Research Article

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

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Abstract
Black cotton soils exhibit high shrinkage and swelling characteristics due to the variation in moisture content. To overcome this problem, many techniques are adopted, among which is the soil stabilization technique. Rapid industrialization and urbanization lead to the generation of waste products; the major by-products are rice husk ash (RHA) and carbide lime (CL). These by-products show excellent pozzolanic property. In this paper, an attempt has been made to stabilize black cotton soil with rice husk ash (RHA) along with carbide lime (CL) and other additives. Based on strength test results, the optimum dosage of RHA and CL was found to be 20% and 8%, respectively. The effect of sodium salts on index properties and unconfined compression strength (UCC) test at different moulding water contents for immediate testing and at different days of curing are studied. Results show that plasticity index of the soil treated with additives was decreased both for immediate and for 7 days of curing period due to the decrease in diffuse double-layer thickness. Soil–RHA–CL composite treated with 1% sodium chloride and 1% sodium hydroxide improves the Unconfined compression strength and shows a better strength compared to carbide lime-treated soil due to the formation of alkali silicate and alkali aluminate hydrated gel along with other cementitious products. The microstructural changes in the stabilized composite can be observed with XRD and SEM analysis. The addition of carbide lime and salts binds the particle with hydrated gel and shows denser environment compared to unstabilized soil.

Keywords Black cotton soil · Rice husk ash · Carbide lime · Unconfined compression strength · Moulding water content

1 Introduction

Expansive black cotton soils (BC soil) in India are suitable for agriculture purposes. The presence of montmorillonite mineral causes high changes in volume due to the influence of moisture content. The alternate swelling and shrinkage due to moisture fluctuations caused by seasonal variations lead to the damage in lightly loaded structures, such as buildings, pavements and pipelines, which are founded on them. Hence, stabilization of such problematic soil is required. Several methods are available to stabilize the BC soil; however, chemical stabilization is accepted to stabilize fine-grained soils [1]. Paddy is one of the major agricultural products of Asian countries. Paddy is milled in order to obtain the carbohydrate-rich raw food known as rice. To enrich the food value, the husk must be removed. Commercial-scale enrichment process is generally carried out in mills. In mills, paddy is converted into three major parts, namely rice grain, bran and husk. Rice grain is used for the production of a range of food products. The oil manufactured from bran, also known as rice bran oil, can be used

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as food as well as a blending agent in lamp oils. The husk is either sold out or fired to generate power for milling operations. The firing process results in a final residue known as ash which is a rich source of amorphous silica. From available literatures regarding rice milling operations, for every 1000 kg of paddy milled, about 220 kg (22%) of husk is produced, and upon burning this quantity of husk, about 55 kg (25%) of ash is generated. Ash residue which accounts for 20% of the 649.7 million tons of rice produced annually worldwide. Rice husk ash (RHA) is available abundantly in India. The annual production of paddy in India is about 100 million tons out of which 4 million tons of RHA is produced annually [2]. Hence, RHA is a major non-hazardous waste and excellent pozzolanic material which can be used effectively in improving the geotechnical properties of soil. However, strength of the RHA-stabilized soil is minimum due to lack of lime content [3]. Hence, calcium-rich additives form excellent pozzolanic products. Carbide lime (CL) is a by-product of acetylene gas production and is produced 2 million tons annually. CL is composed of 70–80% of calcium hydroxide and it resembles the properties of lime and cement [4]. Strength of BC soil treated with lime results in the formation of gelatinous products; lime reacts with water and leads to calcium hydroxide which increases the pH of the solution. The increase in pH dissolves alumina and silica from the soil and RHA composite, leading to the formation of hydrated products. Hydrated products which bind together with soil particle lead to the increases in the strength of soil. Strength of BC soil treated with lime is more on the dry of optimum due to the existence of the flocculated structure, and also enhancement in the strength is observed with the addition of two other materials such as RHA and lime [5, 6]. The addition of industrial and agro-industrial waste such as carbide lime–biomass ash mixture, fly ash and lime mixture along with salts acts as a cementing agent for improving strength of a clayey soil [7–11]. This leads to the development of a large volume of alkali silicates and aluminate hydrated products as opposed to calcium hydrated products. Strength enhancement is better for sodium hydroxide when compared to sodium chloride. This due to amplified pH with sodium hydroxide reacts with additional silica and alumina can produce alkali silicate hydrated gel along with the C-S-H and C-A-S-H. Water–binder ratio is an important factor for strength-gaining process of stabilized soils, especially for pozzolanic reactions involved. To form cementitious compounds through pozzolanic reaction, the available quantities of calcium hydroxide, water, pozzolanic materials as well as their relative proportions are important factors. The further acceleration in the strength of the stabilized composite can be achieved by adding accelerators such as sodium chloride and sodium hydroxide. These accelerators dissolve additional silica and alumina from the composite and lead to the development of additional alkali silicate products. The addition of accelerator such as NaCl leads to large voluminous pozzolanic products which can bind silica particles with high water content, leading to augmented strength [12]. However, studies related to RHA and CL on the strength-gaining process at different moulding water contents were limited. Therefore, an attempt has been made to study the microstructural changes in the stabilized composite which is responsible for the enhancement of the strength properties of soil.

2 Materials and Methodology

2.1 Materials

Materials procured from the sites and their preparation for the study are presented below.

2.1.1 Black cotton soil (BC soil)

BC soil was sampled from an open pit of 1.5 m below the natural ground level from Hubli, Karnataka State, India. The soil was air-dried and pulverized in a ball mill after separating the pebbles and sieved through 425 micron. The basic properties of BC soil are shown in Table 1.

