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Experimental Study on Cement Kiln Dust Based Geopolymer as Subgrade Soil Stabilizer

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***Abstract*: Expansive soil drastically changes phase from being too hard in the summer to becoming slushy in the monsoon season, due to its swell – shrink behavior, that is why engineering properties of the expansive soil must be enhanced before constructing the road infrastructure on such soils. The present research work shows the results of experimental work carried out to enhance the engineering properties of Black Cotton Soil (BCS) by utilizing cement kiln dust (CKD) and cement kiln dust based geopolymer. The efficiency of this binder is discussed in terms of maximum dry density (MDD), optimum moisture content (OMC) and California bearing ratio (CBR) of stabilized soil. In geopolymer synthesis, combination of sodium silicate (SS – Na_2SiO_3) and sodium hydroxide (SH – NaOH) is used as a soluble alkali activator. The discussion of result of alkali activation is done in the form of stabilization of black cotton soil with cement kiln dust. Six different CKD percentages with respect to the total solids (soil + CKD) weight, is used: 5%, 10%, 15%, 20%, 25% and 30%. The three different percentages of cement kiln dust (10%, 20% and 30%) are activated with blend of sodium silicate and 4, 7, 10 and 13 molar concentrations of sodium hydroxide solutions. The ratio of sodium silicate to sodium hydroxide solution by dry mass is kept constant as 2:1. The most effective concentration of alkali activator and dust/soil ratio is determined.**

***Keywords*: Alkaline activators, Black cotton soil, Cement kiln dust, Expansive subgrade soil, Geopolymer, Sodium hydroxide and Sodium silicate, Soil stabilization.**

1. Introduction

The history of the world says that, any country’s economic, industrial, social and cultural development depends on its transportation facilities’ evaluation and advancements. There are three basic forms of transportation has developed, namely Land, Water and Air, which has developed scope of transportation by Roads and Railways, Waterways and Airways, respectively. Transportation by roads includes modern highways such as expressways, national highways and state highways, urban arterials, feeder roads and village roads, which serves the extensive road vehicles and the pedestrians. The objective of the pavement structure is to transmit loads through the underlying layers on the subgrade soil below.

Thickness of the pavement and the characteristics of the materials used in the different layers of pavement are two major parameters which helps in reducing wheel load stress.

A layer of natural soil from identified trench satisfying the defined requirements and well condensed to the desired density to required thickness is known as the subgrade soil. The bottom most layer which supports all other pavement layers and traffic load is subgrade. Elimination of over stress on subgrade soil is essential. The minimum thickness of compacted subgrade required for high volume of traffic is 500 mm.

Tests conducted for an assessment of mechanical properties of the subgrade soil are empirical. California bearing ratio (CBR) test is a most common empirical penetration test. This test has been regulated by the Bureau of Indian Standard (BIS) and has been suggested for assessment of subgrade soil by the Indian Road Congress (IRC).

The soil which has natural tendency of changing phases by swelling and shrinking under different moisture contents are known as expansive soils and it has very low load carrying capacity that is why this type of soils are problematic for light weight structures such as pavements. Expansive soils are commonly found in many parts of Australia, Asia, Africa, Europe and America. Existence of clay minerals like montmorillonite and illite in soils are responsible for its swell – shrink behavior. Remarkable changes to the structures are results of unrestricted distortion and differential movement generated by volumetric changes of these clay minerals.

The method applied for modification of one or more properties of soil to enhance its engineering performance is mentioned as soil stabilization. Methods involved in soil stabilization are physical, physio – chemical and chemical to make the stabilized soil work for its objective as pavement section material.

