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Stabilization Of Expansive Soils Derived from Enugu Shale in Enugu Area, Southeastern Nigeria Using Lime, Cement and Coal Fly Ash Admixtures

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Abstract:-Stabilization of expansive soils from Enugu Shale, in Enugu Area Southeastern Nigeria with lime, cement and coal fly ash admixtures were investigated with the aim of improving the engineering behavior of expansive soils. Samples of expansive soils were treated with lime, cement and coal fly ash admixtures. Lime and cement are chemical additives while coal fly ash is a pozzolan .Engineering performance of treated soils were evaluated using Atterberg limits, California bearing ratio and Maximum dry Density .The Atterberg limits of untreated soil were 42.0%, 22.55% and 4.3% for Liquid limit, Plasticity index and Linear shrinkage . The California bearing ratio of untreated soil was 2.3% and 1.1% for usoaked and soaked expansive soils. The Maximum Dry Density of untreated soil was 1.32 Mg/m^3 .According to the Casagrande's plasticity chart,the soil plots as inorganic clay of medium plasticity which necessitated the need for chemical treatment.The stabilization result showed reduction percentages of 29.76% % (42.0 to 29.5), 56.67% (42.0 to 18.20) for cement,cement-coal fly ash mixes on liquid limit. Also a maximum reduction of 21.43% (42.0 to 33.0), 30.95% (42.0 to 31.2 %) on liquid limit for lime lime-coal fly ash mixes respectively. A higher reduction percentage on plasticity index for cement,cement-coal fly ash mixes and lime and lime-coal fly ash were established as 90.67 % (22.5 to 2.10), 96 % (22.5.5 to 0.90) and 54.67%(22.5 to 10.2),71.56%(22.5 to 6.4) . A remarkable increase in California bearing ratio value of approximately 400 to 500% ,300 to 700% and 300 to 700, 350 to 900% increase in strength gain for lime, lime-coal fly ash and cement, cement-coal fly ash mixes respectively for unsoaked soil samples. Also a strength gain of 100 to 180%, 100 to 200% and 100 to 200%, 100 to 300% was achieved for Lime,Lime-Coal Fly ash and cement, cement coal fly ash samples respectively for soaked samples..The Maximum Dry Density showed the highest percentage increase of 543.95%(1.32 to 8.50 Mg/m^3) and 875.76%(1.32 to 12.88 Mg/m^3) for cement and cement-coal fly ash mixes, and an increase of 415.15%(1.32 to 6.8 Mg/m^3) and 642.42%(1.32-9.8 Mg/m^3). Treatment of the soil resulted in increased strength and reduced swelling potential,however, portland cement provided highly effective clay stabilization, usually with the added benefit of higher strength gain when combined with CFA.

Keywords:- *Expansive soil, Cement,Lime,Coal Fly ash,Stabilization CBR,Atterberg limits,Pozzolan.*

I. INTRODUCTION

Soil stabilization may be defined as the use of additives or admixtures to improve the geotechnical properties and performance of problem soils . Stabilization incorporates the use of additives such as lime or cement as a binder where necessary to reduce swelling and increase strength of soils or may involve an admixture such as coal fly ash, mainly with the aim of increasing bulk size of construction material as well as reducing waste.

Expansive soils in Engineering construction are most times the sub-grade material above which the foundation or sub-base layers are placed. Expansive soils experience significant volume change associated with changes in water contents. According to Jones and Jefferson, (2012), these volume changes can be either in the form of swell or in the form of shrinkage and this is why they are sometimes known as swell/shrink soils. Expansive soils contain expansive clay minerals, such as smectite, that absorb water, the more of this clay a soil contains the higher its swell potential and the more water it can absorb. The process of shrinkage causes cracks, which on re-wetting, do not close-up perfectly and hence cause the soil to bulk-out slightly, and also allow enhanced access to water for the swelling process. Generally, expansive soils are not suitable materials for foundation and other engineering construction, there is therefore need to initiate adequate treatment before usage to prevent structural damage, loss of lives and properties.

It is common practice to use chemical additives to stabilize expansive soils before they are built upon or used for other construction purposes. One of the objectives of using a stabilizer is the ability of a stabilizer to maintain desired properties over the life of a pavement. A report by Broderick and Daniel, (1990) suggested that lime and cement stabilized soils are less vulnerable to attack by organic chemicals in comparison to untreated soils, also a far more dependable result emerges in combination with coal fly ash. Through the stabilization process, the plasticity of soil is reduced, it becomes more workable, and its compressive strength and load bearing properties are improved (Amadi and Okeiyi, 2017). The use of lime, cement, lime-coal fly ash and cement-Coal fly ash have been researched by (Amadi and Okeiyi, 2017; Nnabuihe et al., 2021, Amadi et al., 2020, Okeke et al., 2015).

Lime (CaO) stabilization is a common method of chemical stabilization in which soil is mixed with lime to produce soil-lime. Researches have shown that lime reduces the swelling potential expressed as liquid limit and plasticity index, and increases its optimum water content and strength (Pei et al., 2015) which is required to achieve Maximum Dry Density with adequate compactive effort. Lime stabilization improves the workability and compactability of subgrade soils. These improvements manifest better in moderately to highly plastic clays.

In cement stabilization, the soil is mixed with cement to produce soil-cement. Soil–cement has been used as a base material in many projects, and provides a cheaper alternative and availability when compared with other additives. Cement stabilization improves the engineering properties of the untreated soil.

Fly ash is an additive and as well as an admixture that is used in soil stabilization. It is one of the waste products generated from burning of coal. Two major groups, Class C and Class F fly ash are produced. Burning lignite and sub bituminous coal produces Class C fly ash, while burning of bituminous and anthracite coal produces Class F fly ash. Both classes of fly ash are pozzolanic materials. Pozzolanic materials are siliceous or a siliceous and aluminous material which lacks self-cementing properties, both with the addition of a cementing material will bind to soil and other earth materials. Class F fly ash often requires cementing material , either lime or cement, to form pozzolanic stabilized mixtures (PSMs) since it is not a self-cementing material (Firoozi et al.,2015;Phani and Sharma,2004), also published researches have been done on stabilization of expansive soils using Coal fly ash as a viable alternate to conventional pozzolans (Diaz-Loya et al.,2019; Rajabipour et al.,2020; Ferraro et al.,2016).

The use of coal fly ash as an admixture in construction is one of the ways to reduce waste by recycling. Yang et al., (2020) noted that eco-friendly treatment of low-calcium coal fly ash for high pozzolanic reactivity is a step towards waste utilization in sustainable building material. Burning of coal produces large quantity of waste which is often too expensive to manage with its attendant health effects. Solidification of coal fly ash with an additive is one of the ways to maximize its use in construction, conserve aggregates, reduce risk to health and also save cost of disposal.