2.1.2 Rice husk ash (RHA) and carbide lime (CL)

RHA was collected from Davanagere district, and carbide lime is collected from an oxyacetylene gas welding plant

Table 1 Basic properties of BC soil

Sl No	Properties	Value
1	Colour	Black
2	Particle size distribution	
	Fine sand (%)	4
	Silt (%)	36
	Clay (%)	60
3	Specific gravity	2.65
4	Consistency limits	
	W_L (%)	91
	W_P (%)	39
	S_L (%)	11
5	BIS soil grouping (Bureau of Indian Standard)	CH
6	Compaction parameters	
	OMC (%)	32
	MDU (kN/m^3)	13.00
7	Unconfined compression strength (kPa)	180

at Karnataka State, India, which is in amorphous form. Both RHA and CL are air-dried and passed through 425 micron, and they are oven-dried at 105^0 C for a period of 24 h; physical properties and chemical composition of RHA and CL are shown in Tables 2 and 3. Gradation curves of expansive BC soil and RHA were determined from the grain size analysis, and results are shown in Fig. 1.

2.1.3 Sodium chloride and sodium hydroxide

Chemically pure sodium chloride and sodium hydroxide are used to know the consequence of brackish water on geotechnical properties of BC soil–RHA composite. 1% sodium chloride is added along with carbide lime. In general, maximum salt content in a soil mass does not exceed 1% based on mass of solids. The powerful base sodium hydroxide is capable of forming sodium silicates, by reacting with silica present in RHA. However, higher dosage (exceeding 1%) of sodium hydroxide is not economical [13]. Hence, sodium salts of 1% were used in this study for BC soil–RHA composite.

2.2 Methodology

Index properties and unconfined compression tests for BC soil with varying percentages of RHA and CL along with sodium salts are tested as follows. To arrive optimum percentage of additives, samples were prepared with varying percentages of RHA form 5 to 40%. Similarly CL was added in an increment of 2% up to 16%.

2.2.1 Consistency limits

The consistency limits were determined by following the procedures given in IS: 2720 (Part V)-1985 [14].

2.2.2 Compaction test

The compaction experiment was carried out using mini compaction test device (Sridharan and Sivapullaiah [15]).

Table 2 Physical properties of RHA and CL

Sl. no.	Physical properties	RHA	CL
1	Colour	Grey	Greyish white
2	Specific gravity of solids	1.95	2.1
3	Compaction parameters		
	OMC (%)	84	–
	MDU (kN/m^3)	4.5	–
4	Grain size distribution		
	Silt size (%)	72	94
	Clay size (%)	18	6

Table 3 Chemical composition of RHA and CL

Chemical composition	CL quantity %	RHA quantity %
Silica (SiO_2)	5.71	85
Alumina (Al_2O_3)	2.61	2.5
Ferric oxide (Fe_2O_3)	0.72	0.5
Calcium oxide (CaO)	83.1	1
Magnesium oxide (MgO)	0.8	0.5
Sodium oxide (Na_2O)	0.05	0.3
Potassium oxide (K_2O)	0.08	0.2
Others	0.29	–
Loss on ignition	5.71	11

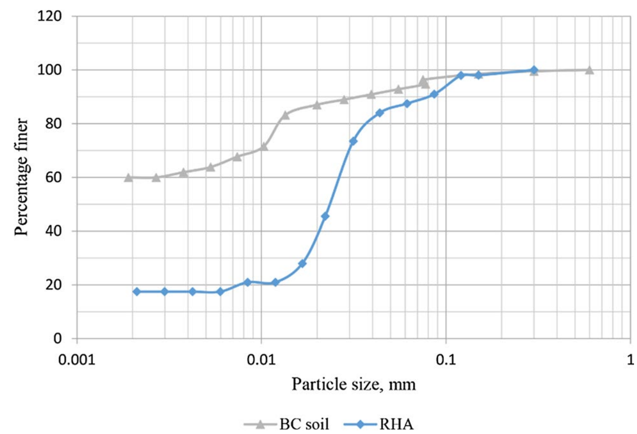

Fig. 1 Gradation curve of BC soil and RHA

2.2.3 Unconfined compression strength test

Unconfined compression strength (UCC) of soil alone as well as the stabilized soil mix was determined as per the procedures IS: 2720 (Part X)-1973 [16].

2.2.4 Preparation of soil sample for unconfined compression strength test

Samples were prepared by incorporating the maximum dry unit (MDU) weight and optimum moisture content (OMC) from the compaction curve and stabilizers such as RHA and CL were mixed to the soil on weight basis of the total soil sample. Tests were carried out at two stages: (1) to arrive optimum dosage of the additives and (2) to know the effects of stabilizers on strength properties of BC soil at different moulding water contents.

For the first series, soil is mixed with varying percentages of RHA on weight basis and UCC tests were

Table 4 Compaction characteristics of expansive BC soil–RHA mixtures

RHA (%)	OMC (%)	MDU (kN/m3)
0	32	13.00
5	33	13.00
10	33	13.00
15	34	12.85
20	34	12.75
25	35	12.55
30	36	12.36
35	37	12.16
40	39	11.77

Table 5 Compaction characteristics of soil and optimum RHA mixture treated with CL

CL (%)	OMC (%)	MDU (kN/m^3)
0	34	12.75
2	34	12.75
4	34	12.65
6	35	12.55
8	36	12.36
10	36	12.36
12	37	12.16
14	37	12.06
16	38	11.96

performed for pre-curing and curing period of 1 week. For the second series, soil is mixed with optimum percentage of additives at three different moisture contents and UCC tests were determined for different curing periods. Moulding water content and densities are shown in Fig. 4.

3 Results and discussion

To find the optimum percentages of RHA and CL, compaction and unconfined compression tests are conducted for varying percentages of RHA and CL and results obtained are discussed and analysed.

3.1 Compaction characteristics of expansive BC soil–RHA mixtures

RHA was mixed with expansive BC soil with an increment of 5 per cent from 5 to 40% with respect to dry weight of soil, and the compaction characteristics of the mixtures are shown in Table 4. Compaction trend of expansive BC soil–RHA mixtures is similar to that of cohesion less soil. This is because clayey soil particles were replaced by inert particles of RHA. The decrease in the MDU varied from 13 to 11.77 kN/m^3. This is due to lower value of specific gravity of RHA in comparison with that of soil [2]. However, the OMC is increased from 32 to 39% which is due to the increase in the specific surface area of soil and RHA particle require more water for compaction.