Investigations have done by many of the researchers to replace the lime and cement by different industrial wastes. Some of these materials have been used to stabilize soil and to develop building materials. Fly ash from various sources (FA), volcanic ash (VA), ordinary Portland cement (OPC), red mud (RM), ground bottom ash (GBA), ground granulated blast furnace slag (GGBFS) (Anant Lal Murmu at el., 2019; Ghadir at el., 2018; Tigue at el., 2018; Partha Sarathi Parhi at el., 2018; My Quoc Dang at el., 2018; S. Mazhar at el., 2018; Jonathan R. Dungca at el., 2018; Hayder H. Abdullah at el., 2017; Shreelakshami at el., 2017 and Ayyappan at el., 2017), crushed brick (CB), recycled crushed aggregates (RCA) and reclaimed asphalt pavement (RAP) (Alireza Mohammadinia, at el., 2016), lime stone dust (LSD) and coal fly ash (CFA) (Robert Brooks at el., 2011) etc. have been used for stabilization of expansive soils.

"Geopolymer", an inorganic binder named and developed by French material scientist Davidovits is being projected as an alternative to cement. The geopolymer is generally formed by the reaction of aluminosilicates and oxides in an alkaline environment (Davidovits at el., 1989). Geopolymer is said to emit 90% less CO_2 as compared to cement (Davidovits at el., 2015b).

The objectives of the present research work are: To study the effect of cement kiln dust on the engineering properties of black cotton soil, to determine the effect of cement kiln dust based geopolymer stabilizer on the engineering properties of black cotton soil and to determine the optimum content of geopolymer based stabilizer for improving the engineering properties of black cotton soil.

The black cotton soil used for this study is obtained from the Rajkot – Morbi Highway, nearby Marwadi University. The study is limited to laboratory investigation of cement kiln dust based geopolymer for use as a subgrade soil stabilizer using the following specified laboratory tests: Standard proctor compaction test [IS – 2720 (Part – 7): 1980] and Soaked and un-soaked California bearing ratio test [IS – 2720 (Part – 16): 1987]

Alkali activated cement kiln dust is utilized as a binder in the soil stabilization. Sodium silicate and sodium hydroxide are used as an alkali activator. Cement kiln dust is obtained from Neon cement plant, Bamanbor, Gujarat.

2. Materials

The materials used in present study are black cotton soil (BCS), cement kiln dust (CKD), sodium hydroxide (SH) and sodium silicate (SS). Black cotton soil was collected from the Rajkot – Morbi Highway, nearby Marwadi University, Gujarat, India and cement kiln dust was collected from the Neon mini plant of cement production from Bamanbor, Gujarat, India. The index properties and chemical composition of BCS and CKD are presented in Table 1 and Table 2, respectively. It can be observed from Table 1 that BCS is a clayey soil of high compressibility and comes under the CH group as per the Indian standard soil classification system (ISSCS).

For laboratory testing, soil was dried in an oven at 110 ^{0}C for 24 hours before using. Dried soil was then pulverized and sieved with 4.75 mm Indian Standard sieve as required for laboratory testing. Maximum dry density (MDD) and optimum moisture content (OMC) of virgin soil is 1.46 gm/cc and 20.83%, respectively. Un-soaked and soaked CBR value of virgin soil is 3.93% and 1.48%, respectively and Compressive strength of black cotton soil is 50.41 kPa.

A combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) was used as an alkaline activator. Sodium silicate was originally in liquid form having molecular weight of 123 gm/mole. While, sodium hydroxide was in flakes form with molecular weight 40 gm/mole. The sodium hydroxide and sodium silicate was brought from Sadguru Chemicals, Gondal, Gujarat, India. The ratio of sodium silicate to sodium hydroxide solution by dry mass was kept as 2:1. This value was chosen because from several studies it was analyzed that influence of the activator combination of higher ratios resulted in higher strength levels.

Table 1
Index properties of BCS

Material	BCS	IS Standard
Specific Gravity	2.64	IS 2720 Part 3
Liquid Limit (%)	81.23	IS 2720 Part 5
Plastic Limit (%)	34.47	IS 2720 Part 5
Plasticity Index (%)	46.76	IS 2720 Part 5
Free Swell Index (%)	70	IS 2720 Part 40
ISSCS	CH	IS 1498
pH	8.81	IS 2720 Part 26

Table 2
Chemical composition of CKD

Material	CKD	Unit
SiO_2	39.34	%
Al_2O_3	5.91	%
CaO	28.24	%
MgO	5.75	%
Fe_2O_3	15.79	%
Na_2O	0.23	%
SO_3	0.27	%

3. Sample Preparation and Testing

In the present study, six different percentages of cement kiln dust by dry weight of total solids were added with black cotton soil namely 5, 10, 15, 20, 25 and 30%, corresponding to ash/soil ratios of 0.056, 0.11, 0.18, 0.25, 0.33 and 0.43. Then, optimum moisture content (OMC), maximum dry density (MDD), un-soaked California bearing ratio test and soaked California bearing ratio tests were experimentally investigated.

