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Stabilisation of Black Cotton Soil Using Red Mud: An Alumina Extraction Byproduct

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Abstract

This study investigates the stability of Black Cotton (BC) soil which is known for its high shrinkage and compressibility difficulties in civil engineering by reinforcing it with Red Mud (RM), an industrial waste by-product from the Bayer aluminium process, and lime [Ca (OH)]. To address the issues of weak BC soil and industrial waste disposal, the BC soil sample was mixed with RM in increments ranging from 10% to 50%, and the effect of adding 4% lime was also investigated. The index and engineering characteristics of these stabilised soil combinations were tested during lengthy curing periods (0, 7, 14, 30, 60, 90, 180, and 365 days), filling a large gap in the literature about the long-term impacts of curing on expansive soils. Scanning Electron Microscope (SEM) examination was performed on the improved combinations to better understand the microstructural alterations that contribute to strength increases. The findings show, that the addition of 30% RM and 4% optimum lime greatly enhanced the engineering qualities of BC soil over time and the strength of the combination enhanced from 40.07 kN/m² to 116.31 kN/m² for immediate testing. Following a 365-day curing period, the UCS rose from 116.31 kN/m² to 615.49 kN/m², demonstrating the effectiveness of this stabilising method for engineering applications. As to the microstructural analysis, adding lime to a mixture of BCS and RM promotes a gradual densification process over time. 30% RM and 4% lime stabilisation efficiently transform the original loose, porous structure into a consolidated matrix with enhanced mechanical properties.

Major Findings: *The study demonstrated that incorporating RM along with lime significantly enhanced the geotechnical properties of BC soil. An extended curing period of up to 365 days improved soil strength and reduced expansiveness. SEM analysis highlighted microstructural transformations that played a major role in the stabilisation process.*

Keywords: Black Cotton (BC) Soil, Curing Period, Lime, Redmud (RM), Scanning Electron Microscope (SEM) and Unconfined Compressive Strength (UCS)

1.0 Introduction

BC soil is generally considered poor soil and causes damage to the structure due to its expansion and high compression properties. Fundamental characteristics of expansive soils are that their deformations are larger than their elastic deformations, and neither traditional elastic nor plastic theory can accurately predict them. Structures are under pressure when soils expand. They are strong enough to break walls, floors, and foundations. Though damage can occur at higher levels if soil expansion causes movement within the structure, the lower layers of the structure often sustain the most damage. As the earth dries and shrinks, harm may result if a structure is constructed while the soil is still expanding. Structural support may be weakened by soil shrinking. Buildings could collapse as a result of this if not properly addressed, movement, which typically occurs irregularly, will seriously harm the structure and pavements that are supported by soil. For example, light buildings and

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pavements may sustain more damage from expansive soil. By using different stabilising procedures, the expansive soils' engineering qualities must be improved to solve these issues. Numerous studies were conducted to analyse the effectiveness of fly ash, copper slag, brick waste, ceramic waste powder, stone slurry, sawdust and lime kiln dust with the soil stabilisation process[1-5]. Many researchers have completed several studies in this field. Expanding soils can be stabilised with admixtures to increase their strength and limit their capacity to alter volume.

Rapid development with industrialisation leads to problems in the disposal of waste products produced by the industries which causes environmental pollution. A rising nation's social and economic development depends on industrial activity, but it also produces a lot of solid and liquid waste. Industrialisation has led to an increase in garbage production and disposal, which is troublesome and requires attention. The production of industrial trash is increasing, which raises concerns about how to dispose of it and lessen its negative environmental effects. Many types of research are done on utilising the waste materials and concentrating on the feasibility and environmental suitability[5-10]. RM is a waste material of an industrial by- product, which is generated after the extraction of minerals from the aluminium industry. Disposal and management of RM is an important environmental issue of any mining industry during its project life because dump releases fine particles into the atmosphere as dust which causes air pollution. Gully erosion also occurs on the surface of RM dumps during the rainy season. It affects the nearby agricultural land and pollutes both surface and underground water sources. To reduce the disposal problem and the environmental[11] hazards, an attempt is made to examine the possibility of using RM as a useful material for geotechnical applications. Stabilisation is one of the effective methods to minimise the hazardous effects and to prevent the uncontrolled release of RM particles into the environment[12-14]. In the above study, RM is a waste industrial by-product which is used to alter and enhance the soil properties by adding some additives. Therefore, this study investigates the stabilisation of BC soil using RM and lime to make the soil durable and resistant to shrinkage and swelling.

