Civil and Sustainable Urban Engineering

Research Article
Volume 4(1), 2024, 55–64
https://doi.org/10.53623/csue.v4i1.427

Chemical and Mechanical Characterisation of Clay Soil Stabilised with Steel Slag and Calcium Carbide Waste

Damilola Ayodele Ogundare[1]*, Oyetunde Oluwafemi Adeleke[1], Ayodeji Theophilus Akinbuluma[2]

[1]Department of Civil Engineering, Faculty of Engineering and Technology, University of Ilorin, P.M.B. 1515, Ilorin, Kwara State, Nigeria
[2]Department of Civil Engineering, Faculty of Engineering, Olusegun Agagu University of Science and Technology, P.M.B. 353, Okitipupa, Ondo State, Nigeria

*Correspondence: engrbamidele@gmail.com

SUBMITTED: 28 March 2024; REVISED: 3 May 2024; ACCEPTED: 8 May 2024

ABSTRACT: Problematic subgrade soil such as clay is expansive by nature and is challenging to work with during pavement construction. In an effort to combat this issue and lower the rate of pavement failure on highway construction projects, cementitious industrial waste materials should be used. This study thus examined the influence of steel slag (SS) and calcium carbide waste (CCW) as stabilisers for clay soil. Chemical and mineralogical analyses of clay soil, SS and CCW were assessed while the stabilised soil were subjugated to Atterberg limit, compaction and california bearing ratio (CBR) tests. The existence of calcium oxide, iron oxide and calcium hydroxide in both the chemical and mineralogical constituents of SS and CCW indicate that they are binding materials which notably influences hardness and contributes more to the strength of the clay soil. With varied amounts of the additives (SS and CCR), the clay soil's liquid limit and plasticity index dropped from 54.0% and 13.8% to 43.5% and 9.2%, respectively. This significantly lowers the clay soil's swell potential, increases its resilience, and decreases its infiltration capacity. The compaction characteristics revealed that SS and CCW enhanced the compactness of the clay soil signifying enhancement of the soil compaction properties. The CBR value of all the stabilised clay soils improve significantly with 40%SS + 60%CCW acquiring the maximum CBR of 17.3% and 29.0% compared with clay soil having CBR of 4.7% and 6.9% in soaked and unsoaked states respectively.

KEYWORDS: Problematic subgrade soil; pavement; industrial waste materials; chemical analysis; CBR

1. Introduction

In the construction of pavements, the subgrade soil is the foundation material and its performance is greatly influenced by the strength characteristics of the subgrade soil. A material's ability to transfer axle load to the subgrade or subsoil determines whether it should be utilized as a base course or sub-base course [1]. Problematic subgrade soils poses difficulty to work with if encountered during construction of highway owing to its proneness to dry and wet cycles, low strength to withstand axle load and volumetric changes. Such subgrade problem soils could be expansive, collapsible, dispersive, soft clay and saline soils which causes detrimental effects to buildings and road structures. Low shear strengths, which are further reduced when wet or under other physical disturbances, are features of clays that are often undesirable in engineering [2]. When the subgrade soil sample obtainable for highway construction is not acceptable for the planned intents, soil stabilisation is necessary. Stabilization is any process which improves a soil material and makes it more stable [3].

Calcium carbide is an industrial waste generated from acetylene gas (C_2H_2) production. The interaction of calcium carbide (CaC_2) with water (H_2O) yields calcium carbide residue [4]. Calcium hydroxide (Ca(OH)) is the main chemical component of calcium carbide residue in slurry [4]. Silica oxide (SiO_2), calcium carbonate ($CaCO_3$), and other metal oxides are the secondary components [4]. China is the largest producer of calcium carbide waste worldwide with 26.08 million tons [5]. About twenty-five thousand (25,000) people in Nigeria are members of the Nigerian Automobile Technicians Association (NATA), and each member generates thirty kilogram of waste residue from calcium carbide on a daily average [6]. Steel slag is a solid waste from steel production [7] with over 12 million tons produced in Europe [8]. Approximately 0.35 to 0.45 million metric tons of steel slag is produced per annum in Nigeria [9]. It's getting more seductive to exercise and reclaim steel slag and calcium carbide waste instead of discarding them.

