Geotechnical Properties of Cement Kiln Dust and Unground Cement Clinker-Admixed Black Cotton Soil

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ABSTRACT

Soils consisting of montmorillonite mineral are highly expansive upon exposure to water, leading to reduction in shear strength. Studies have indicated that cement kiln dust as an admixture to black cotton soil (BC soil) that contains montmorillonite improves both compaction and plasticity index. Addition of unground cement clinker (UCC) alters gradation of stabilized soil, leading to better compaction. The objective of the present study is to use both cement kiln dust (CKD) and unground cement clinker (UCC) as a sustainable admixture to improve plasticity, compaction and shear strength of BC soil. It was found that 12% CKD was optimum in terms of reduction in plasticity with corresponding improvement in compaction. Optimum dosage of CKD was used to comparatively assess the effect of adding unground cement clinker. 12% UCC in combination with optimum CKD indicated denser packing, leading to improvement in compaction properties of BC soil. Shear strength of BC soil admixed with optimum dosage of CKD and UCC with 0-28-day curing period was determined in order to understand the effect of change in compaction characteristics of CKD and UCC-admixed BC soil. Shear strength of BC soil admixed with optimum dosage of cement kiln dust (12% CKD) and optimum dosage of unground cement clinker (12% UCC) was significantly greater when compared to all the combinations used in the study. This indicates that the addition of both cement kiln dust and unground cement clinker leads to sustainable soil improvement.

KEYWORDS: Cement kiln dust, Black cotton soil, Unground cement clinker, Compaction, Unconfined compressive strength.

INTRODUCTION

Black cotton soils occur in some parts of the world including India and have predominantly montmorillonite clay mineral. They are found to exhibit high swelling upon exposure to water and shrinkage when dried with a consequent reduction in shear strength (Patel and Shabu, 2015). This leads to severe damages to road pavements, foundations and infrastructure founded on it. Rapid industrialization and extensive urban growth have led to construction of infrastructure on a large scale even on problematic soils. Houmadi et al. (2009), Cristelo et al. (2012), Fauzi et al. (2010) and Senol et al. (2006) stated that the scarcity of sites for infrastructure has led to find ways for sustainable soil improvement techniques that make the material suitable for infrastructure applications. This has led to development of economical and sustainable techniques by several investigators for improving properties of soil to become suitable for construction. Mamoune and Bekkouche (2011) established models that relate parameters relating swelling of expansive clays to geotechnical parameters by numerical simulation of compression and swelling using oedometer tests that allowed prediction of swelling. Huge numbers of manufacturing plants of Portland Cement (PC) are spread across the world. During the manufacture of PC, several waste by-products are generated, such as cement kiln dust (CKD) and unground cement clinker (UCC) that are rich in free lime content. Due to high alkali content, the disposal and

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recycling of these by-products poses problems. Keller (1978) stated that such waste materials need to be managed responsibly to ensure a clean and safe environment. CKD is a particulate mixture of partially calcined and unreacted raw feed, clinker dust and ash, enriched with alkali sulphates, halides and other volatiles. Khater et al. (2012) mentioned that CKD with its high alkali content can be used to create an unconventional cementitious binder. Several investigations also indicated that this waste by-product including cement can be used as a stabilizer to improve geotechnical properties of problematic soil, such as black cotton soil. Abdullah and Alsharq (2011) have mixed cement at various percentages into expansive soils in a prescribed range of pre-wetting dry densities and moisture contents. It was found that 2% cement was enough to reduce free swelling percentage of 28-day cured specimens. Singh and Sharma (2014) have used waste materials, such as sand, fly ash, tile waste and jute fibers, to blend with clayey soils to develop cheaper construction materials. Optimum mix was developed on the basis of compaction characteristics and was further evaluated in terms of strength and permeability characteristics. It was found that mixing of waste materials brought out significant improvement in geotechnical properties of soils.