This present study explores the benefits of application of coal fly ash as a soil stabilizing agent for expansive soils in the study area and to disregard the need for either removing, excavating or replacing problem clay sub-grade soils to reduce stresses that could lead to structural damage.

II. LOCATION AND GEOLOGY OF THE STUDY AREA

The study area comprises two localities, namely,Enugu shale in Enugu area,and Oji River both in Enugu State. Both of which are within the Anambra Sedimentary basin. They lie within latitudes 05^0 34^1- 05^{0-} 51^1N and Longitudes 007^0 20^1-$007^0 28^1$ E and cover an estimated area of about 80km^2 $^($Fig.1).The study areas are accessible through Agbani road after NNPC station and Oji-River Local Government Area.

The study area is part of the Anambra basin and is one of the major sedimentary basins in Nigeria.The Anambra basin is located in the southeastern part of Nigeria and is bounded to the North by Bida basin and Northern Nigeria massif, to the east by Benue trough, to the west by West African massif, and to the south by Niger delta. The basin is a structural(synclinal) depression and one of the intracratonic basins in Nigeria whose origin is related to the separation of Africa from South America and the opening of South Atlantic Ocean (Ofoegbu,1982).

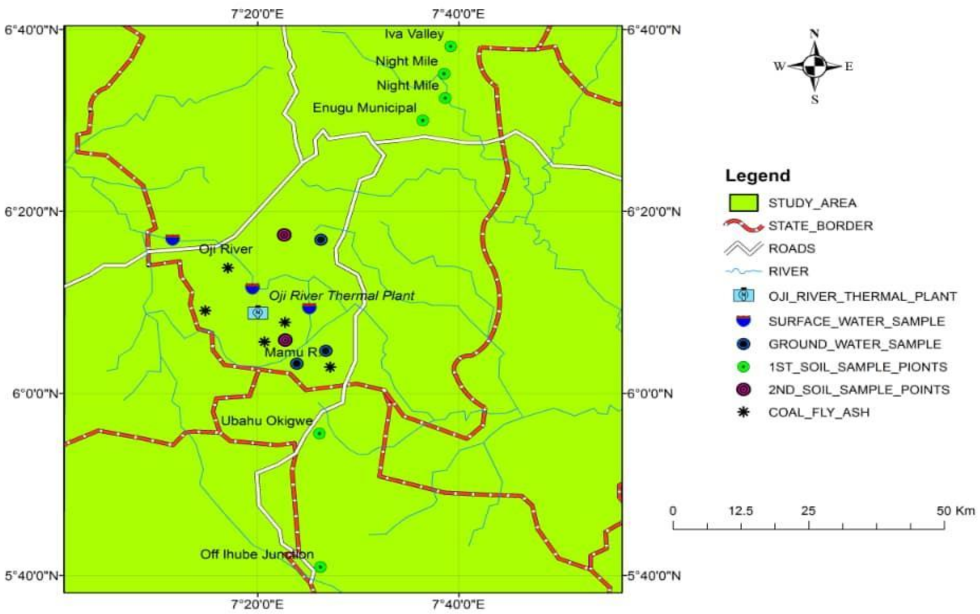

Fig.1. Location map of the study area showing sampling points

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It consists of a nearly triangular shaped embayment covering about 40,000sq.km and having a total sedimentary thickness of about 9km. The sedimentary phase was initiated by the Santonian folding and uplift of the Abakiliki anticlinorium along the NE-SW axis and the consequent dislocation of the depocenter into the Anambra basin on the Northwest and the Afikpo syncline on the Southeast (Short and Stauble, 1967; Murat, 1972). The resulting succession comprises the Nkporo group, (the Nkporo shale and the Enugu Shale members of this group), Mamu and Nsukka formation are all characterized by the presence abundant clay minerals which include Smectite (montmorillonite) which is responsible for the cyclic behavior in the soil samples, Ajali Sandstone overlies the Nsukka Formation which overlies the Imo Formation which, Imo For mation overlies the Ameki Formation which also overlies Ogwashi-Asaba Formation, Table 1(Murat, 1972; Hoque, 1977; Agumanu,1986; Umeji,2006). The Geological map of the study area and the litho-stratigraphic sequence of sedimentary deposits in the Anambra basin, Southeastern Nigeria are shown in Figures 2 and table 1.

These Formations range in age from the Late Cretaceous to Tertiary and was deposited in alternating cycles of regressive and transgressive phases in a continental (swamp) environment which were essential for the formation of coal.

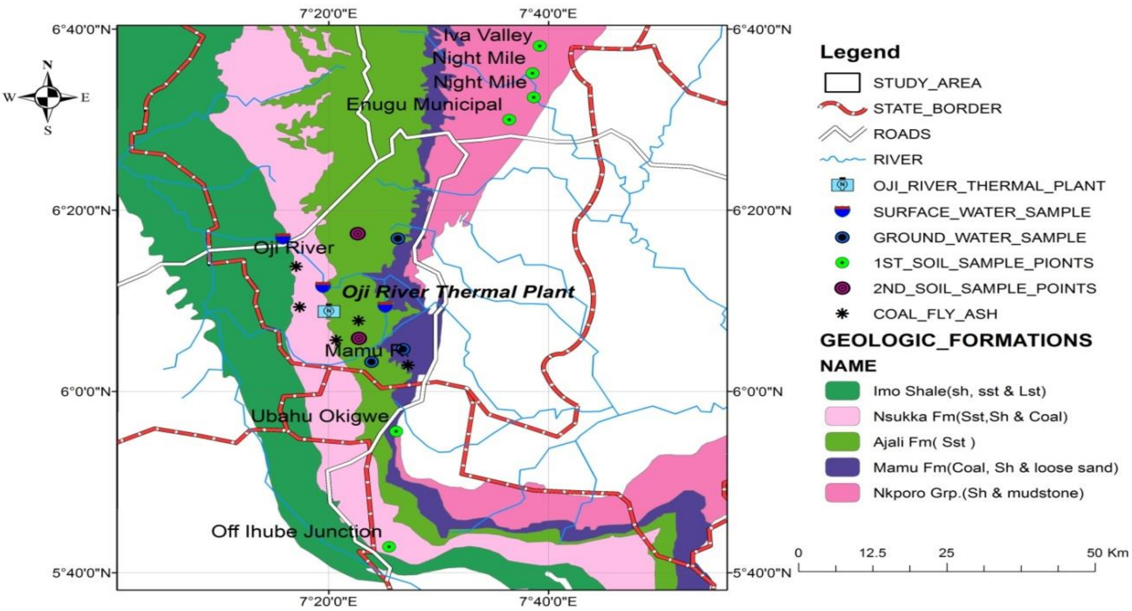

Fig.2. Geological map of the study area (Part of Anambra basin) (adapted from Babatunde, 2010).

