

Geo-Mechanical Enhancement of a Grained Soil blended with Silicate-Portland cement Powder for Usage in Construction Industry.

Abstract

The mechanical as well as geopolymer strength of a lateritic soil from three (3) different localities on Lokoja- Abuja highway where road failure happen was blended with rice husk ash (RSA), cement and sodium silicate activator (SSA), with varying proportions examined via triaxial shear, Atterberg, and Compaction scrutinizes. The outcome displays that cement enhancement enriched the lateritic soil from Liquid limit values of 41.26 at 0% to 44.37 at 8%, but lessens at 10% to 35.68, whereas RHA (Rice husk ash) rises at increased percentages. Likewise MDD enhanced with increased quantities of all the enhancer i.e SSA, cement as well as RHA contents, but OMC for both cement and RHA lessen from 18.66% at 0% to 11.72 and 18.06 correspondently. Further scrutiny reveals cohesion of the soil at 0%, 2%, 4%, 6%, 8% as well as 10% to be 19.01, 39.02, 49.01, 55.03, 58.01 and 65.02 KN/m² respectively, with peak angle of 65⁰ and minimum of 37⁰. This indicates that the cohesion of the enhanced samplings was satisfied since the improved angle of internal friction is beyond the angle that makes soil very plastic which is 28⁰.

Keywords: Geopolymer, Road engineering, Sodium silicate, Rice waste, Shear.

Introduction

In recent times, usage of soil in construction road works has become a major crisis to civil engineers [1], specifically geotechnical engineers because most of soils available do not meet some geotechnical engineering properties, on the other hand [2-3], the need for soil enhancement by either stabilization or modification might be needed for obtaining the required results of the properties [4-6]. Lateritic soils are the most common category of soil encountered during any road construction works in Nigeria, and mostly have low bearing capacity and strength [7-9], due to high quantities of clay in its natural state [10-13]. Lateritic soil having high quantity of clay mineral will possess weak strength under load, particularly when it comes in contact with moisture [14-17]. Similarly, lateritic soil with high quantity of plastic clay instigates cracks as well as damage to civil engineering works for example building foundations, road pavement or any correlated civil engineering project works [18-21].

Soil stabilization or enhancement can be categorized into two sets, precisely mechanical and chemical stabilization [22, 23]. Mechanical stabilization or improvement process signifies the changes in the physical properties [24] or parameters of the soil particles with the help of either revitalize vibrations [25], compaction or both [26], whereas chemical stabilization is a technique utilized for chemical modification between admixture or cementitious material and the pozzolanic materials (soil minerals) for achieving the best result from improving the principal geotechnical properties of the soil [27-31]. The key problem connected with chemical stabilization, especially cement enhancement or stabilization a major chemical stabilization widely accepted [32], consist of the following; high prize of cement production that trigger high cost of stabilized road construction work [33-35], and high discharge of CO₂ during manufacturing process which in turn responsible for global warming [36-38].

In the technologically advanced nations, the universal and cost-effective materials that are frequently used to partly substitute cement without economic significance are classified into industrial-waste as well as agricultural-waste (agro-waste) materials [37-40], for instances, bag asse

ash, wood ash, groundnut shell ash, iron ore tilling, saw dust ash, bone ash, rice hush ash, and coconut shell ash [41-44].

Literature review publicized that projected quantities of kaolin mineral deposit reserve in Nigeria, is roughly 2 billion metric tons [45, 46]. Similarly, metakaolin is the remnant from the burning of kaolin (dehydroxylated kind of kaolin), normally via heating to roughly temperature of 750⁰C [47-49]. In view of the fact that kaolin mineral does not have carbonates, thus no amount of CO₂ is discharged during burning or calcination, as such will minimalize the detrimental impact of CO₂ released during manufacturing of industrially synthetic soil enhancement agent [50-52].

Table 1: Basic and Mechanical strength features of the selected lateritic soil prior to enhancement.

| PROPERTIES | SOIL SAMPLES (CONTROL) | | |
|--|-------------------------------|---------------|---------------|
| | KA | SA | DA |
| Moisture Content (MC) | 6.51 | 7.50 | 5.42 |
| Specific Gravity (SG) | 2.52 | 2.62 | 2.21 |
| Grain Size Distribution | | | |
| Coarse-grain (%) | 90.88 | 93.42 | 91.87 |
| Fine-grain (%) | 09.12 | 06.58 | 08.13 |
| Bulk density (KN/m ³) | 14.64 – 29.76 | 12.23 – 22.36 | 14.63 – 22.76 |
| Atterberg Scrutiny (%) | | | |
| LL | 40.45 | 41.25 | 37.00 |
| PL | 17.09 | 24.59 | 12.00 |
| PI | 23.36 | 16.66 | 25.00 |
| Compaction Investigation | | | |
| Maximum Dry Density (KN/m ²) | 18.65 | 17.80 | 15.19 |
| Optimum Moisture Content (%) | 9.15 | 9.89 | 9.67 |
| CBR (%) | 9.88 | 8.46 | 7.42 |
| Unconfined compressive strength (N/mm ²) | 107.45 | 105.54 | 106.95 |
| Triaxial Scrutiny | | | |
| Cohesion (KN/m ²) | 19 | 18 | 19 |
| Angle of internal friction θ^0 | 23.1 | 22.2 | 23.1 |
| Soil Categorization | A-2-7 | A-2-7 | A-2-4 |
| Colour | Reddish brown | | Brown |
| Soil class | Silty- clayey gravel and sand | | |

2. MATERIALS AND TECHNIQUES

Soil samples utilized in this investigation was collected from three different borrow pit along Lokoja- Abuja express road Federal capital territory (FCT), Nigeria. It was taken at a depth that is below 150mm using the disturbed sampling technique and then air-dried. Portland cement powder (PCP) and sodium silicate activator (SSA) was bought from the local shops while rice husk was collected from a rice mill situated within Kwali town, FCT Nigeria [53, 54]. Rice husk / shell fibre was incinerated into ash in a furnace @ 500⁰C temperature for over six (6) hours, followed by cooling activities before absolutely grounded. Subsequently it was sieved thru 75mm sieve as prescribe in BS 12 [50]. In the same way, Preliminary scrutiny on the collected three lateritic soil sampling were performed in the Civil Engineering Department laboratory, Federal University of Technology, Akure, Ondo State, Nigeria.

3. RESULTS AND DISCUSSION

3.1 Preliminary Tests results

Outcomes of preliminary investigations on the lateritic soil are demonstrated in Table 1. The outcomes displays that the soil is categorized as A-7-6 based on AASHTO classification system.

This implies that it falls below the recommended standard for use for construction work and would therefore require improvement.

3.2 Atterberg limit

Results of Atterberg scrutiny for geopolymer blended Rice Husk Ash (RHA) and sodium silicate activator (SSA) and are presented in Tables 2-4, and Figures 1-3.