Further, several investigations have revealed the effectiveness of CKD in stabilizing highly expansive clay soils. Sayah (1993), Zaman et al. (1992) and Miller and Azad (2000) investigated that CKD and fly ash have been used effectively in stabilizing base courses in road construction in the form of a pozzolanic non-cement concrete with limestone as an aggregate. McCoy and Kriner (1971) reported a wide range of tests on kiln dust compositions for soil stabilization. Unground cement clinker (UCC) is a dark grey coloured material in the form of nodules that is obtained due to heating of ground limestone along with clay at a temperature of about 1400°C-1500°C. During this process, some clinkers remain unground which are called unground cement clinker. The size of unground cement clinker nodules approximately ranges between 1 and 25mm in diameter. Studies by Irudayaraj and Charles (2015) indicated that UCC is mainly composed of calcium silicates, typically in the range of 70-80%, CaO, SiO_2, Al_2O_3 and Fe_2O_3, accounting to more than 95%. Addition of UCC may thus assist cementation due to induced pozzolanic reaction and alter grain size characteristics and gradation of stabilized soil, affecting the overall geotechnical characteristics of stabilized soil. Studies by Collins and Emery (1983) mentioned the use of CKD as an admixture to strengthen BC soil. The advantage of CKD in stabilization of clays is to improve the shear strength and reduce the plasticity index. Studies by Miller and Zaman (2000) and Button (2003) indicated that both CKD and fly ash have been used in stabilizing base courses in road construction in the form of a pozzolanic non-cement concrete with limestone as an aggregate which indicated to have autogenous healing characteristics. State of practice on the use of kiln dust for the stabilization of granular base materials and subgrade soils in highway pavements was also reported. It was also found by these studies that a significant improvement in compressive strength can be obtained using a pozzolanic combination of CKD and fly ash. Parsons et al. (2004) and Todres et al. (1992) presented a summary on the performance of a wide range of soils treated with CKD in terms of durability, plasticity and strength have been presented indicating that the CKD is a viable option for stabilization of subgrade soils. The studies indicated that BC soil admixed with CKD had an overall acceptance zone for CKD achieved at 12% and 16% cement kiln dust content. Rahman et al. (2011) reported an exhaustive literature review on the use of CKD for soil stabilization. Studies by Moses and Saminu (2012) indicated marginal improvement in shear strength with 12-18% CKD and CBR values were around 5-7% at 12% CKD. Yahya and Karagooly (2012) mentioned that the addition of CKD decreases plasticity, liquid limit and activity index, indicating an increase in the workability of the soil. Keerthi et al. (2013), Salahudeen and Akiije (2014), Hamidu et al. (2015), Singh and Jain (2015) and Kumar and Singh (2017) conducted extensive studies on the effect of CKD on several engineering properties of CKD-admixed BC soil and indicated significant improvement in strength with a significant decrease in swell characteristics. A study by Avci and Murat (2018) on clinker efficiency in treating low-plasticity clay (LPC) in comparison with ordinary portland cement (OPC)- treated LPC indicated clinker to be more effective than OPC in reducing swell potential and compressibility and increasing the shear strength of LPC. Though previous literature indicated CKD as an effective stabilizer, very few studies have been made on the use of unground cement clinker (UCC) which is also one of the waste by-products generated in the cement industry. Comparative assessment of compaction characteristics along with alkali activation of BC soil admixed with both CKD and unground cement clinker by Kumar and Devendra (2019) have suggested significant improvement in compaction characteristics and shear strength of BC soil.

The aim of the present study is to characterize the geotechnical properties of BC soil admixed with both CKD and unground cement clinker in combination, so that a sustainable composite admixture can be developed that improves both plasticity and compaction characteristics and shear strength of BC soil. In this regard, various percentages of CKD alone-admixed BC soil were used to determine the optimum percentage of CKD that causes significant improvement in plasticity and compaction properties. Using the optimum CKD thus obtained in combination with unground cement clinker, the geotechnical properties of BC soil in terms of comparative variation in compaction characteristics and shear strength were assessed.

Materials Used

Black Cotton Soil

Black cotton soil was obtained from Gangapura (13.028598° N, 77.895844° E) in Gulbarga district, Karnataka, INDIA, from a depth of 2m below ground level from an open test pit. BC soil is naturally dried and powdered in a soil-grinding mill. Ground soil, passing ASTM sieve no. 40 (BIS: 425-micron sieve), is used in the present study. The grain size analysis of soil indicated around 39% of clay fraction, 21% silt fraction and the rest is made of fine sand. Based on liquid limit and plasticity index, the soil was classified using the Unified Soil Classification System (USCS) as CH, which refers to clay of high plasticity. Table 1 shows properties of BC soil used.

Cement Kiln Dust (CKD)

Cement Kiln Dust (CKD) was obtained from ACC, LTD (unit of Lafargeholcim, India) cement production plant located in Wadi (17.053720° N, 76.991159° E) of Gulbarga district. The chemical composition of the CKD used in the present study is summarized in Table 2. It clearly indicates the presence of free lime (CaO) at around 49% along with silica at 17%. The CKD used in the present study is fine grained with a specific gravity of 2.95 and the percentage finer than no. 200-sieve (75micron) is 100%. The CKD used in the present study is a fine light greyish white powder having larger percentage of alkalis and chloride along with sulphate content that lies within the acceptable limits.

Table 1. Physical properties of black cotton soil

Plasticity Properties	Values
(i) Liquid limit, %	65
(ii) Plastic limit, %	27
(iii) Plasticity index, %	38
(iv) Shrinkage limit, %	10
Specific gravity G	2.65
Particle Size Analysis	
(i) Fine Sand Fraction, %	29.6
(ii) Silt Fraction, %	31.3
(iii) Clay Fraction, %	39.1
Unified Soil Classification (USCS)	**CH**

Table 2. Chemical constituents of CKD

(Courtesy: Civil Aid Technoclinic Pvt., Ltd., Bengaluru)

Constituent	Weight %	Constituent	Weight %
CaO	49.3	SO_3	3.56
SiO_2	17.1	BaO	78.2
Chloride	6.9	Cr_2O_3	0.011
Loss on Ignition	15.8	CuO	0.029
Al_2O_3	4.24	N_2O	0.012
Fe_2O_3	2.89	SrO	0.37
K_2O	2.18	TiO_2	0.34
MgO	1.14	V_2O_3	0.013
Na_2O	3.84	ZnO	65.8
P_2O_2	0.12	ZrO_2	0.011
Equivalent Alkalis (Na_2)+0.65K_2O)	5.27		
Physical Properties			
Specific Gravity	2.95		
Specific Surface Area, cm^2/g	6127		

Unground Cement Clinker (UCC)

Unground cement clinker (UCC) was brought from ACC cement production plant placed at Wadi of Gulbarga District. The chemical composition of the UCC used in the present study is summarized in Table 3. It mainly consists of CaO, SiO_2, Al_2O_3 and Fe_2O_3 accounting for more than 95%. The minor components totalling less than 3% are MgO, TiO_2, P_2O_5 and alkalis. The free lime CaO content is around 64%. Aldieb and Ibrahim (2010) indicated that the clinker is not made of individual oxides, but exists as compounds formed by two or more oxides. The mineral phases are very fine, usually 30-60 µm, and consist mainly of alite, belite, calcium aluminate and alumino-ferrite. The grains of unground cement clinker used in the present study had particles passing no. 40 sieve (0.420mm) at around 9.25% only. The grain size analysis of unground cement clinker used in the present investigation has indicated a uniformity coefficient (C_u) of 1.89, a curvature coefficient (C_c) of 0.735 with mean particle D_{50} being 0.6 mm.

