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Geotechnical viability of sand, cement, and binary stabilisation of superficial soils in the western Niger Delta: an example of Warri City, Southern Nigeria

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Abstract

The pavement performance of superficial soils in southern Nigeria is in decline, most notably due to the use of inferior pavement materials and poor soil conditions. The study, therefore, examines the impact of sand, cement, and binary (sand/cement) stabilisation on soils in an attempt to improve road development in the City of Warri. The natural condition of sixteen (16) soil samples was subjected to consistency tests, classification tests, compaction, and soaked California Bearing Ratio (CBR) analyses as a standard for comparative analysis. The effects of sand, cement, and binary stabilisation on the engineering behaviour and suitability of natural soils were examined using specified road standards, CBR responses, and t-test analysis as bases for comparison with the natural, untreated soils. The properties of natural and treated soils were fed into machine learning predictive models, including Random Forest Models (RFM), Extreme Gradient Boosting (XGBoost) Models, and Explainable Boosting Models (EBM), for CBR prediction evaluation. Results confirmed that sand stabilisation had a significant impact on the soil grade, with a marginal impact on the natural CBR (resulting in a slight boost from the natural range of 3-17.9% to 11-28.8%), while the soil suitability remained constant. Cement-treated soils were improved to subbase/base quality (71.3-193.3%) at 7% weight of cement. Binary stabilisation resulted in base-quality soils (107-272.5%). T-test analyses confirmed that binary stabilisation is the most technically viable solution to the pavement deficiency in the City. The study presents a feasibility resource database for the stabilisation of deficient superficial soils for road development in deltaic environments.

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1. Introduction

The superficial soils in the western Niger Delta are mainly residual lateritic soils in nature (Avwenagha et al. 2014; Avwenagha et al. 2024; Eze-Uzomaka and Omotosho 2008). They are the most widely used material for road pavement design (Arumala and Akpokodjo 1987), notwithstanding their exposures to aggressive rainfall of about 3000mm (Adejuwon 2003), high temperature conditions, and problematic geotechnical soil conditions, which limit their engineering competence. In addition, there is widespread urbanisation, which adversely impacts the superficial soils of the Western Niger Delta (specifically in the City of Warri).

Warri is one of the fastest growing metropolitan cities in the Western Niger Delta with evidence of rapid population growth (Mogborukor et al. 2021; Sajini 2021), widespread installation of medium-heavy residential/ industrial infrastructures (buildings, oil and Gas installations) and heavy vehicular traffic (Ugbe 2011; Avwenagha et al. 2014). These developmental pressures not only stress/ burden the foundation soils but trigger unguided installation of earthworks on problematic soils, which are typical of the Niger Delta and beyond (Okogbue 1989; Puppala et al. 2015; Nwankwoala 2021, 2023; Ugbe 2022). The weak soil conditions, such as high moisture content, high fine content, swelling clays, and lateral soil variation, have resulted in differential settlement, swells, cracks, potholes, and erosion of road pavement as reported by other workers (Akpokodje et al. 1987; Ugbe et al. 2022). These defects have translated to a high cost of road maintenance and haulage of fill materials for soil replacement (Jain et al.2020).

Moreover, it has been noticed that the superficial soils in the western Niger Delta do not exceed a CBR of 30% under natural or untreated conditions (Avwenagha et al. 2014, 2024). This means that the soils cannot function as subbase and base courses under heavy vehicular loads, which are peculiar to the City. Hence, a technical and economic solution to these road failures is soil stabilization. Soil stabilization is the regulated addition of geo-material (stabilisers) to incompetent soils to enhance their engineering performance and suitability for earthwork constructions. The objectives of soil stabilization are to reduce permeability, prevent swelling (Puppala et al. 2015), and improve soil consistency/ strength (Amu and Adetuberu, 2010). There are different stabilisation schemes, but the choice of stabilisation depends on the eco-friendliness (Goodarzi et al. 2015; Latifi et al. 2015; Sathyapriya and Arumairaj 2016; Latifi et al. 2016; Puppala et al. 2015), geotechnical/economic viability of the stabilizer, and the uniqueness of the scheme (Avwenagha et al. 2024). Several researchers have attempted soil stabilization in the Niger Delta (Omotosho and Eze-Uzomaka 2008; Okagbue and Onyeobi 1999; Akpokodje et al.1987, Imafidon et al. 2021; Avwenagha et al. 2024). Omotosho and Eze-Uzomaka (2008) engaged sand, cement, and binary (Mixed sand-cement) stabilisation in the Eastern Niger Delta and produced a subgrade, subbase, and base course quality soil material, respectively. They also established that it is technically and economically unviable for cement stabilization of deltaic laterites to yield a base course-quality soil at 7%wt of cement content. Okagbue and Onyeobi (1999) conducted marble dust stabilization and noticed that deltaic laterites can produce a CBR of 26% at best using 6-8% marble dust. Imafidon et al. (2021) carried out sand and composite stabilization of superficial soils in parts of the western Niger Delta and established that the latter stabilisation is more viable from the economic and technical perspectives. Avwenagha et al. (2024) attempted a stone-dust stabilization of superficial soils in the western Niger Delta and produced subbase-quality soils at 30% stone dust. They (Avwenagha et al. 2024) also reported that stone dust significantly impacts the grading of soils, but marginally affects the quality of soil cohesion/ inter-particle bonding. A similar stabilization was conducted on the superficial soils of India (Mishra et al. 2019), and they reported a subgrade and subbase category of soils based on the Indian road specification standard (MoRTH 2013), which agrees with the Nigerian Road specification scheme (FMW 1997).

Based on the overwhelming dominance of sand over fines (Olurunfemi 1984) and the zero-low cohesion in superficial soils of the Western Niger Delta, the use of cement stabilisation and mixed stabilization (sand+cement) promises to be viable (Puppala et al. 2015; Pillappa 2005). Hence, the focus of the study is to assess the technical and economic viability of cement, sand, and Binary stabilisation as a solution to incessant road failure and road development in the deltaic environment.

The study seeks to:

i. Assess the geotechnical impact of sand, cement, and Binary (sand/cement) stabilisation schemes on the road performance of the soils.
ii. Examine the impact of the sand stabilisation on the compaction and A.A.S.H.T.O. classification signatures of the superficial soils.
iii. Compare the geotechnical viability of each stabilisation scheme using a t-test analysis.
iv. Adopt a more reliable predictive model for the CBR performance of stabilised soils.

The area is located in the western portion and coastal zone of the Nigerian Niger Delta, some 40 kilometres away from the shores of the Atlantic Ocean. The area is a prominent centre of commercial activities in southern Nigeria, which lies between longitudes $5^{0}25^{1}$E-$5^{0}49^{1}$E and latitudes $5^{0}33^{1}$E-$5^{0}37^{1}$N. It occupies a flat, low-lying terrain which is drained and moderately dissected by the River Warri and its network of tributaries, which empty into the sea (Figure 1). The flat terrain is evidenced by a dendritic drainage pattern, which also indicates a homogeneous underlying soil material.

Figure 1 – Location and geographical map of Warri (study area).

2. Local geology

Warri is underlain by a Quaternary to Recent Alluvium known as the Sombreiro-Warri Deltaic Plain sands (Figure 2), which from bottom to top consists predominantly of unconsolidated fine-medium grained sand, reddish brown clayey sand, and silty top soils (Avwenagha et al. 2014b). The thickness of the Quaternary Formation generally does not exceed 120m, and it is predominantly unconfined (Olobaniyi and Owoyemi 2006). The hydraulic conductivity of the sand varies from 3.82×10^{-3} to 9.0×10^{-2} cm/sec, which makes it a potentially productive aquifer (Offodile 1991). The water table is close to the ground surface and varies from 0-4m (Olobaniyi and Owoyemi 2006; Overare et al. 2016). The limited water level fluctuation reflects a high amount of average precipitation recorded in Warri, which is about 3000mm/year (Adejuwon 2012).

Figure 2 - Geologic map of superficial soils and outcropping formations of the onshore Niger Delta (Redrawn and modified from Reijers et al. 2011). The area labelled "16" in the top-left position of the map indicates that the study area (Warri) is resting on the Sombreiro-Warri Deltaic plain sands. The sparse network of rivers within the soil belt implies a mixture of well-drained and poorly drained conditions, which translates into dry land and wet land conditions.

2.1. General Geology of the Niger Delta

The Niger Delta has been thoroughly examined by many geological literatures (e.g., Short and Stauble 1967; Avbovbo 1978; Evamy et al. 1978; Doust and Omatsola, 1990; Osokpor et al. 2015; 2016; Osokpor and Overare 2019; Pastore et al. 2023; Ugwu et al. 2023; Ogbe et al. 2021; Overare et al., 2021, 2024; Bayon et al. 2024; Garzanti et al. 2025). The Quaternary to recent alluvium of the Niger Delta (specifically the Sombreiro deltaic plain sands) is underlain by the major dichronous lithostratigraphic units of the Niger Delta Basin, which, from top to bottom, are the Benin, Akata, and Agbada Formations.