Age	Basin	Stratigraphic Units						
Oligocene-Recent	Niger Delta	Ogwashi-Asaba Fm						
Eocene		Ameki/Nanka Fm/Nsugbe Sandstone (Ameki Group)						
Thanetian		Imo Formation						
Danian	Anambra Basin	Nsukka Formation						
Maastrichtian		Ajali Formation						
		Mamu Formation						
Campanian		Nkporo Fm	Nkporo Shale	Enugu Fm	Owelli Ss	Afikpo Ss	Otobi Ss	Lafia Ss
	Southern Benue Trough	Agwu Formation						

Table 1.. Generalized Regional Stratigraphy of the Anambra basin, after Nwajide, 2013)

III. MATERIALS AND METHOD

A. *Test Materials and Sampling*

➢ *Soil*

Two representative soil samples were collected with a hand-held auger from two different burrow pits within the study area in Enugu Municipal, close to the NNPC fuel station. The sampling locations are clay deposits from Enugu shale. The sample collection was done in accordance with standards specified in (ASTM D1452-07a, 2007).Samples were preserved in polyethylene bags to preserve their moisture, sealed and labeled for identification, and were taken to Imo State Ministry of Works for laboratory analysis.

➢ *Lime.*

Lime is produced through the calcination of limestone at a high temperature. Quicklime is manufactured by chemically transforming calcium carbonate (limestone–$CaCO3$) into calcium oxide(CaO). Quicklime(CaO) was used in this study because of its reputation for reducing atterberg limits (Amadi and Okeiyi, 2017) and increase in soil strength .

➢ *Cement*

Cement(Portland cement) additive was also used in the present study. Cement has been used as a base material and has been adopted as an improved stabilization material in many projects.The process of cementation and the results of soil–cement and soil-lime stabilization are similar, they are used in quantities too small to provide high-strength cementing action. They reduce the plasticity of clay soils.

➢ *Coal Fly Ash*

Coal Fly Ash is a waste generated from burning of coal for different purposes. The coal fly ash used in the investigation was generated from burning coal in a power plant to generate electricity at Oji-River Local Government Area of Enugu state. The waste was collected from a dumpsite within the vicinity of the plant, it was bagged with polyethylene and identified for laboratory analysis. Fractions of the ash passing BS sieve No. 200 (0.075mm) was used in the experiment.

B. *Methods/Laboratory Tests*

The natural soil samples were subjected to some geotechnical tests including Atterberg limits (liquid limit,plasticity index) linear shrinkage, compaction (dry density and moisture content relations) and California Bearing Ratio. Varying percentages of 2,4,6,8,10,12,and 14% and 4,8,12,16,20,24,28 % of lime, and lime-coal fly ash by dry weight of clay soil were used to improve soil. Controls were made at 0% lime and 0% cement corresponding to CBR of natural soil samples before stabilization.Both soil-lime,soil-lime-coal fly ash ,soil-cement and soil-cement-cooal fly ash mixtures were compacted using West African Standard method (1997) with a curing period of 7 days

IV. RESULTS AND DISCUSSIONS.

A. *Atterberg limits*

The results of the liquid limit (wL), plastic limit (wp) and plasticity index (Ip) and linear shrinkage of soils in the study area are summarized in Table 2.. The liquid limit and the plasticity index of the soil were 42.0% and 22.5%. These expansive soils have high liquid limits and plasticity indices values which exceed standards set by the Federal Ministry of Works and Housing (FMWH,1997) for Sub-base materials used in Roads and Bridges construction. A good sub-base material must have a liquid limit and plasticity index of <35% and <12 % respectively. The clay soil in the study area is unsuitable for pavement and foundation works.This high liquid limit values is an indication that the soil has high water holding capacities (Asuri & Keshavamurthy, 2017), as well as poor load bearing capacities which could be responsible for failures on engineering structures through differential heave, thus requiring modification.

The plasticity index shows that the amount of clay mineral is medium to high in the soil sample which could subject the soil to compressibility. The greater the Plasticity index, the greater the compressibility. This may manifest as decrease in soil volume when supporting a load, accentuated by expulsion of moisture and water.

Hazelton and Murphy,2016 acknowledged that liquid limit is directly proportional to the compressibility of a soil and hence its ability to support a load and its trafficability when wet. It can also indicate shrink-swell potential and surface movements. Hicks, 2007 stated that Surface movement can cause expensive damage to inappropriately designed buildings, roads and underground surfaces (Budhu,2015).

The impacts on the environment by problem clay soils have been studied by (Charlie, Osman, & Ali, 1984)and possible ways of averting them studied by many researchers (Al-Mukhtar, Lasledj, and Alcover, 2010; Al-Rawas, Hago, & Al-Sarmi, 2005).

Many properties of clays such as their dry strength, compressibility and their consistency near the plastic limit can be related with the Atterberg limits by means of the Casagrande plasticity chart as shown in Fig. 3. The soils plot as CM(Inorganic Clays of medium plasticity). This further explains the level of plasticity of the soil.The result indicate that over 70% of the soil plot above the A-line, which portends clays of medium plasticity(Tinjum et al.,1997). The result also indicate the presence of little organic matter, any soil that contains a significant amount of organic material recently derived from plant remains (Kazemian, 2017) are not suitable for engineering structures because of its high compressibility and low shear strength. They cause some engineering problems, such as inadequate strength after reinforcement or even failure of composite foundation because of its special engineering properties (Hu et al.,2018).Most natural sedimentary clay contains organic matter, and even a small amount of organic matter will have a great impact on the physical and mechanical properties of

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clay. (Gui et al.,2021) researched on the influence of organic matter on Engineering properties of clay, their findings revealed specific gravity,void ratio and moisture content increase with increase in organic in soils.