Chemical constituents and particle size of CKD and unground cement clinker thus conclusively indicate that addition of both to expansive BC soil to be used in the study assists flocculation with curing. Addition of coarser particles such as unground cement clinker leads to alteration of particle size and gradation. Pozzolanic reaction with curing period in days, due to availability of free lime (CaO), leads to induced cementation, causing an increase in shear strength. The aim of the present experimental study is to comparatively assess the optimum quantity of CKD as well as optimum CKD+UCC that cause significant improvement in geotechnical properties of CKD and unground cement clinker-admixed BC soil.

METHODOLOGY

Optimum dosage of CKD was verified based on variations of liquid limit, plastic limit and shrinkage limit along with plasticity index. In order to further confirm the trend of optimization arrived at from plasticity characteristics, compaction characteristics were studied by adding different percentages of CKD. Based on both reductions in plasticity and compaction characteristics, optimum dosage of CKD was arrived at. Shear strength of BC soil admixed with optimum dosage of CKD and UCC was determined in order to understand the effect of change in compaction characteristics of CKD and UCC-admixed BC soil. BC soil with optimum

CKD was admixed with UCC in order to ensure that the total percentage of both CKD and unground cement clinker does not exceed 50% by weight of the dry soils.

Table 3. Typical constitutents of unground cement clinker (UCC)

(Courtesy: Civil Aid Technoclinic Pvt., Ltd., Bengaluru, India)

Constituent	Values (%)
SiO_2	21.5
Al_2O_3	5.2
Fe_2O_3	2.8
CaO	64.6
MgO	1
K_2O	0.6
Na_2O	0.2
SO_3	1
Loss on Ignition	1.5
IR	0.5
Total	98.9
Free Lime = 1.0% of CaO	
Balance is typically due to small amount of oxides of titanium, manganese, phosphorus and chromium.	
Physical Properties	
Specific Gravity	1.44
Coefficient of Uniformity, (C_u)	1.89
Coefficient of Curvature , (C_c)	0.73

Compaction test was conducted to determine the optimum moisture content (OMC) and maximum dry density (MDD) using the procedure of mini-compaction test suggested by Sridharan and Sivapullaiah (2005). Handling expansive BC soil on the wet side of optimum in standard compaction test is difficult due to considerable bulging during compaction. Mini-compaction test uses a smaller cylindrical mold of 100mm height including collar height, a diameter of 38.1mm and a rammer weight of 800g. Rammer has a diameter of 64mm, a height of 35mm with a central bore of 19mm, so that rammer is kept constant at 160mm for the height of fall. Soil is compacted in three layers in the mold with each layer being given 45 blows to achieve 98% of the MDD that can be obtained from standard compaction test. Since handling smaller volume of clay soil is easier with substantially accurate values of dry density and moisture content, mini-compaction test was employed in the present experimental study. In order to comparatively assess the compaction characteristics, compaction test for BC soil admixed with CKD and unground cement clinker was also done using mini-compaction test. Cement kiln dust was added in different percentages ranging from 4% to 20% to determine optimum CKD. Once the optimum CKD is found, BC soil admixed with optimum dosage of CKD was compacted using unground cement clinker as an admixture along with optimum CKD with UCC being added at various percentages starting from 4% to 30%, to determine the optimum dosage of unground cement clinker in combination with CKD. The weight of CKD and UCC to be added was arrived at based on the dry unit weight of the soil taken for the test. The shear strength of BC soil admixed with CKD at different percentages was assessed in terms of unconfined compressive strength (UCS) to ascertain the optimum dosage of CKD in terms of curing period. Using the optimum dosage of CKD obtained on the basis of plasticity, compaction properties and maximum shear strength, the strength of BC soil admixed with optimum dosages of CKD+UCC was assessed in terms of curing period to arrive at conclusions on the effect of compaction properties of CKD and UCC-admixed BC soil and a comparative assessment of effect of curing on shear strength of CKD+UCC-admixed BC soil was performed.

RESULTS AND DISCUSSION

Effect of CKD on Plasticity Characteristics

The effect of addition of CKD at different percentages to BC soil on plasticity characteristics in terms of Liquid Limit (LL), Plastic Limit (PL) and Shrinkage Limit (SL) was studied in accordance with relevant Indian standards. CKD was added to BC soil ranging from 4% to 20%. The weight of CKD to be added was arrived at based on the dry unit weight of the BC soil taken for the test. Fig. 1 shows variations of LL, PL and SL along with plasticity Index (PI). LL initially increases with CKD at 4% and beyond 4% CKD, the increase in LL becomes marginal. The plasticity index becomes minimum corresponding to 12% CKD-admixed BC soil. Further, shrinkage limit shows a continuous increase with the increase in percentage of CKD. Increase in SL due to that addition of CKD indicates reduction in swelling characteristics of BC soil, as shrinkage limit is a measure of volume reduction of BC soil. Variation of plasticity properties had clearly indicated that maximum reduction in PI occurs for 12% CKD-admixed BC soil. Hence, it can be concluded that 12% CKD produces optimum benefits in terms of reduction in plasticity.