The outcome exhibits that cement enhancer improved the lateritic soil from Liquid limit (LL) values of 41.25 at 0% to 44.36 at 8%, but lessens at 10% to 35.67, but RHA rises at increased percentages. This indicates that RHA also have Portland cement powder key chemical constituents i.e SiO₂, MgO, Al₂O₃, and CaO, and so forth. This is an indication that RHA is a good pozzolana that can assist in the promotion of the cementitious compounds configuration during cement hydration reaction products which is in agreement with investigators like Adeyanju et al. [8], Zhu et al. [10] and Xia [11].

Table 2: Effect of RHA on Atterberg limit test.

| % | Sheda Borrow Pit (SBP) | | | Dabi Borrow pit (DBP) | | | Kwali borrow pit (KBP) | | |
|-------------|------------------------|-------|-------|-----------------------|-------|-------|------------------------|-------|-------|
| | PL | LL | PI | PL | LL | PI | PL | LL | PI |
| 0RHA+6%PCP | 24.59 | 41.25 | 16.66 | 12.01 | 37.00 | 25.01 | 17.09 | 40.45 | 23.36 |
| 2RHA+6%PCP | 10.56 | 27.23 | 16.67 | 3.24 | 23.89 | 20.65 | 06.34 | 25.31 | 18.96 |
| 4RHA+6%PCP | 13.24 | 31.23 | 17.99 | 3.67 | 27.54 | 23.87 | 07.32 | 28.23 | 20.91 |
| 6RHA+6%PCP | 14.35 | 34.56 | 20.21 | 4.34 | 30.12 | 25.78 | 08.34 | 32.12 | 23.78 |
| 8RHA+6%PCP | 15.56 | 37.05 | 21.49 | 4.91 | 32.76 | 27.86 | 08.98 | 35.23 | 26.25 |
| 10RHA+6%PCP | 16.53 | 38.02 | 21.49 | 5.62 | 33.25 | 27.63 | 09.08 | 37.22 | 28.14 |

Table 3: Effect of SSA on Atterberg limit test

| % | Sheda Borrow Pit (SBP) | | | Dabi Borrow pit (DBP) | | | Kwali borrow pit (KBP) | | |
|-------------|------------------------|-------|-------|-----------------------|-------|-------|------------------------|-------|-------|
| | PL | LL | PI | LL | PL | PI | PL | LL | PI |
| 0RHA+6%PCP | 24.59 | 41.25 | 16.66 | 37.00 | 12.00 | 25.00 | 17.09 | 40.45 | 23.36 |
| 2RHA+6%PCP | 12.56 | 20.98 | 8.42 | 19.78 | 11.05 | 8.73 | 14.05 | 20.98 | 6.93 |
| 4RHA+6%PCP | 11.56 | 21.34 | 9.78 | 17.34 | 10.75 | 6.59 | 12.06 | 21.34 | 9.28 |
| 6RHA+6%PCP | 10.75 | 30.67 | 19.92 | 20.67 | 10.04 | 10.63 | 10.05 | 30.67 | 20.62 |
| 8RHA+6%PCP | 19.45 | 31.67 | 12.22 | 21.67 | 9.54 | 12.13 | 9.06 | 31.67 | 22.61 |
| 10RHA+6%PCP | 17.45 | 29.65 | 12.20 | 19.65 | 8.75 | 10.90 | 8.56 | 29.65 | 21.09 |

Table 4: Effect of geopolymer on Atterberg limit test

| % | Kwali Borrow Pit (KBP) | | | Sheda Borrow pit (DBP) | | | Dabi borrow pit (KBP) | | |
|-------------|------------------------|-------|-------|------------------------|-------|-------|-----------------------|-------|-------|
| | LL | PL | PI | LL | PL | PI | LL | PL | PI |
| 0RHA+6%PCP | 40.45 | 17.09 | 23.36 | 41.25 | 24.59 | 16.66 | 37.00 | 12.00 | 25.00 |
| 2RHA+6%PCP | 44.67 | 18.50 | 26.17 | 45.67 | 19.25 | 26.42 | 40.67 | 17.20 | 23.47 |
| 4RHA+6%PCP | 49.52 | 19.50 | 30.02 | 50.12 | 20.45 | 29.67 | 42.75 | 18.50 | 24.25 |
| 6RHA+6%PCP | 57.64 | 31.65 | 25.99 | 59.54 | 32.45 | 27.09 | 54.60 | 30.80 | 23.80 |
| 8RHA+6%PCP | 64.80 | 33.60 | 31.20 | 67.50 | 34.56 | 32.94 | 61.50 | 31.50 | 30.00 |
| 10RHA+6%PCP | 71.60 | 39.50 | 32.10 | 73.56 | 40.56 | 33.00 | 69.60 | 37.60 | 32.00 |

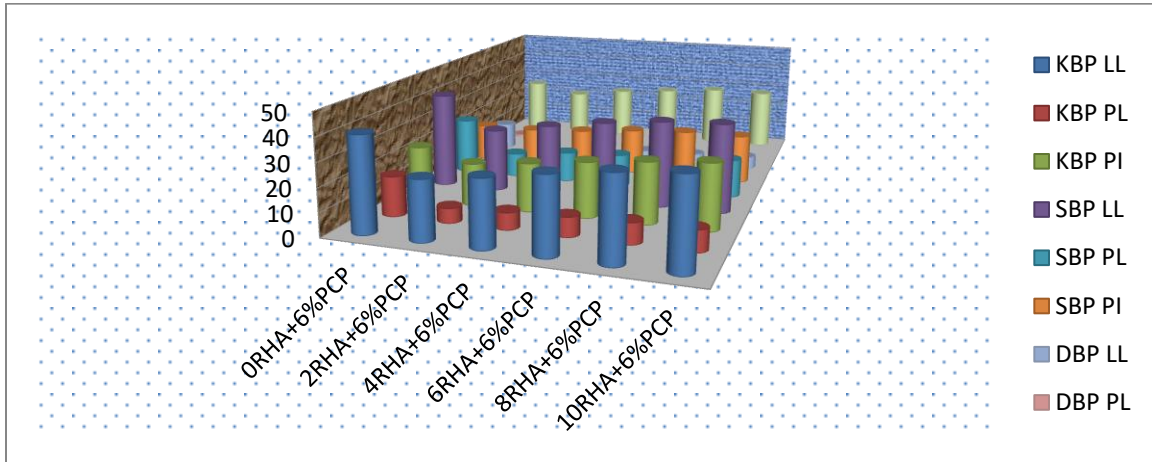


Fig. 1: Impact of RHA on Atterberg limit test.