The properties of weak subgrade soil, such as clay and black cotton soil, have previously been improved by a number of scholars using traditional soil stabilization additives like cement and lime [10, 11]. For this reason, the soil needs to be stabilised using easily available and cheap industrial waste materials (steel slag and calcium carbide waste). Studies have shown the potential use of steel slag and calcium carbide waste as additives for improving the strength properties of expansive soil investigated the ways that expanding soil's engineering characteristics can be enhanced by steel slag [12]. Chu et al. utilized iron tailing sand and calcium carbide slag as modification of expansive soil [13]. In the same vein, Pawar et al. investigated the effect of steel slag and fly ash as single entity stabilizers on the strength of clayey soil [14]. However, no or/little advanced laboratory tests have been done in identifying chemical and mineralogical analysis of the additives (SS and CCW) and clay soil. This study focuses on investigating the use of steel slag and calcium carbide waste as stabilisers for clay sample in terms of chemical and mechanical (strength) analyses.

2. **Materials and Methods**

2.1. Materials.

The clay soil sample was gotten at a depth of 500mm to 1500mm at latitude 7^0 45' 40" North and longitude 4^0 27' 42" East, Osun state, Nigeria. It was gotten in cement sacks and was dried on exposure to air before usage. Also, steel slag sample was taken from Prism Steel Mills Nigeria Limited, Osun State, Nigeria. However, the steel slag samples were air-dried for about one year before being used [15]. The steel slag was classified as basic slag base on its slag basicity using the alkalinity formula according to [16] i.e. $(CaO+MgO)/(SiO_2+Al_2O_3) > 1$. The steel slag were squashed to reduce its diameter less than 425µm using Los Angeles abrasion machine for consistency limits test. Calcium carbide waste (CCW) was amassed from waste dumps generated by welding artisans in Osogbo and its environs Osun State, Nigeria. It was dried on exposure to air and samples passing through 425µm sieve was used to stabilise the clay soil. However, SS-CCW ratios of 25:75%, 30:70%, 35:65% and 40:60% by dry weight of clay soil was selected for this study.

2.2. Test procedure.

2.2.1. X-Ray fluorescence.

An X-ray instrument (Phillips PW-1800) was used for XRF analysis to determine the chemical analysis of samples to detect major and trace elements using X-ray fluorescence, which is enabled by the way atoms behave when they contact with radiation. The material was divided into smaller pieces and crushed to a size of less than 75 microns to create pellets, which were then placed into a sample holder on the Philips PW-1800 x-ray machine for examination [17]. The above processes was also repeated for steel slag and calcium carbide waste.

2.2.2. X-Ray diffraction.

For XRD analysis, the powdered samples were pelletized separately and sieved to 0.074mm. The samples measuring less than two microns were gathered, and the powder was carefully packed into a grid of aluminum alloy measuring 35 mm by 50 mm. The sample holder was then placed through a wide angle Phillips P.W. 1011 Goriometer that was attached to a PM 8220 recorder [18]. The above processes was also repeated for steel slag and calcium carbide waste.

2.2.3. Gradation test.

The gradation test was achieved as detailed in British Standard [19, 20] with International Standard (IS) sieves for fine-grained soil used. 1000g of air-dry subgrade soil was mixed with water to form a sediment and soaked. It was cleansed through sieve of size 75µm till the water flowing through it is substantially clean and the retained subgrade soil on the sieve was dried in an oven. The oven-dried subgrade soil was poured into the IS sieves for fine-grained soil and fixed on a mechanical sieve shaker for 12 minutes.

2.2.4. Specific gravity test.

10g of oven dried subgrade soil at 105^0C was taken and shifted directly to the density bottle from the desiccator and weighed with and without water. This test was achieved in conformity with British Standard [20].

2.2.5. Atterberg limits test.

This test include the liquid limit, plastic limit and plasticity index and was assessed on air-dried clay soil at varying percentages of SS and CCW. Fine soil of 500g retained on sieve size of 425µm was soaked for a day and examined in concurrence with British Standard [20].