Since the variation of plasticity clearly envisages that 12% CKD produces optimum benefits in terms of reduction in plasticity and swelling, morphological and micro-particle changes were studied using SEM images for BC soil alone and BC soil admixed with 12% CKD. Fig. 2 shows the morphological differences exhibited by BC soil +12% CKD compared to SEM images of BC soil alone and CKD alone, respectively. The BC soil alone exhibits smooth textured flaky particles with large pores as in Fig 2(a), particles of CKD alone in Fig 2(b) exhibits micron-sized angular particles and Fig 2(c) exhibits agglomerated angular and flaky particles coated with white patches of free lime and with voids being filled by micron-sized CKD particles that cause changes in plasticity of CKD-admixed BC soil due to associated pozzolanic reaction. In order to further conclude the optimum quantity of CKD that leads to enhancement of shear strength of the stabilized BC soil, which is a function of dry density and water content, compaction test was conducted by admixing BC soil with CKD ranging from 4% to 20%, similar to the percentage of CKD added in order to assess the variation of plasticity.

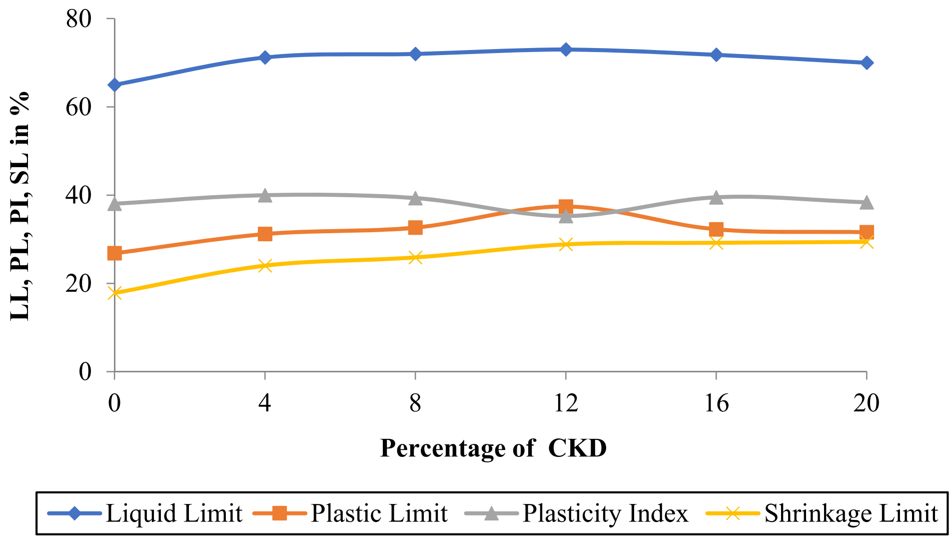
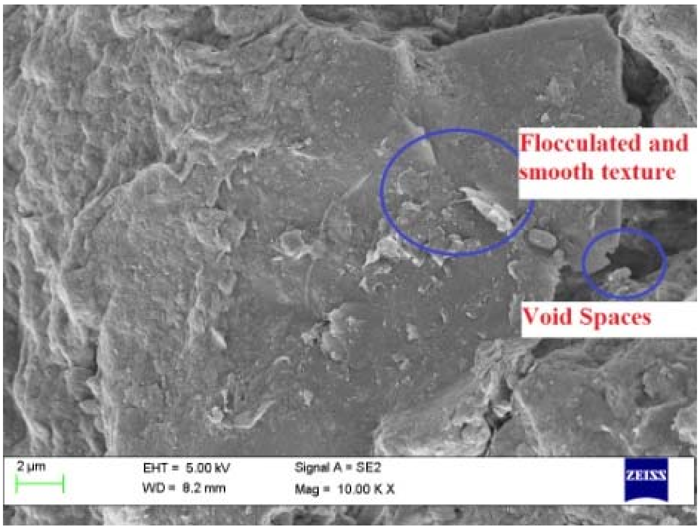
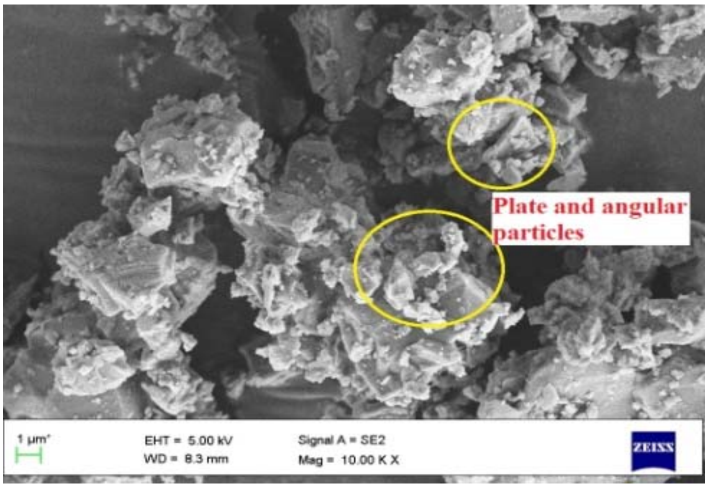