The Benin Formation is Oligocene to Pleistocene in age. It consists predominantly of fresh water, continental friable sands and gravel that are of excellent aquifer properties with occasional intercalation of shales. This Formation contains the most productive and hence the most tapped aquifer in the Niger Delta region, especially in areas north of Warri, where it is shallow. The thickness of the Formation is variable but generally exceeds 2000meters. Detailed studies of the Quaternary deposits overlying the Benin Formation revealed that the sediments were deposited under the influence of fluctuating Pleistocene eustatic sea levels. These sediments vary greatly in type.

The Agbada Formation consists of a sequence of alternating deltaic sands and shales. It is Eocene to Oligocene in age and exceeds 3000meters in thickness. This Formation is the oil reservoir of the Niger Delta Basin. It is rich in microfauna at the base, decreasing upward, and thus indicating an increasing rate of deposition in the Delta front. A fluviatile origin is indicated by the coarsening of the grains and poor sorting. The formation underlies the entire Delta area and may be continuous with the Ogwashi-Asaba and Ameki Formation.

The Akata Formation rests unconformably on the migmatite-gneiss basement complex and forms the basal unit of the Niger Delta stratigraphic pile. This Formation consists of an open marine facies unit dominated by high-pressure carbonaceous shales. The formation ranges in age from Palaeocene to Eocene, and its thickness could exceed 1000 meters.

3. Materials and methods

Field investigations were undertaken by engaging geotechnical surveys such as auger borehole drilling programmes and soil samplings (Pl.1) Sixteen (16) boreholes were drilled to a depth of 4m, and samples were collected at intervals of 0.75m) meter for laboratory examinations (BS5930:2015, BS1377-9: 2022). The GPS coordinates of sampled locations were recorded (Table 1).

Table 1 - Coordinates of the sample locations in Warri.

In compliance with standard test procedures (BS 5930:2015; BS 1377-9:2022), samples recovered from auger holes were subjected to the following testing programmes: sieve analysis, consistency limit tests (such as liquid limit, plastic limit), compaction, and California Bearing Ratio (CBR) analysis (Figure 3). Two types of sieve analyses were engaged in assessing the particle size distribution (PSD) of recovered soil samples, which are dry and wet sieve analyses (BS 1377-2:2022). For dry sieve analysis, 200g of oven-dried soil sample was pulverised to separate the individual grain sizes and passed through a set of sieves arranged from top to bottom in a decreasing order of mesh/ sieve sizes as shown in the sequence: 4.75mm, 2.36mm, 0.84mm, 0.42mm, 0.149mm, and 0.074mm. The sample within the set of sieves was agitated by an electric shaker for 15 minutes. The weight of the sample retained in the individual sieves was recorded, and the percentage by mass of sample passing through each sieve was calculated and plotted against the respective sieve sizes to produce a Particle Size Distribution (PSD) curve from which the PSD of the sample was determined. The wet sieve analysis was conducted when the fine content in a sample is more than 5% (BS 1377-2:2022). By visual examination, some soil samples satisfied this condition, hence the analysis. Soil material of 200g was dried and washed through a sieve No.200 (0.074mm) to separate the fines from the coarse fractions. The coarse fraction is dried and subjected to mechanical sieving using dry sieve analysis (which had earlier been explained).

Figure 3 - Flow chart of the study methods.

The liquid limit was determined using the Casagrande method. Initially, the soil samples were air dried, disaggregated, and passed through a sieve diameter of 0.425mm and thoroughly mixed with a small amount of distilled water until it appeared as a smooth, uniform paste (BS1377-2:2022). A portion of the paste was placed into the cup of the liquid limit apparatus, and then squeezed down to eliminate air pockets and spread into the cup to a depth of about 10mm, thereby forming an approximately horizontal surface. The groove tool was carefully used to cut a clean, straight groove down the centre of the cup, then the crank of the apparatus was turned at a rate of approximately two drops per second, and the number of drops, "N," was counted. When the number of drops exceeded 50, the number of drops on the data sheet was recorded, and then soil samples from the apparatus cup, usually from both ends of the groove, were taken using a spatula. The soil was placed into a moisture can where it was immediately weighed, covered, and placed in an oven for about 16 hours. The soil remaining in the apparatus cup was later placed into the porcelain dish as the apparatus cup was cleaned and dried for a second and third round of analysis, which was done by gradually increasing the moisture content of the paste to achieve groove closure at lesser blows. Finally, a graph of moisture content was plotted against the number of blows. The moisture content at the 25th blow gave the liquid limit.

A 20g dry soil sample was used for the plastic limit test. This was mixed with distilled water to form a uniform paste until the soil was at a consistency where it could be rolled without sticking to the hands. By rolling between the palm and the glass plate, an ellipsoidal mass was formed. The mass was rolled until it formed a thread of 3mm in diameter, having cracks on its surface. The thread was broken into several pieces and placed into a moisture can and sealed. The Can was then oven dried for 16 hours, and finally, the moisture content of the set of threads was determined. The whole procedure was repeated three times to obtain three determinations. The average value of the moisture content gave the plastic limit of the soil.

For sand stabilisation test, Coastal Plain Sands (also known as sharp sand, which had less than 5% fines) were sourced from River Ologbo in the Western Niger Delta. A regulated proportion of the sands in the range of 30-55% weight of the soil sample (depending on the soil grade of the sample) was thoroughly mixed with 3kg of the soil samples from sixteen (16) locations of the study area, and each was subjected to the standard proctor compaction test in compliance with BS1377(1990). OMC and MDD values of each sample were used to prepare a 6kg compacted specimen for CBR analysis, which was conducted after being wax cured for 6days and soaked for 24hours in water as prescribed by FMW (1997).

For cement stabilisation test, 3kg of soil specimens from all the study locations were mixed with ordinary Portland cement in conformity with B.S. 12 (1990). Regulated proportions of cement in the range of 7-11% by weight of the specimen were added depending on the soil's AASHTO classification, as in Table 2. Cement mixed specimens were subjected to the standard proctor compaction test from which the OMC and MDD were used to produce a 6000g cement-stabilised specimen for CBR analysis after being wax-cured for 6days, soaked in water for 24hours, and allowed to drain for 15minutes.

Table 2 - Modified Cement Content Requirements of AASHTO. Soil Groups.

The Binary (Sand + Cement) Stabilisation test was engaged in order to enhance the technical and economic viability of soil stabilization, bearing in mind the costly nature of cement. In this case, 3kg of 16 soil samples were thoroughly mixed with sharp sands in the range of 30-55% by weight to improve their AASHTO soil group. Following the upgrade, a uniform cement proportion of 7% was mixed with the soil specimen in compliance with the provisions of BS6229 (1990). Thereafter, a 3000g specimen mixed with sand and cement was subjected to the standard proctor compaction test from which the OMC and MDD were used to prepare a specimen for CBR analysis after the sample was wax cured for 6days, soaked in water for 24 hours, and allowed to drain for 15minutes in agreement with BS6228(1990) and FMW, (1997).

For reasons of management of time and stress in conducting a series of analyses for an adequate quantity of stabilisers and quality CBR performance, three predictive models (Random Forest, Extreme Gradient Boosting, and Enabling Boosting Machine models) were employed. Each model was trained on a unified dataset encompassing soil physical features, including sand and cement content, fine percentage, plasticity characteristics, optimal moisture content (OMC), and maximum dry density (MDD). An interaction term (Sand × Cement) was incorporated to elucidate the synergistic effects between stabilising agents. The dataset was divided into an 80/20 training-testing ratio. R^2 (coefficient of determination) was employed to assess goodness-of-fit, whilst MSE (mean squared error) quantified the average prediction error. Cross-validation was employed to ensure performance reliability, and feature importance was assessed for each model to identify the input variables that most significantly influenced CBR prediction.

4. Results

4.1 Natural Soil Condition

The Table 3 shows the compaction and geotechnical properties of the superficial soils in their natural state. The sand content ranges from 3.5-87.2% with an average value of 73.13%. The highest sand content was recorded in BH11, while the least sand content was noticed in BH1. The dominance of sand over fines was noticed in all boreholes except BH1, which has 3% and 97% sand and fines, respectively.

Table 3 - Compaction and geotechnical properties of the superficial soils in their natural state

4.1.1 Liquid limit

The liquid limits ranged from 14.5%-69.0% with an average of 28.2%. The highest liquid limit was noticed in BH3, while the least in BH11 (Table 3). The liquid limits of the soils are generally low (<35%) except for BH 16 with a value of 69%. A similar trend applies to the Plasticity index (PI), which ranged from 11.08-22.0% with generally low PI of less than 12% except BH1 with a value of 22%.

4.1.2 Optimum Moisture Content (OMC) and Maximum Dry Density (MDD)

The Optimum Moisture Content (OMC) ranged from 8.41-23.0% and averages 9.91%, which implies a general dominance of low OMC except for BH1 (Table 3). The Maximum Dry Density (MDD) ranged from 1.395-1.944g/cm^3. In this case, there is generally high MDD (with an average of 1.8696 g/cm^3). The variation trend in OMC and MDD translated into California Bearing Ratio (CBR), which ranged from 3-17.90%. (Figure 4). The average CBR value (14.3%) implies a dominantly low CBR on the scale of road performance standards (FMW, 1997). Hence, soil stabilisation is needed.