2.2.6. Standard proctor compaction.

This test was done using Standard Proctor as stated in British Standard [21] and conducted to examine the connection between maximum dry density (MDD) and optimum moisture content (OMC) of the virgin soil (clay soil) and stabilised clay soils.

2.2.7. California bearing ratio.

California bearing ratio test was employed to rate the strength of unstabilised and stabilised clay soil. Individual optimum moisture content gotten from the compaction test was used to compact the stabilised and unstabilised clay soil in the CBR mould [22]. The CBR machine plunger penetrates the compacted soil at interval of 0.5mm till 12.5mm while the load particular to individual penetration is noted and loads at 2.5mm and 5mm penetrations were used to calculate the CBR as shown in Equation 1. British Standard gives the comprehensive test procedure [23].

$$\text{CBR (\%)} = \frac{\text{Observed load}}{\text{Standard load}} \times 100 \quad (1)$$

3. Results and Discussion

3.1. X-Ray Fluorescence.

The chemical constituents as shown in Table 1 indicate that the clay soil is characterised by 56.46% silica (SiO_2), 29.02% aluminium oxide (Al_2O_3) and 4.75% iron oxide (Fe_2O_3). The silica-sesquioxide, (S-S) ratio of the soil is 2.99 which confirms that the soil is non-lateritic (clay) owing to its high degree of laterisation. However, steel slag and calcium carbide waste are characterized by 38.11% and 68.50% calcium oxide (CaO) which conforms to previous investigation [24, 8] in which steel slag content is between 25% and 40% while that of calcium carbide waste content was greater than another investigation (61.41%) affirming the additives as binding and cementitious material [25].

Table 1. Chemical constituents of clay soil, SS and CCW.

Oxide	Percentage Constituents (%)		
	Clay Soil	SS	CCW
SiO_2	56.46	12.00	6.50
Al_2O_3	29.02	4.70	2.53
Fe_2O_3	4.75	19.40	3.23
TiO_2	1.25	0.29	0.02
CaO	1.75	38.11	68.50
P_2O_5	0.04	2.20	0.25
K_2O	0.98	0.40	7.92
MnO	0.08	12.25	0.02
MgO	4.75	0.16	0.64
Na_2O	0.90	0.15	0.60
LOI	0.02	10.16	2.01

3.2. X-Ray diffraction.

The presence of non-expanding clay minerals (ferrite and mullite) as shown in Figure 1 indicate that the clay soil had not gone through high rate of metamorphism and have great bond for water. The prominent mineralogical constituents of SS (Figure 2) are iron oxide, mica and quartz. The existence of iron oxide helps to impact the chemical reaction with calcium and aluminium which notably influences the hardness and strength of the soil. Figure 3 indicate that CCW contains calcium hydroxide (CaOH), tricalcium silicate (C_3S), calcium silicate (Ca_2SiO_4), Rosenhahnite ($Ca_3Si_3O_8$) and calcium carbonate ($CaCO_3$). The presence of main component (CaOH) indicate that it can react with siliceous materials through pozzolanic reactions which contributes more to the strength of the soil.

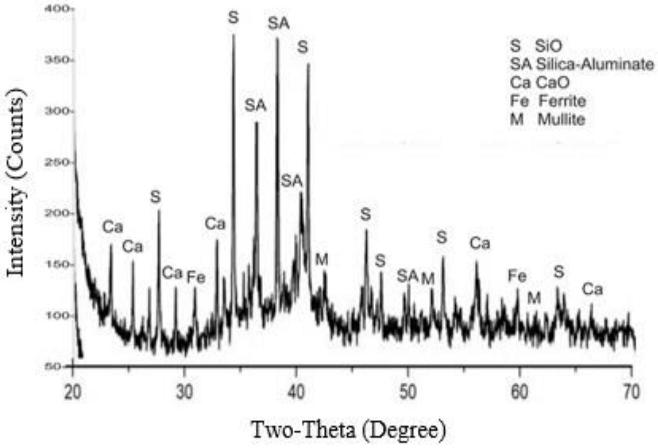

Figure 1. X-ray diffraction of clay soil.