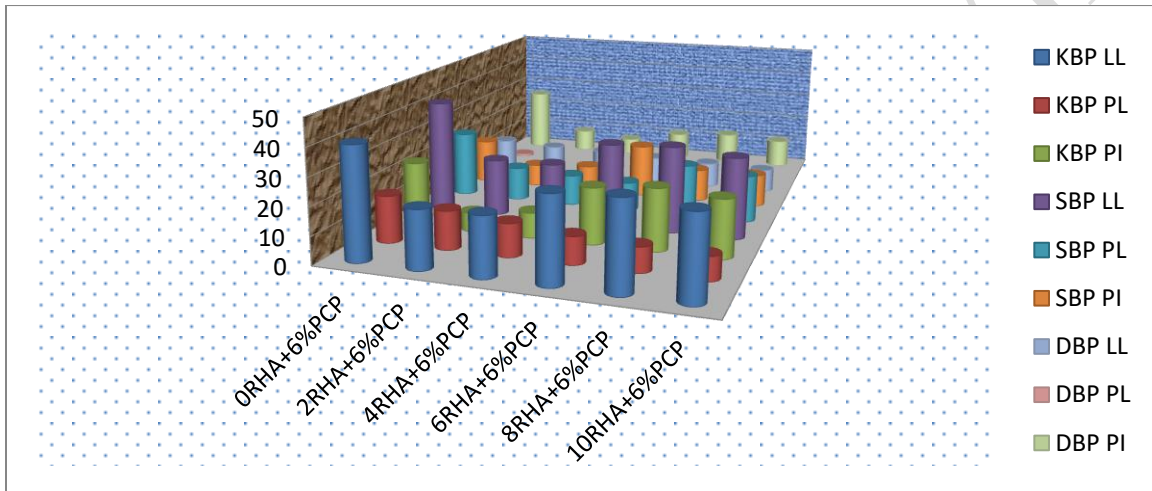


Fig. 2: Impact of SSA on Atterberg limit test.

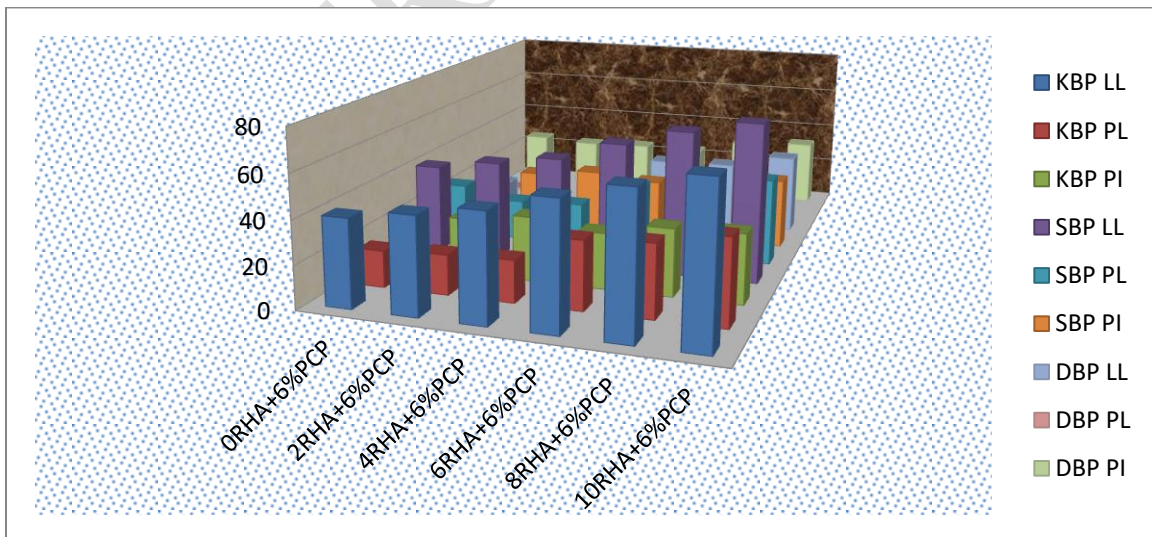


Fig. 3: Impact of geopolymer on Atterberg limit test.

3.3 Effect of compaction

Results of compaction test for geopolymer, SSA and RHA are displayed in Tables 5-7, and Figures 4-6. The figure depicts that adding cement, RHA as well as KCP enriched both the OMC and quantities of the MDD correspond to increasing of cement, RHA and KCP percentage. The increase in OMC is perhaps a consequence of two reasons:(1) the introduced water becomes extra and held with the flocculant soil structure resulting from cement interface, and (2) exceeding water absorption by RHA as a result of its porous physiognomies, as testified by Abdullah [3]. Above all, enhancement of lateritic soil dry density after introduction of improver is a sign of improvement for both RHA and PCP, even if it **increases** the dry density gradually. **Poona et al.** [1] reveals an opinion that the change-up in dry density occurs because of both the particles size and specific gravity of the soil and stabilizer. Increasing dry density indicates that it need high compactive energy (CE) to attain its MDD, thus make construction more durable and cost effective Xu et al. [2], Wattex [5] and Agashua et al [53].This increase in the dry density can be due to the particle flocculation and agglomeration caused by the slowly cation exchange in the soil-stabilizer mixture.

Table 5: Effect of SSA on compaction test

| % | KA | | SA | | DA | |
|-------------|--------------------------|---------|--------------------------|---------|--------------------------|---------|
| | MDD (mg/m ³) | OMC (%) | MDD (mg/m ³) | OMC (%) | MDD (mg/m ³) | OMC (%) |
| 0RHA+6%PCP | 1.342 | 16.85 | 1.456 | 17.75 | 1.572 | 18.65 |
| 2RHA+6%PCP | 1.360 | 16.90 | 1.460 | 18.79 | 1.580 | 18.70 |
| 4RHA+6%PCP | 1.385 | 17.01 | 1.465 | 19.02 | 1.588 | 18.75 |
| 6RHA+6%PCP | 1.400 | 17.13 | 1.475 | 19.30 | 1.592 | 18.79 |
| 8RHA+6%PCP | 1.420 | 17.30 | 1.479 | 19.40 | 1.598 | 18.82 |
| 10RHA+6%PCP | 1.440 | 17.45 | 1.483 | 19.45 | 1.602 | 18.86 |

Table. 6: Effect of RHA on compaction test

| % | KA | | SA | | DA | |
|-------------|--------------------------|---------|--------------------------|---------|--------------------------|---------|
| | MDD (mg/m ³) | OMC (%) | MDD (mg/m ³) | OMC (%) | MDD (mg/m ³) | OMC (%) |
| 0RHA+6%PCP | 1.342 | 16.85 | 1.456 | 17.75 | 1.572 | 18.65 |
| 2RHA+6%PCP | 1.520 | 15.92 | 1.680 | 16.34 | 1.620 | 16.72 |
| 4RHA+6%PCP | 1.720 | 15.60 | 1.895 | 15.89 | 1.870 | 14.60 |
| 6RHA+6%PCP | 1.920 | 14.95 | 1.980 | 15.04 | 2.020 | 13.95 |
| 8RHA+6%PCP | 2.150 | 13.48 | 2.190 | 14.02 | 2.250 | 12.48 |
| 10RHA+6%PCP | 2.345 | 12.11 | 2.450 | 12.21 | 2.465 | 11.71 |