Sodium silicate and sodium hydroxide were used as an alkaline activators and ratio of sodium silicate to sodium hydroxide was kept as 2:1. Four different molar concentrations of alkaline activator (4, 7, 10 and 13 M) were prepared and added in three different percentages of cement kiln dust (10%, 20% and 30%) by dry weight of total solids to black cotton soil. The amount of alkaline activator added was same as the optimum moisture content obtained from the standard proctor test performed on the soil stabilized by cement kiln dust. Then, soaked and un-soaked California bearing ratio of different samples were investigated. Evaluation of soaked CBR of geopolymer treated soil samples were done after 4 days of curing in water tank.

The activator solution was prepared at least 24 h before being used, so that the temperature increase due to the exothermic reaction between the silicate and hydroxide was dissipated.

Table 3 and Table 4 shows the details of CKD modified and alkali activated CKD modified black cotton soil specimens, respectively.

Table 3
Details of CKD modified BCS specimens

Sr. No.	Name of the Mix	Particulars of the Mix
1.	BCS + 5% CKD	BCS + 5% CKD by weight of total solids
2.	BCS + 10% CKD	BCS + 10% CKD by weight of total solids
3.	BCS + 15% CKD	BCS + 15% CKD by weight of total solids
4.	BCS + 20% CKD	BCS + 20% CKD by weight of total solids
5.	BCS + 25% CKD	BCS + 25% CKD by weight of total solids
6.	BCS + 30% CKD	BCS + 30% CKD by weight of total solids

Table 4
Details of the alkali activated CKD modified soil specimens

Sr. No.	Name of the Mix	Particulars of the Mix
1.	BCS + 10% CKD + 4 M Activator	Soil + 10% CKD by weight of total solids + 4 Molar activator same as OMC obtained from SPC test
2.	BCS + 20% CKD + 4 M Activator	Soil + 20% CKD by weight of total solids + 4 Molar activator same as OMC obtained from SPC test
3.	BCS + 30% CKD + 4 M Activator	Soil + 30% CKD by weight of total solids + 4 Molar activator same as OMC obtained from SPC test
4.	BCS +10% CKD + 7 M Activator	Soil + 10% CKD by weight of total solids + 7 Molar activator same as OMC obtained from SPC test
5.	BCS + 20% CKD + 7 M Activator	Soil + 20% CKD by weight of total solids + 7 Molar activator same as OMC obtained from SPC test
6.	BCS + 30% CKD + 7 M Activator	Soil + 30% CKD by weight of total solids + 7 Molar activator same as OMC obtained from SPC test
7.	BCS + 10% CKD + 10 M Activator	Soil + 10% CKD by weight of total solids + 10 Molar activator same as OMC obtained from SPC test
8.	BCS + 20% CKD + 10 M Activator	Soil + 20% CKD by weight of total solids + 10 Molar activator same as OMC obtained from SPC test
9.	BCS + 30% CKD + 10 M Activator	Soil + 30% CKD by weight of total solids + 10 Molar activator same as OMC obtained from SPC test
10.	BCS + 10% CKD + 13 M Activator	Soil + 10% CKD by weight of total solids + 13 Molar activator same as OMC obtained from SPC test
11.	BCS + 20% CKD + 13 M Activator	Soil + 20% CKD by weight of total solids + 13 Molar activator same as OMC obtained from SPC test
12.	BCS + 30% CKD + 13 M Activator	Soil + 30% CKD by weight of total solids + 13 Molar activator same as OMC obtained from SPC test