2.0 Materials and Methodology

2.1 BC Soil

The Deccan plateau region of northwest India is home to most BC soils, sometimes called expansive soils. They are frequently observed in Maharashtra, Madhya Pradesh, Gujarat, and Karnataka. It encompasses more than 20% of India's land area. This black soil is known as



Figure 1. BC soil sample.

Table 1. Engineering and index properties of BC soil and red mud

Properties	BC Soil Value	Redmud Value
Colour	Black	Red
SG	2.57	2.88
Gravel (%)	10.26	0
Sand (%)	5.30	14.30
Silt (%)	5.01	7.30
Clay (%)	79.43	78.40
LL (LL) (%)	51.5	45.50
PL (PL) (%)	37.2	32.30
Plasticity Index (PI) (%)	14.3	13.20
IS Classification	CH	15.70
MDD in (KN/m^3)	15.60	20.71
OMC in (%)	23.05	118.46
UCS in KPa	67.97	15.70

BC dirt because it is ideal for growing cotton. It contains various clay minerals, including iron, magnesium, and montmorillonite. The BC soil (Figure 1) used in this investigation came from the Davangere District in Karnataka State, India.

The Engineering and index properties of BC soil are shown in Table 1.

2.2 Redmud

RM is an industrial waste produced during the Bayer process, which turns bauxite ore into aluminium. India produces more than 4.7 million tons of RM annually. When RM material is disposed of without appropriate procedures, it poses numerous health risks. It is a very alkaline substance that contains complex silicates, calcite, gibbsite, goethite, and hematite. RM (Figure 2) was acquired for the current study from HINDALCO (Hindustan Aluminium Corporation), located in Belagavi, Karnataka, India.



Figure 2. RM sample.

2.3 Lime [Ca (OH)$_2$]

Lime improves the soil's ability to bind. The most often used kind of lime for stabilising the soil is hydrated lime, or [Ca(OH)$_2$]. The source of lime used in this investigation was sourced from Nice Chemicals Private Ltd. in Kochi, Kerala State, India.

In the study, 4% lime is taken as an optimum percentage with the combination. 4% lime is obtained from the experimental investigation done by finding Atterberg's limit with BC soil by varying 1-8 % lime.

2.4 Methodology

The BC soil was treated with RM and lime before the experimental study was conducted. The work was divided into two groups: BC soil + RM (ranging between 10 and 50%) and BC soil + RM (varying between 10 and 50%) + 4% Lime. In this case, 4% lime was used since it is the ideal amount obtained by the experiment conducted by varying 1 to 8 % lime to the weight of BC soil. Specific Gravity (SG), Atterberg's limits, compaction test, and UCS test were used for investigations. Every experiment was conducted in compliance with Indian standards and guidelines. The best combinations were found and Scanning Electron Microscopy (SEM) analysis was done for the combinations.

3.0 Results and Discussions

3.1 Specific Gravity (SG)

The SG of the combinations, BC soil added with varied percentages of RM and lime were determined by density bottle method and the outcome derived are in Table 2. SG value rises with a rise in the percentage of the RM and the SG increases more when lime is added.

Table 2. SG of BC soil with different percentages of RM

Mixtures	Specific Gravity
BC Soil Alone	2.53
RM Alone	2.88
BC SOIL+10% RM	2.65
BC SOIL+20% RM	2.67
BC SOIL+30% RM	2.68
BC SOIL+40% RM	2.69
BC SOIL+50% RM	2.71
BC SOIL+10% RM+ 4%LM	2.53
BC SOIL+20% RM+ 4%LM	2.58
BC SOIL+30% RM+ 4%LM	2.59
BC SOIL+40% RM+ 4%LM	2.62
BC SOIL+50% RM+ 4%LM	2.75

3.2 Atterberg's Limit

The Atterberg's limit includes LL, PL and SL. Tests were carried out to find the Atterberg limit values for both combinations.

3.2.1 Liquid Limit (LL)

LL test was conducted on BC soils supplemented with different percentages of RM and lime. LL for BC soil and RM alone were 58.4% and 50.5% respectively during the immediate testing. Addition of 10% red mud to BC soil, LL reduced to 49.7%. As the percentage of red mud increased to 50%, LL decreased further to 46.5%. Addition of 10% RM and 4% lime to BC soil, LL reduced to 43.2%. As red mud increased to 50% and lime to 4%, LL further decreased and the immediate test showed LL to be 40%. The decrease in LL is because of the reduction in the difference in thickness between the layers, which results in reduced water retention[15].

