Geotechnical Properties Improvement of Erosion Susceptible Soil with Caustic Soda (A Case Study of Ekosodin, Benin City)

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Abstract: The presence of the University of Benin (UNIBEN) makes the Ekosodin community economically vital, with local businesses benefiting from the spending of students and staff. Consequently, it is essential to address the problem of soil erosion in the area to facilitate ongoing development and growth. The aim of this study was achieved by collecting four soil samples and analysing various properties such as specific gravity, particle size distribution, Atterberg limits, optimum moisture content, maximum dry density, cohesion, angle of internal friction, and California bearing ratio. The study also examined the impact of adding caustic soda at different concentrations. The resulting unstabilized soil exhibited AASHTO class A-6 and A-7-6 characteristics, featuring a significant proportion of clayey soil with more than 35% passing through sieve No 200, resulting in a fair to poor subgrade rating in pavement design and significant compressibility. Nevertheless, as the percentage of caustic soda increased, there was a reduction in the liquid limit, plastic limit, plasticity index, optimum moisture content, and angle of internal friction. Additionally, higher maximum dry density, cohesion, unsoaked and soaked California Bearing Ratio (CBR) values were recorded with increased caustic soda content. The highest soaked soil CBR value of 26.0% was achieved with a 10% caustic soda stabilization. Therefore, chemical stabilization using caustic soda is recommended for erosion-prone soil in Ekosodin, as it transforms the area's soil from a poor subgrade or foundation to a robust load-bearing material suitable for building and road construction.

Keywords: Caustic soda; Erosion; Ekosodin; Geotechnical properties; Soil improvement

1. Introduction

Soil erosion is the term for the separation and movement of soil by natural factors such as gravity, ice, wind, or flowing water. This erosion typically takes the following three forms: sheet, rill, and gully erosion (Okengwo, et al., 2015). The soil in Ekosodin, Benin City Nigeria, was investigated to be highly susceptible to erosion caused by flowing water due to its geotechnical properties such as poor graded soil with low clay content, low erodibility index, and high precipitation (Ojeaga & Afolabi, 2022). Other factors include sloppy terrain, improper drain termination, lack of erosion control structure, low vegetation cover and bad land use (Ehiz and Omougbo, 2013). Over time, flowing water on the ground surface caused Ekosodin erosion,

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resulting in a large gully forming. This gully has disrupted the local wildlife ecology and has had a negative impact on road construction projects. Additionally, it has destroyed this area's agricultural lands, natural vegetation, and residential buildings. (Okengwo, et al., 2015). While the water that infiltrated into the soil and the pore-water pressure build-up within the soil create foundational and slope instability for both roads, buildings, and the existing gully (Egbueri, et al., 2021). Improvement of the soil is essential in this case to minimize the negative effect of the water content in the soil to a safe level.

The soil improvement involves a process of changing one or more soil characteristics mechanically or chemically to produce an improved soil material with the intended engineering properties. Soil stabilization is a process that aims to improve the load-bearing capacity of soil, as well as its shear strength, filtration, and drainage system permeability. It also helps to enhance the soil's resistance to weathering and traffic usage. The process typically involves physical or mechanical methods, such as adjusting the soil's particle size composition and altering the grain size fractions to reduce the void ratio. Chemical methods involve chemical additives reacting with soil particles, forming a strong structure that binds soil grains. By comparing the two methods of soil improvement, the chemical method was most recommended for erosion susceptible soil as it yields soil of higher quality and greater strength and durability than mechanical and physical methods (Olaniyan, et al., 2020).

Caustic soda is a non-volatile, whitish, and odourless substance, which can easily react with the water in the soil to generate a powerful compaction aid giving a higher density for the same compactive effort (Olaniyan, et al., 2020). Wang, et al. (2021) studied the effect of caustic soda on the unconfined compressive strength and plasticity of soft soil and observed an increasing strength and better ductility of the soft soil. A study was conducted to investigate the effects of using caustic soda to stabilize muddy soil and activate steel slag. The study aimed to understand how mixing cement and slag powder with silty soil under varying caustic soda levels affects their behaviour (Yan-kai, et al., 2017). Despite this positive effect, caustic soda has on soil properties, the quantity introduced must be moderated, as a negative effect can be observed at higher concentrations of this alkali interaction due to its ability to form new compounds or mineralogical changes in the behaviour of some soils (Rao & Chittaranjan, 2010).