Locations	Liquid limit %	Plastic limit %	Plasticity Index%	Shrinkage limit
Enugu Shale	42.0	19.45	22.55	4.3%

Table .2. Results of Atterberg limits from sample location within the study area

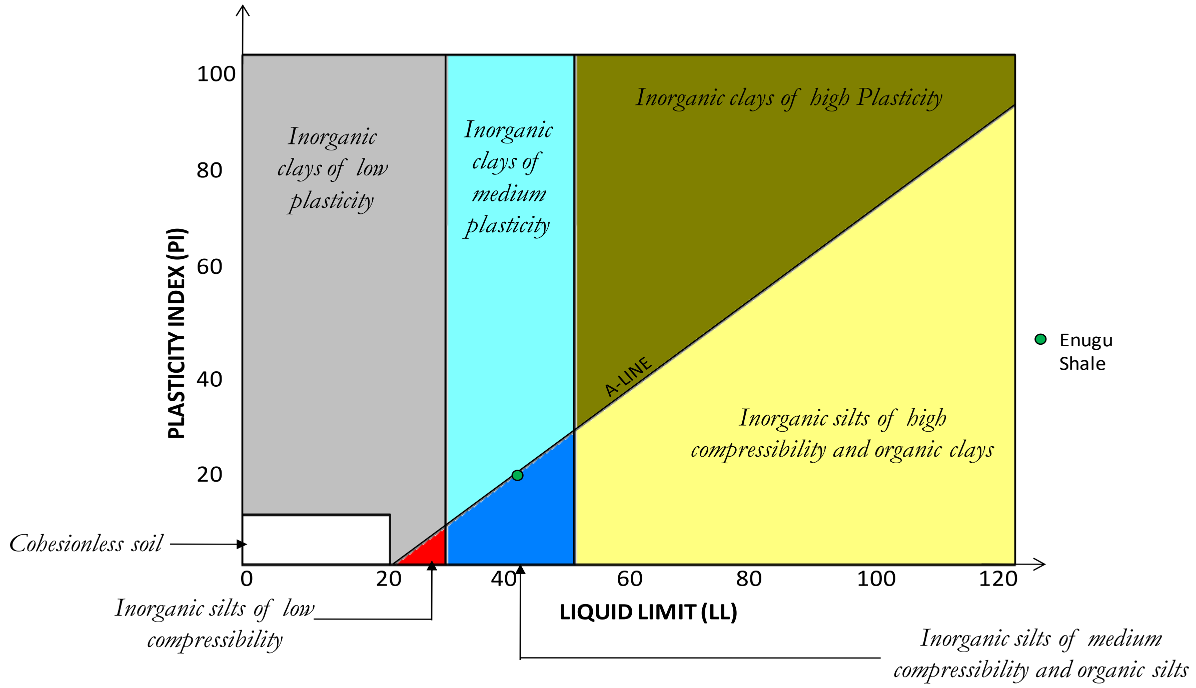

Fig 3. Plasticity chart of the Enugu shale, Anambra Basin (Unified Soil Classification System, 1988, as cited in Park and Santamarina, 2017)

- *Atterberg Limits of Cement,cement-coal fly ash treated soil from Enugu Shale*

Soil improvement techniques are required to overcome problems in soils with shrink and swell behavior and to improve the soil's ability to withstand structures imposed on it. Atterberg limit tests show information about the reaction of soil to water (Soil consistency). Cement contents of 2,2.5,3,3.5,4,4.5and 5% and Cement- Coal fly ash contents of 5,7.5,10,12.5,15,17.5, and 20 % by dry weight of clay soil were used to improve soil.

Results of the extent of reduction in plasticity index and Liquid limits when modified with various percentages of cement, cement-CFA, are shown on Tables 3 and 4 while the graphical representation is shown in figures 4 and 5.

On addition of 2-5% of cement, and 2-5% cement-5-20% CFA to the soil, average reduction percentage of 29.76% and 56.67% were achieved for liquid limit, on addition of 2-5% of cement, and 2-5% cement-5-20% CFA to the soil, average reduction percentage of 90.67% and 96% were achieved for Plasticity Index.At these reductions,the soil would be able to support foundations as well as pave ments.

In a similar study, okeke et al.,2015 observed a reduction of Plasticity index from 33.60 to 13.3% and a reduction of 56.60 to 43.21% from expansive soils in the same sedimentary basin, and Ozotta and Okeke also achieved a reduction of liquid limit from 38 to 29.5% and a plasticity index reduction of 18 to 14.25% using cement.

Reduction in soil plasticity and swelling/shrinkage potential are one the benefits of soil stabilization. For Cement, Cement-CFA modifications, reductions were possible because of hydration reaction. This chemical processes worked effectively on fine-grained granular materials due to their large surface area in relation to their particle diameter(Sherwood, 1993) accentuated by their flat and elongated shaped particles. Hydration process starts when cement is mixed with water and soil for a desired application resulting into hardening phenomena. The hardening (setting) of cement will enclose soil as glue,thereby reducing the swelling potential and increase in strength, but it will not change the structure of soil. During hydration process,cementing compounds of calcium–silicate–hydrate (C–S–H) and calcium–aluminate–hydrate (C–A–H) are formed and excess calcium hydroxide (CaOH) is released, approximately 31% by weight (Parsons and Milbourn,2003). Formation of C–S–H and C–A–H occurs when crystals begin forming a few hours after the water and cement are mixed; crystals will continue to form as long as unreacted cement particles and free water remain within the mixture(khan et al., 2015). The other significant effects of soil–cement stabilization is reduction in shrinkage and swell potential, increase in strength, and resistance against the effect of moisture, freeze, and thaw.

- *Maximum Dry Density of Cement, Cement-Coal fly ash treated soil from Enugu Shale*

Modification with cement increased the Maximum Dry Density (MDD) of expansive soils from Enugu shale, Southeastern Nigeria. Cement contents of 2,2.5,3,3.5,4,4.5and 5% and Cement- Coal fly ash contents of 5,7.5,10,12.5,15,17.5, and 20 % by dry weight of clay soil were used to improve soil. The results of maximum dry density (MDD) after stabilization of expansive soil is presented in tables 3 and 4.The variations of maximum dry density versus cement, Cement CFA mixes are presented in Fig.6. The figures indicate that the dry density generally increased with more additives added which is mainly due to strength gain from the hydration process which takes place immediately after cement comes into contact with water. This process involves hardening of soil mix; this hardening was facilitated by enough compactive effort and timely compaction to avert bond breakage and loss of strength. Bond breakage and loss of strength occurs when there is a delay in compaction after mixes with additives. From the graph, the highest MDD was achieved at 4.5% cement additive, 4.5% cement and 17.5% CFA additives respectively. Upon stabilization, MDD increased from 2% application and peaked at 4.5 % application, there was a remarkeable reduction at further application to 5%.This means that further addition of mixes from 5% cement will not produce additional strength. This may be due to insufficient availability of silica and/or alumina in the soil for pozzolanic reaction. Generally mixes with CFA showed significant increase in MDD as evidenced from Peak points on the graph. These results agree with that reported by (Prusinski & Bhattacharja, 1999).