Table. 7: Effect of geopolymer on compaction test

| % | KA | | SA | | DA | |
|-------------|--------------------------|---------|--------------------------|---------|--------------------------|---------|
| | MDD (mg/m ³) | OMC (%) | MDD (mg/m ³) | OMC (%) | MDD (mg/m ³) | OMC (%) |
| 0RHA+6%PCP | 1.342 | 16.85 | 1.456 | 17.75 | 1.572 | 18.65 |
| 2RHA+6%PCP | 1.760 | 17.80 | 1.890 | 19.80 | 1.890 | 19.54 |
| 4RHA+6%PCP | 1.850 | 18.01 | 1.970 | 20.02 | 1.970 | 20.00 |
| 6RHA+6%PCP | 1.920 | 19.05 | 2.250 | 20.80 | 2.250 | 21.20 |
| 8RHA+6%PCP | 1.980 | 19.45 | 2.480 | 21.40 | 2.480 | 21.75 |
| 10RHA+6%PCP | 2.050 | 19.80 | 2.560 | 21.60 | 2.560 | 22.20 |

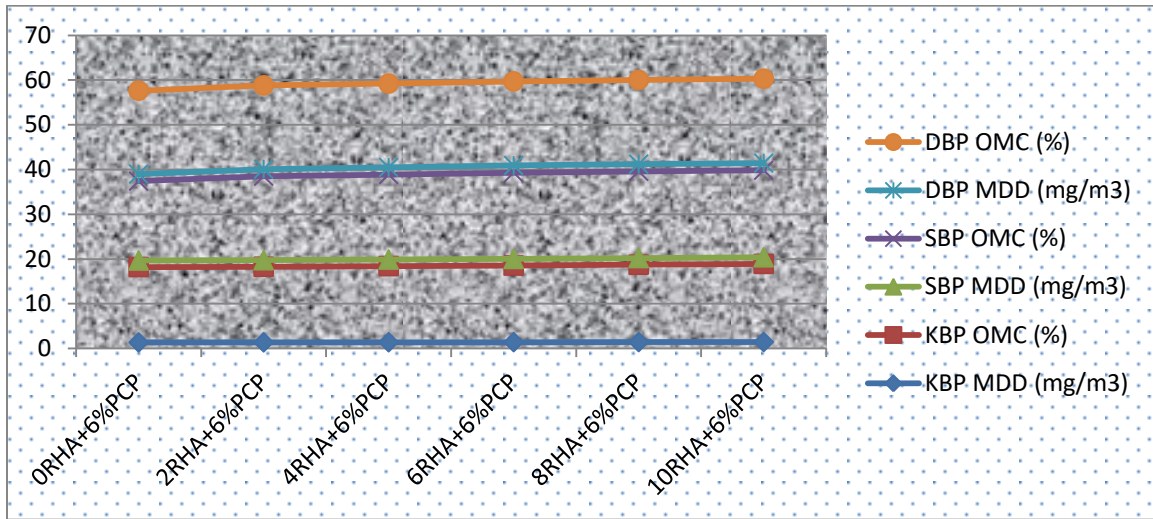


Fig. 4: Impact of SSA on compaction test

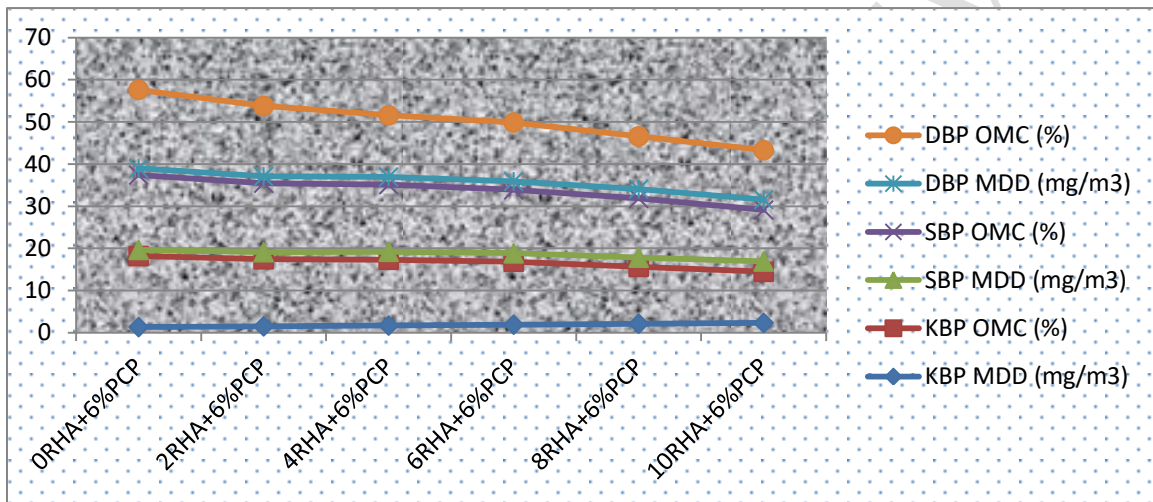


Fig. 5: Impact of RHA on compaction test

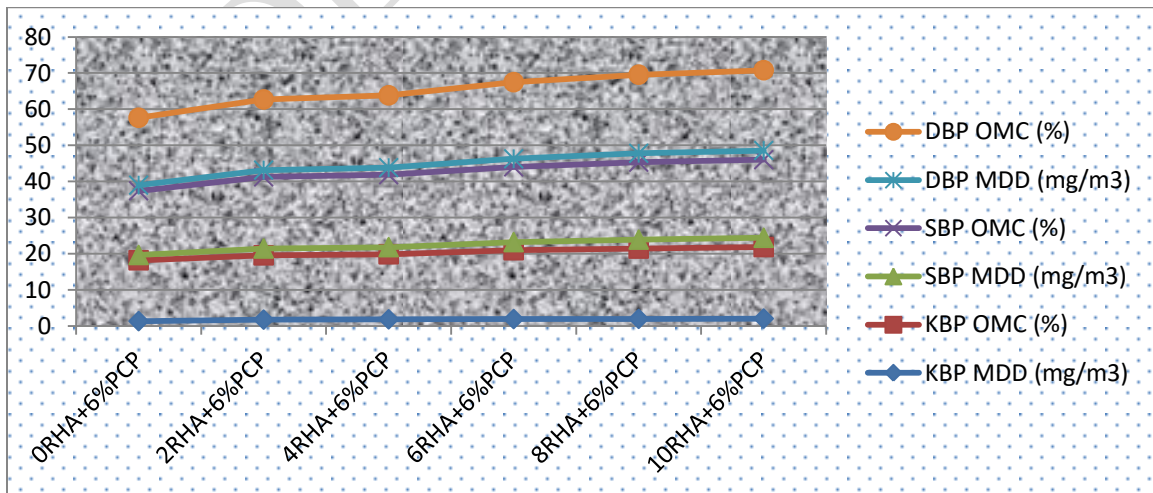


Fig. 6: Impact of geopolymer on compaction test

3.4 Effect of Triaxial test

Results of triaxial test for RHA, SSA and geopolymer are shown in Tables 8-10, and graphically Figures 7-9. The scrutiny result shown the impact of various percentages of RHA, SSA and geo polymer on the soil sampling stabilized. The highest cohesion (C) of 19KN/m², 11KN/m² and 65KN/m² was achieved at 10% and frictional angle of 27°, 19° and 57° for RHA, SSA and geo polymer respectively. Likewise site visitation, some laboratory experiment and apparatus utilized for this research is presented in Fig. 11-14.

Table 8: Effect of RHA on compaction test.

| % | KBP | | SBP | | DBP | |
|-------------|-------------------------------|-----------------------------------|-------------------------------|-----------------------------------|-------------------------------|-----------------------------------|
| | Cohesion (KN/m ²) | Frictional Angle (Θ) ⁰ | Cohesion (KN/m ²) | Frictional Angle (Θ) ⁰ | Cohesion (KN/m ²) | Frictional Angle (Θ) ⁰ |