Figure 4 - Natural CBR distribution of superficial soils in Warri. Note that the natural CBR distribution of the entire city does not exceed 18% which confirms that the untreated CBR of the soils is generally low and limited to subgrade quality (FMW 1997, Avwenagha et al., 2024). Moreover, on the CBR scale of 3-18%, over 80% of the City is marked by relatively medium-high CBR (as indicated by the green–yellow zone covering BH2-12), while about 20% of the area is pockets of low-medium CBR (which is indicated by the yellow-green zone; BH1, BH13-16).

4.1.3 Influence of sand, cement, and binary (sand+cement) stabilisation on natural soils

In response to sand stabilisation at 30% sand addition, there was a general decline in the natural soil consistency limits and OMC (Tables 3 and 4). The average fines, liquid limit, plastic limit, plasticity indices of the natural superficial soils declined from 30.4 -21.5%, 28.2-19.97%, 19.06-15.08%, 9.91-5.68%, and 11.45-10.75% respectively (Tables 3 and 4). These declines translated into an overall increase in average MDD (from 1.8696 to 1.9426 g/cm^3) and average CBR (from 14.3 to 22.865%). This implies that by the effect of sand stabilisation, there is an average increase in soil CBR and MDD by 30% and 3.9% respectively.

Table 4 - Results of sand stabilisation of the superficial soils

The trend of variation between consistency limits and compaction characteristics of soil (OMC and MDD) in sand stabilization is similar to those of cement and binary (sand/cement) stabilisation (Table 5), but their impacts on natural soil CBR differ (Figure 5A-C). The Cement stabilization of samples from BH 2-16 and BH 1 was conducted using 7% and 11% cement, respectively (BS12-1990, Table 6). In response to cement stabilisation using 7% weight of cement (for BH2-16) and 11% (for BH1 only). The average natural MDD and CBR increased from 1.8696-1.9193g/cm^3 and 14.3-166.94%. By effect of binary stabilisation (30% sand+7% cement) on the natural soils, the natural CBR increased by 110-272.5% with an average increase by 212% (for BH 2-16, Figure 5) while that of BH1 increased by 130% (at 55% sand for the what sample and 7% sand for other samples). The CBR values of all soil samples increased progressively with response to cement, sand, and Binary stabilisation (Figure 5A-C).

Table 5 - Results of cement stabilization of the superficial soils

Figure 5 - CBR trend maps of superficial soils in Warri, under conditions of sand, cement, and binary stabilisation, respectively. The green, yellow, and orange colour codes are lower, middle, and upper CBR levels in the CBR scale of the respective stabilisation schemes. Under natural/plain conditions of stabilisation (Figure 3), the CBR of the soils ranged from 3-18%. (A) Sand stabilisation - the CBR ranged from 11-28% which indicates improved subgrade-quality. (B) The CBR scale improved to a range of 71.3-193.3%, which falls within the class of subbase to base course quality soils. (C) Composite / Binary stabilisation - the distribution ranged from 107-272.5%, which depicts soil improvement to a class of slightly subbase to dominantly base course quality soils (FMW,1997).

Table 6 - Results of binary (sand+cement) stabilisation of the superficial soils.

4.1.4. T-test analyses

Statistical evaluation of the impact of cement, sand, and Binary (sand+cement) stabilisation on the natural CBR of superficial soil was achieved through t-test analysis (Table 7). The Test results show that the difference between the variance (V_1=15.59686) of natural/untreated CBRs and that of sand–stabilised CBRs (V_2=24.9581) is less than 100% (i.e, V_2-V_1=9.36124). This validates the use of t-test analysis with assumed equal variance in this case (i.e, the case of natural CBR against sand-stabilised CBR). However, the difference between the variance of natural CBRs and those of cement and Binary (sand+cement) stabilised CBRs is more than 100% (i.e, their variances are twice that of the natural CBRs). This enabled the t-test analysis using assumed unequal variance.

Table 7 - Geotechnical impact Assessment of sand, cement, and binary stabilisation using two-sample t-test assuming equal/unequal variance

While statistical parameters such as α=0.05 were constant, other statistical P-values were in the order of 1.16E-05-2.56E-05, 3.93E-11-7.87E-11, and 1.06E-12-2.13E-12 under sand, cement, and Binary stabilization, respectively. All P-values were less than 0.001 and less than the α-value (0.05), but their levels of difference from the α-value were significantly widening with response to sand, cement stabilisation, and binary stabilisation, respectively (Table 7).

4.1.5 Predictive Stabilisation Models

This paper examined three distinct machine learning methods for predicting the California Bearing Ratio (CBR) In soil stabilisation: Random Forest, XGBoost, and Explainable Boosting Machine (EBM). Each of the models possesses unique advantages, and their appropriateness differs according to accuracy, interpretability, and computational efficiency (Table 8).

Table 8 – Model comparison table

5. Discussion

5.1 Compaction and classification behaviour of soils under natural conditions

The suitability of superficial soils for road pavement construction depends on their classification and compaction characteristics (Avwenagha et al. 2014a; Tse and Ogunyemi 2016; Avwenagha et al. 2024). The general dominance of sand over fines in almost the entire sample locations (specifically BH2-16), with an average of 73.13% sand content and less than 35% fines) confirms the soils are mainly granular soils of excellent subgrade quality based on the AASHTO classification scheme. However, the reverse dominance of 97% fines over 7% sand over fines in BH1 implies the minor presence of clayey soil material with poor subgrade quality. The granular soils with liquid limit (LL) values (<14.5%-69.0%, Table 2) and Plasticity index (PI) (<11.08-22.0%) are further classified as A2-4, 2-6 and 2-7 while the clayey/silty- clayey soils with LL (14.5-69.0%) and PI (11.08-22%) are grouped as A-4, A-6 and A7-5.

Moreover, the range of the Optimum Moisture Content (OMC) of the soils (8.41-23.0%) indicates that the superficial soils are sands and clayey/silty soils (Arora 2003), and the average of OMC (9.91%) implies a general dominance of sands (Arora 2003). This further corroborates the granular and silty/clayey soil classification by the AASHTO scheme.

A shift in the soil classification from A-7, A-6, A-4 to A-2 and OMC from 23.0-8.41% shows a gradual increase in soil consistency, which has resulted in the CBR range from 3-17.90% under natural/ plain conditions of compaction (Table 3 and Figure 4). This range of CBR demonstrates that the soils are competent subgrade but incompetent subbase and base courses for road construction, as their CBRs are less than 30% and 80% respectively (FMW1997). This pavement deficiency of superficial soils in a deltaic environment had been noticed by many researchers (Omotosho and Eze-uzomaka 2008; Avwenagha et al. 2014a; Imafidon et al. 2021; Etim et al. 2022; Avwenagha et al. 2024). Hence, there is a need for soil stabilisation to improve the engineering performance, consistency, and soil waterproofing effect of soils (Amu and Adetuberu 2010).

5.1.1 Impact of sand stabilization

In response to sand stabilisation using 30% weight of sand, there was an improvement in the natural soil grade, resulting in a decrease in liquid limit, plastic limit, and Plasticity indices of the natural soils (Figure 6). The impact of the stabilisation on soil grade is that natural soils, which were predominantly of A2-4, A2-6, A-6, and A-3, and A7-5 characteristics, were upgraded to A2-4 and A-3, and A2-6. This translated to an increase in CBR from a natural range of 3-17.9% to 11-28.80% (Table 4, Figures 4 and 5A). The low-high plasticity, clayey/silty soil materials, which were dominantly of A7-5, A-6, and A-4 characteristics, were upgraded to low plasticity clays of A2-6 and A2-4 characteristics, which resulted in elevated CBR of 9.5-28.3% (Table 4, Figures 5A and 7). The elevated CBR range did not exceed the 30% FMW standard, which shows the soils have improved in subgrade quality but remain incompetent sub-base and base-course materials for road construction (FMW 1997). This implies that sand stabilisation mainly improves the subgrade quality of deltaic soils, not their performance to subbase quality (Omotosho and Eze-uzomaka, 2008; Avwenagha, 2021). This is because it significantly impacts on AASHTO soil grade but has a negligible impact on the inter-particle bonding of soils.

Figure 6 - Impact of sand Stabilisation on soil consistency limits. Note that the natural soils (blues point) initially were distributed across the medium-low (ML) to medium-high (MH) plasticity silt zones. Upon sand-stabilization, the sample points (as indicated by blue arrows) drifted towards the left, away from the ML-MH zone, and downwards along the low-plasticity soil zone (as indicated by the blue arrows). This implies that sand stabilization decreases the plasticity index and liquid limits of soils and consequently increases soil consistency (strength/stiffness).

Figure 7 - CBR Response to Sand, cement, and Binary stabilisation. Note that the parallel lines (coloured with blue, green, and dark blue) are standard limits (FMW 1997) that define subgrade, subbase, and base-quality soils in road pavement designs. The wavy lines indicate the magnitude of CBR recorded at various sample locations (No.1-16) under plain/natural, sand, cement, and Binary-stabilised conditions. CBR responses under plain and sand stabilisation were within the subgrade quality limit (blue line at 30% CBR). The response partly exceeded the Cement-stabilised base limit (Dark blue line at 180% CBR) during cement stabilisation, while over 95% of the responses exceeded the base limit under conditions of Binary (Cement + sand) stabilisation. The increasing CBR trend shows that all the stabilisation schemes increase soil density, reduce void ratio, and Water Holding Capacity (WHC). While soil-cement matrix interaction increases inter-particle bonding during cement stabilisation, Binary (Cement + sand) stabilisation increases both inter-particle bonding and soil grade, which are the prevailing factors of Stabilisation. Hence, the Highest CBR response from Binary Stabilisation.