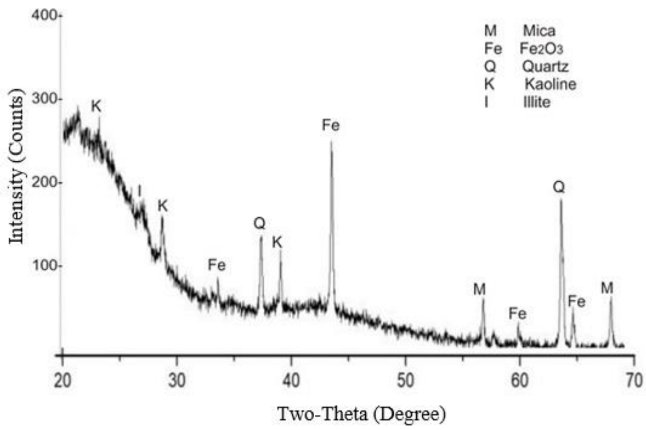

Figure 2. X-ray diffraction of steel slag.

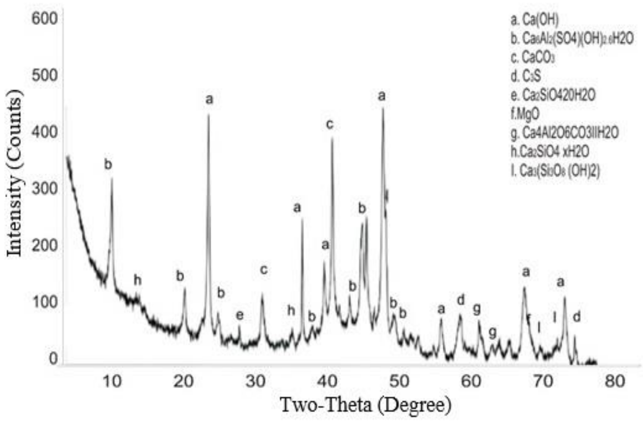

Figure 3. X-ray diffraction of calcium carbide waste.

3.3. Preliminary and geotechnical properties of clay soil.

The preliminary and geotechnical properties of clay soil are shown in Table 2. It is evident that the proportion of fines in the clay soil is significant (40.4%). This indicate that the clay soil is not suitable for subgrade and base materials because its value is higher than the standard specifications (≤ 35%) by Federal Ministry of Works and Housing in Nigeria [26], hence, the clay soil has a tendency to shrink and swell repeatedly during alternate wet and dry seasons of the tropical climatic areas of the world, like southwestern Nigeria. Also, the clay soil is categorised as A-7-6(8) and inorganic clay of high plasticity (CH) base on American Association of State Highway Transportation Official (AASHTO) soil classification system and Unified Soil Classification System (USCS) denoting the soil as weak subgrade material [22]. The specific gravity of the clay soil is 2.58 and is classified as inorganic soils because it's within the range of specific gravity for clay minerals (2.44 to 2.92) as reported by [27]. However, the specific gravity of calcium carbide waste (1.78) is less than the specific gravity of the clay soil [28].

Table 2. Preliminary and geotechnical properties of the clay soil

S/N	Properties	Value
1	Gradation test	
	Particle size (≤ 0.075mm) (%)	59.6
	Particle size (0.075mm – 4.75mm) (%)	40.4
	AASHTO classification	A-7-6
	USCS classification	CH
2	Atterberg's limits	
	(a) Liquid Limit (%)	54.0
	(b) Plastic Limit (%)	40.2
	(c) Plasticity Index (%)	13.8
3	Specific gravity (G_s)	2.58
4	Compaction Characteristics	
	(a) Maximum dry density (kN/m^3)	17.0
	(b) Optimum moisture content (%)	26.0
5	California Bearing Ratio	
	(a) Unsoaked value (%)	6.90
	(b) Soaked value (%)	4.70

