Clay soil stabilization using cement kiln dust

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Abstract. This research investigated the suitability of cement kiln dust (CKD) on the stabilization of clayey soil extracted along a failed road section of Sango, Ota. Since CKD does not need any further processing or treatment, it is cheap as it is a waste product from cement production and can be utilized in powdery form. The suitability of CKD as a stabilizer is dependent on its performance on problematic soil. For this study, it was mixed with clayey soil in varying proportions of 7.5, 10, 12.5 and 15%. For each combination, several geotechnical tests were carried out. The result shows that the unsoaked CBR of the clay soil increased from 1.49 to 28.6%, and thus indicates that the soil mixed with 10% CKD showed the best mechanical improvement after a curing period of 7 days. Other curing periods were observed. In addition to CBR improvement, other tests such as Atterberg limits, Proctor compaction, and free swell, tests revealed that the geotechnical properties of the stabilized soils increased with an increase in the amount of CKD by dry weight of the soil. It is noted that the use of CKD at 10% was more economical and environmentally beneficial. This research shows the beneficial use of industrial wastes such as CKD in the stabilization of soils, which is line with sustainable waste management practices.

Key words: Cement kiln dust; soil stabilization; sustainability; soil modification;

1. Introduction

Cement is the single most used material in the construction industry with an annual production exceeding 3.4 billion tonnes in 2012, and consequently, 4.3 billion tonnes by 2014 [1 - 3]. To supply this high demand for cement annually, a huge pressure is placed on natural resources such as limestone and coal. Studies and reports from China where more than 60% of the world cement is manufactured, revealed that annually, a billion tonnes of limestone, hundred million tonnes of coal, sixty billion kw/h electricity and one hundred and eighty million tonnes of clay are used to produced 2.53 billion tonnes of cement. Subsequently, due to the need for huge emission and energy for production, the cement industry is regarded as one of the major sources of greenhouse gases (GHG) in the world [4 -6]. Different studies has detailed the impact of cement emission on the environment and people within the environment [7 - 9].

Several studies has stated that cement demand and production would increase to 5 billion tonnes by the year 2050, putting more pressure on the natural resources and environment [10]. Therefore, there is a need to either minimize the use of raw materials in production or to reduce the amount of cement used in construction. Cement is also extensively used in pavement construction, among which includes interlayer stabilization using cement [11]. Stabilization of soil with cement is a well-established technique as the improvement of pavement interlayers by cement addition is based on the development...
of primary and secondary products such as calcium silicates hydrates (CSH), Calcium aluminates hydrates (CAH) as well as Ca(OH)$_2$ [12]. A look at the typical composition of both OPC and lime which significantly improve soil strength, shows that the high percentage of silicon dioxides (SiO$_2$), Calcium oxide (CaO) and Alumina oxide (Al$_2$O$_3$) is responsible for their effectiveness [13, 14]. To this end, researchers have been exploring the possibilities of waste showing pozzolanic potential in pavement interlayer stabilization.

Waste materials examined as stabilizers ranges from industrial to agricultural waste [15 - 23]. The total volume of waste generated annually is 2.1 billion tonnes which would increase to 3.4 billion tonnes by the year 2050 [24]. The successful application of waste for stabilization would reduce the need for cement for stabilization. Studies using these wastes have successfully improved weak soil strength, even better than the use of cement in stabilization in some cases.

For every tonne of cement produced, 0.6 to 0.7 tonnes of CKD is produced [25 - 27]. Since high volume of cement is produced annually, the global volume of Cement kiln dust (CKD) generated is 2.4 to 2.8 billion tonnes yearly. Consequently, the volume generated will increase annually. Similar chemical reaction and hydration products observed in cement has been discovered in CKD stabilized soil. Therefore, stabilization with CKD, in substitute to cement is practically possible for large scale city or national project. The effectiveness of CKD in soil stabilization is dependent on both its physical and chemical characteristics [28, 29]. Particle distribution, percentage of CaO, SiO$_2$, alkali and sulfate content affects the stabilization effectiveness of CKD.

For this study, the stabilization of failed road section along Abeotuta-Lagos road close to the cement plant was examined. There are several failed sections along these road due to various reasons among which includes the presence of weak soils. These rehabilitation or reconstruction will require a huge sum of money due to the presence of weak soil. The possibility of using CKD generated and dumped in open dump site with no economic or environmental benefit was investigated. To this end various tested as listed in Table 1 were carried out to assess the possibility of CKD, thereby reducing the construction cost.