CEMENT	OMC%	MDD MG/M^3	LIQUID LIMIT %	PLASTICITY INDEX%	LINEAR SHRINKAGE%
0	22.9	1.32	42.0	22.5	4.3
2 % CEMENT	21.0	2.77	40.8	19.5	Within limits
2.5%CEMENT	19.1	4.19	39.2	18.3	Within limits
3.0%CEMENT	17.0	5.60	38.0	12.0	Within limits
3.5%CEMENT	15.0	7.60	36.0	10.1	Within limits
4.0%CEM ENT	13.7	9.40	34.5	7.25	Within limits
4.5%CEMENT	12.2	11.40	32.0	4.18	Within limits
5.0%CEMENT	13.0	8.50	29.5	2.10	Within limits

Table 3: Effects of treatment with cement on OMC,MDD and Atterberg limits of expansive soils from Enugu Shale

CEMENT+CFA PERCENTAGES	OMC%	MDD MG/M^3	LIQUID LIMIT %	PLASTICITY INDEX%	LINEAR SHRINKAGE%
0	22.9	1.32	42.0	22.5	4.3
2 % CEMENT 5.0%CFA	19.7	3.22	40.1	18.4	Within limits
2.5%CEMENT7.5%CFA	16.6	5.02	36.0	14.0	Within limits
3.0%CEMENT 10%CFA	13.4	7.52	32.4	10.2	Within limits
3.5%CEMENT 12.5%CFA	10.4	10.52	28.6	6.8	Within limits
4.0%CEM ENT 15.0%CFA	7.4	13.32	25.2	2.80	Within limits
4.5%CEMENT 17.5%CFA	4.8	16.82	22.4	1.80	Within limits
5.0%CEMENT 20% CFA	6.40	12.88	18.20	0.90	Within limits

Table 4: Effects of treatment with cement,cement-coal fly ash on MDD and Atterberg limits of expansive soils from Enugu Shale.

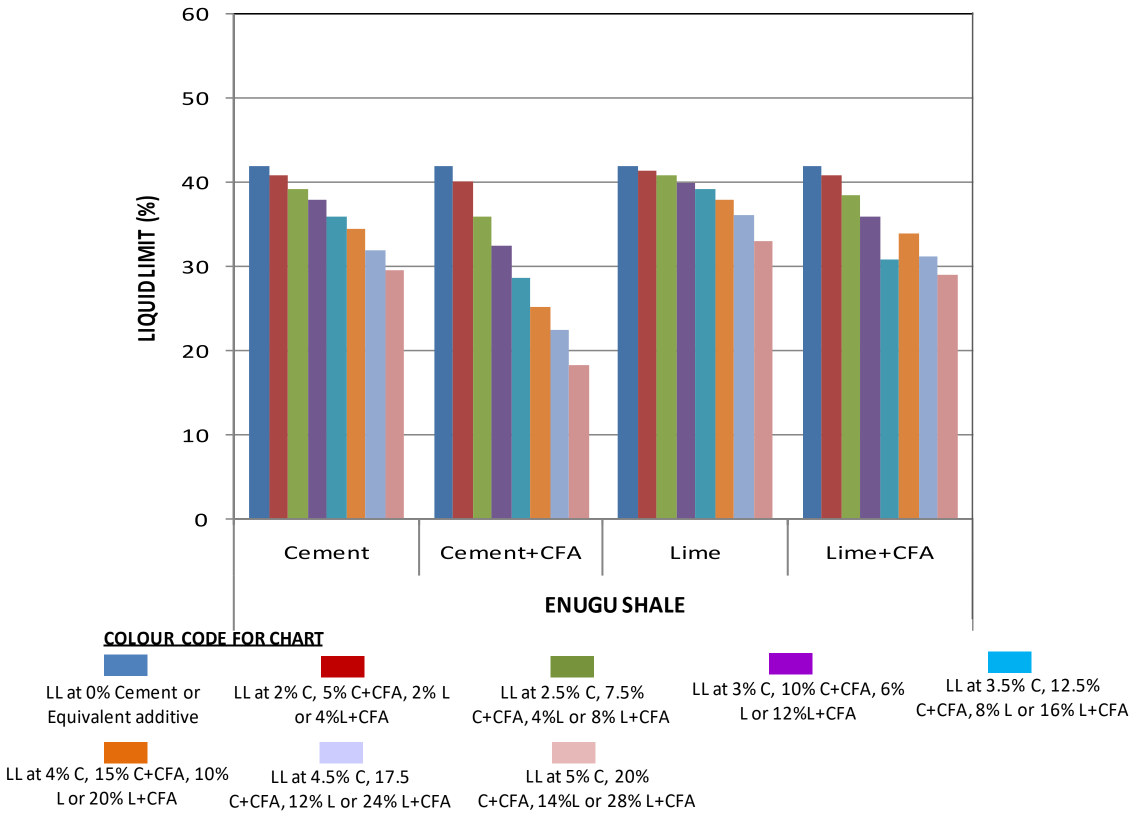

Fig.4. 2d Column Chart Plot of Effect of Additives on Liquid Limit of Expansive Soil From Enugu Shale