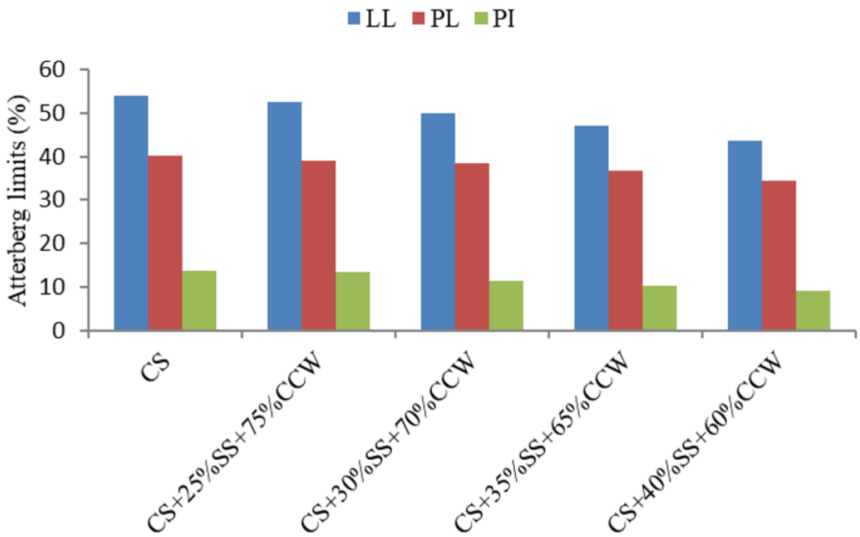

Figure 4. Consistency limit properties of clay soil stabilised with SS and CCW.

Also, the specific gravity of the steel slag (3.00) is 22% and 4% higher than the calcium carbide waste and clay soil respectively. Data in Figure 4 showed that the liquid limit of the clay soil (54.0%) does not meet the required specification (i.e ≤ 50%) for subgrade material as specified by Federal Ministry of Works and Housing in Nigeria [26]. However, when added with varying content of additives (SS and CCW), the liquid limit and the plasticity index for the stabilised clay soil decreases from 54.0% and 13.8% to 43.5% and 9.2% respectively which enhanced its resilience and reduce the infiltration capacity of the soil.

3.4. Compaction characteristics.

As demonstrated in Figure 5, varying content of additives increase the maximum dry density and decrease the optimum moisture content. The increase in maximum dry density (17.0kN/m^3 to 26.5kN/m^3) for the stabilised clay soil is based on the high specific gravity of steel slag used which increases the compactness of the clay soil signifying enhancement of the soil properties as also investigated by Bandyopadhyay et al. [29]. Moreover, the drop in OMC (from 26.0% to 15.0%) may be related to the higher affinity of calcium carbide residue for water reduction and the lower affinity of steel slag for water. This persist with earlier study by [30, 31].

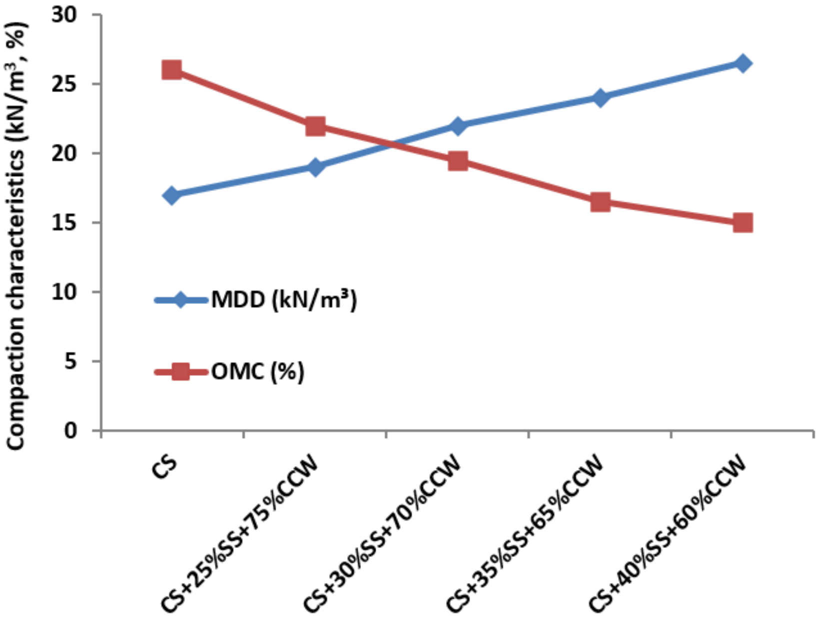

Figure 5. Compaction characteristics of clay soil stabilised with SS and CCW.