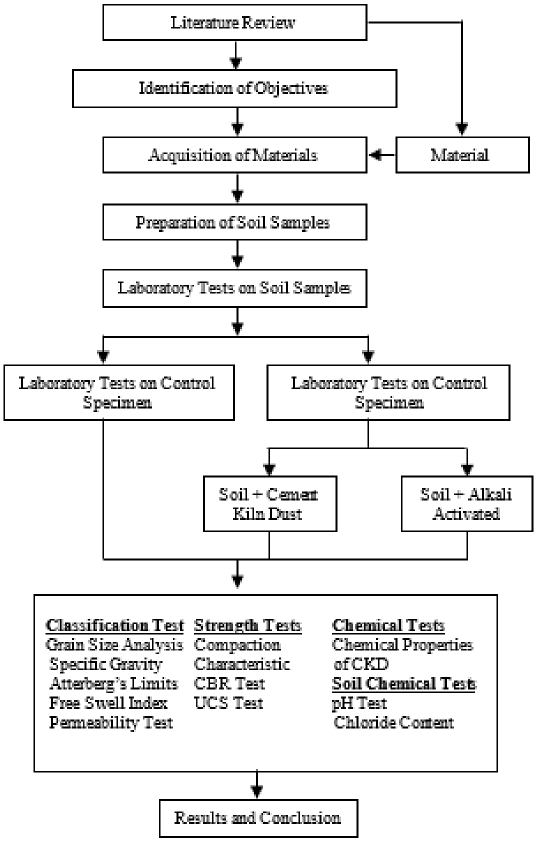

Fig. 1. Flow chart of proposed methodology

4. Results and Discussion

A. Compaction characteristics

The compaction characteristics of black cotton soil partially replaced with cement kiln dust is shown in Fig. 2 and 3. Fig. 1 shows the variation of MDD with varying CKD contents. Initially on addition of 5% CKD, the MDD of the un-stabilized soil increased from 1.46 gm/cc to 1.52 gm/cc. Further addition of CKD (10%) resulted in an incline in the MDD to 1.53 gm/cc. Further addition of 5% incremental dosages i.e., 15% and 20% of CKD to the soil resulted in a sudden increase in the value of the MDD to a maximum value of 1.62 gm/cc, which was obtained at a dosage of 20% CKD. After that point, MDD starts decreasing with the addition of 5% incremental dosages i.e., 25%, 30%.

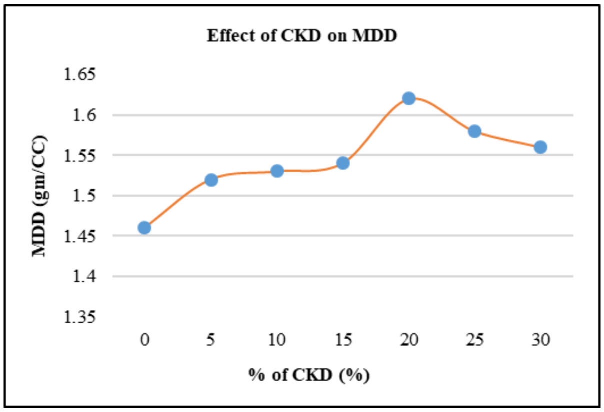

Fig. 2. Graphical representation of effect of CKD on MDD of soil

The variation in OMC with partial substitution of BCS with CKD is shown in Fig. 3. Initially on addition of 5% CKD, the OMC of the un-stabilized soil increased from 20.83% to 21.21%. Further addition of CKD (10%) resulted in an incline in the OMC to 23.36%. Further addition of 5% incremental dosages i.e., 15%, 20%, 25% and 30% of CKD to the soil resulted in a gradual increase in the value of the OMC to a value of 27.90%, which was obtained at a dosage of 30% CKD.