| 0RHA+6%PCP | 19.1 | 23.1 | 18.1 | 22.1 | 19.0 | 23.2 |
| 2RHA+6%PCP | 11.2 | 26.0 | 11.0 | 25.0 | 11.1 | 25.1 |
| 4RHA+6%PCP | 10.0 | 28.2 | 11.2 | 28.1 | 10.0 | 28.2 |
| 6RHA+6%PCP | 16.1 | 21.0 | 16.1 | 20.0 | 15.2 | 20.0 |
| 8RHA+6%PCP | 10.2 | 29.1 | 10.2 | 28.1 | 10.3 | 29.4 |
| 10RHA+6%PCP | 19.1 | 27.2 | 18.0 | 26.2 | 19.0 | 27.2 |

Table 9: Effect of SSA on compaction test.

| % | KBP | | SBP | | DBP | |
|-------------|-------------------------------|-----------------------------------|-------------------------------|-----------------------------------|-------------------------------|-----------------------------------|
| | Cohesion (KN/m ²) | Frictional Angle (Θ) ⁰ | Cohesion (KN/m ²) | Frictional Angle (Θ) ⁰ | Cohesion (KN/m ²) | Frictional Angle (Θ) ⁰ |
| 0RHA+6%PCP | 19 | 23 | 18 | 22 | 19 | 23 |
| 2RHA+6%PCP | 8 | 15 | 8 | 15 | 8 | 15 |
| 4RHA+6%PCP | 9 | 16 | 9 | 16 | 9 | 16 |
| 6RHA+6%PCP | 10 | 18 | 10 | 18 | 10 | 17 |
| 8RHA+6%PCP | 10 | 18 | 10 | 18 | 10 | 18 |
| 10RHA+6%PCP | 11 | 19 | 11 | 19 | 11 | 18 |

Table 10: Effect of geopolymer on compaction test

| % | KBP | | SBP | | DBP | |
|-------------|-------------------------------|-----------------------------------|-------------------------------|-----------------------------------|-------------------------------|-----------------------------------|
| | Cohesion (KN/m ²) | Frictional Angle (Θ) ⁰ | Cohesion (KN/m ²) | Frictional Angle (Θ) ⁰ | Cohesion (KN/m ²) | Frictional Angle (Θ) ⁰ |
| 0RHA+6%PCP | 19.1 | 23.1 | 18.2 | 22.0 | 19.0 | 23.1 |
| 2RHA+6%PCP | 39.2 | 37.0 | 37.3 | 32.3 | 39.2 | 37.2 |
| 4RHA+6%PCP | 49.3 | 40.2 | 44.0 | 37.2 | 49.3 | 40.3 |
| 6RHA+6%PCP | 52.0 | 48.1 | 49.1 | 41.1 | 52.3 | 48.1 |
| 8RHA+6%PCP | 58.1 | 53.2 | 56.2 | 48.2 | 58.2 | 53.2 |
| 10RHA+6%PCP | 65.2 | 57.0 | 60.1 | 52.0 | 65.1 | 57.2 |