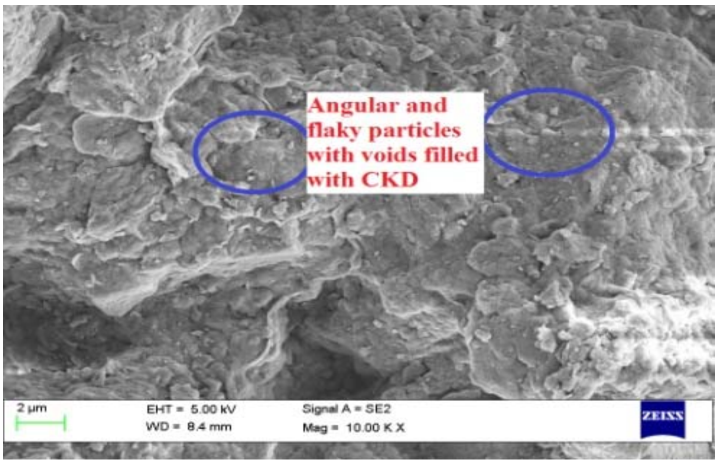
Figure (1): Variation of plasticity characteristics of CKD-admixed BC soil



(a) BC soil alone

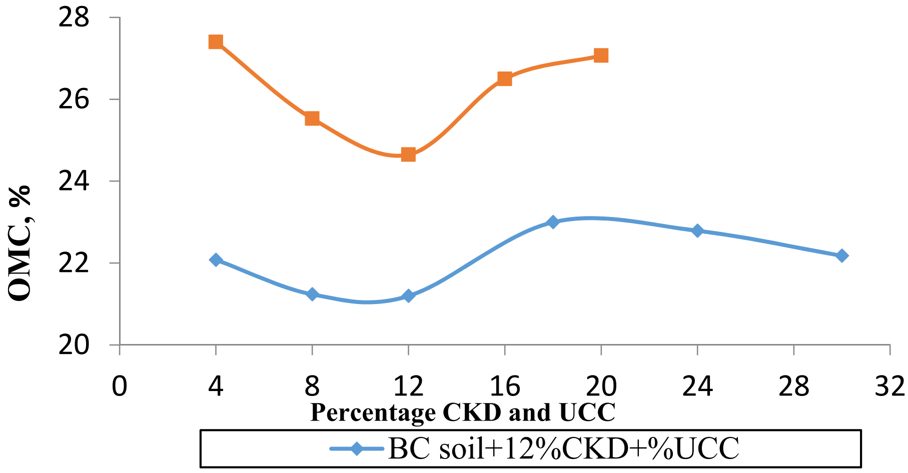


(b) CKD alone

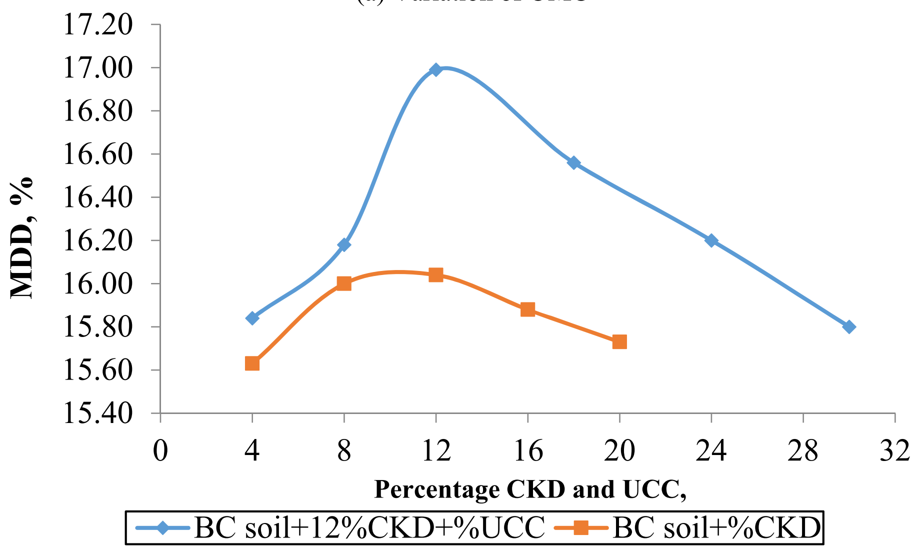


(c) BC soil+12%CKD

Figure (2): SEM images of BC soil alone, CKD alone and BC soil +12%CKD



(a) Variation of OMC



(b) Variation of MDD

Figure (3): Comparitive variation of OMC and MDD for BC soil admixed with 12%CKD and for BC Soil+12%CKD admixed with different percentages of UCC