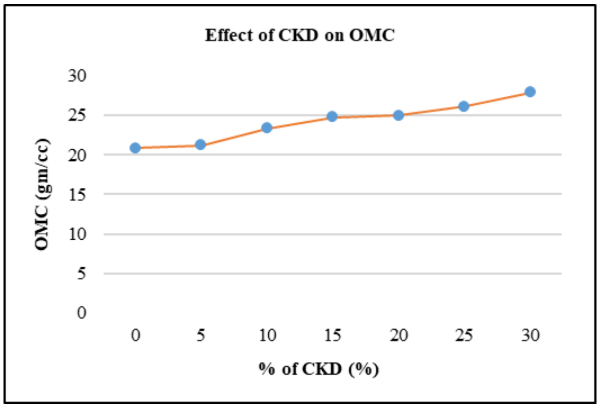

Fig. 3. Graphical representation of effect of CKD on OMC of soil

B. Un-soaked California bearing ratio

Fig. 4 Shows effect of replacement of soil by CKD on Un-soaked California bearing ratio test. Initially on addition of 5% CKD, CBR value of un-stabilized soil increased from 3.93% to 5.67%. Further addition of 5% incremental dosages i.e., 10%, 15%, 20% of CKD to the soil by dry mass of total solids resulted in a gradual increment in the value of CBR to the maximum value of 9.26%, which was obtained at a partial replacement of soil by 20% CKD. Further addition of 5% incremental dosages of CKD to the soil resulted in decrement in the value of CBR to the 8.30%, which was obtained at a 30% CKD replacement.

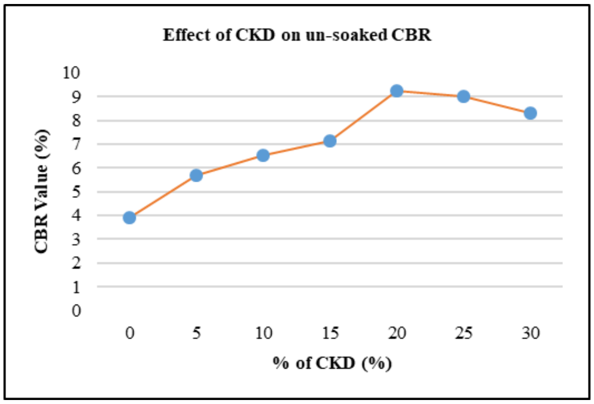

Fig. 4. Graphical representation of effect of CKD on un-soaked CBR of soil

C. Soaked California bearing ratio

Fig. 5 shows effect of replacement of soil by CKD on soaked California bearing ratio test. Initially on addition of 5% CKD, soaked CBR value of soaked soil increased from 1.48% to 1.66%. Further addition of 5% incremental dosages i.e., 10%, 15%, 20% of CKD to the soil by dry mass of total solids resulted in a gradual increment in the value of CBR to the maximum value of 5.07%, which was obtained at a partial replacement of soil by 20% CKD. Further addition of CKD by 5% replacement of soil reduces CBR value.

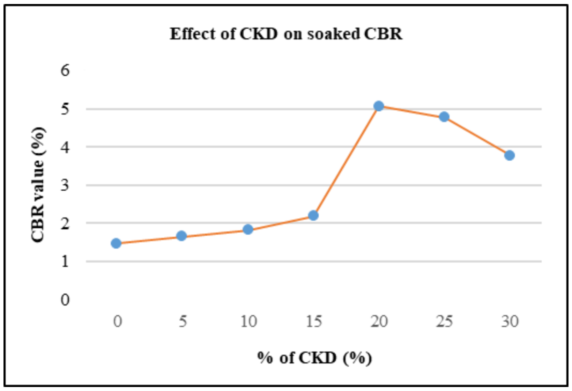

Fig. 5. Graphical representation of effect of CKD on soaked CBR of soil

D. Discussion of test results of CKD based geopolymer modified soil sample

Fig. 6 shows the CBR value of all samples treated with CKD based geopolymer, obtained from un-soaked CBR and soaked CBR. From the results, it is clear that the maximum CBR value of un-soaked specimen is 20.31%, which is of the 7 Molar activated soil replaced by 20% CKD. Same as, the soaked specimen of 7 Molar activated soil replaced by 20% CKD gives highest CBR of all after 4 days of soaking in water tank, which is 54.50%.