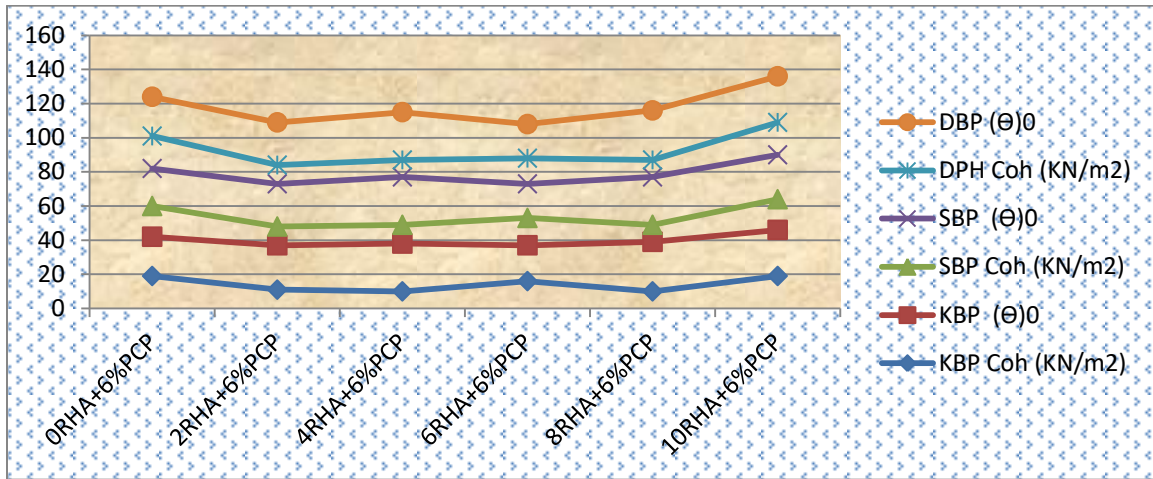


Fig. 7: Impact of RHA on compaction test

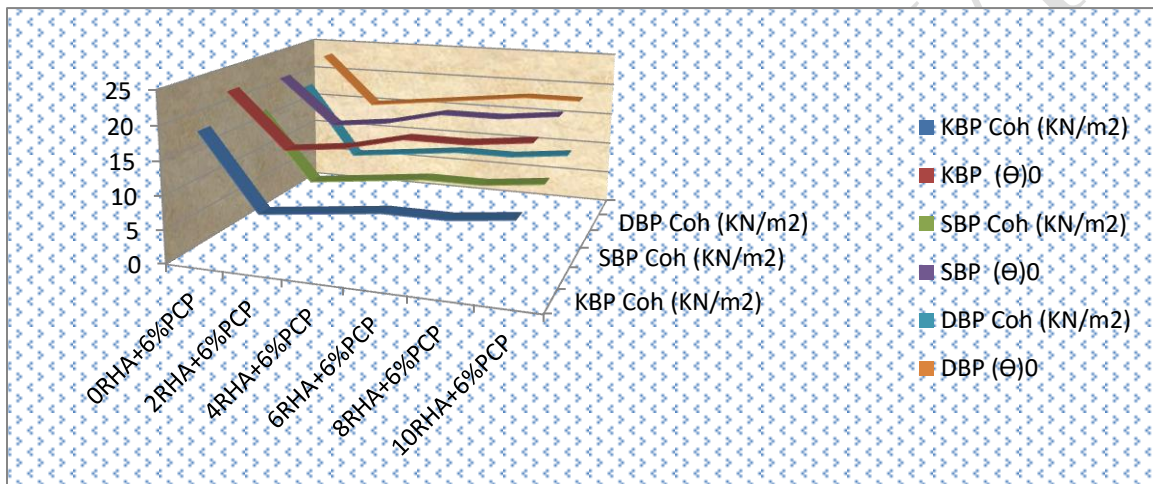


Fig. 8: Impact of SSA on compaction test

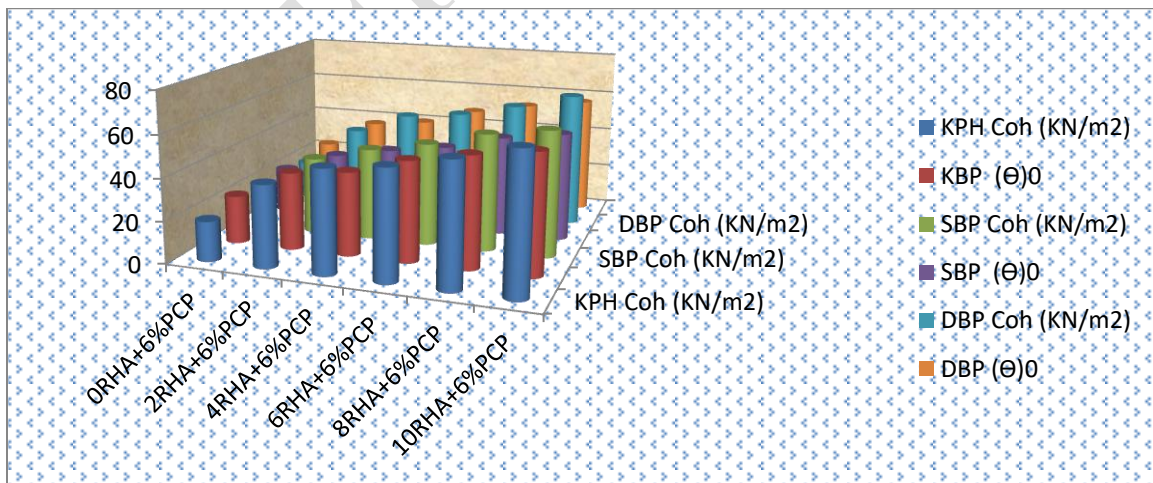


Fig. 10: Triaxial tests result for RHA, sodium silicate and geopolymer mix.



Fig.11: Samples collection at Dabi site where Dantata and Sawoe Construction Company is using for Gwagwalada-Kwali road construction.



Fig 12: Samples and rice husk ash at Federal University of Technology Akure Geotechnical lab.



Fig. 12: Specific gravity and Atterberg limit test in progress.



Fig. 13: Atterberg limit test in progress.

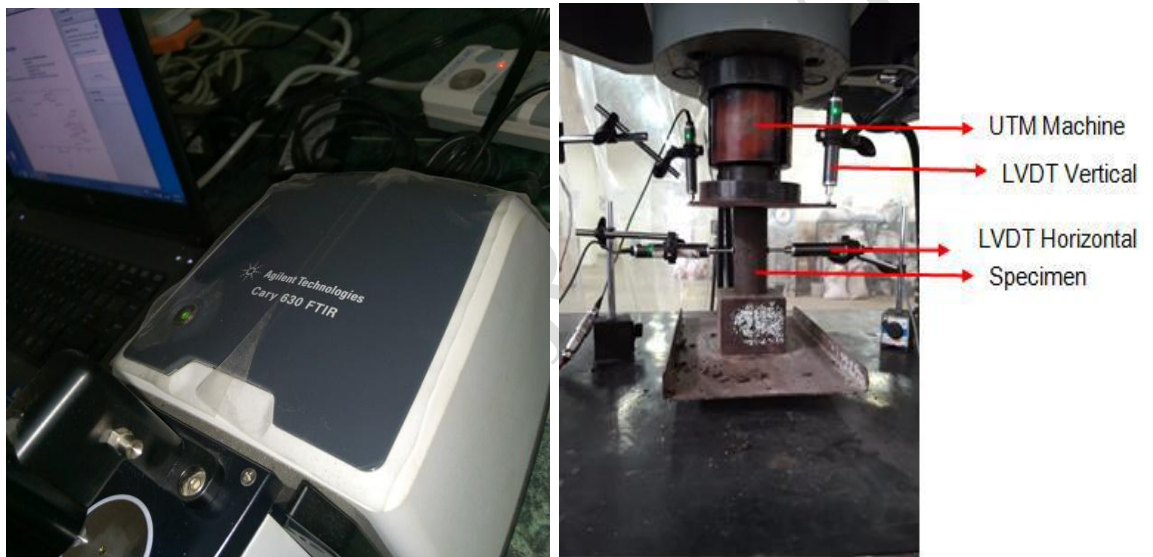


Fig. 14: FTIR apparatus and Set up compressive strength.

Conclusions

From the analysis the investigations on KCP-SSA stabilized soils shows that the lateritic soil was categorized as A-7-6 soil. Besides, at 6% contents, the scrutiny showed a general **improvement** in MDD and OMC with increase in SSA as well as RHA contents. Addition of RHA-SSA requires a lesser amount of SSA to obtain improved strength as compared to cement-improved soils. Further, the highest cohesion of 19KN/m^2 , 11KN/m^2 and 65KN/m^2 was achieved at 10% and frictional angle of 27° , 19° and 57° for RHA, SSA and geopolymer respectively. Hence, Sodium silicate activator together with rice husk ash was confirmed to be a good enhancer for lateritic soil stabilization using 6% as their control.