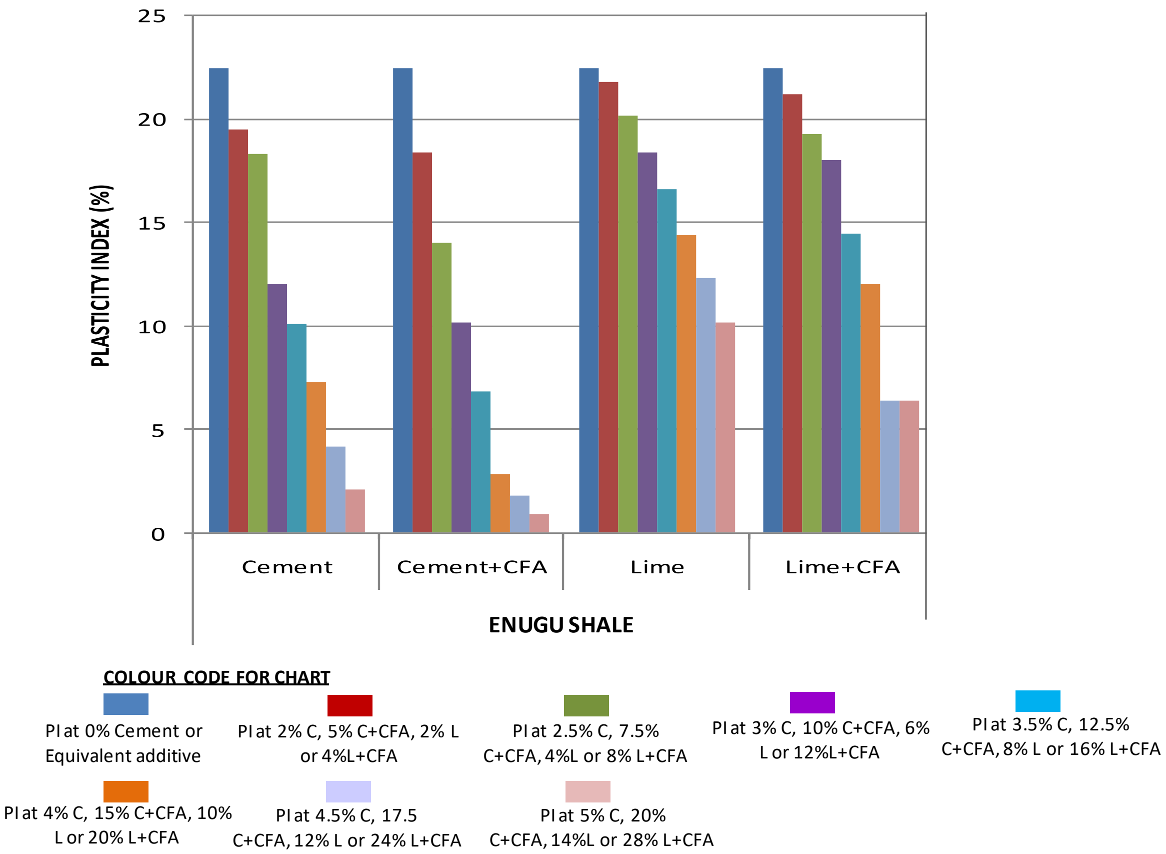

Fig.5. 2d Column Chart Plot of Effect of Additives on Plasticity Index of Expansive Soil From Enugu Shale

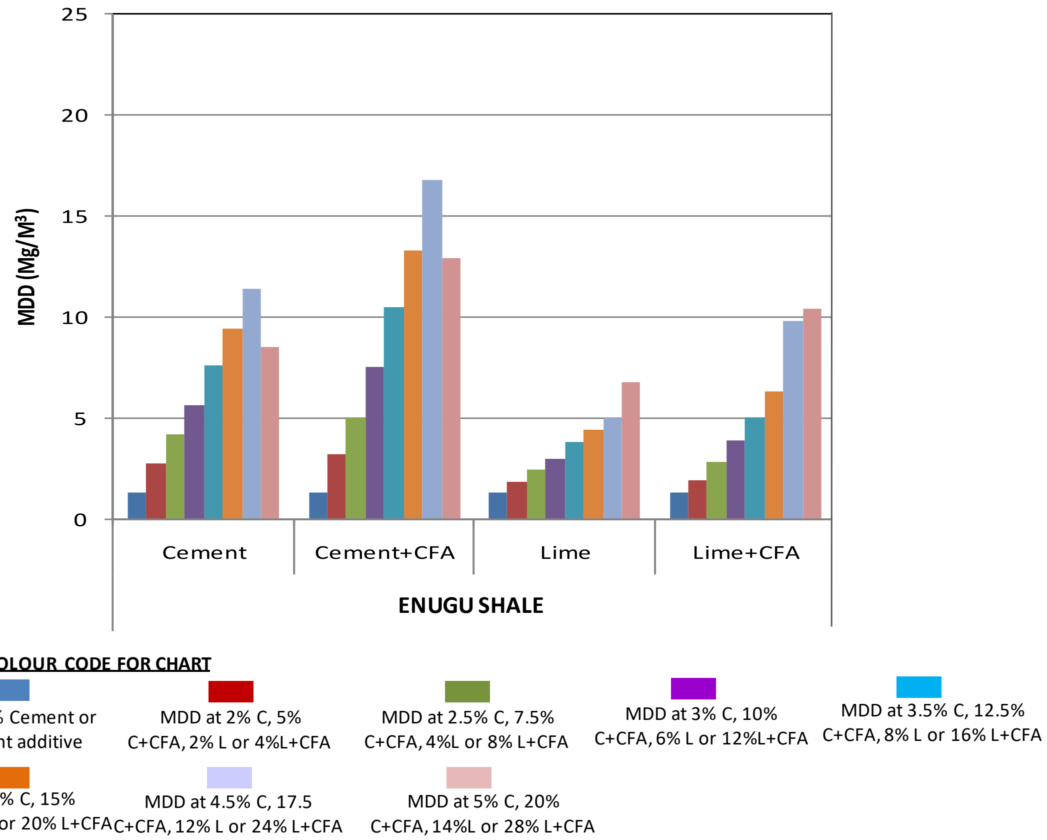

Fig.6. 2d Column Chart Plot of Effect of Additives on Maximum Dry Density of Expansive Soil From Enugu Shale