### 2. Material

#### 2.1 Clay soil

The soil stabilized in this study was collected at Ifo, Ifo local government, Ogun state in the southwestern part of Nigeria (6°47'07.4"N 3°12'12.2"E). The physical properties and chemical composition of the soil are listed in the Table 1 below. As shown in Table 1, the soil is weak and it is classified as S1, since the CBR is less than 2%. Such subgrade requires special treatment before use in construction. Hence, for pavement construction, stabilization is necessary.

| Soil properties          | Characteristics          | Units | Value   |
|--------------------------|--------------------------|-------|---------|
| Classification           | AASTHO                   | A-2-7 |         |
| Physical properties      | Natural moisture content | %     | 8       |
|                          | Specific gravity         |       | 2.42    |
| Atterberg limits         | Liquid limits            | %     | 116.83  |
|                          | Plastic limit            | %     | 35.29   |
|                          | Plasticity index         | %     | 81.54   |
Stabilizers

The stabilizer used for this study is cement kiln dust (CKD). The CKD was collected from a cement production plant at Ewekoro, Ogun state, near a failed road section. The typical chemical composition of CKD is presented in Table 2. There are four different effects; the chemical composition of CKD can have on soil stabilization. First, CKD with high percentage of free CaO, (above 15%) and low alkalies, i.e. (less than 4% $K_2O$ OR 3%$Na_2O$) which result in increased in strength of the clayey soil. Second, low percentage of free CaO and high percentage of alkalies such as 7% water soluble $K_2O$ or higher percentages of $Na_2O$ more than 3%, results in reduction of compressive strength. Thirdly, free CaO percentage ranging from 8 to 15% (moderate free lime content), with low alkalies (less than 4% $k_2o$ or 3% $Na_2O$, which would result in an increase in strength gained and durability as well as reduction in swelling. The last possible CKD has LOI less than 9%, but with moderate alkalies i.e. above 3% $Na_2O$, there will be reduction in plasticity index as well as improvement in compressive strength.

The stabilizer has a high percentage of Calcium Oxide (CaO), followed by Silicon dioxide ($SiO_2$).

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2.3 Sample preparation and Laboratory tests

Preparation of samples for the series of tests carried out in this study was guided by the standards listed in Table 3. For the modified soil, the natural soil was initially oven-dry, then thoroughly mixed with various stabilizers at prescribed percentages as listed in Table 4. Afterward, the required amounts of water were added and mixing was carried out until a homogenous mix was achieved.

Comprehensive geotechnical tests were carried out to access both the natural soil and modified soil mixtures. The tests performed include Atterberg limits, free swelling, Proctor Compaction test, and California bearing ratio (CBR). The standards and procedures followed for each test carried out on the natural soil as well as the modified soil is listed in Table 3. The mixture table for the study is shown in Table 4.

Atterberg limit tests were performed in accordance with ASTM D4318, the soil was sieved through 425 μm sieve and the limits were recorded after 24 hours. The moisture-density relationship was accessed using the Proctor compaction test. The test indicates the maximum dry density (MDD)
and the corresponding optimum moisture content (OMC) for the natural soil and the modified soil. For this test, after achieving a homogenous mix, the test was carried out immediately to prevent voids formation, which would reduce the dry density.

Curing effects were observed in California Bearing Ratio (CBR) for the period of 96 hours for soaked condition and periods of 7, 14 and 28 days for unsoaked condition.

| Table 3. The standards followed for each test. |
|---------------------------------------------|
| **Test**                                   | **Specification** |
| Atterberg limit                            | ASTM D4318       |
| Specific gravity                           | ASTM D854        |
| Compaction test (OMC and MDD)              | ASTM D698        |
| Swelling potential test                    |                  |
| CBR – California bearing ratio             | ASTM D1883-05    |

| Table 4. Mixture table and notation.       |
|-------------------------------------------|
| **S/N** % Soil | % CKD | **Notation** |
|----------------|-------|--------------|
| 1              | 100   | 0            | NAT          |
| 2              | 92.5  | 7.5          | CKD 1        |
| 3              | 90    | 10           | CKD 2        |
| 4              | 87.5  | 12.5         | CKD 3        |
| 5              | 85    | 15           | CKD 4        |