5.1.2 Cement stabilization

The technical and economic viability of cement stabilisation is determined by the AASHTO soil grade of the natural soil (BS12: 1990). Hence, the granular soil grades (A2-4, A-3, A2-6) were stabilised with 7% cement, while the clayey/silty soil grades (A-6 and A7-5) were stabilised with 10% and 11%weight of cement, respectively (Table 5). Upon cement stabilisation, the natural CBR of low-high plasticity silty/clayey soils (A-6 and A7-5) increased from a range of 3-10.60% to 71.3-128% at 10-11%weight of cement contents. The stabilisation also increased the natural CBR of the granular soils from the range of 13.70%-16.20% to 130.30-193% at 7% cement content. The low-fines presence in granular soils reduces water demand and water-cement ratio in cement hydration (to form Calcium-Silicate-Hydrate gel), which enhances soil particle bonding to produce a denser and more impermeable soil (Wei and Ku 2020, Xiu et al., 2021). The relatively high CBR response of granular soil to cement stabilisation confirms that the effectiveness of cement stabilisation increases with decreasing soil cohesion and fines content. This stabilisation favours granular soils and validates similar works (Aiban 1994; Pillappa 2005; Venkatarama et al. 2012; Puppala et al. 2015; Wei and Ku 2020; Xiu et al. 2021). Except for BH8, BH12, and BH25 with CBR above 180% at 7% weight of cement content, other soils with lower CBR values (below 180%) under cement–stabilised condition, have been upgraded from their subgrade to a sub-base status, but remain incompetent base-course materials as their CBR is less than 180% under cement-stabilised conditions (FMW1997, Figure 7). Contrary to other works (Omotosho and Eze-uzomaka, 2008), samples of BH8, BH12, and BH25 show that cement-stabilisation of deltaic laterites to base quality (i.e, above 180% CBR) could be viable at 7% weight of cement. Further cement stabilisation beyond 7% wt. of Cement would be economically unviable (FMW 1997).

5.1.3 Binary (sand+cement) stabilisation

With the intent of producing base-quality soils as well as enhancing cement economy using cheap and readily available materials like sand, the binary stabilisation was engaged. Due to the impact of binary stabilisation, the naturally fines-dominated soil of BH1 was upgraded to granular soils (precisely, A2-4) by the addition of 30% sand (for samples BH12-25) and 55% sand (for BH1) at a uniform 7%wt of cement. General addition of 7% weight of cement improved the natural CBR range of 3-17.90% to 110-229.50% with average values of 212% (Table 5, Figure 5C). Effective cement stabilisation is also enabled by cementitious hydration reaction (that is, cement-soil-water reaction), which is favoured by relatively high sand content over fines (Roshan et al. 2022; Amadi et al. 2025). The CBR results show that binary stabilisation predominantly reduces cohesion by sand addition, thereby improving the AASHTO soil grade for effective cement stabilisation. Superficial soils of the area responded most positively to binary stabilisation, resulting in higher CBR values. The CBR (110-229.50%) indicates the soils are base course quality-compliant except for sub-base quality produced at BH20 (CBR-79%, Table 6). This exception is because sand addition to the cohesionless (A-3) soil in BH 20 resulted in a high sand-cement ratio. The ratio effect, weakened soil cementation, resulting in lower CBR than even those of cement-stabilised soils. All the explored stabilisation schemes have not only impacted the CBR of the soils but have also impacted the geometry and position of the compaction curves of representative soil samples (Figure 8).

Figure 8 - Graphical impact of plain, sand, cement, and Binary stabilisation. Note that with response to plain, sand cement, and Binary stabilisation, there is a shift in the compaction curves from right to left while the steepness of the curves increases. The leftward shift and increasing steepness imply decreasing OMC and increasing MDD/soil grading, respectively. These changes ultimately translated to increasing CBR.

5.1.4 Geotechnical impact assessment of soil stabilisation using Two-Sample T-Test assuming equal variance

From a t-test perspective, the fall of P-values below 0.001 implies that the stabilisation schemes had a strong impact on the CBR of the natural soils. Moreover, the sequential fall in P-values below α implies a significantly increasing impact of sand, cement, and Binary (sand + cement) stabilisation on the natural soils. The order of impact confirms that binary (sand + cement) stabilisation is the most technically viable scheme of them all. The Test means that the increasing impact is not by chance but by some obvious reasons. From the geotechnical point of view, the variation in impact is due to a gradual improvement in AASHTO soil grade and inter-particle bonding of the untreated soils under the influence of the various stabilisation schemes (with progress from sand through cement to binary stabilisation). This further validates the low, medium-high, and high CBRs recorded by the soils in response to these stabilisation schemes (Tables 3 to 6).

5.1.5 Performance evaluation of statistical models

The Random Forest served as the preliminary baseline model. It exhibited mediocre performance with an R^2 score of roughly 0.46 and a mean squared error (MSE) of about 46.5. Random Forest models exhibit resilience to overfitting and yield satisfactory findings with minimal modification, rendering them appropriate for exploratory research.

XGBoost (Extreme Gradient Boosting) was subsequently utilised on the identical dataset. It surpassed Random Forest in both accuracy and error minimisation, attaining a superior R^2 score (0.51) and reduced MSE (42.3). XGBoost is recognised for its capacity to model intricate, nonlinear connections and frequently produces superior outcomes in tabular data contexts.

EBM (Explainable Boosting Machine), implemented here, merits attention. EBM offers an interpretable model framework akin to Generalised Additive Models (GAMs), enhanced by the application of boosting. It would enable engineers and domain specialists to visualise the exact impact of each feature on the CBR prediction. Although marginally less precise than XGBoost, its transparency renders it suitable for critical decision-making.

6. Conclusions

The Geotechnical stabilisation and prediction modelling of superficial soils in Warri under the influence of sand, cement, and binary stabilisers has resulted in the following findings:

1. Granular soils of A-2 and A-3 signatures are the dominant natural characteristics of the deltaic laterites.
2. Untreated stabilisation of the deltaic laterites does not exceed subgrade quality.
3. Sand stabilisation greatly affects the AASHTO soil grade, but has a slight impact on the CBR performance of the deltaic soils
4. Subbase-quality stabilisation of deltaic soil is technically and economically viable at 7% weight of cement content.
5. Subbase-quality and base course-quality stabilisation are viable under cement and binary stabilisation, respectively.
6. Binary (sand+cement) stabilisation is the most viable solution to pavement deficiency from the geotechnical and t-test perspectives.
7. Extreme Gradient Boosting (XG boost) machine learning model is a more viable option than the Random Forest Model (RFM) and Extreme Boosting Machine (EBM) model in CBR prediction of treated superficial soils.

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OME					■	
GOA	■				■	

A - Study design/ Conceptualization **B** - Investigation/ Data acquisition
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E - Review/Editing **F** - Supervision/Project administration

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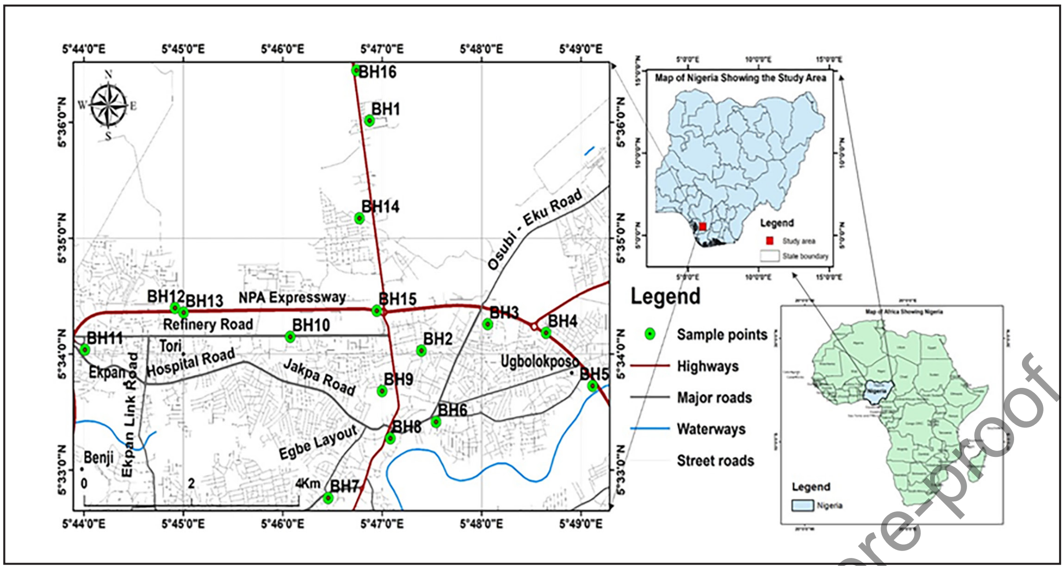

Figure 1 – Location and geographical map of Warri (study area).