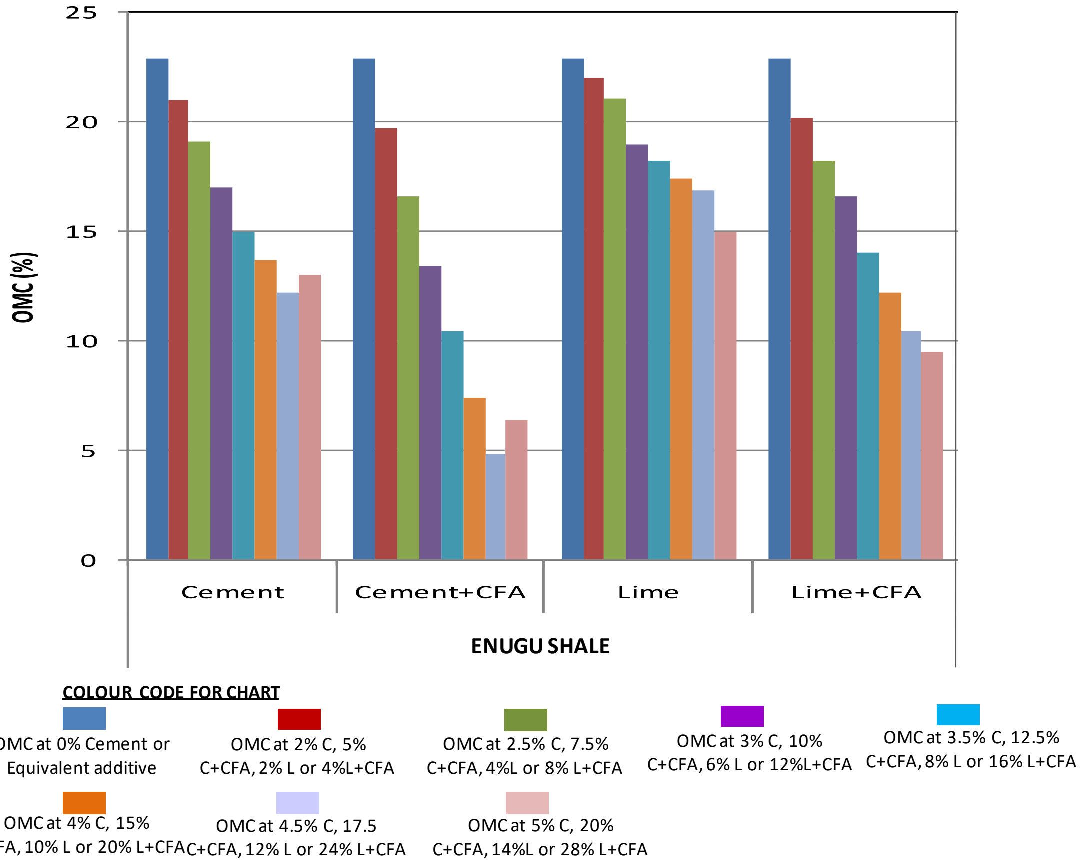

Fig.7. 2d Column Chart Plot of Effect of Additives on Optimum Moisture Content of Expansive Soil From Enugu Shale

- *Atterberg Limits of Lime, Lime-Coal fly ash treated soil from Enugu Shale*

Tables 5 and 6 show the extent of reduction,and reduction percentages of liquid limit and plasticity index of the soil when treated with various percentages of lime and li me-Coal fly ash. Graphical representations are shown on figures 4 and 5. Varying percentages of 2,4,6,8,10,12,and 14% and 4,8,12,16,20,24,28 % of lime, and lime-coal fly ash by dry weight of clay soil were used to improve soil.

On addition of 2-14% lime, and 2-14% lime-2-14%-4-28%CFA to the soil, Plasticity Index reduced from 22.5 to 10.2% and 22.5 to 6.4% which represents a reduction percentage of 54.67 and 71.56 respectively.Again, application of 2-14% lime, 2-14% lime-4-28%CFA on expansive soil, Liquid limit reduced from 42 to 33% and 42 to 31.2% which represents a reduction percentage of 21.43 and 30.95% . An increase in plasticity index may result in higher swelling pressures and an increase in the swelling potential of the untreated soils due to enlarged voids within the mass of the expanded soils, and hence higher pressure required to reduce voids(Abbey etal.,2020). The effects on pavement designs and foundation are high settlement and instability, low permeability and shear strength. Stabilization would reduce the values on these parameters and enable the soil to become better construction materials .

For a similar class of soil, Ozotta and Okeke,2015 observed that the liquid limit reduced from 38% to 29.8% on addition of lime, while plasticity index reduced from 18% to 13.5% on addition of lime. Effect of combination of lime and coal fly ash on the plasticity of soft clayey soils was studied by Nnabuihe et al.,2021, the outcome of Lime-Coal fly ash saw a reduction of Plasticity index and liquid limit from 59% to 49% and 36% to 10% respectively. Similar behaviors have also been reported by several researchers such as Manasseh,2008 and Modarres,2015.

Lime, lime-CFA Atterberg limits reduction occurred by cation exchange capacity rather than cementing effect brought by pozzolanic reaction (Sherwood, 1993). In soil modification, as clay particles flocculates, transforms natural plate like clays particles into needle like interlocking metalline structures. Clay soils turn drier and less susceptible to water content changes (Roger et al., 1993). Lime stabilization may refer to pozzolanic reaction in which pozzolana materials reacts with lime in presence of water to produce cementitious compounds (Sherwood, 1993, EuroSoilStab, 2002).

A recent study by (Mahedi, Cetin, & White, 2020) carried out performance evaluation and comparism of Cement, Lime, and Fly Ashes in Stabilizing Expansive Soils, in their investigations,Specimens were subjected to Atterberg limits tests(LL/PI) using cement-CFA admixtures, test results indicated that cement was preferable for higher strength at shorter curing times (7 days), while lime produced the maximum strength at longer curing periods (90 days). It was deemed that 10% to 12% calcium oxide lime (CaO) in stabilizers was optimum for stabilizing expansive soils.Volumetric swelling of the soils also decreased during stabilization.

LIME PERCENTAGES	OMC%	MDD MG/M^3	LIQUID LIMIT %	PLASTICITY INDEX%	LINEAR SHRINKAGE%
0	22.9	1.32	42.0	22.5	4.3
2% LIME	22.0	1.85	41.4	21.8	Within limits
4%LIME	21.1	2.4	40.9	20.2	Within limits
6% LIME	19.0	3.0	39.9	18.4	Within limits
8%LIME	18.2	3.8	39.2	16.6	Within limits
10%LIME	17.4	4.4	38.0	14.4	Within limits
12%LIME	16.9	5.0	36.2	12.3	Within limits
14%LIME,	15.0	6.8	33.0	10.2	Within limits

Table 5: Effects of treatment with lime on MDD and Atterberg limits of expansive soils from Enugu Shale

LIME+CFA PERCENTAGES	OMC%	MDD MG/M^3	LIQUID LIMIT %	PLASTICITY INDEX%	LINEAR SHRINKAGE%
0	22.9	1.32	42.0	22.5	4.3
2% LIME,4% CFA	20.2	1.9	40.9	21.2	Within limits
4%LIME,8% CFA	18.2	2.8	38.5	19.3	Within limits
6% LIME, 12%CFA	16.6	3.9	36.0	18.0	Within limits
8%LIME, 16%CFA	14.0	5.0	30.8	14.5	Within limits
10%LIME,20%CFA	12.2	6.3	34.0	12.0	Within limits
12%LIME,24%CFA	10.4	9.8	31.2	6.4	Within limits
14%LIME,28%CFA	9.5	10.4	29.0	6.4	Within limits

Table 6: Effects of treatment with Lime-CFA on MDD and Atterberg limits of expansive soils from Enugu Shale

- *Maximum Dry Density of Lime, Lime-Coal fly ash treated soil from Enugu Shale*

The results of maximum dry density(MDD) after stabilization is presented in tables 5 and 6.The variations of maximum dry density versus lime, Lime-CFA mixes are presented in Fig.6. Varying percentages of 2,4,6,8,10,12,and 14% and 4,8,12,16,20,24,28 % of lime, and lime-coal fly ash by dry weight of clay soil were used to improve soil. From the graph, the highest MDD was achieved at 14% lime additive,14% lime and 28% CFA respectively. Upon stabilization, MDD increased from 4% application and peaked at 28% application which was the highest mix used for the stabilization.This means that further addition of mixes from 28% cement and above would produce additional strength.. Generally mixes with CFA showed significant increase in MDD as evidenced from Peak points on the graph. The main chemical processes of lime treatment are base-exchange (which leads to flocculation/change in soil gradation) and pozzonanic action due to the reaction between lime, aluumina and silica. This is a long term reaction which strengthens the soil-lime-CFA mixtures. Strength increase in soil-lime mixture is therefore due to base-exchange and strength increase due to soil-cement-CFA mixtures is due to hydration(Afrin, 2017).

