XRD pattern.
- EDAX results that increase in accumulation of Silica, Alumina and oxide in stabilized BC soil which leads in forming cementitious compound by filling voids.
- In case of Lithomargic soil, Micrograph shows that soil structure treated with bio enzyme shows good interlocking property between soil particles.XRD patterns show the presence of kaolinite and quartz in lithomargic soil.
- EDAX results shows that increase in accumulation of iron content with the presence of calcium silicate hydrate interaction between soil particles and results in denser inter assembly of voids.
- In case of locally available soil (Red soil), micrograph shows reduction in pores forming more integrated structure of stabilized soil. XRD pattern have shown that there is significant amount of quartz and kaolinite.
- EDAX results increase in accumulation of silica and iron content which plays a very important role in pozzolanic reaction and primary source for forming cementitious compounds thus resulting in interfacial bonding between particles.

5.REFERENCES

[1] A. A. Firoozi, C. G. Olgun, A. A. Firoozi, and M. S. Baghini, "Fundamentals of soil stabilization," International Journal of Geo-Engineering, vol. 8, no. 1, Dec. 2017, doi: 10.1186/s40703-017-0064-9.
[2] R. A. Velasquez, M. O. Marasteanu, and R. M. Hozalski, "Investigation of the effectiveness and mechanisms of enzyme products for sub-grade stabilization," International Journal of Pavement Engineering, vol. 7, no. 3, pp. 213–220, 2006.
[3] R. Renjith, D. J. Robert, C. Gunasekara, S. Setunge, and B. O'Donnell, "Optimization of enzyme-based soil stabilization," Journal of Materials in Civil Engineering, vol. 32, no. 5, May 2020, doi: 10.1061/(ASCE)MT.1943-5533.0003124.
[4] A. U. R. Shankar, "Bio-enzyme stabilized lateritic soil as a highway material," 2009. [Online]. Available: https://www.researchgate.net/publication/283120095
[5] D. C. Sekhar and S. Nayak, "SEM and XRD investigations on lithomargic clay stabilized using granulated blast furnace slag and cement," International Journal of Geotechnical Engineering, 2017. doi: 10.1080/19386362.2017.1351421
[6] J. Wu, L. Wang, and L. Meng, "Analysis of mineral composition and microstructure of gravel aggregate based on XRD and SEM," Road Materials and Pavement Design, vol. 18, pp. 139–148, Jul. 2017, doi: 10.1080/14680629.2017.1329869.
[7] G. P. Ganapathy, S. K. Sekar, B. K. Gnanavel, and V. Ramakrishnan, "Bio-enzymatic stabilization of a soil having poor engineering properties," International Journal of Civil Engineering, vol. 15, no. 3, pp. 401–409, May 2017, doi: 10.1007/s40999-016-0056-8.
[8] C. Venkatasubramanian and G. Dhinakaran, "Effect of bio-enzymatic soil stabilization on unconfined compressive strength and California bearing ratio," Journal of Engineering and Applied Sciences, vol. 6, no. 3, pp. 295–298, 2011.
[9] H. N. Ramesh and B. V. Manjunatha, "Justification of strength properties of microstructural changes in the black cotton soil stabilized with rice husk ash and carbide lime in the presence of sodium salts," SN Applied Sciences, vol. 2, no. 3, Mar. 2020, doi: 10.1007/s42452-020-2226-1.
[10]"Soil Map of India | Define Types of Soils in India." [Online].Available: https://www.mapsofindia.com/maps/india/soilsofindia.htm. [Accessed: Jan. 22, 2024].
[11] S. A. N. Mohd Yusoff, M. Azmi, and H. Ramli, "Laboratory investigation of Terrazyme as a soil stabilizer," in Proc. Int. Conf. Global Network for Innovative Technology (IGNITE), 2017, pp. 030014 (1–8).
[12] S. A. Ola, The geology and geotechnical properties of the black cotton soils of northeastern Nigeria, 1978.
[13] R. K. Etim, A. O. Eberemu, and K. J. Osinubi, "Stabilization of black cotton soil with lime and iron ore tailings admixture," Transportation Geotechnics, vol. 10, pp. 85–95, Mar. 2017, doi: 10.1016/j.trgeo.2017.01.002.
[14] S. E. Mousavi, "Utilization of silica fume to maximize the filler and pozzolanic effects of stabilized soil with cement," Geotechnical and Geological Engineering, vol. 36, no. 1, pp. 77–87, Feb. 2018, doi: 10.1007/s10706-017-0305-x.
[15] P. Akula and D. N. Little, "Analytical tests to evaluate pozzolanic reaction in lime stabilized soils," MethodsX, vol. 7, Jan. 2020, Art. no. 100928, doi: 10.1016/j.mex.2020.100928.
[16] S. Topolinski, "Unconfined compressive strength properties of a cement-organic soil composite," in IOP Conference Series: Materials Science and Engineering, vol. 471, no. 4, Art. no. 042018, Institute of Physics Publishing, Feb. 2019, doi: 10.1088/1757-899X/471/4/042018.
[17] K. M. N. S. Wani and B. A. Mir, "Unconfined compressive strength testing of bio-cemented weak soils: A comparative upscale laboratory testing," Arabian Journal for Science and Engineering, vol. 45, no. 10, pp. 8145–8157, Oct. 2020, doi: 10.1007/s13369-020-04647-8.
[18] Y. Yi, C. Li, and S. Liu, "Alkali-activated ground-granulated blast furnace slag for stabilization of marine soft clay," Journal of Materials in Civil Engineering, vol. 27, no. 10, pp. 04014146 (1–7), 2015, doi: 10.1061/(ASCE)MT.1943-5533.0001220.
[19] G. N. Eujine and S. Chandrakaran, "Accelerated subgrade stabilization using enzymatic lime technique," Journal of Materials in Civil Engineering, vol. 29, no. 9, pp. 04017085 (1–7), 2017, doi: 10.1061/(ASCE)MT.1943-5533.0001963.
[20] P. Agarwal and S. Kaur, "Effect of bio-enzyme stabilization on unconfined compressive strength of expansive soil," International Journal of Research in Engineering and Technology, vol. 3, no. 5, pp. 2321–7308, 2014.
[21] R. Brazetti and S. R. Murphy, "General usage of bio-enzyme stabilizers in road construction in Brazil," in Proc. 32nd Annual Meeting on Paving, Brazil, Oct. 2000