3.5. California bearing ratio.

Figure 6 shows the laboratory soaked and unsoaked CBR values of clay soil stabilised with steel slag and calcium carbide waste. The increase ranged from 4.7 to 17.3% and 6.9 to 29.0% with the maximum CBR values of 17.3% and 29.0% obtained at 40%SS+60%CC for both soaked and unsoaked conditions respectively compared with the clay soil with CBR value of 4.7% (soaked) and 6.9% (unsoaked). This is in consonance with the findings of [32]. The increase in CBR values, which are higher than the recommended standards set by the Federal Ministry of Works and Housing in Nigeria [26] (≥ 10%) and AASHTO [22] (10% - 25%) for pavement subgrade strength, demonstrates the effectiveness of steel slag and calcium carbide waste toward improving the strength, stiffness, bearing capacity, and stability of the clay soil.

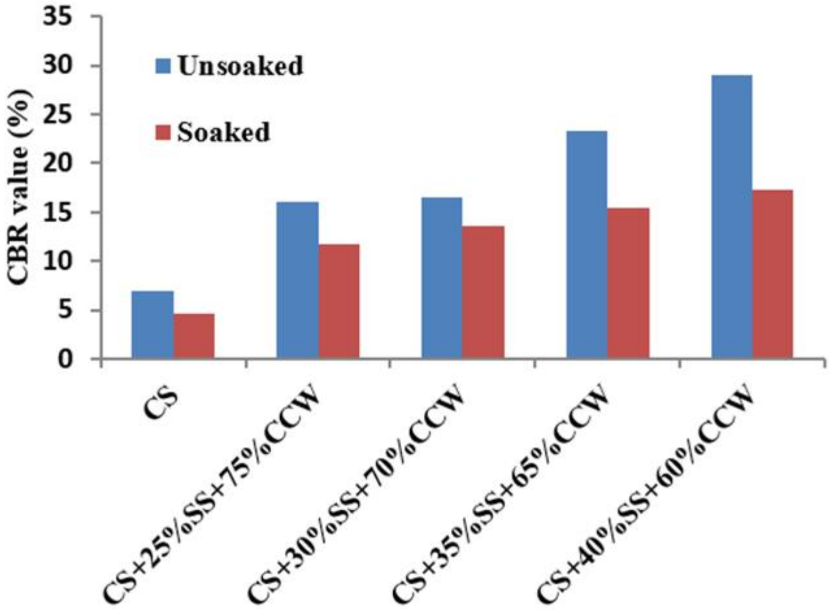

Figure 6. Laboratory soaked and unsoaked CBR values of clay soil stabilised with SS and CCW.

4. Conclusions

This study investigated the use of steel slag and calcium carbide waste for mechanical stabilisation of clay soil. The presence of iron oxide, calcium hydroxide, and calcium oxide in both the chemical and mineralogical constituents of SS and CCW indicate that they are binding materials, which helps to impact the chemical reaction with calcium and aluminium and can react with siliceous materials through pozzolanic reactions which notably influences hardness and contributes more to the strength of the soil samples. The clay soil was categorised as A-7-6(8) and CH (inorganic clay of high plasticity) based on AASHTO and USCS classifications implying weak highway subgrade material. The additives (SS and CCW) decrease the plasticity index of the clay sample (13.8% to 9.2%) by 33% and as a result enhanced its resilience, reduce its infiltration rate and volume change. The compaction characteristics indicate that, with increasing additive (SS and CCW) amount, the maximum dry density of the clay soil increases (17.0 to 26.5kN/m^3) while the optimum amount of water reduces (26.0 to 15.0%). This is why the clay soil becomes more compact, indicating an improvement in the soil's characteristics. The high specific gravity of steel slag, its reduced specific gravity, and the stronger affinity of calcium carbide residue for water reduction are the reasons of this. As a result of the additives (SS and CCW) with 40%SS+60%CCW, the clay soil's soaked and unsoaked CBR improved in the laboratory evaluation, with maximum values of 17.3% and 29.0% obtained in comparison to 4.7% and 6.9% for the clay soil in both soaked and unsoaked states.