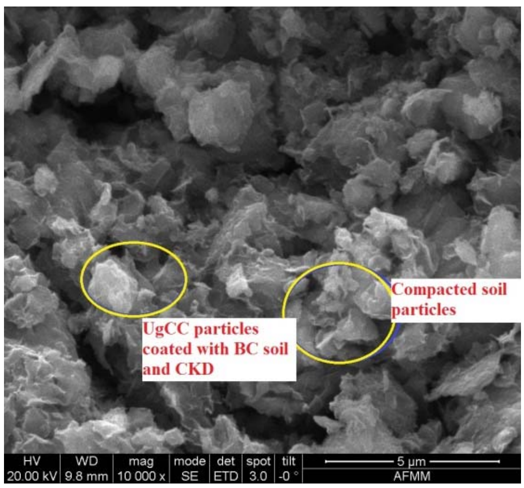


Figure (4): SEM images of BC soil +12%CKD+12% UCC

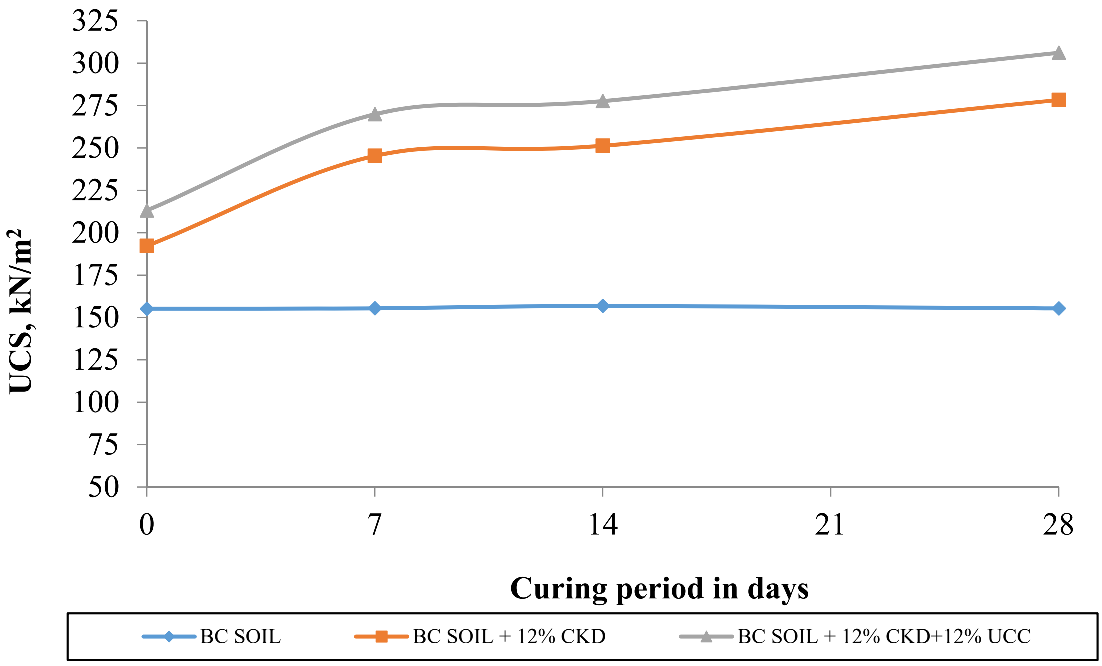


Figure (5): UCC *versus* curing period for BC soil alone, BC soil +12% CKD and BC soil +12% CKD + 12% UCC

Effect of CKD on Compaction Characteristics of BC Soil

Mini-compaction test was conducted by adding CKD in percentages ranging from 4% to 20% using the procedure explained in the methodology section. The moisture-density relationship was arrived at and compared with that of BC soil alone. The variation of maximum dry density (MDD) is in conformity with the trend of decreasing optimum moisture content (OMC) with increasing MDD. It was found that the maximum reduction in OMC with corresponding maximum increase in MDD occurs at 12% CKD. Beyond 12% CKD, compaction test results indicate an increase in OMC with a corresponding reduction in dry density. The results obtained are in conformity with earlier studies by Parsons et al. (2004) and Todres et al. (1992) who had conducted extensive studies on a wide range of soils using CKD as an admixture. The trend in the results clearly indicates that the addition of CKD up to 12% causes flocculation and agglomeration of the soil particles due to exchange of cations, as envisaged in the study by Oriola and Moses (2010). Table 4 summarizes the results of maximum dry density (MDD) and optimum moisture content (OMC) obtained for CKD-admixed BC soil. Morphological analysis obtained in SEM shown in Fig.5 also clearly corroborated the fact that addition of fine particles of CKD was able to fill the voids within the soil matrix, thus increasing the dry density. However, beyond 12% CKD, the dry density decreases with an increase in OMC. This is attributed to the fact that addition of fine particles such as CKD increases the specific surface requiring more water to lubricate. Hence, the increase in percentage of water consequently decreases the dry density as more space is occupied by the increased percentage of water. Further, the decrease in MDD beyond 12% CKD is also attributed to the brittle nature of soil with higher CKD that aids flocculation and aggregation of soil particles. Based on changes in plasticity characteristics as well as compaction characteristics of CKD-admixed BC soil, it can be concluded that 12% CKD produces optimum benefits in terms of maximum reduction in PI and OMC as well as maximum increase in MDD.

Compaction Characteristics of BC Soil Admixed with Optimum CKD and Unground Cement Clinker

The optimum CKD for the BC soil used in the present investigation was found to be 12%. Further, the BC soil used in the present investigation was classified as CH; i.e., clay of high compressibility. Since in many infrastructure applications, highly compressible soils pose settlement problems, one of the economical options is to minimize the settlements in sub-soil by altering the particle size distribution to produce better compaction.