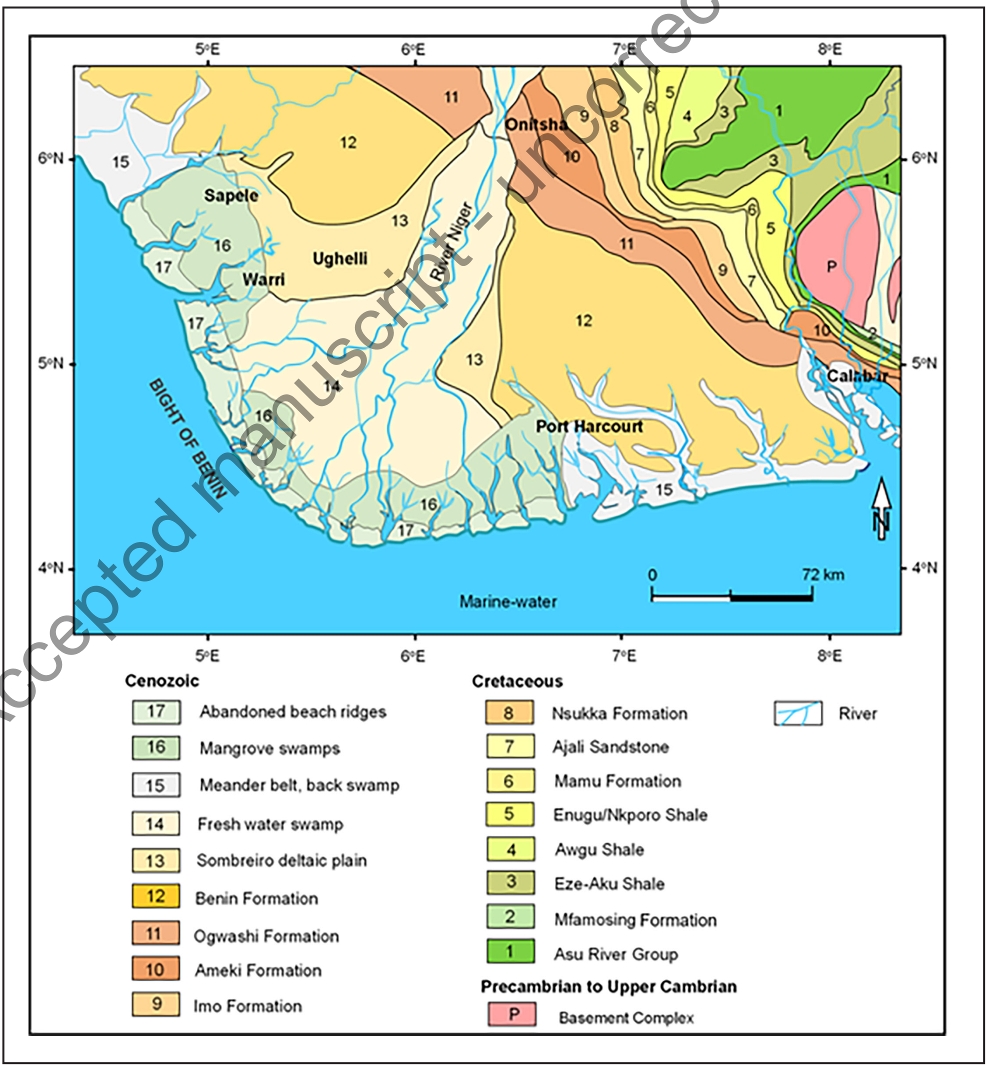

Figure 2 - Geologic map of superficial soils and outcropping formations of the onshore Niger Delta (Redrawn and modified from Reijers et al. 2011). The area labelled "16" in the top-left position of the map indicates that the study area (Warri) is resting on the Sombreiro-Warri Deltaic plain sands. The sparse network of rivers within the soil belt implies a mixture of well-drained and poorly drained conditions, which translates into dry land and wet land conditions.

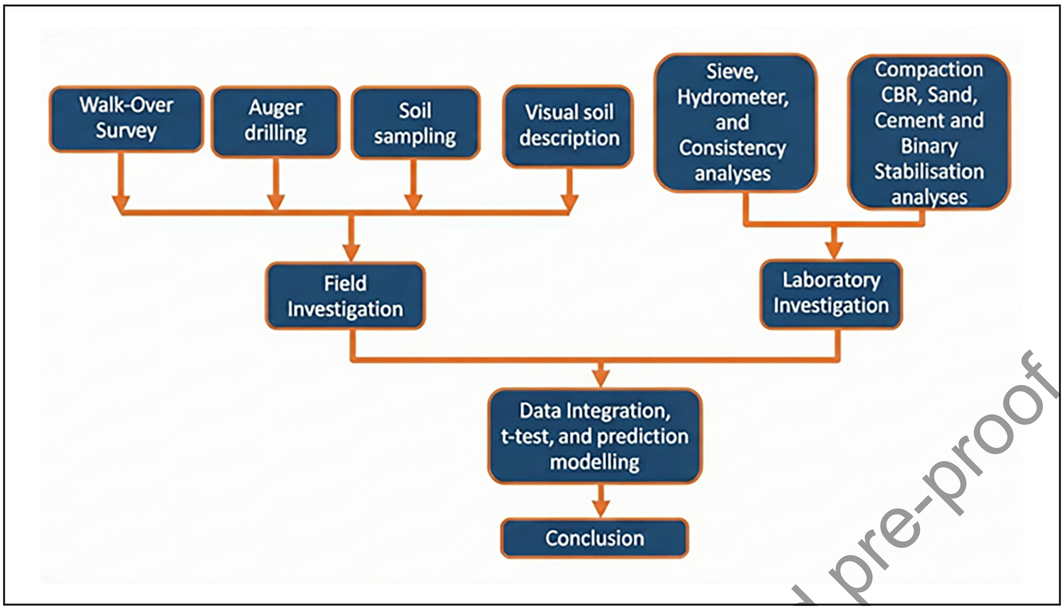

Figure 3 - Flow chart of the study methods.

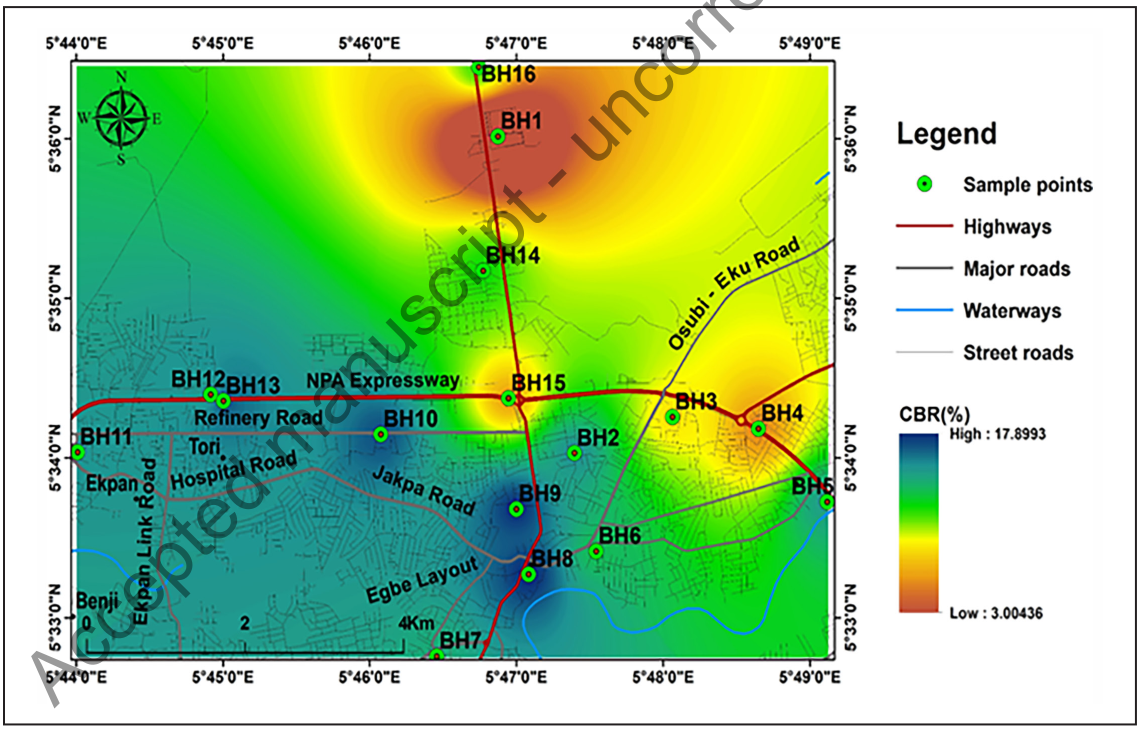

Figure 4 - Natural CBR distribution of superficial soils in Warri. Note that the natural CBR distribution of the entire city does not exceed 18% which confirms that the untreated CBR of the soils is generally low and limited to subgrade quality (FMW 1997, Avwenagha et al., 2024). Moreover, on the CBR scale of 3-18%, over 80% of the City is marked by relatively medium-high CBR (as indicated by the green–yellow zone covering BH2-12), while about 20% of the area is pockets of low-medium CBR (which is indicated by the yellow-green zone; BH1, BH13-16).