3.2 Compaction characteristics of expansive BC soil–RHA mixtures treated with carbide lime

The compaction characteristics of CL-treated expansive BC soil–RHA mixture are tabulated in Table 5. The increase in optimum moisture content of CL-treated expansive BC soil–RHA mixture is found due to reaction between soil–RHA and CL which creates more air void spaces. The increase in air void spaces consumes more water due to the formation of flocculated structure. MDU of carbide lime-treated expansive soil–RHA mixture declines with the rise in carbide lime. This is due to the lower specific gravity of composite, and also formation of flocculated structure resists the compaction for a fixed compactive effort [2].

3.3 Optimization of RHA and carbide lime for BC soil

The UCC increased marginally for BC soil–RHA mixture for immediate testing and 7 days of curing. The increase in strength is due to the substitution of soil with a non-cohesive RHA particle. The strength of the soil and RHA composite increases up to 20% of RHA content, beyond which strength reduces due to lower density of soil–RHA composite. The early marginal increase in strength is due to the agglomeration of soil particle since RHA possesses angular and sub-angular particle which increases the frictional properties of the composite and leads to agglomeration, resulting in the increase in the strength [17]. Hence, 20% RHA is chosen as optimum dosage for the stabilization of soil–RHA mixture. Figure 2 shows the effect of various percentage of RHA on strength parameters for immediate and 7 days of curing period.

The addition of RHA is only a mechanical stabilization, and the strength is almost lost upon saturation. Additional calcium-based additives such as CL to the BC soil–RHA mixture enhance the strength further. The variation of strength of CL-treated BC soil–RHA mixture is shown in Fig. 3. From the results, it was found that strength of the composite increased significantly with the addition of CL up to 8%. This is due to pozzolanic reaction of BC soil–RHA–CL composite; it is a known fact that cementing materials like calcium silicate hydrate reaction (C-S-H) and calcium aluminate hydrate (C-A-H) formed during

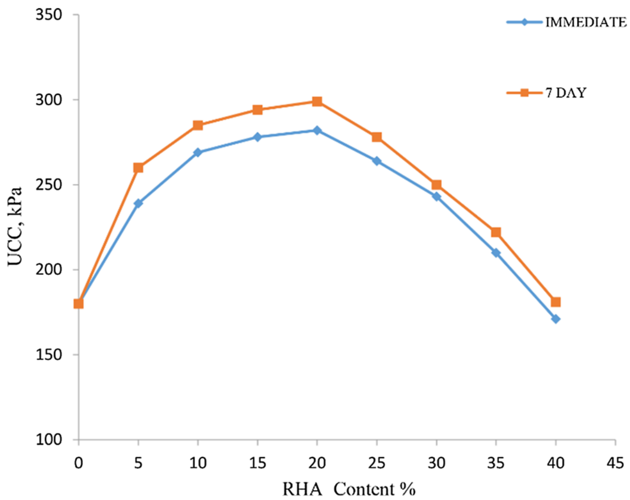

Fig. 2 Effect of various percentages of RHA on the UCC of BC soil for immediate and 7 days of curing period

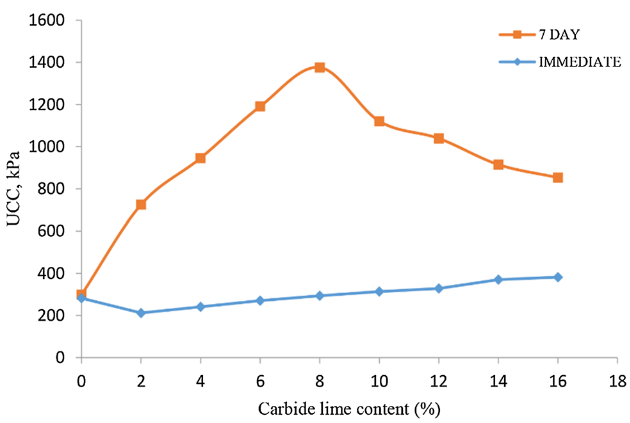

Fig. 3 Effect of variation of percentage of CL on the UCC of BC soil and RHA composite for immediate and 7 days of curing

pozzolanic reactions between soluble silica and alumina from clay- and residual-free calcium from lime filled the void space between clay particles [18]. The addition of CL to the BC soil–RHA mixture increases the pH of the solution. The increase in pH dissolves reactive silica and alumina from the soil–RHA composite, leading to the development of pozzolanic gel such as C-S-H gel and C-A-S-H gel. These compounds coat and bind the soil together which hardens with time, thereby increasing the soil strength. The strength corresponds to CL content of 8% that is chosen as optimum dosage. Further addition of CL decreases the strength which is due to unreacted carbide lime which disturbs the system. Hence, 8% CL is found to be optimum [19].

3.4 Index properties of BC soil–RHA mixtures treated with CL and sodium salts

Optimum dosage of RHA and CL was found to be 20% and 8%, respectively, from the unconfined compression strength test. No change in the consistency limits was observed when optimum dosage of RHA is mixed with soil at immediate as well as for 7-day tests; the results are shown in Table 6. The effect of curing is insignificant on consistency limits of BC soil–RHA mixtures [2]. The inclusion of CL to the BC soil and RHA mixture, liquid limit and plastic limit of the mixture increases for both immediate and 7-day tests as it resembles the property of lime. The addition of lime to soil–RHA composite decreases the diffused double-layer thickness and creates flocculation of the soil particles, which decreases the plasticity index [20]. The addition of RHA to the BC soil increases the shrinkage limit due to non-swelling properties of RHA. Results show that induced lime increases the shrinkage limit of soil–rice hush ash mixtures. This attributes to the increase in the attractive forces between the soil–RHA and carbide lime which leads to the development of flocculated mixtures. When concentration of 1% sodium salts added to the BC soil both the liquid limit and the plastic limit increase for 7 days of curing period due to conversion of calcium silicate hydrate (C-S-H) gel to sodium calcium silicate hydrate (S-C-S-H) gel, which rests between the reactive silica, it is more roomy for the accumulation of water [12]. The addition of CL increases the shrinkage limit for immediate and 7-day tests, which provides calcium ions that reacts with the soil–RHA particle and leads to flocculated structure,