This is due to the addition of fine-grained BC soil with red mud mixture. As the treatment time increases, the LL of BC soil decreases up to 50% with red mud, which results in reduced flocculation and less water formation in large pores of the sample. As the red mud increases, the flocculation effect gradually weakens. The changes in LL of BC soil with combinations are given in Table 3.

3.2.2 Plastic Limit (PL)

The PL of BC soil is 30.1% and the addition of 10% RM to BC soil reduced the PL to 25.90% immediately after the test. Moreover, the PL of BC soil continued to decrease as the percentage of RM increased to 50%. With the addition of 10% RM and lime percentage in BC soil, the PL dropped to 29.40%. The reduction in the PL leads to a decrease in the thickness of the diffusion layer and mixing of particles. With the curing time, the PL of BC soil, and RM mixture increased because of the flocculation and rise in water content in the large voids of the flocculated sample. The PL of BC soil, RM and lime mixture increases when the flocculation and water content in the large area of the flocculation sample increases[16,17]. The change in PL with RM and lime at different periods is given in Table 4.

Table 3. LL of BC soil and RM mixtures with curing

Mixtures	LL (%)			
	Curing period in days			
	0	7	14	30
BC SOIL alone	58.4	-	-	-
RM alone	50.5	50.1	49.8	49.6
BC SOIL+10%RM	49.70	48.1	47.9	47.7
BC SOIL+20%RM	48.60	47.2	46.6	45.9
BC SOIL+30%RM	47.60	46.8	45.3	44.5
BC SOIL+40%RM	47.10	45.4	45.1	44.2
BC SOIL+50%RM	46.50	42.4	43.5	43.7
BC SOIL +10%RM+4% LIME	43.2	41.6	41.4	41.2
BC SOIL +20%RM+4% LIME	42.1	40.7	40.1	39.4
BC SOIL +30%RM+4% LIME	41.1	40.3	38.8	38
BC SOIL +40%RM+4% LIME	40.6	38.9	38.6	37.7
BC SOIL +50%RM+4% LIME	40	35.9	37	37.2

Table 4. PL of BC soil and RM mixtures for various curing periods

Mixtures	Curing period days			
	0	7	14	30
BC SOIL alone	8.4	-	-	-
RM alone	14.5			
BC SOIL+10%RM	14.16	14	13.91	13.78
BC SOIL+20%RM	15.56	14.66	14.56	14.86
BC SOIL+30%RM	15.96	15.26	15.16	15.46
BC SOIL+40%RM	15.66	15.16	15.56	17.26
BC SOIL+50%RM	17.26	15.66	17.26	16.66

3.2.3 Shrinkage Limit (SL)

The SL of BC soil alone is 8.40%. With the incorporation of 10% RM into the BC soil, the lower limit increased to 14.16%. As the RM content was raised to 50%, the SL further increased to 17.26%. Because of the flocculation of clay particles, the SL of BC soil and RM combination increased for immediate lime treatment testing.

SL rises with curing. This implies that the flocculation of clay particles is enhanced by the addition of lime both immediately and during the curing process[18,19]. The rise in SL is brought on by flocculation brought on by cation exchange and particle agglomeration responses with curing. The SL somewhat increases as the cure period increases[20,21]. After extended curing, this causes the particles to aggregate and increases the diluting effect of flocculation; the longer the curing period, the higher the SL. The change in the SL of expanded BC Soil added with RM at different periods is given in Table 5.

3.3 Compaction Characteristics

Following Indian standards, the Standard Proctor Test (SPT) and mini-compaction test apparatus were used to find the compaction characteristics of all the combinations.

Table 5. SL of BC soil and RM mixtures with curing

Mixtures	Curing period days			
	0	7	14	30
BC SOIL alone	8.4	-	-	-
RM alone	14.5			
BC SOIL+10%RM	14.16	14	13.91	13.78
BC SOIL+20%RM	15.56	14.66	14.56	14.86
BC SOIL+30%RM	15.96	15.26	15.16	15.46
BC SOIL+40%RM	15.66	15.16	15.56	17.26
BC SOIL+50%RM	17.26	15.66	17.26	16.66

The change in Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of BC Soil added with various amounts of RM are shown in Table 6.