Addressing the issue of erosion-susceptible soil in the Ekosodin community is vital due to its economic implications. By improving soil conservation practices, the community can enhance agricultural productivity, promote environmental conservation, support infrastructure development, tap into tourism potential, and enhance resilience to natural disasters. These efforts will contribute to sustainable economic growth, improved livelihoods, and the overall well-being of the community (Ojeaga & Afolabi, 2022). Therefore, this study was focused on testing the effect of caustic soda additives on erosion susceptible soil in Ekosodin, Benin City, to improve its geotechnical properties.

2. Methodology

2.1 Study Area

Ekosodin as shown in Figure 1, is a community located at the east of Isihor in Ovia Northeast Local Government Area of Edo state Benin City. It is bounded by the University of Benin on the south, Evbhomhore community in the West, Isihor in the North and the Ovia River in the East. The Ekosodin community is located within the longitude 5° 37' 7.89" to 5° 37' 37.75" East and latitude 6° 24' 29.92" to 6° 25' 31.35" North.

The study area is underlain by sedimentary formation of the South Sedimentary Basin. The geology is generally marked by top reddish earth, composed of ferruginized or literalized clay sand.

Figure 1: Map of Benin City showing Ekosodin (Source: Google Map)

It constitutes part of the Benin Formation which is made up of over 90% massive, porous, coarse sand with thick clay/shale interbeds having high groundwater retention capacity. Geologically, Ekosodin comprises of the Benin formation; alluvium; drift/topsoil and Azagba-Ogwashi (Asaba-Ogwashi) formation (Ihkile, 2016).

2.2 Materials

The materials used for this study are presented in Figure 2.

a	b

Figure 2: (a) Caustic soda and (b) Soil Samples

2.2.1 Collection and Preparation of Soil Samples

About 300kg of disturbed soil samples were collected from four points in Ekosodin at a depth of 1.0m from the ground surface using a hand auger. Some quantities of the samples were placed in an airtight polythene sheet, transported to the geotechnical laboratory and allowed to dry, while the larger lumps of soil were pulverized into smaller crumbs.

2.2.2 Caustic Soda

Caustic soda, which was an inorganic alkali with strong alkaline properties, was typically available in solid form as white, translucent pellets or flakes and was bought from a chemical store in Benin – City.

2.3 Methods

The index and engineering soil property tests were conducted on the natural soils to classify the soils. The classification tests include specific gravity test, particle size distribution tests; Atterberg's limits tests which are the liquid limit and plastic limit test, compaction tests to determine the optimum moisture content and maximum dry density, unconsolidated undrained triaxial test to determine the cohesion and angle of internal friction, and the California bearing ratio. All test procedures were carried out according to BS EN 1997-2-2007.

3 Results and Discussion

3.1 The Classification of the Soil Based on its Index and Engineering Properties

The soil properties investigated in this study in its non-stabilized state, were the specific gravity, particle size distribution, liquid limit, plastic limit, plasticity index, optimum moisture content, maximum dry density, cohesion, angle of internal friction and California Bearing Ratio; and all results are presented in Table 1.

Table 1: The Soil Index and Engineering Properties

Soil Properties		**Point 1**	**Point 2**	**Point 3**	**Point 4**
Specific Gravity		2.25	2.37	2.20	2.36
Percentage Passing British Standard (BS) Sieve Size	1.18mm	97.7	98.1	98.2	98.5
	0.425mm	76.8	72.2	75.4	79.0
	0.075mm	43.4	35.6	42.3	42.7
Liquid Limit (%)		50.4	39.7	50.6	42.0
Plastic Limit (%)		25.5	20.1	21.2	20.8
Plasticity Index (%)		24.9	19.5	29.4	21.2
Optimum Moisture Content (%)		15.7	14.8	15.9	14.8
Maximum Dry Density (g/cm^3)		1.63	1.65	1.63	1.66
Cohesion (kN/m^2)		32.0	27.0	31.0	32.0
The angle of Friction (°)		5.45	7.02	8.14	6.49
California Bearing Ratio (%)	Unsoaked	8.3	17.3	6.5	12.9
	Soaked	5.1	8.4	1.0	8.1
AASHTO Classification		A-7-6	A-6	A-7-6	A-7-6

3.1.1 The Specific Gravity

The range of specific gravity values of the different test samples was 2.20 to 2.37. This result depicts soil with more inorganic granular grain, silica and/or iron mineral, and a significant fine content (Bowles, 2012; DD ENV 1997-2, 2000; AASHTO M145-91, 2012).