References

1. Pooria G, Mostafa Z, Nazanin M, Mohammad S, Jie L, Navid R. Shear strength and life cycle assessment of volcanic ash-based geopolymer and cement stabilized soil: A comparative study. *Transportation Geotechnics* 31 (2021) 100639
2. Xu Zifang, Ye Dongdong, Dai Tao & Dai Yan (2021) Research on Preparation of Coal Waste-Based Geopolymer and Its Stabilization/Solidification of Heavy Metals, *Integrated Ferroelectrics*, 217:1, 214-224, DOI: 10.1080/10584587.2021.1911314
3. Abdullah H. Cyclic behaviour of clay stabilised with fly-ash based geopolymer incorporating ground granulated slag. *Transp Geotech* 2021;26: 100430.
4. Suksiripattanapong C. Evaluation of polyvinyl alcohol and high calcium fly ash based geopolymer for the improvement of soft Bangkok clay. *Transp Geotech* 2021;27:100476.
5. Wattez T. Interactions between alkali-activated ground granulated blastfurnace slag and organic matter in soil stabilization/solidification. *Transp Geotech* 2021;26:100412.
6. Venkatesh N, Mallikarjuna R, Sudheer R, Rama C. Strength and durability characteristics of GGBS geopolymer stabilized black cotton soil 2021 *Materials Today: Proceedings* 43(4), DOI: 10.1016/j.matpr.2021.01.939.
7. Upshaw M and Cai C. S (2021). Feasibility study of MK-based geopolymer binder for RAC applications: Effects of silica fume and added CaO on compressive strength of mortar samples. *Case Studies in Construction Materials* Volume 14, e00500
8. Adeyanju Emmanuel, Okeke Chukwueloka Austin, Akinwumi Isaac and Busari Ayobami (2020). Subgrade stabilization using Rice Husk Ash-Geopolymer (GPHA) and Cement Klin Dust (CKD).
9. Wang, S.; Xue, Q.; Zhu, Y.; Li, G.; Wu, Z.; Zhao, K. Experimental study on material ratio and strength performance of geopolymer improved soil. *Constr. Build. Mater.* **2020**, *267*, 120469. [CrossRef]
10. Zhu, Y.; Chen, R.; Lai, H. Stabilizing Soft Ground Using Geopolymer: An Experimental Study. In *Proceedings of the CICTP 2020*,
11. Abdullah, H.H.; Shahin, M.A.; Walske, M.L. Review of Fly-Ash-Based Geopolymers for Soil Stabilisation with Special Reference to Clay. *Geosciences* **2020**, *10*, 249. [CrossRef]
12. Rivera, J.F.; Orobio, A.; Mejía De Gutiérrez, R.; Cristelo, N. Clayey soil stabilization using alkali-activated cementitious materials. *Mater. Construcción* **2020**, *70*, 211. [CrossRef]
13. Zhu, Y.; Chen, R.; Lai, H. Stabilizing Soft Ground Using Geopolymer: An Experimental Study. In *Proceedings of the CICTP 2020*, Xi'an, China, 14–16 August 2020; American Society of Civil Engineers (ASCE): Reston, VA, USA; pp. 1144–1155.
14. Dheyab, W.; Ismael, Z.T.; Hussein, M.A.; Huat, B.B.K. Soil Stabilization with geopolymers for low cost and environmentally friendly construction. *Int. J. Geomate* **2019**, *17*, 271–280. [CrossRef]
15. E. Adeyanju, C. Okeke. (2019). Exposure effect to cement dust pollution : a mini review , *SN Appl. Sci.* 1. 1–17. <https://doi.org/10.1007/s42452-019-1583-0>.
16. N. Wen, Y. Zhao, Z. Yu, M. Liu, A sludge and modified rice husk ash-based geopolymer: synthesis and characterization analysis, *J. Clean. Prod.* 226 (2019) 805–814. <https://doi.org/10.1016/j.jclepro.2019.04.045>.
17. A.A. Alshaba, T.M. Abdelaziz, A.M. Ragheb (2018). Treatment of collapsible soils by mixing with iron powder. 3737–3745. <https://doi.org/10.1016/j.aej.2018.07.019>.
18. M.A. Rahgozar, M. Saberian, J. Li, Soil stabilization with non-conventional eco-friendly agricultural waste materials: An experimental study, *Transp. Geotech.* 14 (2018) 52–60. <https://doi.org/10.1016/j.trgeo.2017.09.004>.
19. N. Yoobanpot, P. Jamsawang, K. Krairan, P. Jongpradist, S. Horpibulsuk, Reuse of dredged sediments as pavement materials by cement kiln dust and lime treatment, *Geomech. Eng.* 15 (2018) 1005–1016. <https://doi.org/10.12989/gae.2018.15.4.1005>.