3. Results and discussion

3.1 Effect on the consistency limits
The Plasticity index (PI) of a soil or soil mixture indicates its expansive activity and is used primarily for soil classification. Different soil type possess different PI, highly expansive soil possess high PI as in the case of Na-montmorillonite [29 - 30]. Fig. 1 below shows the effects of the stabilizers on the plasticity index and linear shrinkage. Improved soil samples showed reduction in the plasticity index with the addition of CKD. The addition of CKD at various percentage results in a significant reduction of liquid limit which in turn reduced in the plasticity index (PI) of the stabilized soil. The best plasticity index reduction was achieved at 10% CKD modified soil where the natural soil index reduced from 81.54 to 28.6%. However, the lowest linear shrinkage was recorded against the soil stabilized with 7.5% CKD. Increase in linear shrinkage was observed with all the improved soil mixture. The optimum percentage for plasticity reduction using CKD is 7.5 to 10%.

As mentioned earlier, the physical (fineness) and chemical composition (free lime content, alkali and sulfate content) of the CKD significantly affects the performance of the stabilizer for plasticity index reduction [31]. The high percentage of CaO, has being documented by different studies to be significantly responsible for the improvement in plasticity index as a result of cation ion exchange of Ca$^{2+}$ in the soil mixture. This reduces the affinity of the soil to water, as the clay minerals are modified. In addition to ion exchange, fineness of the CKD as well as the presence of high alkali and sulfate content affects it reactivity. [29] observed that CKD with high free lime as well as moderate alkalies (= 4.6%, Na$_2$O) leads to reduction in plasticity [28]. In cases where the free lime content is low, reduction in liquid limit and PI, is relatively low. For plasticity limit, the addition of CKD either slightly increase plasticity limit or causes little or no changes. A reduction in plasticity index is a clear indicator of soil improvement as it aids workability [32].
3.2 Effects on free swelling.

Apart from the improvement in plasticity limit, the reduction of the free swelling of the natural soil was reduced significantly. It was discovered that according to [33], the degree of expansion is medium. However, the addition of CKD at various percentages, changes the degree of expansion from medium to low as indicated in Fig 2. The change in degree of expansion is due to isomorphous substitution, which modifies the clay mineral layers and the water layer thickness. The addition of CKD modifies the water layer thickness, reducing the amount of water film. The lowest free swelling was observed at CKD with 7.5%, different studies has documented the expansion of CKD itself at certain percentages, yet, at the percentages investigated, the free swelling was reduced.

![Figure 1: Effect of stabilizer on Atterberg limit.](image)

3.3 Effect on the compactability.

The results as illustrated in Fig. 3 depicts that an increase in Optimum moisture content (OMC) and Maximum dry density (MDD), was observed as the percentage of CKD is increased. Different mechanisms are responsible for the increase in MDD. Such mechanisms include filler effects, specific gravity of the stabilizer and flocculation. The fineness of the CKD reduces the void within the soil while the effects of higher specific gravity of the CKD to the soil, induced increased MDD. The demand for more water for these mixtures is observed to be due to need for water for hydration products. The addition of CKD has being observed to increase the pH of the soil mixture due to the presence of
hydroxide ion from Calcium carbonate formed in the soil mixture. This indicates the need for higher compactive energy to attain MDD when stabilization with CKD is carried out [34]. The might lightly increase compaction cost during construction.

3.4 Effect on CBR.

Fig. 4 shows the effects of the stabilizer on the California bearing ratio of the soil samples. It was observed that the addition of CKD at various percentages ranging from 7.5 to 15% improves the soil strength significantly. The results indicated that the optimum CKD percentage is 10%, which corresponds with the plasticity index. The result also indicates as established by various research works that curing periods significantly improve soil strength due to development of hydration products. Different research have revealed the production of calcium hydroxide which is absorbed by the clay, modifying the clay microstructure, thereby improving the mechanical strength of the stabilized soil [35]. The CBR value of the CKD stabilized soil improved the strength gained by 96.4% from 7 to 28 days. The results indicated that the use of CKD at 7.5% addition is optimum. Soaked CBR tests indicated a similar pattern to that of unsoaked as the addition of CKD efficiently improved the soaked CBR values from 0.5% to 16.01% at 10% CKD addition. The peaked for soaked CBR was achieved with 15% CKD addition, a CBR value of 16.8%.