3.1.2 The Soil Particle Size Distribution Based on the BS Sieve Analysis

Particle size distribution represents the relative proportions of different grain sizes in the soil composition. Table 1 above presents the percentage of the total soil mass that passes through the BS sieve No 10, 40 and 200 respectively. According to AASHTO M145-91 (2012), soil grains that are retained on each of these three sieve sizes represent the gravel, sand (coarse and medium) and fine sand respectively. While the percentage that passes through the BS sieve No. 200, represents the silt and clay content of the soil.

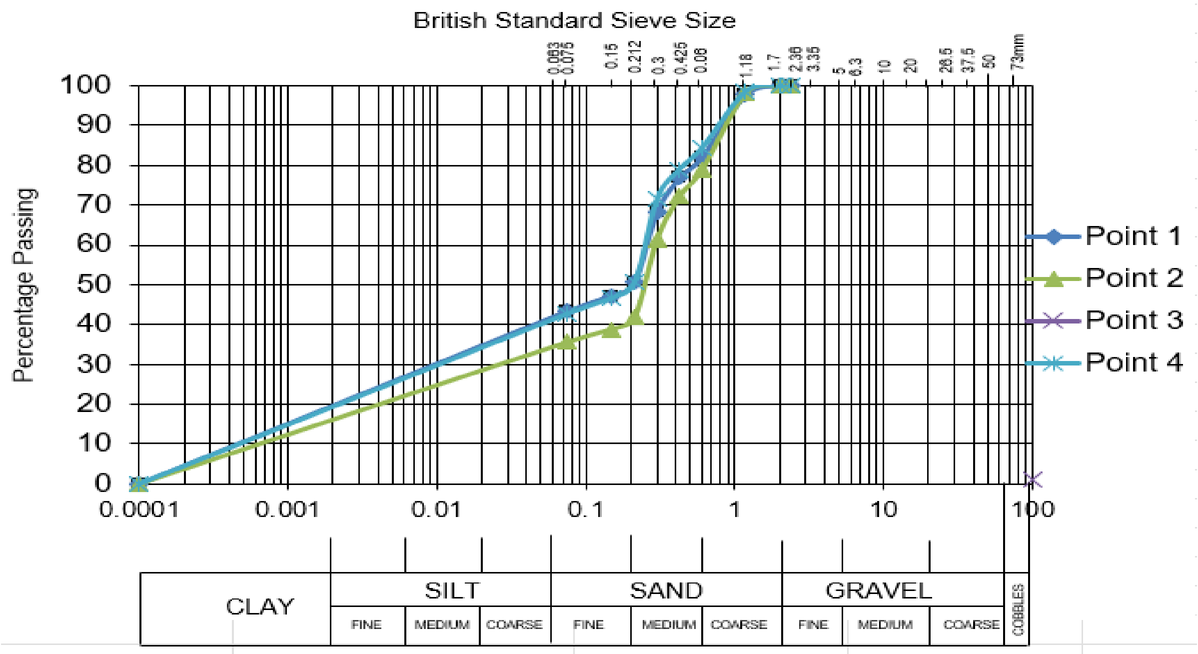

Figure 3: Sieve Analysis Graph of Soil Samples

As observed from the sieve analysis at point 1, the proportion of gravel in the soil was 2.26%, coarse and medium size sand 20.91%, fine sand 33.44%, and silt and clay 43.39%. Similarly, point 2 has 1.88% gravel, 25.96% coarse and medium sand, 36.57% fine sand, and 35.59% silt and clay. Point 3 has 1.77% gravel, 22.84% coarse and medium sand, 33.04% fine sand, 42.35% silt and clay. Point 4 has 1.53% gravel, 19.48% coarse and medium sand, 36.31% fine sand, 42.68% silt and clay.