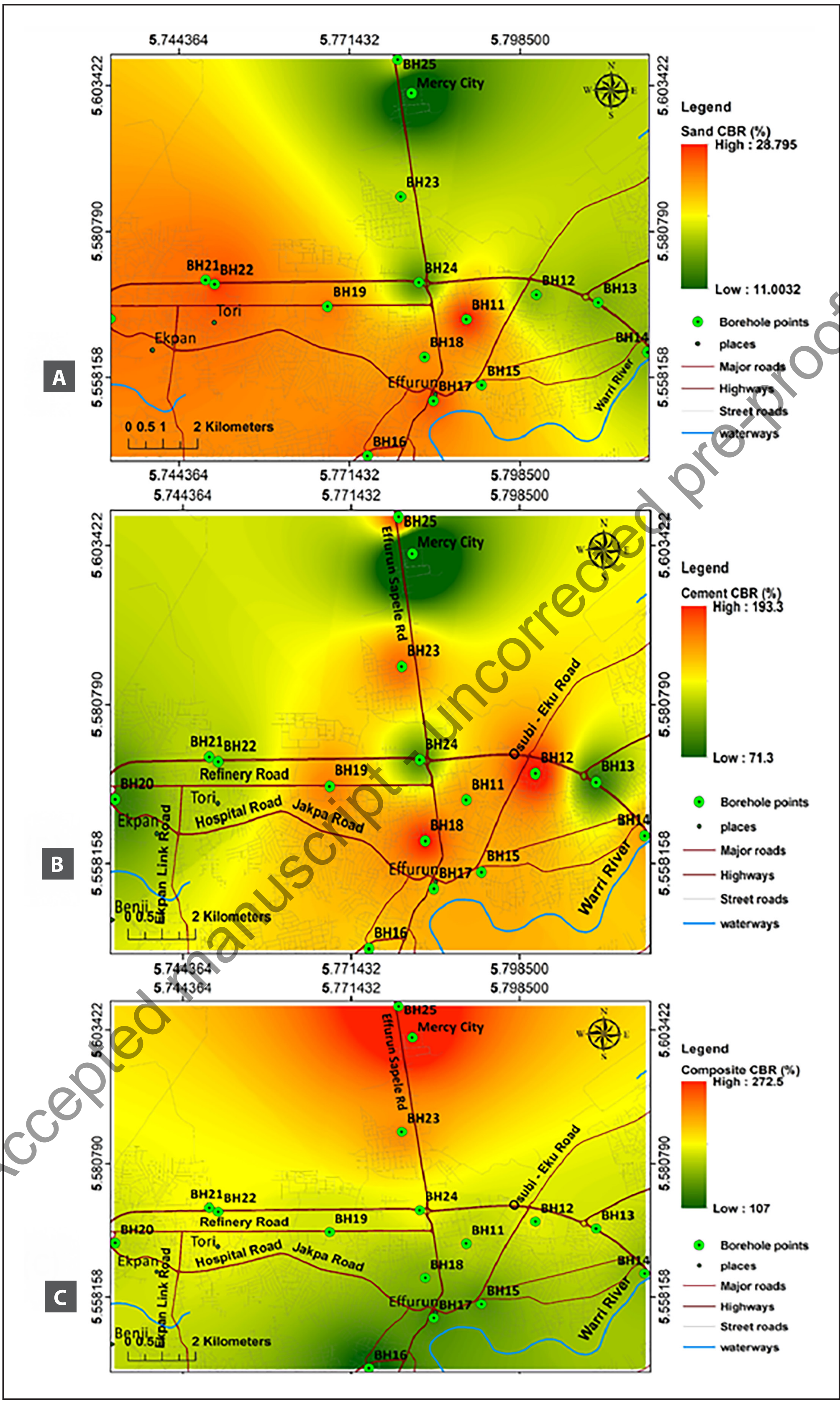

Figure 5 - CBR trend maps of superficial soils in Warri, under conditions of sand, cement, and binary stabilisation, respectively. The green, yellow, and orange colour codes are lower, middle, and upper CBR levels in the CBR scale of the respective stabilisation schemes. Under natural/plain conditions of stabilisation (Figure 3), the CBR of the soils ranged from 3-18%. (A) Sand stabilisation - the CBR ranged from 11-28% which indicates improved subgrade-quality. (B) The CBR scale improved to a range of 71.3-193.3%, which falls within the class of subbase to base course quality soils. (C) Composite /Binary stabilisation - the distribution ranged from 107-272.5%, which depicts soil improvement to a class of slightly subbase to dominantly base course quality soils (FMW,1997).

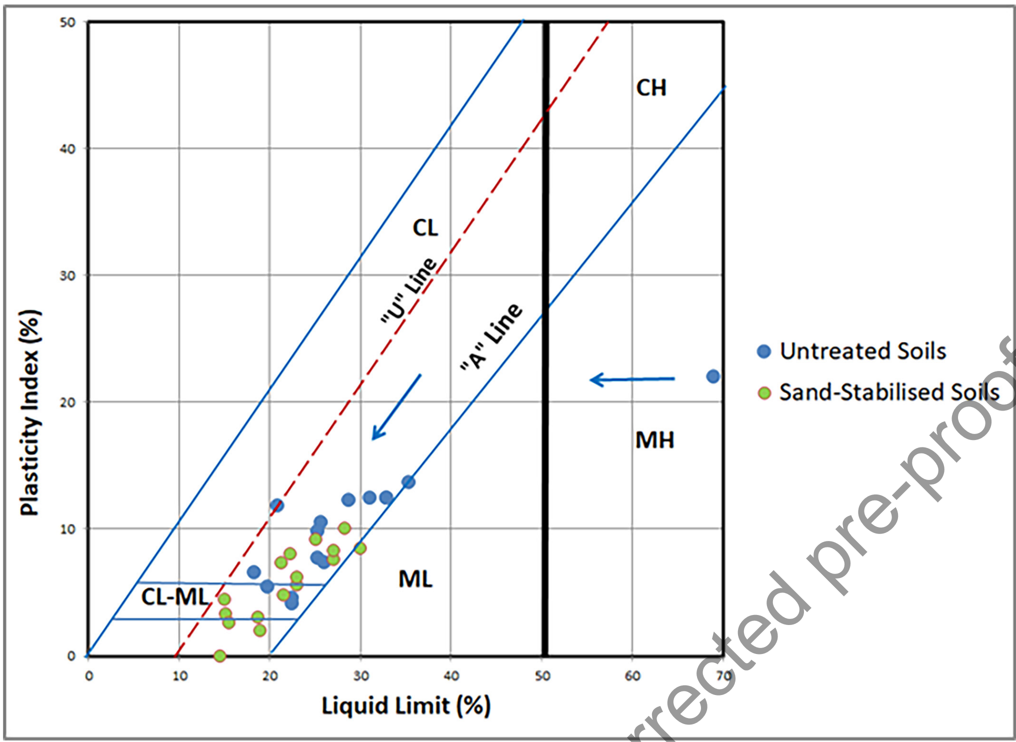

Figure 6 - Impact of sand Stabilisation on soil consistency limits. Note that the natural soils (blues point) initially were distributed across the medium-low (ML) to medium-high (MH) plasticity silt zones. Upon sand-stabilization, the sample points (as indicated by blue arrows) drifted towards the left, away from the ML-MH zone, and downwards along the low-plasticity soil zone (as indicated by the blue arrows). This implies that sand stabilization decreases the plasticity index and liquid limits of soils and consequently increases soil consistency (strength/stiffness).