Table 6 Effect of optimum percentages of RHA, CL and sodium salts on the consistency limits of BC soil after immediate and 7 days of curing

Mix proportions	LL (%)		PL (%)		SL (%)		PI (%)	
	Immediate	7 Days	Immediate	7 Days	Immediate	7 Days	Immediate	7 Days
BC alone	91	90	39	40	11	11	52	50
BC soil + 20% RHA	90	92	49	48	14	14	41	44
BC soil + 20% RHA + 8% CL	99	105	84	94	30	32	15	11
BC soil + 20% RHA + 8% CL + 1% NaCl	101	105	86	95	30	33	15	10
BC soil + 20% RHA + 8% CL + 1% NaOH	103	108	86	97	31	34	17	11

yielding higher shrinkage limit [20]. Shrinkage limit of stabilized soil increases with sodium salts; this is due to increased bond strength and enhanced soil–lime reactions. It is interesting to observe that, while curing with lime alone, enhanced flocculation is observed and leads to the formation of rigid skeleton which resist towards the shrinkage [11].

3.5 Compaction characteristics of alkali-treated soil, optimum RHA and optimum CL mixture

The sodium salts, namely sodium hydroxide and sodium chloride, were added, and it was observed that marginal changes in the compaction characteristics of BC soil–RHA–CL were observed. The addition of 1% of any sodium salt changes the nature of the compaction curve. The MDU reduces with a marginal rise in OMC [21]. Figure 4 shows the effect of RHA, CL and sodium salts on compaction characteristics of BC soil.

3.6 Influence of density–moisture content for strength properties of stabilized soil mixed with RHA carbide lime along with the addition of sodium salts

The influence of dry density and moisture content on UCC of RHA stabilized BC soil in the presence of carbide lime and sodium salts was determined for 95% of the dry unit weight, and the corresponding moisture content is taken on either side of optimum conditions.

3.6.1 Effect of RHA on the strength properties of BC soil

The addition of RHA to the BC soil leads to the agglomeration of soil and RHA particle. Even though the density is low, the angular and sub-angular particle of RHA increases the frictional properties, thereby increasing the strength of the composite which is not so significant [17]. Figure 5 shows effect of RHA on the strength properties of BC soil. Strength of the soil–RHA composite is more on the dry of optimum condition due to the flocculated structure of the blended soil mass than at optimum and wet of optimum. Strength of blended BC soil–RHA composite is minimum on the wet of optimum due to higher water-holding capacity of RHA and also the existence of dispersed structure.

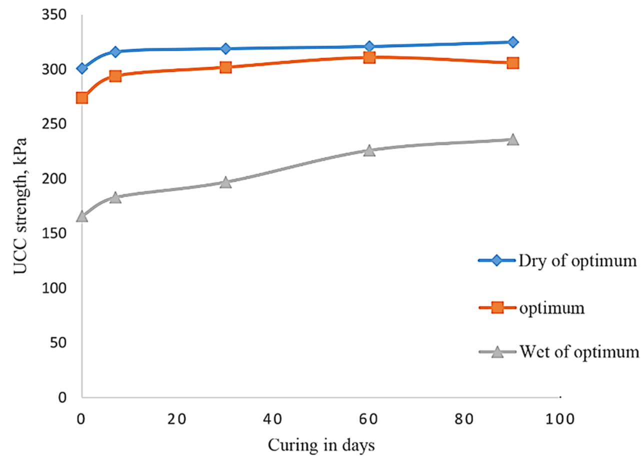

Fig. 5 Variation of strength of BC soil + RHA mixture at different moulding water contents

3.6.2 Improvement in strength of CL-treated BC soil–RHA mixture compacted at three significant moisture content and dry density

The unconfined compression strength of soil and optimum RHA mixture treated with 8% carbide lime compacted at different moulding water contents for a curing periods of immediate to 90 days is shown in Fig. 6.

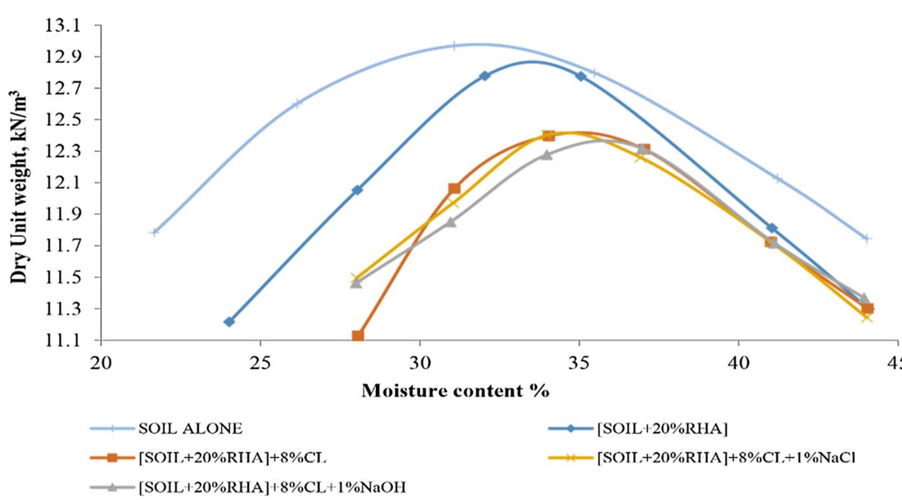

Fig. 4 Effect of RHA, CL and sodium salts on compaction properties of expansive BC soil

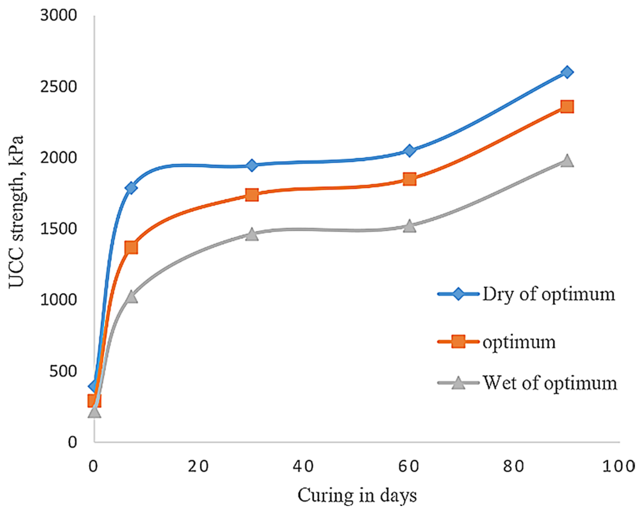

Fig. 6 Variation of strength of BC soil + RHA + CL composite at different moulding water contents