According to BS 1377: Part 2 (1990), the soil gradation can be determined by evaluating the coefficient of uniformity C_u and coefficient of curvature C_c through equations 1 and 2 below. The average effective size of the soil, D_{10}, which is the corresponding particle size at 10% fine passing, was approximately evaluated from Figure 3 as 0.00045mm. Similarly, D_{30} and D_{60} were evaluated as 0.009mm and 0.25mm respectively.

$$C_u = \frac{D_{60}}{D_{10}} = \frac{0.25\ mm}{0.00045\ mm} = 555 \tag{3.1}$$

$$C_c = \frac{{D_{30}}^2}{D_{10} \times D_{60}} = \frac{0.009^2\ mm^2}{0.00045 \times 0.25\ mm^2} = 0.72 \tag{3.2}$$

The C_u value obtained from the soil sample was greater than 6.0, indicating that the soil particles are not uniform in size. However, the C_c value did not fall within the range of 1.0 and 3.0, which is representative of well-graded soil. This leads to the conclusion that the soil sample at point 1 is poorly graded, with some soil grain fractions either missing or present in very small or excessive quantities compared to others. This evaluation is based on the BS 1377: Part 2, 1990 standard. Similarly, from Figure 3, Point 2 had a D_{10}, D_{30} and D_{60} of 0.0006, 0.025mm and 0.28mm respectively. The resulting C_u and C_c values were 4.67 and 3.72 respectively, which depicts a poorly graded soil with voids due to some missing intermediate soil particles.

Point 3 had D_{10}, D_{30} and D_{60} of 0.00047, 0.01mm and 0.26mm respectively. The resulting C_u and Cc values were 553 and 0.82 respectively, which depicts a poorly graded soil with voids due to some missing intermediate soil particles.

Point 4 had D_{10}, D_{30} and D_{60} of 0.00047, 0.01mm and 0.26mm respectively. The resulting C_u and C_c values were 553 and 0.82 respectively, which depicts a poorly graded soil with voids due to some missing intermediate soil particles.

3.1.3 Atterberg Limits

The Atterberg limits which showed the consistency of the fine grain in the soil composition based on the influence of the soil water content were determined through Liquid limit (LL) and Plastic limit (PL). Also, the soil plasticity was determined by evaluating the difference between the LL and PL to obtain the plasticity index.

The LL values at Point 1, Point 2, Point 3 and Point 4 respectively, were presented in Table 1 above as 50.38%, 39.66%, 50.59%, and 41.99%. While the PL values at Point 1, Point 2, Point 3 and Point 4 respectively, were 25.53%, 20.12%, 21.18%, and 41.99%. The PI was evaluated as 24.85%, 19.53%, 29.41%, and 21.22% for Point 1, Point 2, Point 3 and Point 4 respectively. According to the Unified Soil Classification System, the plasticity level of the soil samples based on their liquid limits and plasticity index is CH, CI, CH, and CI at points 1, 2, 3, and 4 respectively. CI and CH represent soil with intermediate and high plasticity respectively (DD ENV 1997-2, 2000; Bowles, 2012). Also, they are very susceptible to a high level of compressibility (BS 1377: Part 2, 1990; AASHTO M145-91, 2012).

3.1.4 Compaction

The compaction test results of soil samples obtained at points 1, 2, 3, and 4 respectively, were obtained from the dry density versus average moisture content relationship of the B.S 2.5kg rammer compaction method as seen in Figure 4 below.