Since unground cement clinker is one of the cement industry waste by-products that are generated during the grinding process and having large round shaped particles, it can be used as a sustainable material to alter grain size characteristics and hence gradation of compressible clays. Further, the constituents of unground cement clinker indicate that it is mainly made of CaO and SiO_2 with a free-lime content of 1%. Hence, the addition of unground cement clinker along with CKD will not only alter grain size characteristics, but also will assist pozzolanic reactions, forming cementitious compounds. Addition of unground cement clinker along with CKD hence bound to alter compaction characteristics which will have a bearing on optimum quantity of CKD as well as optimum quantity of unground cement clinker. Thus, compaction test was performed for BC soil admixed with optimum 12% CKD and the percentage of unground cement clinker was varied from 4% to 30% in order to ensure that the total percentage of both CKD and unground cement clinker does not exceed 50% by weight of the dry soils. Table 4 shows summarized values for MDD obtained for BC soil admixed with CKD as well as BC soil admixed with UCC along with optimum CKD. Fig. 3 shows comparative variation of MDD and OMC for BC soil +12% CKD and BC soil + 12% CKD with different percentages of unground cement clinker. The variation in MDD as well as OMC clearly indicates that addition of unground cement clinker alters particle size characteristics of BC soil admixed with optimum CKD. Addition of coarser particle such as unground cement clinker achieves greater packing and hence greater MDD, with corresponding reduction in OMC due to reduction in specific surface in comparison to BC soil admixed with CKD.

The trend in results has clearly indicated that 12% unground cement clinker in combination with 12% CKD admixed to the soil was able to achieve maximum MDD with corresponding minimum OMC. This is attributed to greater packing due to the addition of unground cement clinker. Presence of free CaO in unground cement clinker helps achieve better mixing of clay particles due to flocculation resulting into a well-packed structure, consequently reducing the plasticity and enhancing compaction. SEM images of BC soil+ 12% CKD + 12% UCC shown in Fig. 4 indicate that the unground cement clinker particles were coated with clay and CKD and there is considerable reduction in voids due to dense packing, in comparison to SEM image of BC soil+ 12% CKD shown in Fig. 2(c). Hence, the trend in the results has clearly indicated that the addition of unground cement clinker along with optimum CKD shifts the curve further left and upward indicating better compaction with higher density at lower moisture content which is desired in many infrastructure applications in order to reduce compressibility, such as in highway and railway embankments that may necessitate the use of compressible clays that need to be procured from nearby burrow areas.

Shear Strength of BC Soil Admixed with Optimum CKD and Unground Cement Clinker

Increase in strength is a function of curing period and unconfined compressive strength (UCS) test is one of the most simple and common tests that can be used to evaluate physical shear strength of stabilized soil as a function of curing period. Thus, to verify the effect of different percentages of CKD on shear strength of CKD-admixed BC soil as a function of curing period, UCS test was conducted by admixing BC soil with different percentages of CKD ranging from 4% to 20% and curing the specimen in a controlled desiccator for a period ranging from 0 to 28 days. All the samples were compacted to have corresponding MDD and remoulding water content obtained in the corresponding compaction test for the said combinations. Table 5 summarizes values of unconfined compressive strength obtained for BC soil alone and BC soil admixed with different percentages of CKD at different curing periods. For a given percentage of CKD, an increase in curing period increases UCS. Further, maximum UCS has been obtained corresponding to 12% CKD at 28 day-curing. A marginal increase in UCS has been observed when the percentage of CKD was varied between 8% and 12% and increase was in the range of 3.7% at 28-day curing, indicating stability in terms of strength gain at the end of 28-day curing.

Table 4. MDD and OMC obtained for BC soil admixed with CKD as well as for BC soil admixed with optimum CKD and UCC

BC Soil + %CKD			BC Soil + 12%CKD + %UCC		
% CKD	**MDD (kN/m²)**	**OMC (%)**	**%UCC**	**MDD (kN/m²)**	**OMC (%)**
4	15.63	27.5	4	15.85	22.08
8	16	25.53	8	16.18	21.25
12	**16.05**	**24.65**	**12**	**16.99**	**21.86**
16	15.88	26.5	18	16.56	23.00
20	15.73	27.07	25	16.20	22.79
			30	15.80	22.18

Table 5. Unconfined compressive strength (UCS) for BC soil admixed with different percentages of CKD at different curing periods

Curing Period →	**0 Days**	**7 Days**	**14 Days**	**28 Days**
% of CKD ↓	UCS (kN/m²)	UCS (kN/m²)	UCS (kN/m²)	UCS (kN/m²)
0	155.15	155.55	156.80	155.38
4	181.89	212.27	223.98	252.08
8	195.13	235.25	252.39	272.17
12	192.21	255.35	251.32	278.33
16	178.69	221.35	258.53	253.03
20	163.70	211.80	219.79	222.59

Since 12% UCC in combination with 12% CKD was found to be optimum based on compaction characteristics, UCS test was performed by curing the specimens at 0,7,14 and 28 days for BC Soil+12%CKD+12%UCC. Fig.5 shows comparative variation of UCS obtained for BC soil alone, BC soil+12%CKD and BC soil+12CKD+12%UCC at different curing periods. Similar to CKD-admixed BC soil, all the samples with optimum 12%CKD along with 12% unground cement clinker were compacted to have corresponding MDD and remoulding water content obtained in the corresponding compaction test. The trend in the results clearly indicates that for a given period of curing, the UCS obtained for BC soil+12%CKD+12%UCC is larger than that obtained for BC soil alone as well as that obtained for BC soil+12% CKD. This is attributed to the possible denser packing of unground cement clinker-admixed BC soil+12% CKD which is also evidenced in compaction characteristics wherein greater MDD at lower OMC was obtained for BC+12% CKD+12%UCC.