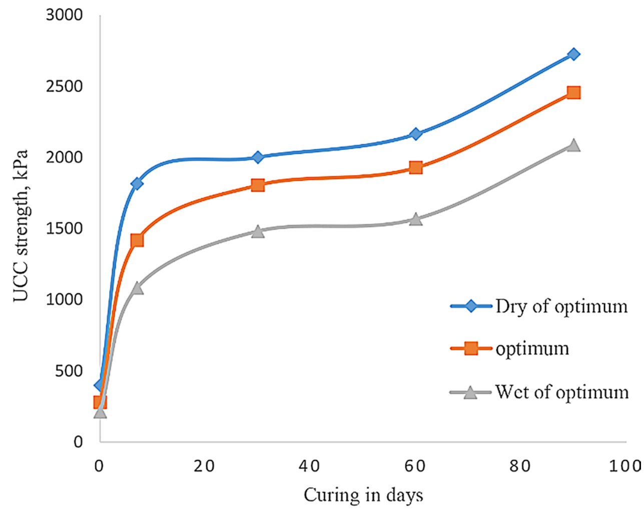

Fig. 7 Effect of NaCl on the strength properties of BC soil + RHA + CL composite at different moulding water contents

As seen from the previous studies, the addition of RHA is only a mechanical stabilization. To improve strength further, calcium-rich carbide lime is added to the BC soil–RHA mixture. The addition of carbide lime to the BC soil–RHA composite increases pH of the composite which dissolves alumina and silica from RHA and BC soil mixture and reacts with carbide lime, leading to the development of cementitious compounds such as C-S-H gel and C-A-S-H gel which increases the strength of the composite [1]. At wet of optimum conditions, the water held within flocs of the pozzolanic compounds leads to the decrease in the strength. As shown in Fig. 6, the strength of the CL-stabilized soil is more when compacted on the dry of optimum irrespective of curing periods than that of compacted on optimum and wet of optimum. The strength is significantly improved within 7 days of curing as compared to other days of curing since the pozzolanic reaction is time dependent [22].

3.6.3 Improvement in strength of the RHA-stabilized BC soil in the presence of CL and sodium salts

The compressive strength of BC soil + 20% RHA mixture treated with 8% carbide lime and 1% sodium chloride, and 1% sodium hydroxide compacted for three significant combinations of moisture content and dry unit weight, after curing periods from immediate to 90 days is presented in Figs. 7 and 8.

As seen from results, the addition of sodium salts to the stabilized composite increases the strength of the composite due to the formation of additional cementitious compounds. The strength of the composite is higher and varies from 398 to 2726 kPa and 396 to 2980 kPa for immediate to that of 90 days of curing period. Strength of the composite compacted on optimum and wet of optimum and varies from 280 to 2455 kPa and 322 to 2609 kPa and 212 to 2087 kPa and 234 to 2347 kPa for immediate to that of 90 days of curing period, respectively.

The addition of NaCl to the composite reacts with lime in the presence of water and leads to the formation of sodium calcium silicate. The addition of sodium salts increases the pH of the composite and reacts with high silica content of RHA and BC soil, leading to alkali silicates and aluminates compounds such as C-S-H, C-A-S-H, S-C-A-S-H and S-C-S-H [21]. Thus, compressive strength of the blended composite enhances. The addition of NaOH decreases the cohesion value and increases the angle of internal friction, and the addition of sodium hydroxide to

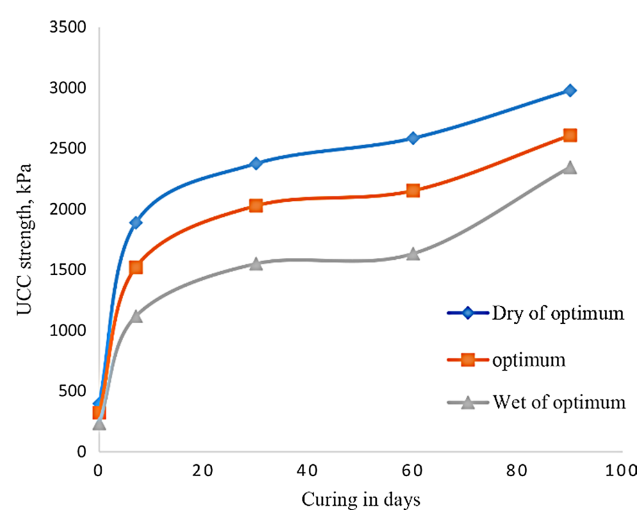

Fig. 8 Effect of NaOH on the strength properties of BC soil + RHA + CL composite at different moulding water contents

the soil sample leads to the formation of new compounds [23]. The increase in strength with NaOH is apparent within first day due to the formation of sodium alumina silicate which binds the BC soil–RHA composite. The formation of these compounds eliminates the void spaces in the stabilized soil matrix, resulting in the improvement in the strength. The strength of sodium salt-treated samples shows higher on the dry of optimum condition compared to optimum and wet of optimum conditions; this is due to the existence of the flocculated structure on the dry of optimum condition.

4 Microstructural study on the strength enhancement of the composite

The mineralogical analysis of the stabilized soil is helpful in determining the changes in the mineralogical phases due to pozzolanic reactions. The changes in microstructural development of soil are due to additives which play a significant role in altering the basic properties and the mechanical behaviour of stabilized soils.

4.1 X-ray diffraction studies on the stabilized soil

XRD analysis helps for the better understanding of change in mineralogical stages of the stabilized soil. All the XRD patterns of vertical scales are normalized to 0–1 for the better comparisons of the stabilized soils.