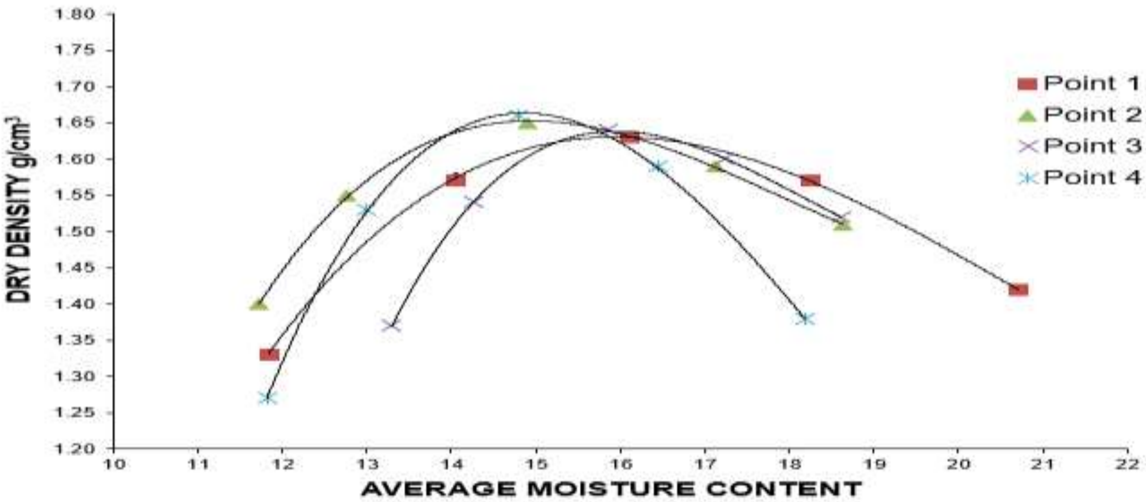

Figure 4: Compaction Graph of Soil Samples at Points 1, 2, 3, and 4

From the compaction graph below, the values of the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) were 1.63g/cm3, 1.65g/cm3, 1.63g/cm3, 1.66g/cm3 and 15.7%, 14.8%, 15.9%, 14.8% for point 1, point 2, point 3 and point 4 respectively. The range of MDD, and OMC values depict an inorganic clayey soil (BS 1377: Part 2, 1990 and Bowles, 2012)

3.1.5 California Bearing Ratio Test

The California bearing ratio (CBR) is a standardized penetration test used to evaluate the mechanical strength of soil subgrades and base courses. The CBR of the soil samples at 2.5mm and 5.0mm penetration of the standard plunger in the soaked and unsoaked state, was evaluated through the given equations 3.3 and 3.4 below and the average CBR values were presented in table 1 above.

$$CBR_{2.5mm} = \frac{Measured\ Load\ at\ 2.5mm\ Penetration}{136\ kN} \times 100\% \tag{3.3}$$

$$CBR_{5.0mm} = \frac{Measured\ Load\ at\ 5.0mm\ Penetration}{205\ kN} \times 100\% \tag{3.4}$$

According to the Federal Ministry of Works and Housing, FMWH (2013), the critical CBR value for pavement design is the soaked CBR value and the minimum soaked CBR value for a good subgrade material is 5%. Soil samples from points 1, 2 and 4 had a soaked CBR value of 5.12%, 8.42% and 8.09% respectively, which do satisfy the FMWH minimum specification for a good subgrade. However, the soil sample at point 3 had a CBR value of 0.99% which does not satisfy the FMWH specification of a subgrade material.

3.1.6 Shear Strength Parameters from U-U Triaxial Test

The U-U Triaxial test determines the maximum shearing resistance of the soil under pressure before failure occurs. Under the normal pressures of 100 kN/m2, 205 kN/m2 and 310 kN/m2, the relationship between measured shear stress at failure and normal applied stress was obtained for soil samples at points 1, 2, 3, and 4 through the Mohr's circle graphs. The cohesion (c) and (ϕ) values were then taken as the intercept and slope of the straight-line graph respectively (BS 1377: Part 7, 1990).

At Point 1, the soil cohesion and angle of internal friction were 32.0 kN/m2 and 5.45° respectively. Likewise, Points 2, 3, and 4 had a soil cohesion of 27.0 kN/m2, 31.0 kN/m2, and 32.0 kN/m2 respectively; and angle of internal friction of 7.02°, 8.14°, and 6.49°respectively. This depicts a clayey soil with high clay content (BS 1377: Part 2, 1990, and Bowles, 2012).

3.1.7 AASHTO Soil Classification System

The American Association of State Highway and Transportation Officials (AASHTO) soil classification is based on the particle size distribution, Liquid limit, and the Plasticity index of the soil. As seen in Figure 5 below, the soil samples at point 1, 3, and 4 were classified as A-7-6, while soil samples at point 2 was classified as A-6.