Table 6. Compaction characteristics of BC Soil treated with different percentages of RM

Mixtures	MDD (kN/m^3)	OMC (%)
BC SOIL alone	15.8	25.9
RM alone	15.7	22.25
BC SOIL+ 10% RM	16.1	23.4
BC SOIL+ 20% RM	16.6	21
BC SOIL+ 30% RM	16.8	20
BC SOIL+ 40% RM	16	24
BC SOIL+50% RM	16.3	22
BC SOIL+10%RM+4% LIME	16.20	27.27
BC SOIL+20%RM+4% LIME	16.80	23.53
BC SOIL+30%RM+4% LIME	16.30	24.00
BC SOIL+40%RM+4% LIME	17.00	24.87
BC SOIL+50%RM+4% LIME	16.80	25.34

The MDD BC Soil are and 25.9%, When 10% and OMC of 15.8 kN/m^3 respectively. of RM is added to BC soil, the MDD slightly increases to 16.1 kN/m^3 and OMC decreases to 23.4%. When the amount of RM is increased and mixed with BC Soil the MDD increases and OMC decreases. This variation is the result of the repulsive nature of the soil and accordingly the prevention of compaction[22]. Although the weight of red mud residues is greater the soil becomes more compact. The reduction in the discontinuity rate was more striking with the rise in MDD. When the back pressure decreases OMC gradually decreases and the OMC of the mix decreases with the addition of red mud with low absorption capacity. Adding 4% lime to the mix increased the MDD to 16.2kN/m^3 and OMC to 27.27%. With the rise in red mud, MDD increases with a marginal increase in OMC. The rise in MDD and OMC is attributed to the clay which prevents consolidation[23], while the improvement in the OMC may lead to the increase in additional water stored in flocculant soils.

3.4 Strength Behaviour

The unconfined compression strength tests were conducted as per IS: 2720 (part 10)-1973 first revision using an unconfined compression test apparatus at a strain rate of 1.25 mm/min. The specimen to be tested was placed centrally in between the lower and upper platforms of the testing machine. The proving ring readings were noted for each 20 divisions on a deformation dial gauge. The loading was continued until three or more consecutive readings of the load dial showed a decreasing or a constant load or a strain of 20% had been reached.

The UCS test for the combinations was carried out for various curing periods for immediate test followed by 7, 14, 30, 60, 90, 180 and 365 days. The UCS of the BC Soil is 40.07 kN/m^2 for instantaneous testing. In addition to 10-50% by weight of RM to BC soil, the strength increased from 40.07 kN/m^2 to 116.07 kN/m^2 for immediate testing. At 30% of adding RM to the BC soil, the strength rises to 450.51 kN/m^2, thereafter the combination strength marginally decreases. The reduction in the strength of BC soil beyond 30% adding of RM may be due to weak bonding between the soil particles of BC soil with RM or may lead to the rise in the thickness of the diffuse double layer, thereby leading to a decrease in strength[24,25]. Hence, 30% of RM to the BC soil has been chosen as the optimum percentage. The variations of strength by adding various quantities of RM varying from 10 to 50% are as given in Table 7. The addition of 4% of lime content was considered as the optimum percentage. This is attributed to the gain in strength with lime-treated mine tailings with BC soil involves two reactions such as hydration and pozzolanic reaction[26,27]. The hydration of lime dissociates in the water and produces calcium hydroxide. As a result, the pore fluid's pH and calcium content rises.

The strength obtained for various combinations is listed below. The hydrous alumina present in RM slowly reacts with calcium ions found in lime to produce insoluble compounds of Calcium Alumina Hydrate (CAH Secondary cement type products) and this secondary reaction is called the pozzolanic reaction, which contributes to the rise in the strength[28,29]. The