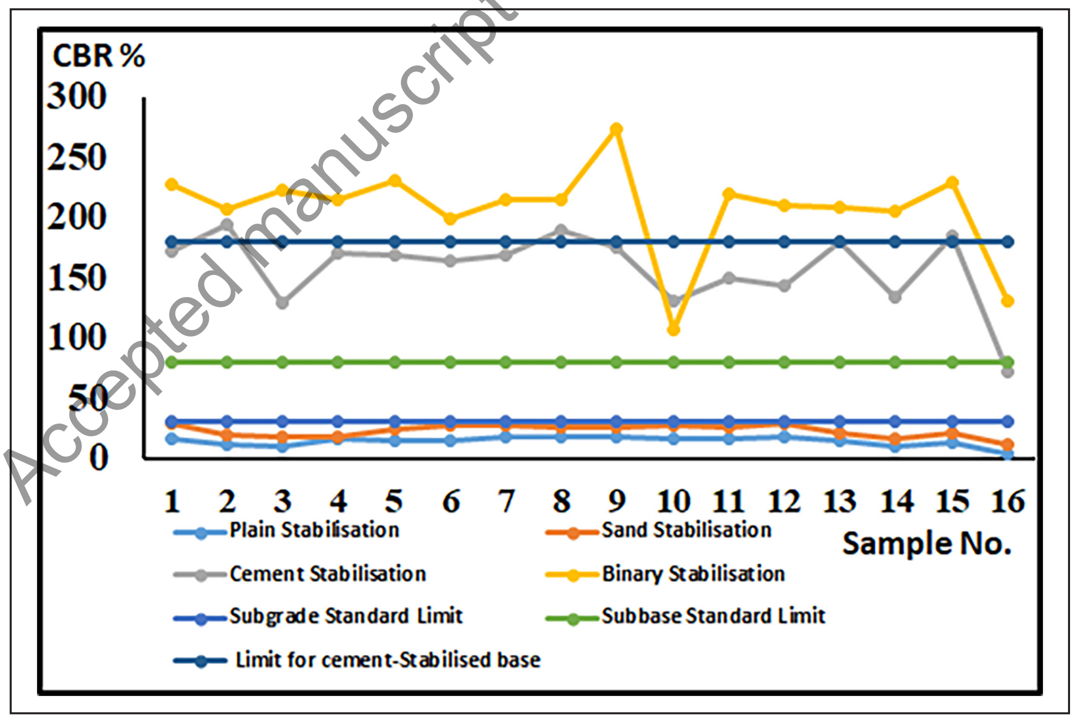

Figure 7 - CBR Response to Sand, cement, and Binary stabilisation. Note that the parallel lines (coloured with blue, green, and dark blue) are standard limits (FMW 1997) that define subgrade, subbase, and base-quality soils in road pavement designs. The wavy lines indicate the magnitude of CBR recorded at various sample locations (No.1-16) under plain/natural, sand, cement, and Binary-stabilised conditions. CBR responses under plain and sand stabilisation were within the subgrade quality limit (blue line at 30% CBR). The response partly exceeded the Cement-stabilised base limit (Dark blue line at 180% CBR) during cement stabilisation, while over 95% of the responses exceeded the base limit under conditions of Binary (Cement + sand) stabilisation. The increasing CBR trend shows that all the stabilisation schemes increase soil density, reduce void ratio, and Water Holding Capacity (WHC). While soil- cement matrix interaction increases inter-particle bonding during cement stabilisation, Binary (Cement + sand) stabilisation increases both inter-particle bonding and soil grade, which are the prevailing factors of Stabilisation. Hence, the Highest CBR response from Binary Stabilisation.

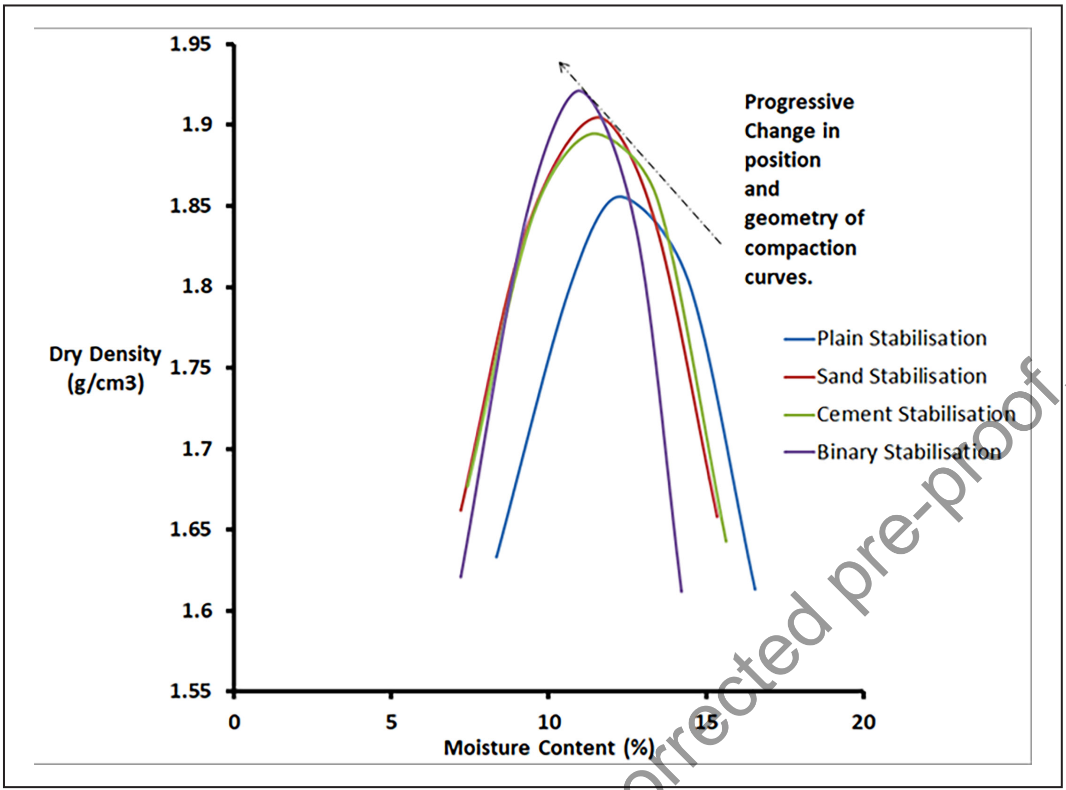

Figure 8 - Graphical impact of plain, sand, cement, and Binary stabilisation. Note that with response to plain, sand cement, and Binary stabilisation, there is a shift in the compaction curves from right to left while the steepness of the curves increases. The leftward shift and increasing steepness imply decreasing OMC and increasing MDD/soil grading, respectively. These changes ultimately translated to increasing CBR.

Table 1 - Coordinates of the sample locations in Warri.

S/N	Sample location	Coordinates
1	BH1(Mercy City)	N05^{0}36’00.81’’, E005^{0}46’52.5’’
2	BH2 (Effurun GRA)	N05^{0}34’01.8” E005^{0}47’23.8”
3	BH3 (PTI Junc.)	N05^{0}34’15.4” E005^{0}48’03.8”
4	BH4 (Ebrumede)	N05^{0}34’11.0” E005^{0}48’39.0
5	BH5 (Ugbomoro)	N05^{0}33’43.5” E005^{0}49’07.1”
6	BH6(Alegbo)	N05^{0}33’24.9” E005^{0}47’32.6”
7	BH7 (Sokoh Estate)	N05^{0}32’45.5” E005^{0}46’27.5”
8	BH8 (Airport Junction)	N05^{0}33’16.3” E00^{5}047’05.0”
9	BH9 (Okoloba Junction)	N05^{0}33’40.8” E005^{0}47’00.0”
10	BH10 (Mekavaal Hotel)	N05^{0}34’08.9” E005^{0}46’04.6”
11	BH11 (Ekpan Fly-Over)	N05^{0}34’02.2” E005^{0}44’ 00.6”
12	BH12 (Niger Cat)	N05^{0}34’23.8” E005^{0}44’ 55.0”
13	BH13 (Burrow Pit)	N05^{0}34’21.4” E005^{0}45’ 00.2”
14	BH14 (Army Estate)	N05^{0}35’10.3” E005^{0}46’ 46.4”
15	BH15 (ShopRite)	N05^{0}34’22.4” E005^{0}46’ 56.8”
16	BH16 (Kola Garden Hotel)	N05^{0}36’26.9” E005^{0}46’ 44.6”

Table 2 - Modified Cement Content Requirements of AASHTO. Soil Groups.

S/N	A.A.S.H.T.O Soil Group	Range of Cement content (wt%)
1	A-1-a	4-6
2	A-1-b	4-7
3	A-2	5-8
4	A-3	6-9
5	A-4	7-11
6	A-5	8-12
7	A-6	9-13
8	A-7	10-14

Source: BS6229 (1990)

Table 3 - Compaction and geotechnical properties of the superficial soils in their natural state

Borehole Number	Depth (m)	% Sand	% Fine	Liquid Limit	Plastic Limit	Plasticity Index	USCS	AASHTO	OMC %	MDD g/cm³	CBR %
BH1	0-3	3.50	96.50	69.00	47.00	22.00	MH	A7-5	23	1.395	3.00
BH2	0-4	78.00	22.00	18.40	11.90	6.50	CL	A2-4	10.43	1.901	16.20
BH3	0-4	65.50	34.50	31.10	18.70	12.40	CL	A2-6	9.72	1.944	11.90
BH4	0-4	60.40	39.60	33.00	20.60	12.40	CL	A-6	9.80	1.925	10.10
BH5	0-4	78.20	20.80	25.40	17.70	7.70	CL	A2-4	11.82	1.901	15.90
BH6	0-4	72.20	27.80	25.70	15.20	10.50	CL	A2-4	11.78	1.892	15.00
BH7	0-4	74.30	25.70	22.50	18.40	4.10	CL	A2-4	9.10	1.927	15.50
BH8	0-4	79.20	20.80	25.40	15.60	9.80	CL	A2-4	9.42	1.886	17.90
BH9	0-4	82.30	17.70	19.80	14.40	5.40	CL	A2-4	9.87	1.925	17.80
BH10	0-4	75.20	24.80	26.10	18.80	7.30	CL	A2-4	8.41	1.904	17.30
BH11	0-4	87.20	12.80	14.50	NP	NP	CL	A-3	12.64	1.906	16.20
BH12	0-4	76.80	23.20	22.50	18.00	4.50	CL	A2-4	12.20	1.856	15.80
BH13	0-4	81.50	18.50	21.00	18.50	11.80	CL	A2-4	12.13	1.881	17.30
BH14	0-4	70.20	29.80	33.00	20.60	12.40	CL	A2-6	9.61	1.944	14.10
BH15	0-4	60.10	39.90	35.40	21.40	13.60	CL	A-6	12.30	1.826	10.60
BH16	0-4	67.50	32.50	28.80	16.60	12.20	CL	A2-6	10.98	1.902	13.70