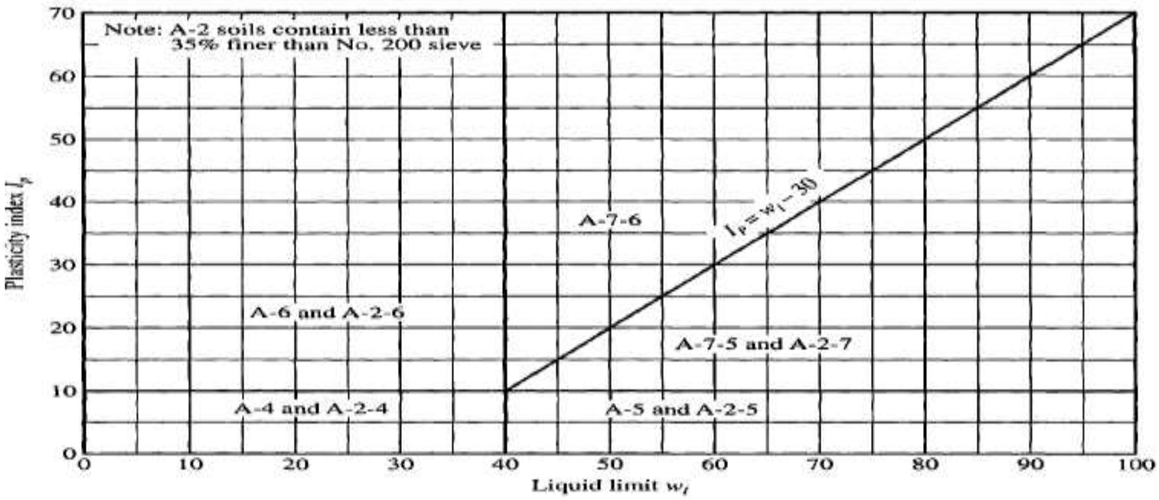

Figure 5: AASHTO Soil Classification

A-6 and A-7-6 soil classes represent soils with significant constituent materials of clayey soil and more than 35 percent of the total soil sample passing BS sieve No. 200. They are generally rated as fair to poor subgrade materials.

3.2 The Effect of Caustic Soda Stabilization on the Soil Properties

The effect of the caustic soda addition to the soil at a proportion of 2%, 4%, 6%, 8% and 10% respectively is presented in Figure 6. This was determined by analysing the data variation in the soil liquid limit, plastic limit, plasticity index, maximum dry density (MDD), optimum moisture content (OMC), cohesion (c), angle of internal friction (ø), and soaked California bearing ratio (CBR). Figure 6 presents the summary of the Laboratory results on the caustic soda stabilization.

The addition of the caustic soda to the soil to a maximum percentage of 10 reduced the liquid limit from 50.38% to 25.44% in soil samples at points 1; 39.66% to 25.49% in point 2; 50.59% to 26.20% in point 3; and 41.99% to 28.22% in point 4. Similarly, the plastic limit reduced from 25.53% to 11.47%, 20.12% to 10.96%, 21.18% to 14.22%, and 20.77% to 16.04% for soil samples at points 1, 2, 3, and 4 respectively. The plasticity index of the soil from the four sampling points decreased from their original values of 24.85%, 19.53%, 29.41% and 21.22% to 13.97%, 14.53%, 11.98% and 12.18% respectively at the addition of the 10% Caustic soda. These observations of a decreasing pattern in the Atterberg limits based on the addition of caustic soda to the soil were also confirmed by Neeladharan (2017). The maximum dry density of the soil from the four sampling points were increased from their original values of 1.63 g/cm3, 1.65 g/cm3, 1.63 g/cm3, 1.66 g/cm3 to 1.79 g/cm3, 1.77 g/cm3, 1.80 g/cm3, and 1.79 g/cm3 respectively at the addition of the 10% caustic soda. While the optimum moisture content decreased from their original values of 15.7%, 14.8%, 15.9%, and 14.8% to 13.30%, 13.80%, 11.20%, and 10.30% for soil in points 1, 2, 3, and 4 respectively.