Table 7. UCS of BC soil for different curing days

UCS (kN/m²)								
	Curing period in days							
Mixtures	**0**	**7**	**14**	**30**	**60**	**90**	**120**	**365**
BC SOIL alone	40.07	53.62	51.77	61.07	38.53	51.53	51.83	40.07
BC SOIL+10% RM	56.2	74.37	110.74	191.44	132.0 2	58.95	59.73	308.7
BC SOIL+20%RM	115.6 0	150.69	124.62	92.41	129.4 6	61.3	77.64	230.17
BC SOIL+30%RM	116.0 7	175.97	178.32	221.40	167.8 5	133.61	158.0 6	450.51
BC SOIL+40%RM	119.9 3	140.68	149.63	188.83	156.8 3	126.09	140.0 8	324.55
BC SOIL+50%RM	109.5 7	168.38	98.86	104.25	114.6 4	75.44	77.55	379.86
BC SOIL+10%RM+4% LIME	108.5 3	43.97	117.21	211.87	204.6 0	208.05	249.6 2	478.85
BC SOIL+20%RM+4% LIME	112.8 3	69.03	262.62	125.76	231.3 5	186.56	262.9 8	455.88
BC SOIL+30%RM+4% LIME	116.3 1	145.01	137.68	204.8	388.3 3	333.91	344.4 4	615.49
BC SOIL+40%RM+4% LIME	108.8 3	219.64	213.44	121.55	216.4 7	268	264.9 5	570.02
BC SOIL+50%RM+4% LIME	66.55	62.78	372.05	129.70	207.9 1	245.93	262.9 8	566.59

variation of the strength of BC soil mixed with varying percentages (10-50 %) of RM with optimum lime is given in Table 7.

3.5 Mineralogical and Morphological Analysis

Tests using a scanning microscope (SEM) were performed to examine the stabilised soils' structural behaviour. Finding the changes in the mineralogical phases brought on by pozzolanic reactions requires a mineralogical examination of the stabilized soil that has been treated. The chemical and mineralogical makeup of each soil as well as the additives affect these interactions. The geotechnical characteristics and mechanical behaviour of these stabilised soils are greatly influenced by the microstructural and microstructural development changes brought about by the addition of additives[30]. The current study examined the alterations in the microstructural and mineralogical characteristics of fine-grained expansive black cotton soil treated with RM and lime.

The experiment result of BC soil mixed with 30% RM and lime combination achieves the highest strength when compared to the other combinations added to BC soil. SEM analysis was conducted for BC soil, 30% RM and 4% lime combinations for random three curing periods. Figure 3 consists of a series of SEM micrographs showing the microstructural evolution of a mixture of BC soil, RM and lime over different time intervals: 7 days, 120 days, and 365 days. The micrographs are taken at different magnifications: 20µm, 50µm and 500µm. The addition of lime to RM is expected to improve its cohesive properties and hence, increase its compressive strength[30]. The UCS