![Figure 2: Effect of stabilizer on free swelling.](image-url)
Figure 3: Effect of stabilizer on compaction.
4. Conclusion

A study to determine the effectiveness of CKD generated in a cement plant in Ogun state, Nigeria for stabilization of soft clayey soil along failed road section near the plant is reported. The use of CKD on weak soil would reduce construction cost, extended service life of roads, and sustainability of the environment, the use of CKD in subgrade improvement is paramount. The following conclusion can be observed.

- The addition of CKD reduces the plasticity due
- Increase in OMC and MDD was observed as a result of filler effects, development of hydration products and variation in specific gravity.
- Reduction in free swell from medium degree of expansion to low was observed as the CKD was added due to modification of the clay minerals.
- Mechanical strength improvement was observed with CKD at all combinations, and increased strength was recorded as curing days increased due to formation of hydration product.
- The addition of CKD at 10% was observed to be the optimum percentage for unsoaked CBR with 1,792% percent improvement at 7 days and 3638% at 28 days. However, for soaked CBR, the 10% addition, lead to 2,774 % improvement. Although the optimum for soaked CBR is 15% to 2,915% improvement, as more CKD in the system encouraged the formation of hydration product with the availability of more moisture in the soil mixture. However, due to only a slight difference in the soaked improvement with 15% when compared to 10% and the optimum performance of 10% in unsoaked condition, the optimum for CKD addition is 10%.
- The addition of CKD improves workability and reduces cost as the required pavement thickness is reduced.

References

[1] Song J, Yang B, Chen T, and Alsaedi A 2016 Life-cycle environmental impact analysis of a typical cement production chain Appl. Energy 164 916–23.
[2] Adeniran J, Yusuf R, Fakinle B, and Sonibare J 2018 Air quality assessment and modelling of pollutants emission from a major cement plant complex in Nigeria Atmos. Pollut. Res.

[3] Zhang P, Zheng Y, Wang K, and Zhang J 2018 A review on properties of fresh and hardened geopolymer mortar Compos. Part B 152 79–95.

[4] Kaddatz K. T., Rasul M. G., and Rahman A 2013 Alternative fuels for use in cement kilns: Process impact modelling, Procedia Eng. 56 13–20.

[5] Habert G, Espinoze J, Lacaille D, and Roussel N 2011 An environmental evaluation of geopolymer based concrete production : reviewing current research trends J. Clean. Prod. 19 1229–38.

[6] Harley J 2007 The Impact of Cement Kilns on the Environment.

[7] Pascal M 2013 A review of the epidemiological methods used to investigate the health impacts of air pollution around major industrial areas J. Environ. Public Health.

[8] Davidson C, Phalen R, and Solomon P 2005 Airborne particulate matter and human health: A review Aerosol Sci. Technol. 39 737–49.

[9] Valavanidis A, Fiotakis K, and Vlachogianni T 2008 Airborne particulate matter and human health: Toxicological assessment and importance of size and composition of particles for oxidative damage and carcinogenic mechanisms J. Environ. Sci. Heal. - Part C Environ. Carcinog. Ecotoxicol. Rev. 26 339–62.

[10] Ninla P, Balo A, Kamseu E, Chinje U, Delplancke M, and Rahier H 2014 Influence of the processing temperature on the compressive strength of Na activated lateritic soil for building applications, Constr. Build. Mater. 65 60–66.

[11] Busari A, Dahumsi and Akinmusuru J 2019 Sustainable concrete for rigid pavement construction using de-hydroxylated Kaolinitic clay: Mechanical and microstructural properties Constr. Build. Mater. 211 408–15.

[12] Zhang M, Zhao M, Zhang G, Nowak P, Coen A, and Tao M 2015 Calcium-free geopolymer as a stabilizer for sulfate-rich soils Appl. Clay Sci.108 199–207.

[13] Cui S, Wang J, Wang X, Du F, and Wang P 2018 Mechanical behavior and micro-structure of cement kiln dust-stabilized expensive soil, Arab. J. Geosci. 11 521.