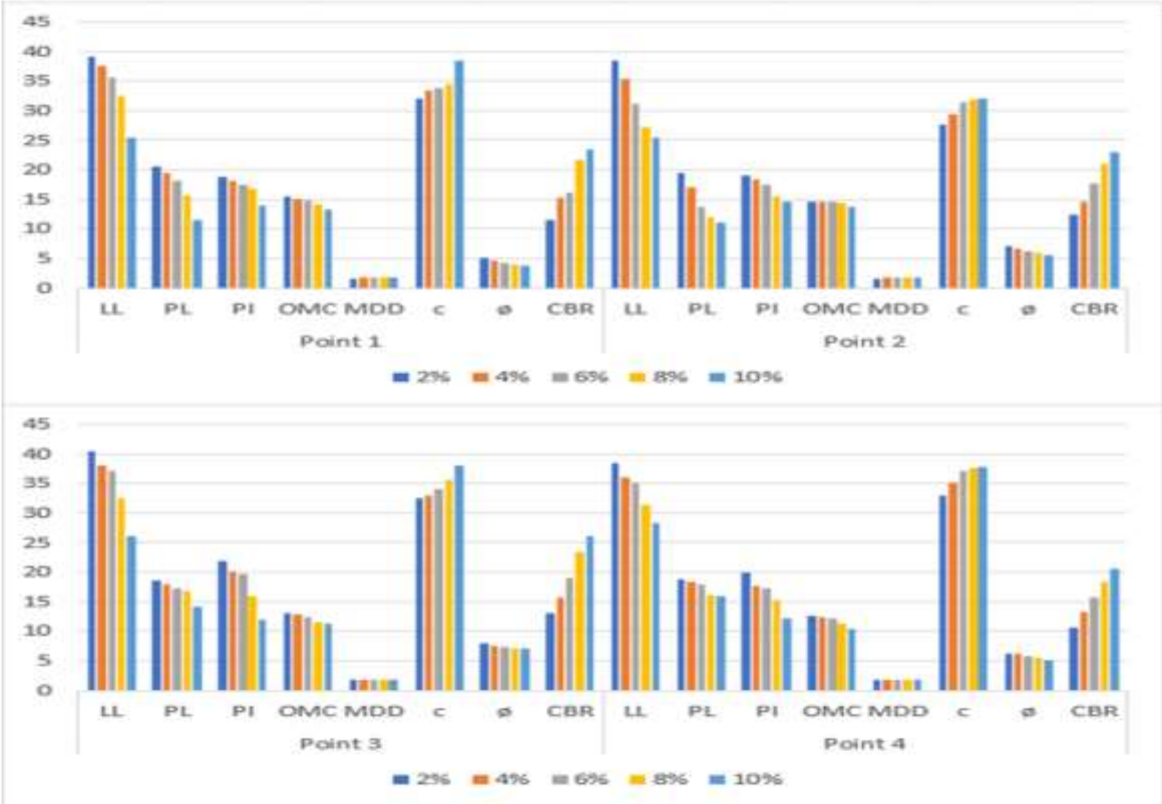

Figure 6: Effect of the Caustic Soda Stabilization on the Soil Samples.

These observations of an increasing and decreasing pattern in the MDD and OMC respectively, based on the addition of caustic soda to a soil were also confirmed by Zangana (2012).

The addition of the caustic soda to a maximum percentage of 10 decreased the angle of internal friction from their original values of 5.45°, 7.02°, 8.14°, and 6.49° to 3.75°, 5.54°, 7.06°, and 5.17° for soil in points 1, 2, 3, and 4 respectively. While caustic soda stabilization to a maximum percentage of 10 increased the cohesion from their original values of 32.0 kN/m2, 27.0 kN/m2, 31.0 kN/m2, and 32.0 kN/m2 to 38.60 kN/m2, 32.00 kN/m2, 38.04 kN/m2, and 37.86 kN/m2 for soil in points 1, 2, 3, and 4 respectively. Similarly, an increase in the California bearing ratio values was observed both in the unsoaked and soaked state at all sampling points. Comparing the soaked CBR values at 10% caustic soda stabilization of 23.45%, 22.99%, 26.00%, and 20.50% for soil in points 1, 2, 3, and 4 respectively as seen in Table 4.2 above, with the general specifications of sub-grade materials for roads by the Federal Ministry of Works (FMWH, 2013), which stated that soil with CBR soaked values greater than five percent (5%) are suitable subgrade material for road pavement; the soil in all investigated areas are therefore fit as a good subgrade material.

4. Conclusions

The soil in Ekosodin was classified as A-6 and A-7-6 class soil based on its index and engineering properties. These soil classes typically contain clayey soil with more than 35% fine passing BS sieve No 200. They also have a fair to poor subgrade rating in pavement design and a significant level of plasticity. An analysis of the addition of caustic soda to the soil was conducted. The maximum percentage of caustic soda used was 10%. The Atterberg limits, Compaction, and California Bearing Ratio (CBR) test results were examined. As the percentage of caustic soda increased, there was a decrease in the liquid limit, plastic limit, plasticity index, optimum moisture content, and angle of internal friction values at the natural state of the soil.