Acknowledgement

The assistance of Mr Y. Adegbile of the geotechnical laboratory, Federal Polytechnic Ede, Nigeria is indeed appreciated for the laboratory works.

Competing Interest

The authors does not identify any competing interests.

References

[1] Abe, O.E. (2019). Comparison between strength properties of lateritic soils stabilized with banana leaf ash and oil palm frond ash. *International Research Journal of Innovations in Engineering and Technology, 3*(1), 20–23.

[2] Dauda, A.M.; Akinmusuru, J.O.; Dauda, O.A.; Durotoye, O.T. (2018). Geotechnical properties of expansive soil stabilized with periwinkle shells powder. *Agricultural Journal*, *13*(3), 56–59. https://doi.org/10.36478/aj.2018.56.59.

[3] Thagesen, B. (2016). Tropical rocks and soils, in: highway and traffic engineering in developing countries. Chapman and Hall, London.

[4] Du, Y.J.; Zhang, Y.Y.; Liu, S.Y. (2011). Investigation of strength and california bearing ratio properties of natural soils treated by calcium carbide residue. *Geo-Frontiers: Advances in Geotechnical Engineering*, 1237–1244. https://doi.org/10.1061/41165 (397)127.

[5] Zhang, S.; Li, J.; Li, G.; Nie, Y.; Qiang, L.; Bai, B.; Ma, X. (2021). Life cycle assessment of acetylene production from calcium carbide and methane in China. *Journal of Cleaner Production, 322*(8), 129055. https://doi.org/10.1016/j.jclepro.2021.129055.

[6] Chukwudebelu, J.A.; Igwe, C.C.; Taiwo, O.E.; Tojola, O.B. (2013). Recovery of pure slaked lime from carbide sludge: case study of Lagos State, Nigeria. *African Journal of Environmental Science and Technology*, *7*(6), 490-495. https://doi.org/10.5897/AJEST12.093.

[7] Yi, H.; Xu, G.; Cheng, H.; Wang, J.; Wan, Y.; Chen, H. (2012). An overview of utilization of steel slag. *Procedia Environmental Sciences, 16*(6), 791–801. https://doi.org/10.1016/j.proenv.2012.10.108.

[8] Motz, H.; Geiseler, J. (2001). Products of steel slags: an opportunity to save natural resources. *Waste Management*, *21*(3), 285-293. https://doi.org/10.1016/s0956-053x(00)00102-1.

[9] Akinwumi, I.I. (2012). Utilization of steel slag for stabilization of a lateritic soil. M.Eng. Research Project, Department of Civil Engineering, Covenant University, Ota, Nigeria.

[10] Okonkwo, U.N.; Kennedy, C. (2023). The effectiveness of cement and lime as stabilizers for subgrade soils with high plasticity and swelling potential. *Saudi Journal of Civil Engineering*, *7*(3), 40–60. https://doi.org/10.36348/sjce.2023.v07i03.001.

[11] Abdalla, T.A.; Salih, N. (2020). Hydrated lime effects on geotechnical properties of clayey soil. *Journal of Engineering, 26*(11), 150–169. https://doi.org/10.31026/j.eng.2020.11.10.

[12] [Kabeta, W.F.; Lemma, H. (2023). Modeling the application steel slag in stabilizing expansive soil. *Modeling Earth Systems and Environment*, *9*, 4023–4030. https://doi.org/10.1007/s40808-023-01734-1.

[13] Chu, C.; Zhan, M.; Feng, Q.; Deng, Y.; Li, D.; Zha, F.; Hou, X. (2022). Expansive soil modified by iron tailing sand and calcium carbide slag as subgrade material. *Environment, Development and Sustainability, 25*, 10393–10410. https://doi.org/10.1007/s10668-022-02498-x.

[14] Pawar, K.; Handibagh, G.; Dohitare, M.; Tondale, A.; Dalvi, R. S. (2022). Influence of steel slag addition on strength characteristics of clayey soil. *International Journal for Research in Applied Science & Engineering Technology*, *10*(IV), 2472–2480. https://doi.org/10.22214/ijraset.2022.41790.