CBR of BC Soil Admixed with Optimum CKD and UCC

CBR method used to design flexible pavement is a measure of penetration resistance offered by soil subgrade. Since the present experimental investigation has clearly indicated that the shear strength of CKD and UCC-admixed BC soil has shown substantial increase in shear strength, CBR was conducted by admixing the soil with 12% CKD and 12% CKD + 12% UCC which represented optimum percentage conditions. The samples were cured in the desiccator for 7 and 28 days and at the end of 7- and 28-day curing, CBR test was conducted in soaked condition. For the case of soaked condition, the sample was kept submerged in water for 4 days with 2.5 kg surcharge at the top. Table 6 summarizes the values of CBR obtained for BC soil alone in comparison with those obtained for BC soil admixed with 12% CKD and 12%CKD+12%UCC. It can be seen that a substantial increase in CBR has been obtained when BC soil is admixed with both CKD and UCC. CBR obtained after 28-day curing shows a substantial increase of around 213% in comparison to unsoaked CBR obtained for BC soil alone. This is attributed to the fact that there is a substantial increase in dry density of compacted admixture of BC soil+12%CKD+12%UCC as envisaged in Table 4, which indicates maximum value of dry density with substantial decrease in OMC. This is attributed to the fact that the grain size as well as gradation of the UCC-admixed BC soil change leading to substantial increase in dry density.

Table 6. Variation in CBR for BC soil admixed with CKD and UCC

CBR Penetration in mm	2.5		5	
CBR in % of BC soil alone (Unsoaked)	1.90		1.74	
CBR in % of BC soil alone (Soaked)	0.76		0.87	
Curing Period in Days	**7 DAYS**	**28 DAYS**	**7 DAYS**	**28 DAYS**
CBR in % of BC soil+12%CKD	2.28	2.66	2.03	2.03
CBR in % of BC soil+12%CKD+12%UCC	4.56	5.96	4.64	5.51

Addition of both CKD and UCC alters compaction characteristics, significantly improving shear strength and CBR, which is essential in many infrastructure applications. For the case of BC soil admixed with CKD alone, it can be envisaged that the pozzolanic reaction due to cation exchange of CaO depends on curing period. It has been found that the stability in shear strength and CBR occurs at around 28 days as most of the pozzolanic reactions seem to be complete at around 28 days, since the trend in the results indicates no significant variation in shear strength between 14- and 28-day curing.

CONCLUSIONS

The present study aims to assess the changes in compaction characteristics that are correlated to changes in shear strength as a function of curing period and finally the CBR, due to addition of optimum CKD as well as UCC. The results have been comparatively analyzed to arrive at conclusions on major geotechnical properties of CKD and UCC-admixed BC soil. Based on the present experimental investigation, the following major conclusions were drawn:

The associated morphological changes due to addition of CKD to BC soil indicate flocculation affecting the changes in plasticity of CKD-admixed BC soil. It was found that LL initially increases when the percentage of CKD increases, but beyond 4% CKD, the increase is marginal. The plasticity index becomes minimum corresponding to 12% CKD-admixed BC soil. Continuous increase in shrinkage limit with increase in percentage of CKD indicates reduction in swelling characteristics of BC soil. Variations of plasticity index indicate that 12% CKD produces optimum benefits in terms of reduction in plasticity.

Compaction characteristics of CKD-admixed BC soil indicated maximum reduction in OMC with corresponding maximum increase in MDD at 12% CKD, due to associated effect of flocculation and agglomeration of the soil particles caused by exchange of cations. Based on the preset experimental study, for the BC soil used in the present study, 12% CKD can be considered as optimum in terms of maximum increase in dry density with a significant decrease in optimum moisture content.

Additions of coarser particle of UCC along with 12% optimum CKD in BC soil indicate that UCC alters gradation of BC soil, leading to greater packing and hence greater MDD. The corresponding reduction in OMC observed in compaction test is due to reduction in specific surface due to addition of coarser particles of UCC, in comparison to BC soil admixed with CKD.

Presence of more percentage of free CaO in UCC along with CKD helps achieve better mixing of clay particles due to flocculation resulting into a well-packed structure. The morphological structure of particles in the SEM image of UCC-admixed BC soil indicates considerable reduction in voids due to dense packing, in comparison to BC soil+ 12% CKD. The trend in the results indicated that the addition of UCC along with optimum CKD achieves better compaction with higher density at lower moisture content, which is desired in many infrastructure applications.

The effect of curing period of CKD-admixed BC soil on unconfined compressive strength (UCS) indicated maximum strength gain corresponding to 12% CKD at 28-day curing. UCS obtained for BC soil admixed with optimum 12% CKD along with optimum 12% UCC is found to be larger than that obtained for BC soil alone as well as those obtained for combinations of BC soil+12% CKD, which is due to denser packing achieved for UCC-admixed BC soil along with 12% CKD.

A significant increase in dry density with corresponding reduction in OMC obtained for compacted admixture of BC soil+12%CKD+12%UCC is the reason for the substantial increase of around 213% in CBR value at 28- day curing in comparison to unsoaked CBR obtained for BC soil alone.

The trend in the results clearly indicates that the addition of both cement kiln dust and unground cement clinker leads to development of a sustainable soil improvement process causing corresponding reduction in plasticity with associated significant gain in shear strength. For BC soil admixed with CKD alone, the pozzolanic reaction due to cation exchange of CaO depends on the curing period. The trend in the results thus indicates reduction in compressibility of expansive soils that is a prerequisite for many infrastructure applications.

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