However, there was an increase in the maximum dry density, cohesion, soaked and unsoaked CBR values in the natural state of the soil. The soaked CBR values at 10% caustic soda stabilization were found to be 23.45%, 22.99%, 26.00%, and 20.50% for soil in points 1, 2, 3, and 4, respectively. These values exceed the general FMWH specifications of sub-grade materials for road design, which state that soil with CBR-soaked values greater than 5% are suitable subgrade materials for road pavement. Therefore, the soil in all investigated areas was deemed a good subgrade material after the caustic soda stabilization. In conclusion, the chemical stabilization of caustic soda is recommended for erosion-susceptible soil in Ekosodin. This process improved the soil sample from poor subgrade or foundation soil to good load-bearing and subgrade capacity soil for building and road construction.

References

AASHTO M145-91. (2012). Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes. Washington DC: American Association of State Highway and Transportation Officials.

Bowles, J. E. (2012). Engineering Properties of Soils and their Measurements (4th ed.). New Delhi: McGraw Hill Education (India) Private Limited.

BS 1377: Part 2. (1990). Method of Test for Soils for Civil Engineering Purposes. Classification tests. London, UK: British Standard Institute.

BS 1377: Part 7. (1990). Methods of Test for Soils for Civil Engineering Purposes; Shear Strength tests (total stress). London, UK: British Standards Institute.

BS EN 1992-2 (2007) Eurocode 7 -Geotechnical design -Part 2: Ground investigation and testing European Standard

DD ENV 1997-2. (2000). Eurocode 7: Geotechnical design - Part 2: Design assisted by laboratory testing. United Kingdom, UK: European Commitee for Standardization.

Egbueri J. C. Chinanu O. Unigwe, Michael E Omeka, Daniel A.Ayejoto. (2023). Urban Ground Water quality assessment using pollution indicators and Multivariate Statistical tools: A case study in Southeast Nigeria. International Journal of Environmental Analystical Chemistry.

Ehiz O.S,Uwadia Nicholas Omougbo. (2013). Evaluating factors responsible for Gully development at the University of Benin. Journal of Emerging Trend in Engineering and Applied Science.

FMWH. (2013). Federal Republic of Nigeria; Federal Ministry of Works; Highway Manual Part 1: Design (Vol. III). Abuja, Nigeria: Pavements and Materials Design.

Ihkile, C. I. (2016). Geomorphology and Hydrology of the Benin Region, Edo State, Nigeria. International Journal of Geosciences, Volume 7, pp. 144 - 157.

Neeladharan C., Vinitha V., Priya B., Saranya S. (2017). Stabilisation of Soil by using tile waste with Sodium Hydroxide as Binder. International Journal of Innovative Research in Science, Engineering and Technology https://doi.org/10.15680/IJIRSET.2017.0604094.

Ojeaga, K., & Afolabi, S. (2022). Geotechnical characterization of Soil susceptibility to Gully Erosion, Capitol, University of Benin, Benin City, Edo State, Nigeria. NIPES Journal of Science and Technology Research, 4(2), 318-323. Retrieved from https://doi.org/10.37933/nipes.e/4.2.2022.31

Okengwo O. N., Osita Okeke, Chikwendu Njoku Okereke, Paschal A. C. (2015). Geological and Geotechnical Studies of Gully Erosion at Ekwulobia, Oko and Nanka Town, Southeastern Nigeria. Electronic Journal of Geotechnical Engineering Vol 20. Pp 114 – 122

Olaniyan, F. A., Adelekan, I. O. and Nwokocha, E. E. (2020) The role of Local Government in Reducing Disaster caes and vulnerabilities in IbadanCity, Nigeria. Urban Africa Risk Knowledge Working Paper.

Rao A.V. Narasimha, Chittaranjan M. (2010). Harmful effects of certain Industrial wastes on geotechnical properties of soils - A review. Nature Environment and Pollution Technology.

Wang X, Jianye Zhao, Yunyun Xu, Zixi Wang, Shuai Lv. (2021) Strength experiment of soft soil solidified by composite powder of steel slag (SS) and ground granulated blast-furnace slag (GGBS) activated by caustic soda. Institute of Electrical and Electronics Engineering (IEEE) https://ieeexplore.ieee.org/document/9654463

Yan-kai1 WU, HU Xiao-shi, HU Rui, SHI Yu-bin, HAN Tian, YU Jia-li. (2017) Experimental study on caustic soda-activated steel slag powder in muddy soil. Chinese Journal of Geotechnical Engineering. https://doi.org/10.11779/CJGE201712006