20. Roychand R. Development of zero cement composite for the protection of concrete sewage pipes from corrosion and fatbergs. *Resour Conserv Recycl* 2021; 164:105166.
21. Igibah C, Agashua L and Sadiq A (2020). Influence of hydrated lime and bitumen on different lateritic soil samples: Case study of Sheda-Abuja, Nigeria. *IJET*, 1-7.
22. Rivera J. Fly ash-based geopolymer as A4 type soil stabiliser. *Transp Geotech* 2020;25:100409.
23. Seyhan F, Sedef D, Gülgün Y and Jamal M. (2020). Characteristics of Engineered Waste Materials Used for Road Subbase Layers. *KSCE*.
24. Adeyanju Emmanuel, Okeke Chukwueloka Austin, Akinwumi Isaac and Busari Ayobami (2020). Subgrade stabilization using Rice Husk Ash-Geopolymer (GPHA) and Cement Klin Dust (CKD).
25. Farhangi V, Karakouzian M, Geertsema M. Effect of micropiles on clean sand liquefaction risk based on CPT and SPT. *Appl Sci* 2020;10(9):3111.
26. Saberian M, et al. Application of demolition wastes mixed with crushed glass and crumb rubber in pavement base/subbase. *Resour Conserv Recycl* 2020;156: 104722.
27. Rezazadeh Eidgahee D, Rafiean AH, Haddad A. A novel formulation for the compressive strength of IBP-based geopolymer stabilized clayey soils using ANN and GMDH-NN approaches. *Iranian J Sci Technol, Trans Civil Eng* 2020;44(1): 219–29. MolaAbasi H, et al. Evaluation of the long-term performance of stabilized sandy soil using binary mixtures: A micro-and macro-level approach. *J Cleaner Prod* 2020:122209.
28. Abdullah, H.H.; Shahin, M.A.; Walske, M.L.; Karrech, A. Systematic approach to assessing the applicability of fly-ash-based geopolymer for clay stabilization. *Can. Geotech. J.* **2020**, *57*, 1356–1368. [CrossRef]
29. Khasib, I.A.; Daud, N.N.N. Physical and Mechanical Study of Palm Oil Fuel Ash (POFA) based Geopolymer as a Stabilizer for Soft Soil. *Pertanika J. Sci. Technol.* **2020**, *28*, 149–160. [CrossRef]
30. Ghadakpour M, Choobbasti AJ, Kutanaei SS. Experimental study of impact of cement treatment on the shear behavior of loess and clay. *Arabian J Geosci* 2020; 13(4):184.
31. Abdulkareem M, et al. Environmental and economic perspective of waste-derived activators on alkali-activated mortars. *J Cleaner Prod* 2020;280:124651.
32. Vitale, E.; Russo, G.; Deneele, D. Use of Alkali-Activated Fly Ashes for Soil Treatment. In *Geotechnical Research for Land Protection and Development*; Calvetti, F., Cotecchia, F., Galli, A., Jommi, C., Eds.; Lecture Notes in Civil Engineering; Springer International Publishing: Cham, Switzerland, 2020; Volume 40, pp. 723–733. ISBN 978-3-030-21358-9.
33. Abdullah, H.H.; Shahin, M.A.; Walske, M.L. Geo-mechanical behavior of clay soils stabilized at ambient temperature with fly-ash geopolymer-incorporated granulated slag. *Soils Found.* **2019**, *59*, 1906–1920. [CrossRef]
34. Sharma, P.K.; Singh, J.P.; Kumar, A. Effect of Particle Size on Physical and Mechanical Properties of Fly Ash Based Geopolymers. *Trans. Indian Inst. Met.* **2019**, *72*, 1323–1337. [CrossRef]
35. Tan, T.; Huat, B.B.K.; Anggraini, V.; Shukla, S.K.; Nahazanan, H. Strength Behavior of Fly Ash-Stabilized Soil Reinforced with Coir Fibers in Alkaline Environment. *J. Nat. Fibers* **2019**, 1–14. [CrossRef]
36. Dheyab, W.; Ismael, Z.T.; Hussein, M.A.; Huat, B.B.K. Soil Stabilization with geopolymers for low cost and environmentally friendly construction. *Int. J. Geomate* **2019**, *17*, 271–280. [CrossRef]
37. Teing, T.T. Effects of Alkali-Activated Waste Binder in Soil Stabilization. *Int. J. Geomate* **2019**, *17*, 82–89. [CrossRef]

38. Yaghoubi M, Arulrajah A, Disfani MM, Horpibulsuk S, Darmawan S, Wang J. Impact of field conditions on the strength development of a geopolymer stabilized marine clay. *Appl Clay Sci* 2019;167:33–42.
39. Jahandari S, Saberian M, Zivari F, Li J, Ghasemi M, Vali R. Experimental study of the effects of curing time on geotechnical properties of stabilized clay with lime and geogrid. *Int J Geotech Eng* 2019;13(2):172–83.
40. N. Wen, Y. Zhao, Z. Yu, M. Liu, A sludge and modified rice husk ash-based geopolymer: synthesis and characterization analysis, *J. Clean. Prod.* 226 (2019) 805–814.
41. <https://doi.org/10.1016/j.jclepro.2019.04.045>.
42. Amiri E, Emami H. Shear strength of an unsaturated loam soil as affected by vetiver and polyacrylamide. *Soil Tillage Res* 2019;194:104331.
43. Chang Ilhan, Cho Gye-Chun. Shear strength behavior and parameters of microbial gellan gum-treated soils: from sand to clay. *Acta Geotech* 2019;14(2):361–75.
44. Elandaloussi R, et al. Effectiveness of lime treatment of coarse soils against internal erosion. *Geotech Geol Eng*, 2019. 37(1): p. 139-154.
45. Pradhan Subhasis, Tiwari BR, Kumar Shailendra, Barai Sudhirkumar V. Comparative LCA of recycled and natural aggregate concrete using Particle Packing Method and conventional method of design mix. *J Cleaner Prod* 2019;228: 679–91.
46. D. Kuang *et al.*, Influence of angularity and roughness of coarse aggregates on asphalt mixture performance. *Constr Build Mater.* **200**, 681 (2019). DOI: 10.1016/j.conbuildmat.2018.12.176. [Crossref], [Web of Science ®], [Google Scholar]
47. E.A. Adeyanju, C.A. Okeke. (2019a) Clay soil stabilization using cement kiln dust, in: IOP Conf. Ser. Mater. Sci. Eng. pp. 1–10.
48. E. Adeyanju, C. Okeke. (2019b). Exposure effect to cement dust pollution : a mini review , *SN Appl. Sci.* 1. 1–17. <https://doi.org/10.1007/s42452-019-1583-0>.
49. A.A. Alshaba, T.M. Abdelaziz, A.M. Ragheb (2018). Treatment of collapsible soils by mixing with iron powder. 3737–3745. <https://doi.org/10.1016/j.aej.2018.07.019>.
50. N. Wen, Y. Zhao, Z. Yu, M. Liu, A sludge and modified rice husk ash-based geopolymer: synthesis and characterization analysis, *J. Clean. Prod.* 226 (2019) 805–814. <https://doi.org/10.1016/j.jclepro.2019.04.045>.
51. N. Wen, Y. Zhao, Z. Yu, M. Liu, A sludge and modified rice husk ash-based geopolymer: synthesis and characterization analysis, *J. Clean. Prod.* 226 (2019) 805–814. <https://doi.org/10.1016/j.jclepro.2019.04.045>.
52. Mohsenia M, Kazemi M, Koushkbashi M, Zehta B & Behforouze B (2019). Evaluation of mechanical and durability properties of fiber-reinforced lightweight geopolymer composites based on rice husk ash and nano-alumina. *Construction and Building Materials*, 209, Pg 532-540.
53. Gutiérrez, Erick; Riquelme, Adrián; Cano, Miguel; Tomás, Roberto; Pastor, José Luis (2019). "Evaluation of the Improvement Effect of Limestone Powder Waste in the Stabilization of Swelling Clayey Soil". *Sustainability*. 11 (3): 679. doi:10.3390/su11030679.
54. Agashua Lucia O and Ogbiye Adebajji S (2018). Influence of Cement, Bitumen and Lime on Some Lateritic Soil Samples as Pavement Material. *IOP Conf. Series: Materials Science and Engineering* 413 (2018) 012012 doi:10.1088/1757-899X/413/1/012012.
55. Agashua Lucia O, Igibah Ehizemhen C and Sadiq, Abubakar. (2018). The Impact of Bituminous additive on Lateritic Soil with Varying Percentage for long lasting soil stabilizer.
56. A. Alhmed, N. Nagy, E.N. Naggar, T. Kamei, Stabilisation of soft soil with recycled plaster admixtures., in: *Proc. Inst. Civ. Eng. - Gr. Improv.*, 2018: pp. 1–9. <https://doi.org/doi.org/10.1680/jgrim.16.00038>.