[15] Huang, Y.; Bird, R.N.; Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements. *Resources Conservation and Recycling*, *52*(1), 58–73. https://doi.org/10.1016/j.resconrec.2007.02.002.

[16] Tossavainen, M.; Engstrom, F.; Yang, Q.; Menad, N.; Larsson, M. L.; Bjorkman, B. (2007). Characteristics of steel slag under different cooling conditions. *Waste Management 27*(10), 1335–1344. https://doi.org/10.1016/j.wasman.2006.08.002.

[17] Margui, E.; Queralt, I.; Grieken, R.V. (2016). Sample preparation for X-ray fluorescence analysis. *Encyclopedia of Analytical Chemistry*, 1–25. https://doi.org/10.1002/9780470027318.a6806.pub4.

[18] Bunaciu, A. A.; Udristioiu, E. G.; Aboul-Enein, H. Y. (2015). X-ray diffraction: Instrumentation and applications. *Critical Reviews in Analytical Chemistry*, *45*(4), 289–299. https://doi.org/10.1080/10408347.2014.949616.

[19] BS 1377-1 (1990). Methods of Test for Soils for Civil Engineering Purposes – Part 1: General Requirements and Sample Preparation, British Standards Institution.

[20] BS 1377-2 (1990). Methods of Test for Soils for Civil Engineering Purposes – Part 2: Classification Tests, British Standards Institution.

[21] BS 1377-4 (1990). Methods of Test for Soils for Civil Engineering Purposes – Part 4: Compaction-Related Tests, British Standards Institution.

[22] AASHTO (1986). Standard specification for transportation, material and methods of sampling and testing. 14th Edition, Amsterdam Association of State Highway and Transportation Official, Washington D.C.

[23] BS 1377-9 (1990). Methods of Test for Soils for Civil Engineering Purposes – Part 9: In-Situ Tests, British Standards Institution.

[24] Shi, C. (2004). Steel slag-its production, processing, characteristics, and cementitious properties. *Journal of Materials in Civil Engineering*, *16*(3), 230–236.

[25] Joel, M.; Edeh, J. (2014). Stabilization of Ikpayongo laterite with cement and calcium carbide waste. *Global Journal of Pure and Applied Sciences*, *20*(1), 49–55. https://doi.org/10.4314/gjpas.v20i1.8

[26] Nigeria General Specification, Bridges and Road Works (1997). Federal Ministry of Works and Housing: Abuja, Nigeria, 11, (Revised).

[27] Emesiobi, F.C. (2000). Testing and quality control of material in civil and highway engineering. Blue Print Publishers, Port Harcourt.

[28] Quadri, H.A.; Abiola, O.S.; Odunfa, S.O.; Azeez, J.O. (2020). Assessment of calcium carbide waste and calcined clay as stabilizer in flexible pavement construction. *Arid Zone Journal of Engineering, Technology & Environment*, *16*(1), 109–119.

[29] Bandyopadhyay, T.S.; Singh, A.A.; Pandey, V.; Singh, J.P. (2016). Stabilization of soil using GGBS and calcium carbide residue. *International Journal of Innovative Research in Science, Engineering and Technology*, *5*(9), 17023-17030. https://doi.org/10.15680/IJIRSET.2016.0509074.

[30] Al-Homidy, A.A.; Dahim, M.; Abd El Aal, A.K. (2017). Improvement of geotechnical properties of Sabbkha soil utilizing cement kiln dust. *Journal of Rock Mechanics and Geotechnical Engineering*, *9*(4), 749-760. https://doi.org/10.1016/j.jrmge.2016.11.012.

[31] Afzali, M.H.; Sharma, A. (2023). Sustainable utilization of calcium carbide residue along with polypropylene fiber waste materials for accessing swelling and strength characteristics of black cotton soil. *IOP Conference Series: Earth and Environmental Science*, *1101*(1), 012003. https://doi.org/10.1088/1755-1315/1110/1/012003.

[32] Quadri, H.A.; Abiola, O.S.; Odunfa, S.O.; Azeez, J.O. (2019). Evaluation of blends of calcium carbide residue waste and iron slag dust as stabilizer in flexible pavement construction. *Federal University Lafia Journal of Science & Technology*, *5*(2), 95–101.