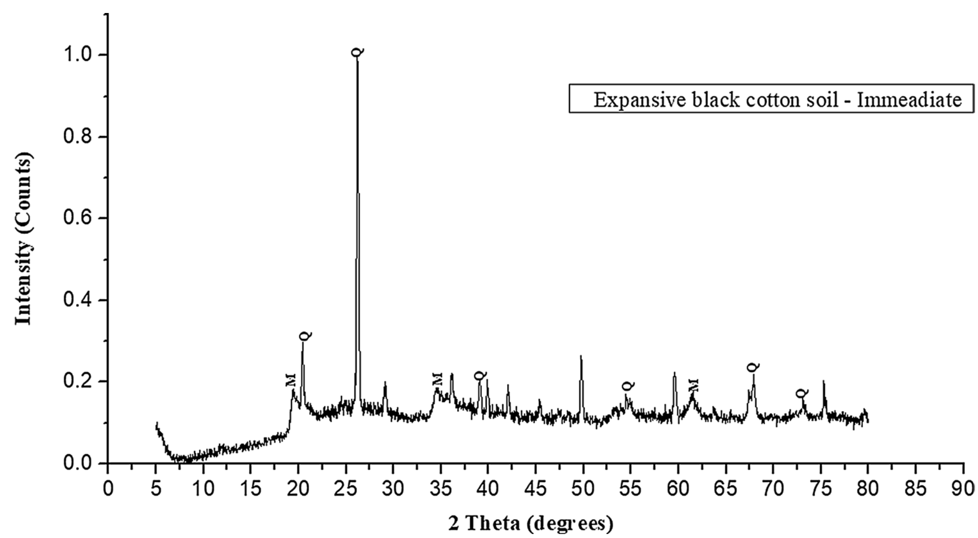

Fig. 9 XRD spectrum for BC soil alone

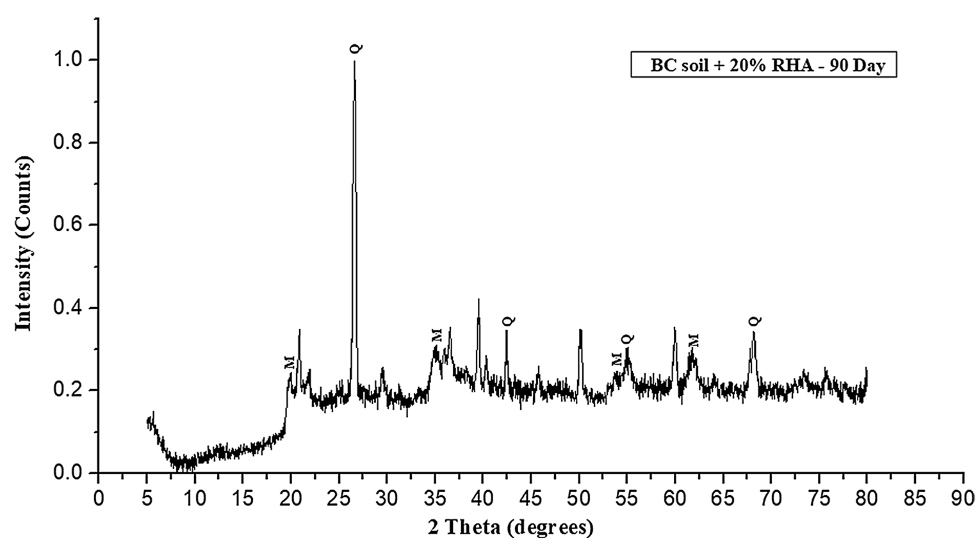

Fig. 10 XRD spectrum for BC soil + 20% RHA mixture at 90 days of curing period

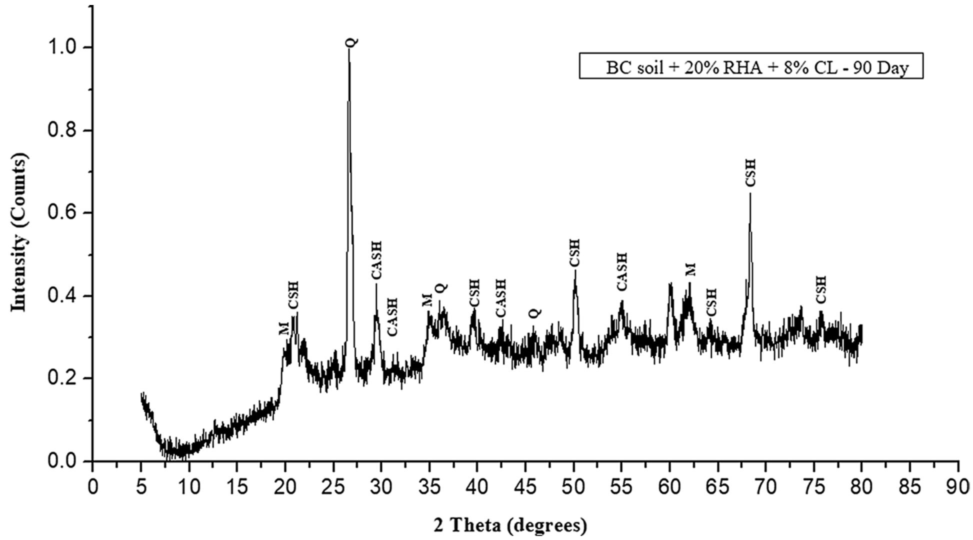

Fig. 11 XRD spectrum for BC soil + 20% RHA + 8% CL mixture at 90 days of curing period