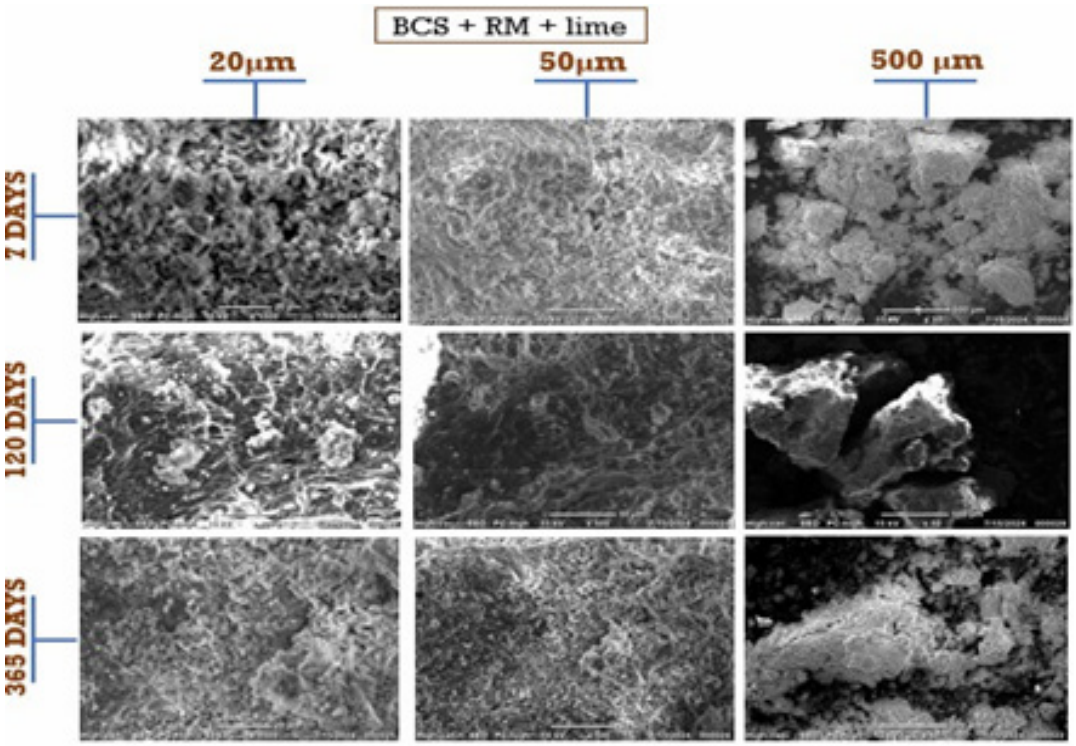


Figure 3. SEM images of expansive BC soil treated with RM and lime.

of BC soil is 40.07 KN/m^2 on immediate testing. In addition to RM and optimum lime, the strength increased marginally to 116.07 KN/m^2 on immediate testing and strength further increased to 344.44 KN/m^2 and 615.49 KN/m^2 respectively for 120 days and 365 days of curing period as shown in Table 7. The purpose of these images is to observe the change in the material's morphology over time because of the chemical reactions and physical changes within the mixture.

Figure 4, 5, 6 shows the Energy Dispersive X-Ray Spectroscopy (EDS) micrographs of RM with lime for 7 days, 120 days and 365 days of cured samples are studied and the EDX of the combinations are explained. The most prominent peaks correspond to elements with the highest

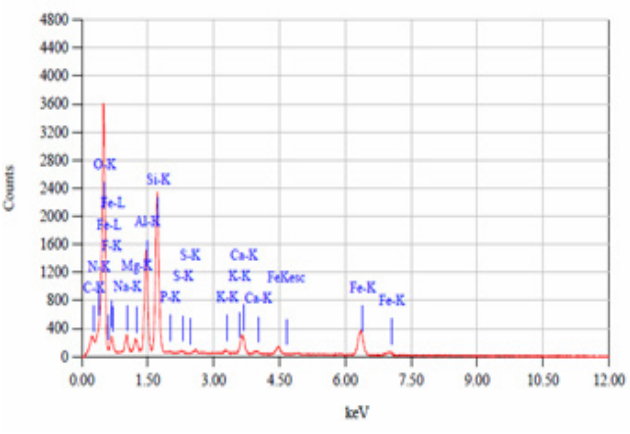


Figure 4. EDS micrograph of BC soil, RM and lime for a 7-day curing period.

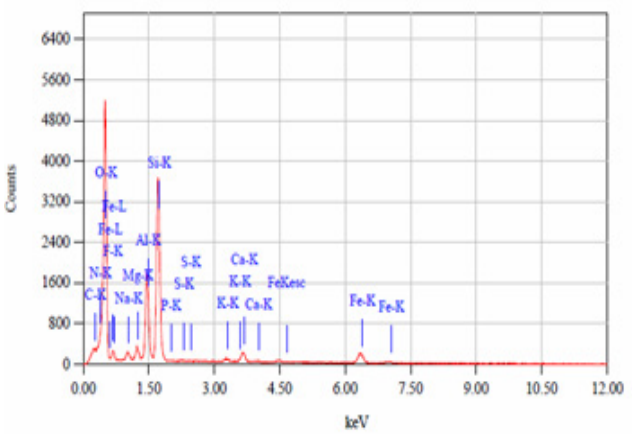


Figure 5. EDS micrograph of BC soil, RM and lime for 120 days of curing period.

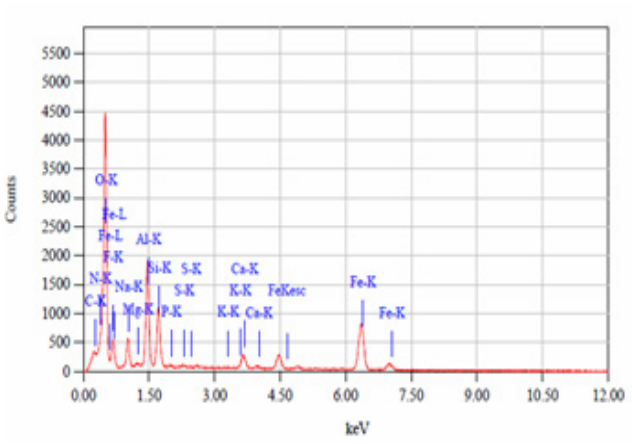


Figure 6. EDS micrograph of BC soil, RM and lime for a 365-day curing period.