[14] Amadi A 2014 Enhancing durability of quarry fines modified black cotton soil subgrade with cement kiln dust stabilization Transp. Geotech. 1 55–61.

[15] Kang G, Cikmit A., Suchida T, Honda H, and sang Y 2019 Strength development and microstructural characteristics of soft dredged clay stabilized with basic oxygen furnace steel slag, Constr. Build. Mater. 203 501–13.

[16] Liu L, Zhou A, Deng Y, Cui Y, Yu Z, and Yu C 2019 Strength performance of cement/slag-based stabilized soft clays, Constr. Build. Mater. 211 909–18.

[17] Kumar Y, Gaurav K, Kishor R, and Suman K 2017, Stabilization of alluvial soil for subgrade using rice husk ash, sugarcane bagasse ash and cow dung ash for rural roads, Int. J. Pavement Res. Technol.10 254–61.

[18] Gupta D and Kumar A 2017 Performance evaluation of cement-stabilized pond ash-rice husk ash-clay mixture as a highway construction material J. Rock Mech. Geotech. Eng 9 159–69.

[19] Behnood A 2018 Soil and clay stabilization with calcium- and non-calcium-based additives: A state-of-the-art review of challenges, approaches and techniques, Transp. Geotech. 17 14–32.

[20] Hasan H, Dang L, Khabbaz H, Fatahi B, and Terzaghi S 2016 Remediation of Expansive Soils Using Agricultural Waste Bagasse Ash, Procedia Eng. 143 1368–75.

[21] Oluwatuyi E 2018 Ameliorating effect of milled eggshell on cement stabilized lateritic soil for highway construction Case Stud. Constr. Mater. 9 e00191.

[22] Shalabi I, Asi M, and Qasrawi Y 2017 Effect of by-product steel slag on the engineering properties of clay soils J. King Saud Univ. - Eng. Sci. 29 394–99.

[23] Adebanji O, Ayobami B, and Emmanuel A 2018 Pavement interlayer material improvement using industrial waste: Review of literatures Int. J. Civ. Eng. Technol. 9 1114–22.
[24] Cody E 2018 World Bank: Global waste generation could increase 70% by 2050 | Waste Dive 2018. [Online] Available: https://www.wastedive.com/news/world-bank-global-waste-generation-2050/533031/ [Accessed: 2019].

[25] Al-Refai O. and Al-Karni A 2018 Experimental Study on the Utilization of Cement Kiln Dust for Ground Modification J. King Saud Univ. - Eng. Sci. 11 217–31.

[26] Okafor O. and Egbe A 2013 Potentials of cement kiln dust in sub-grade improvement 32 109–16.

[27] Miller A. and Azad S 2000 Influence of soil type on stabilization with cement kiln dust 89–97.

[28] Rahman M and Rehman S 2011 Literature review on cement kiln dust usage in soil and waste stabilization and experimental investigation 7 77–87.

[29] Peethamparan S. and Olek J 2008 Study of the Effectiveness of Cement Kiln Dusts in Stabilizing Na-Montmorillonite Clay 20 137–46.

[30] Savage P 2007 Evaluation of Possible Swelling Potential of Soil 26th South. African Transp. Conf. 277–83.

[31] Mosa M, Taher H., and Al-jaberi L. A 2017 Case Studies in Construction Materials Improvement of poor subgrade soils using cement kiln dust Case Stud. Constr. Mater. 7 138–43.

[32] Pourakbar S, Asadi A, Huat B and Fasihnikoutalab M 2015 Stabilization of clayey soil using ultrafine palm oil fuel ash (POFA) and cement, Transp. Geotech. 3 24–35.

[33] Indian Standard, IS : 1498 – 1970 2000 Classification and Identification of Soils for General Engineering Purposes, Bureau of Indian Standards, New Delhi (ReaffIrmed 2007), 1–24.

[34] Basha A, Hashim R, Mahmud B., and Muntohar A. 2005 Stabilization of residual soil with rice husk ash and cement Constr. Build. Mater. 19 448–53.

[35] Peethamparan S, Olek J, and Diamond S. 2009 Cement and Concrete Research Mechanism of stabilization of Na-montmorillonite clay with cement kiln dust Cem. Concr. Res. 39 580–89.