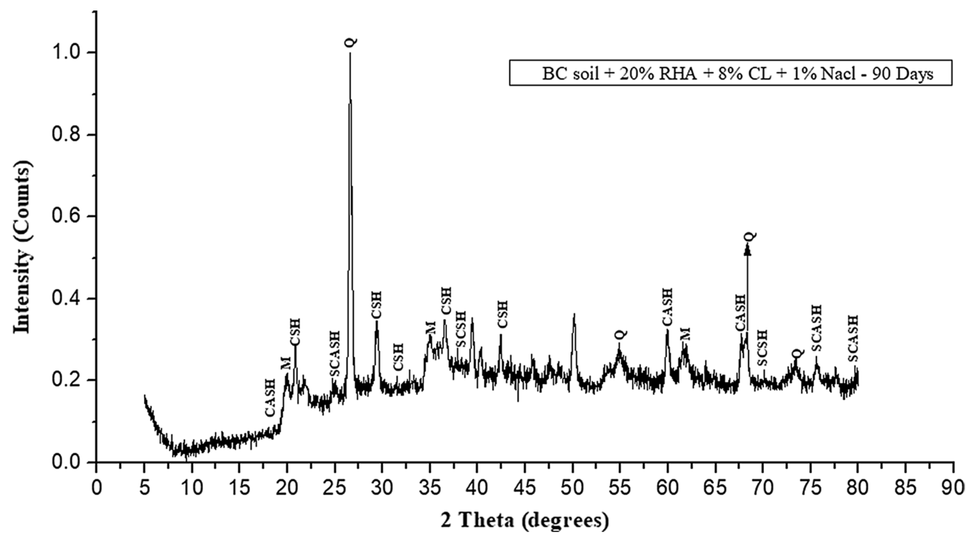

Fig. 12 XRD spectrum for BC soil + 20% RHA + 8% CL + 1% NaCl mixture at 90 days of curing period

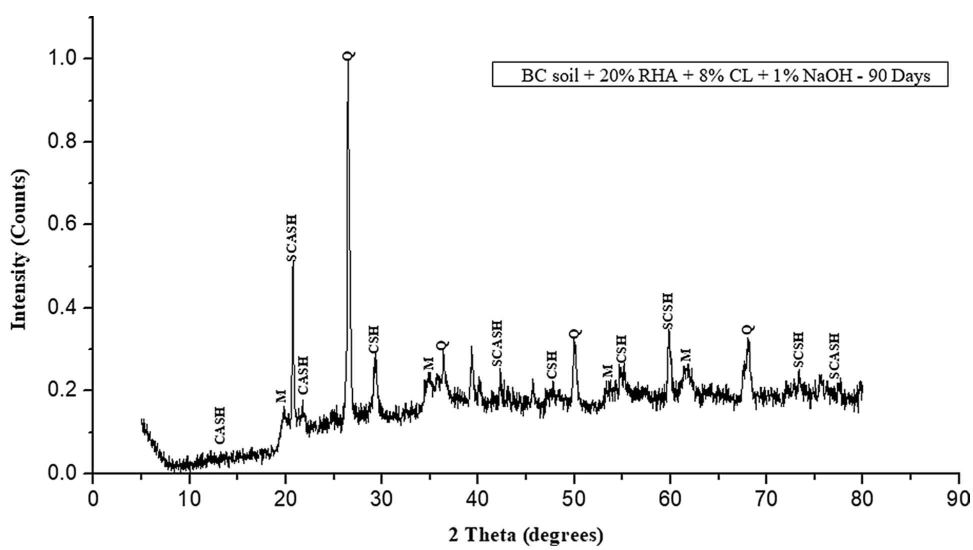

Fig. 13 XRD spectrum for BC soil + 20% RHA + 8% CL + 1% NaOH mixture at 90 days of curing period

The XRD pattern of powdered BC soil alone tested at immediate is shown in Fig. 9. The XRD pattern of the stabilized soil with the addition of RHA, CL and sodium salts is shown in Figs. 10, 11, 12 and 13. The major crystalline mineral of BC soil having a pronounced peak of montmorillonite (M) was seen at several d spacings, indicating susceptibility for the swell shrink behaviour of the soil. Similarly soil stabilized with rice husk content shows more pronounced peak of quartz (SiO_2) at several d spacings. Compared to the soil alone, the addition of RHA shows more pronounced peak due to the presence of dominant mineral quartz (Q). However, the strength of blended composite is not significantly improved due to the absence of the formation of pozzolanic products. The addition of RHA to the soil is a mechanical stabilization, and hence, strength improvement in the stabilizing process is very minimal and it is due to the agglomeration of soil and RHA particle [15]. The strength with respect to the CL and sodium salts is due to the formation of pozzolanic products, and these products were found at several *d* spacings which are responsible for the strength enhancement of the composite. The lime and accelerators increase the pH of the composite, the calcium ions and sodium ions react with dissolved alumina and silica of the composite, leading to the hydration products such as S-C-S-H, S-C-A-S-H, C-A-H, C-A-S-H and C-S-H gels [8–10, 21]. These compounds bind and coat the soil particle, increasing the strength of the composite.

4.2 SEM analysis of unstabilized and stabilized soil

BC soil alone has a plane smooth and flaky structure as shown in Fig. 14. The addition of RHA to the soil samples is a mechanical interlocking effect which brings changes in the soil structure, as shown in Fig. 15. (The images were magnified at 2500 × magnification.) SEM images show that there is an angular and sub-angular particle which reduces the pore air void spaces of the sample within the soil and changes the soil structure by agglomeration which increases the marginal improvement in strength of BC soil [17]. The cementitious gel is formed by the addition of CL and sodium salts which fill the void spaces within the sample. This coats and binds the individual grain, resulting in the reduction of migrating ions into the pores which results in a rigid structure. The morphology of the 90-day samples is shown in Figs. 15, 16 and 17. The addition of carbide lime, sodium chloride and sodium hydroxide shows denser environment than the RHA-treated sample of the 90-day curing period. This denser morphology is caused by the filling of the cementitious products from the pozzolanic reaction in the pore space. The denser morphology with curing time is associated with the strength increase [8–10].