Table 4 - Results of sand stabilisation of the superficial soils

Borehole Number	Depth (m)	modifying sand (wt%)	% Fine	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	OMC (%)	MDD (g/cm³)	USCS	AASHTO	CBR (%)
BH1	0-3	30.00	35.50	30.00	21.50	8.50	14.88	1.810	CL	A2-6	11.00
BH2	0-4	30.00	18.00	15.10	10.70	4.40	9.46	1.989	CL	A2-4	28.80
BH3	0-4	30.00	27.90	27.10	19.50	7.60	11.51	1.905	CL	A2-4	19.10
BH4	0-4	30.00	33.10	27.10	18.80	8.30	11.80	1.889	CL	A2-4	18.70
BH5	0-4	30.00	17.10	23.00	17.40	5.60	11.35	1.889	CL	A2-4	18.70
BH6	0-4	30.00	22.20	21.30	14.00	7.30	11.95	1.948	CL	A2-4	24.10
BH7	0-4	30.00	20.20	19.00	17.00	2.00	12.32	1.961	CL	A2-4	26.70
BH8	0-4	30.00	15.10	23.00	16.80	6.20	8.52	1.962	CL	A2-4	27.50
BH9	0-4	30.00	12.50	15.20	11.90	3.30	9.20	1.979	CL	A2-4	25.70
BH10	0-4	30.00	20.60	21.50	16.70	4.80	9.07	1.988	CL	A2-4	26.20
BH11	0-4	30.00	11.60	14.50	-	-	10.34	1.966	CL	A-3	26.70
BH12	0-4	30.00	16.20	15.50	12.90	2.60	10.36	1.961	CL	A2-4	26.20
BH13	0-4	30.00	14.20	18.70	15.70	3.00	9.53	1.990	CL	A2-4	28.60
BH14	0-4	30.00	23.20	28.30	18.30	10.00	9.20	1.972	CL	A2-4	20.40
BH15	0-4	30.00	30.80	25.10	15.90	9.20	11.91	1.921	CL	A2-4	17.00
BH16	0-4	30.00	25.30	22.30	14.30	8.00	10.60	1.952	CL	A2-6	20.40

Table 5 - Results of cement stabilization of the superficial soils

Borehole Number	Depth (m)	Cement Content (wt %)	% Fine	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	OMC (%)	MDD (g/cm³)	USCS	AASHTO	CBR (%)
BH1	0-3	11.00	35.50	69.00	47.00	22.00	12.72	1.622	MH	A7-5	71.3
BH2	0-4	7.00	22.00	18.40	11.90	6.50	9.30	1.979	CL	A2-4	171.7
BH3	0-4	7.00	34.50	31.10	18.70	12.40	10.99	1.921	CL	A2-6	**193.3**
BH4	0-4	10.00	39.60	33.00	20.60	12.40	11.74	1.882	CL	A-6	128.5
BH5	0-4	7.00	20.80	25.40	17.70	7.70	11.25	1.935	CL	A2-4	170.0
BH6	0-4	7.00	27.80	25.70	15.20	10.50	11.84	1.920	CL	A2-4	168.7
BH7	0-4	7.00	25.70	22.50	18.40	4.10	11.21	1.941	CL	A2-4	163.4
BH8	0-4	7.00	20.80	25.40	15.60	9.80	8.46	1.939	CL	A2-4	168.0
BH9	0-4	7.00	17.70	19.80	14.40	5.40	9.12	1.964	CL	A2-4	**189.2**
BH10	0-4	7.00	24.80	26.10	18.80	7.30	8.95	1.965	CL	A2-4	175.6
BH11	0-4	7.00	12.80	14.50	-	-	10.29	1.964	CL	A-3	130.0
BH12	0-4	7.00	23.20	22.50	18.00	4.50	10.22	1.941	CL	A2-4	150.3
BH13	0-4	7.00	18.50	21.00	11.80	9.20	9.48	1.983	CL	A2-4	143.3
BH14	0-4	7.00	29.80	33.00	20.60	12.40	9.12	1.917	CL	A2-6	178.9
BH15	0-4	10.00	39.90	35.00	21.40	13.60	11.82	1.901	CL	A-6	133.6
BH16	0-4	7.00	32.50	28.80	16.60	12.20	10.55	1.934	CL	A2-6	**185.0**

Table 6 - Results of binary (sand+cement) stabilisation of the superficial soils.

Borehole Number	Depth (m)	Modifying Sand (%)	Cement (Wt %)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	OMC (%)	MDD (g/cm³)	USCS	AASHTO	CBR (%)
BH1	0-4	55	7	30.00	21.50	8.50	14.67	1.771	CL	A2-6	130.7
BH 2	0-4	30	7	15.10	10.70	4.40	9.52	1.997	CL	A2-4	227.00
BH 3	0-4	30	7	27.10	19.50	7.60	10.99	1.921	CL	A2-6	207.40
BH 4	0-4	30	10	27.10	18.80	8.30	11.62	1.894	CL	A-6	221.70
BH 5	0-4	30	7	23.00	17.40	5.60	11.43	1.943	CL	A2-4	214.60
BH 6	0-4	30	7	21.30	14.00	7.30	12.12	1.953	CL	A2-4	229.90
BH 7	0-4	30	7	19.00	17.00	2.00	11.61	1.975	CL	A2-4	198.80
BH8	0-4	30	7	23.00	16.80	6.20	8.20	1.970	CL	A2-4	215.20
BH9	0-4	30	7	15.20	11.90	3.30	8.32	1.996	CL	A2-4	215.10
BH10	0-4	30	7	21.50	16.70	4.80	9.12	1.995	CL	A2-4	272.50
BH11	0-4	30	7	14.50	-	-	9.48	1.964	CL	A-3	**107.00**
BH12	0-4	30	7	15.50	12.90	2.60	10.45	1.968	CL	A2-4	219.20
BH13	0-4	30	7	18.70	15.70	3.00	9.02	1.996	CL	A2-4	210.10
BH14	0-4	30	7	28.30	18.30	10.00	9.01	1.979	CL	A2-6	207.60
BH15	0-4	30	10	25.10	15.90	9.20	11.21	1.926	CL	A-6	204.70
BH16	0-4	30	7	22.30	14.30	8.00	10.18	1.961	CL	A2-6	229.50

Table 7 - Geotechnical impact Assessment of sand, cement, and binary stabilisation using two-sample t-test assuming equal/unequal variance

S/N	CBR of Natural soils (%)	Sand stabilization		Cement Stabilization		Binary Stabilization	
		CBR (%)	t- Test Results (equal variance)	CBR (%)	t- Test Results (unequal variance)	CBR (%)	t- Test Results Unequal Variance)
1	16.20	28.80	Variance (V_1) 15.59686 Variance (V_2) 24.9581 t-stat: -5.06401 **P(T<=t) (one tail: 1.16E-05** α:0.05 Df = 28 tcritical (one tail): 1.701131 **P(T<=t) (two tail: 2.56E-05** tcritical (two tail): 2.048407	171.7	Variance (V_1) 15.59686 Variance (V_3) 1006.822 t-stat: -17.2562 **P(T<=t) (one tail: 3.93E-11** α:0.05 Df = 14 tcritical (one tail): 1.76131 **P(T<=t) (two tail: 7.87E-11** tcritical (two tail): 2.144787	130.7	Variance (V1) 15.59686 Variance (V4) 1141.507 t-stat: -22.53 **P(T<=t) (one tail: 1.06E-12** α:0.05 Df = 14 tcritical (one tail): 1.76131 **P(T<=t) (two tail: 2.13E-12** tcritical (two tail): 2.144787
2	11.90	19.10		**193.3**		227.00	
3	10.10	18.70		128.5		207.40	
4	15.90	18.70		170.0		221.70	
5	15.00	24.10		168.7		214.60	
6	15.50	26.70		163.4		229.90	
7	17.90	27.50		168.0		198.80	
8	17.80	25.70		**189.2**		215.20	
9	17.30	26.20		175.6		215.10	
10	16.20	26.70		130.0		272.50	
11	15.80	26.20		150.3		**107.00**	
12	17.30	28.60		143.3		219.20	
13	14.10	20.40		178.9		210.10	
14	10.60	17.00		133.6		207.60	
15	13.70	20.40		**185.0**		204.70	
16	3.00	11.00		71.30		229.50	

wo-sample t-test assuming equal/unequal variance

Table 8 – Model comparison table

Criteria	Random Forest	XGBoost	EBM (Explainable Boosting Machine) Model
R^2 Score	0.46	.51	0.44
Mean Squared Error	46.5	42.3	48.0
Interpretability	Moderate	Low	High
Speed (Training Time)	Fast	Moderate-Fast	Moderate-Slow
Hyperparameter Tuning	Minimal	Required	Minimal
Best Use Case	General robustness	High accuracy tasks	Stakeholder transparency
Feature Insights	Ranked importance	Ranked importance	Visual additive feature plots