concentration in the sample. For instance, the O-K peak (oxygen) is the more intense and it suggests a high oxygen content. The occurrence of multiple peaks for elements like iron (Fe-L, Fe-K) indicates the detection of both L and K emission lines, suggesting that the sample contains a significant quantity of iron. Peaks for lighter elements like carbon (C-K), sodium (Na-K), and magnesium (Mg-K) are also present, indicating their presence in the sample, though in lower quantities compared to oxygen and iron. The spectrum shows peaks for silicon (Si-K), aluminium (Al-K), and sulphur (S-K), suggesting these elements as a part of the sample's composition.

The EDX spectrum gives a detailed view of elemental composition which shows that it is rich in oxygen, silicon, and iron, with observing contributions from other elements like aluminium, magnesium, calcium and Sulphur. The composition shows that the sample is likely a natural mineral or an industrial material with diverse elemental constituents.

4.0 Conclusion

This study assessed how lime and RM affected the BC Soil's Liquid Limit (LL) across various curing times. According to the findings, RM considerably decreased the LL of BC soil, suggesting increased stability and decreased flexibility. The LL dropped as the RM percentage rose; the biggest drop was seen at 50% RM. This implies that RM can successfully reduce BC soil's LL, which may help with soil stabilization initiatives in engineering applications.

The PL of BC Soil rose with the addition of RM and 4% lime during all curing times, with a discernible increase over time. This rise is probably the result of the pozzolanic interaction between the soil and lime, which enhances the soil's range of flexibility and structural integrity, making it more resilient and appropriate for use in engineering applications. After 30 days of curing, the mixture containing 50% RM and 4% lime had the highest PL, demonstrating the beneficial stabilizing impact of lime when combined with RM.

RM significantly raises the SL of BC soil, suggesting a lower chance of shrinking and a higher resilience to volume changes during drying. This impact was most noticeable at increasing RM percentages, where the SL steadily improved in comparison to untreated BC soil, reducing the soil's vulnerability to cracking caused by shrinkage. The SL values were also affected by the curing process; changes were noted over time for various RM percentages. After 30 days of curing, mixtures containing 40% and 50% RM showed an increase in SL, indicating that longer curing improves soil stability by further reducing shrinkage. These results demonstrate how well RM stabilises BC soil, increasing its suitability for building, particularly in regions where shrinkage and swelling occur.

The findings showed that adding RM to BC soil increased its MDD and somewhat decreased its OMC, suggesting improved compaction properties. More specifically, adding up to 30% RM increased MDD and decreased OMC, indicating better soil density and structure. According to these results, BC Soil can be stabilised and its compaction qualities improved with a balanced addition of RM and lime. This is advantageous for the soil's possible application in infrastructure and building projects.

The addition of RM and 4% lime both considerably increase the UCS value. Combinations of BC soil, RM, and 4% lime were used to assess the effect of curing on UCS. The longer the curing period, the higher the UCS value. The soil-RM and lime mix with a 30% RM and 4% lime combination yielded the highest UCS. From 40.07 kN/m^2 to 116.31 kN/m^2 for immediate testing. Following a 365-day curing period, the UCS rose from 116.31 kN/m^2 to 615.49 kN/m^2. Therefore, compared to soil and RM combinations, soil-RM-4% Lime combinations provide greater UCS strength.

As to the microstructural analysis, adding lime to a mixture of BCS and RM promotes a gradual densification process over time, leading to a more compact and stable structure after 365 days. This is a sign of hydration and pozzolanic processes, which progressively strengthen the matrix and decrease porosity. When long-term stability and durability are needed, such microstructure enhancements may increase the material's potential for use in waste immobilisation, soil stabilisation, or building. This work demonstrates that, over the span of a year, lime stabilisation efficiently transforms the original loose, porous structure into a consolidated matrix with enhanced mechanical properties.

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6.0 Author Contributions

Supriya M J: Conceptualisation, data curation, methodology, investigation and writing the original draft. A J Krishnaiah: Supervision and report editing. Authors have agreed to publish the version of the manuscript.

7.0 Author Designation

M. J. Supriya: Research scholar
A. J. Krishnaiah: Research supervisor

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