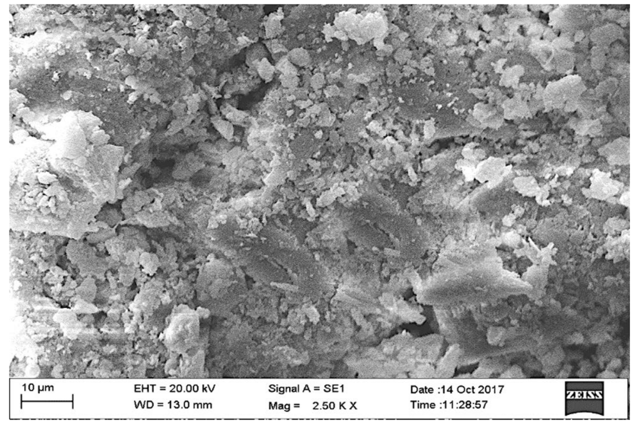

Fig. 15 SEM image of BC soil + 20% RHA + 8% CL mixture for 90 days of curing period

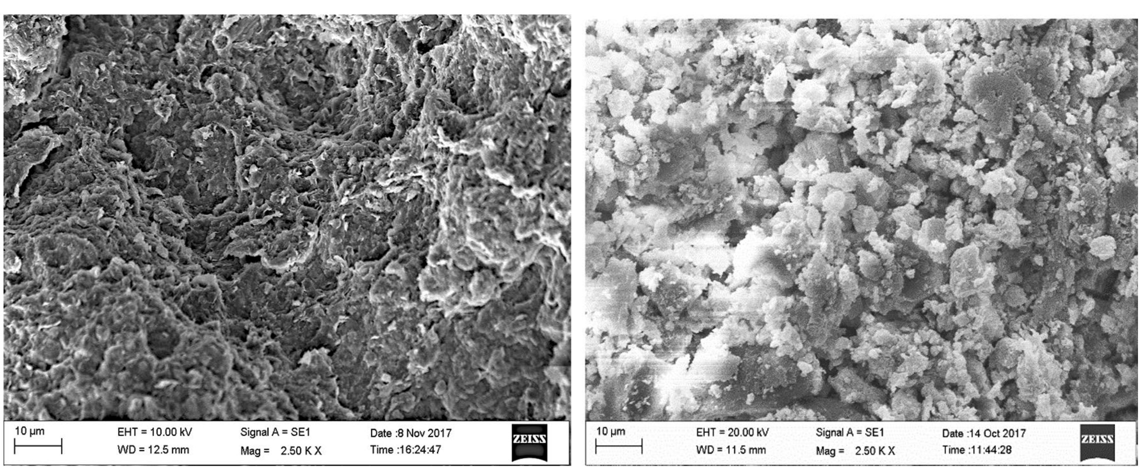

Fig. 14 SEM image of BC soil alone and BC soil + 20% RHA mixture at 90 days of curing period

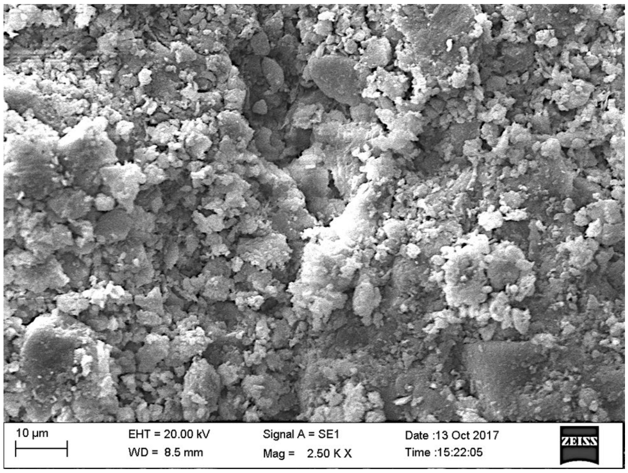

Fig. 16 SEM image of BC soil + 20% RHA + 8% CL + 1% NaCl mixture at 90 days of curing period

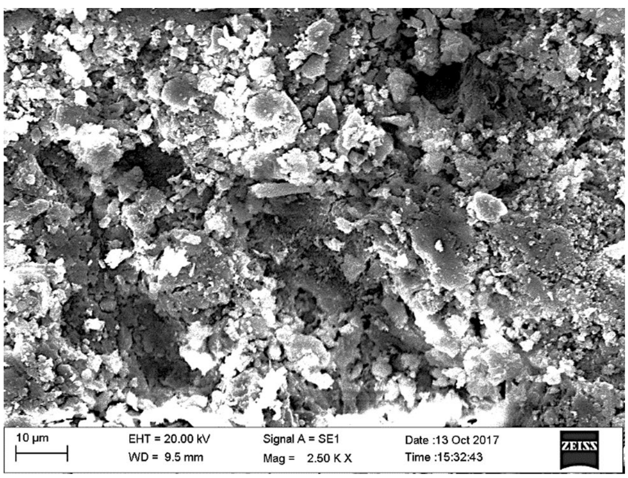

Fig. 17 SEM image of BC soil + 20% RHA + 8% CL + 1% NaOH mixture at 90 days of curing period

5 Conclusions

Strength development of soil mixed with various combinations of additives compacted for three significant combinations of moisture content and dry unit weight is determined for various curing days. The following conclusions were drawn after detailed analysis of results.

1. The addition of sodium chloride and sodium hydroxide further enhances the workability of BC soil–RHA–CL composite due to the formation of alkali silicate hydrated gel which is more voluminous.
2. The inclusion of RHA and CL to the BC soil reduces MDU and increases OMC; the change in the compaction characteristics is due to lower specific gravity and higher water retention capacity of stabilizers which creates flocs which holds the water with in the flocs which increases the optimum moisture content.
3. Strength of BC soil-treated RHA is observed due to the agglomeration of soil and RHA particle which increases the angle of internal friction of the composite. Further strength is improved with the addition of CL due to the development of cementitious products.
4. The BC soil stabilized using RHA has not shown any substantial improvement in strength with curing due to lack in lime content. The strength of the RHA-stabilized BC soil is more when compacted at the dry of optimum condition, due to flocculated structure of soil when it is compacted using lower moisture content. Marginal improvement in the RHA-stabilized BC soil is due to the agglomeration of BC soil and RHA composite.
5. The strength of BC soil–RHA mixture treated with CL and additives such as sodium chloride and sodium hydroxide increases with curing as a result of chemical reactions taking place in the composite. The strength of the composite is more when compacted on the dry of optimum for all curing periods due to flocculated structure. Strength increment is due to the development of cementitious compounds such as C-S-H and C-A-S-H along with S-C-A-S-H and S-C-S-H.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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