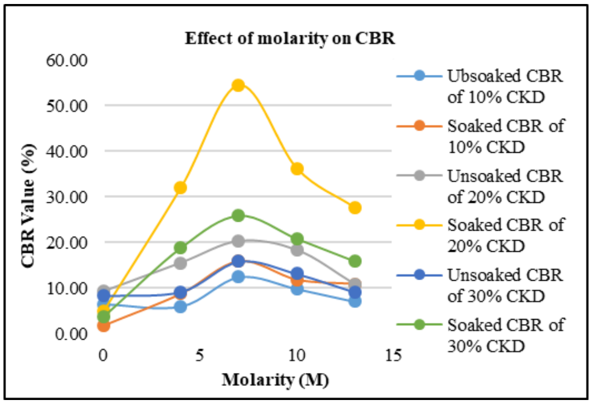

Fig. 6. Graphical representation of effect of molarity on CBR of geopolymer modified specimens

5. Conclusion

The stabilization of an expansive black cotton soil has been done to improve mechanical strength of pavement subgrade soil. In the present study, stabilization of black cotton soil with cement kiln dust and cement kiln dust based geopolymer was discussed. The effectiveness of these binders, namely stabilizing agent – cement kiln dust and geopolymer precursor cement kiln dust synthesized by blend of sodium silicate and different molar concentrations of sodium hydroxide was discussed in terms of MDD, OMC and Soak – Un-soak CBR.

Based on the obtained results of experiments of CKD modified soil sample, there of following conclusions can be draw:

- Maximum dry density of CKD modified black cotton soil was gradually increased up to 20% CKD replacement of soil. Further addition of CKD resulted in decrement in MDD of soil. MDD was increased from 1.46 gm/cc to 1.62 gm/cc. Increment in MDD of modified soil at 20% CKD replacement was 10.96%.

- MDD depends on the size of particles and specific gravity of soil and stabilizer. Thus, reason behind increment in MDD is denser arrangement of BCS and CKD particles.
- Addition of 5% incremental dosages of CKD, caused inclination in optimum moisture content of modified soil. As maximum densification of finer particles requires higher amount of water. Increment in OMC of modified soil at 20% CKD replacement was 19.92%.
- The un-soaked CBR value of CKD treated soil increased from 3.93% to 9.26% at 20% CKD replacement of soil. Further 5% increment in CKD replacement resulted in reduction in CBR value. Increment in Un-soaked CBR value at 20% CKD replacement was 135.62%.
- The soaked CBR value of CKD treated soil increased from 1.48% to 5.07% at 20% CKD replacement of soil. Same as un-soaked CBR, further addition of 5% CKD soil caused reduction in CBR value of soil. Soaked CBR value of 20% CKD replacement was increased by 242.57%.
- The highest un-soaked and soaked CBR value of CKD modified soil achieved was at 20% CKD replacement of soil because of its maximum dry density was highest of all.

Based on the results of experiments of CKD based geopolymer modified soil sample, there of following conclusions can be draw:

- The un-soaked and soaked CBR value of geopolymer modified black cotton soil found to vary with percentage of cement kiln dust and concentration of alkali solution.
- Maximum un-soaked CBR value of geopolymer treated sample was 20.31%, which was obtained with 20% CKD and 7 Molar alkali solution. Increment in un-soaked CBR value of geopolymer treated sample was 416.79% and 119.33% from virgin soil and CKD modified soil, respectively.
- The increment in CBR is due to Pozzolanic reaction between soil and CKD and higher dissolution of alumino – silica ions from the precursor.
- Maximum soaked CBR value of geopolymer treated sample was 54.50%, which was obtained with 20% CKD and 7 Molar alkali solution.
- Soaking of geopolymer treated sample in water tank for four days resulted in acceleration of chemical reaction between soil and cement kiln dust in the presence of water by giving higher soaked CBR value.
- Hence, 20% CKD replacement and 7 Molar concentration of alkali solution is considered as optimum content of geopolymer based stabilizer for improving the engineering properties of black cotton soil.
- According to the code of flexible pavement design – IRC-37 (2018), effective subgrade CBR should be more than 5%. So, from the results of geopolymer treated samples, all the specimens achieves sufficient CBR value in both un-soak and soak case to be used as the stabilized subgrade material.

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