- *Optimum Moisture Content of Lime, Lime-Coal fly ash and Cement,Cement-Coal fly ash treated soil from Enugu Shale*

Results of Optimum Moisture content is represented in tables 3-8, and 9-11.From the graph (Fig.7), OMC reduced with lime,lime-CFA,cement,Cement-CFA applications, suggesting that this reduction allowed for maximum compaction required for effective stabilization of all soil samples.

Parameter	**Untreated**	**Stabilized with cement**	**(%) Increase**	**Stabilized with cement/CFA admixture**	**(%) Increase**	**Stabilized with lime%**	**(%) Increase**	**Stabilized with lime/CFA Admixture**	**(%) Increase**
Unsoaked (%)	2.3	300-700		350-900		400-500		300-700	
Soaked	1.1	100-200		100-300		100-180		100-200	
MDD (mg/m^3)	1.32	8.50	543.95%	12.88	875.76%	6.8	415.15%	9.8	642.42%

ATTERBERG LIMITS

Parameter	**Untreated**	**Stabilized with cement**	**Reduction (%)**	**Stabilized with cement/CFA admixture**	**Reduction (%)**	**Stabilized with lime%**	**Reduction (%)**	**Stabilized with lime/CFA Admixture**	**Reduction (%)**
LL (%)	42.0	29.5		18.20		33.0		31.2	
PI (%)	22.5	2.10		0.90		10.2		6.4	

Table 7: Summary of Effects of Stabilized Expansive Soil from Enugu Shale Southeastern Nigeria using Lime, Cement and Coal Fly Ash Admixtures.

Note: Optimum Stabilization Percentages Lime = 6% Cement = 5% Lime/CFA/ soil = 6:28:82 Cement/CFA/soil = 5:20:81

California Bearing Ratio.

LOCATION	UNSOAKED%	SOAKED%
Enugu Shale	2.3	1.1

California Bearing ratio of natural soil

Table 8:Summary of California Bearing Ratio of natural soil(soaked and unsoaked)

- *Effects of Cement,Cement-Coal fly ash stabilization on CBR of expansive soil from Enugu Shale*

The CBR of cement and cement -CFA stabilized soil data were summarized in tables 9 and 10, graphically, they is represented in figure 8. The results reveal that the CBR of the soil samples increased after stabilization meaning that the soil gained enough strength to withstand volume change associated with it. The CBR value increased at every increase in content of cement and coal Fly ash. A more significant trend is seen in the Cement-CFA results. At these percentages of additives, approximately 300-700% and 350-900% increase in strength from additives after modification were achieved for cement and cement-CFA respectively for unsoaked samples. Also,approximately 100-200% and 100-300% increase in strength from additives after modification were achieved for cement and cement-CFA for soaked and soaked samples respectively. Maximum increase in strength was achieved after 7 days of curing with 5% and 20% cement, and cement-CFA additives respectively. These percentages represent optimum cement and optimum cement-CFA additives required to achieve maximum strength to withstand repetitive load for pavement design. Again these values indicate that soaking generally reduced the CBR of all samples.

Cement, cement-CFA additives enhanced not only soil strength, but also volume stability, and durability that was achieved through pozzolanic reaction. Class F fly ash consists of siliceous and aluminous pozzolans but lacks self-cementitious properties. It can be activated with the addition of cement to create pozzolanic mixtures. The pozzolanic activity is initiated by the addition of water and results in the formation of cementitious compounds, which modify the engineering properties of the soil (Sumesh et al; 2010).

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Pozzolanic reactions take place slowly, over months and years, and can further strengthen a modified soil as well as reduce plasticity and improve gradation.

SOIL+CEMENT PERCENTAGES	CBR VALUE	
	UNSOAKED	SOAKED
0	2.3	1.0
2% Cement	351	117
2.5% Cement	624	195
3% Cement	737	230
3.5% Cement	729	227
4% Cement	792	247
4.5% Cement	814	254
5.0% Cement	832	277

Table 9: Effects of treatment with cement on CBR of expansive soils from Enugu Shale

SOIL+CEMENT+CFA PERCENTAGES	CBR VALUE	
	UNSOAKED	SOAKED
0	2.3	1.0
2% Cement 5%CFA	318	109
2.5% Cement 7.5%CFA	626	216
3% Cement 10% CFA	887	305
3.5% Cement 12.5%CFA	824	284
4% Cement 15.0%CFA	654	225
4.5% Cement 17.5%CFA	814	280
5.0% Cement 20.0%CFA	872	350

Table 10: Effects of treatment with cement-coal fly ash on CBR of expansive soils from Enugu Shale

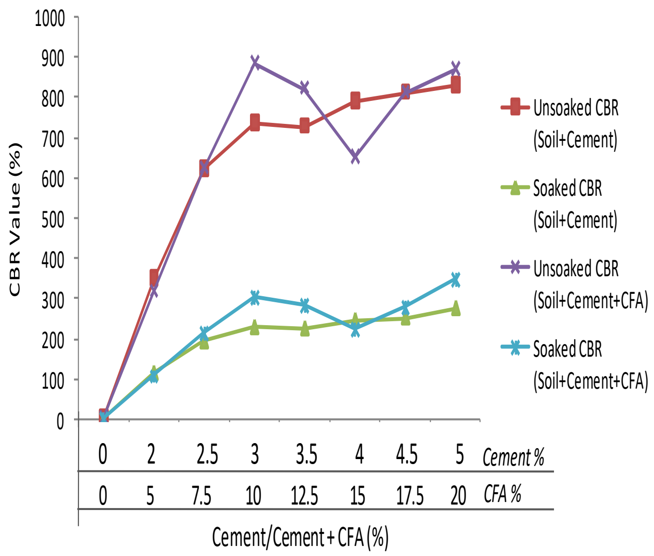

Fig. 8. CBR of cement, and cement+CFA treated Enugu shale soil

- ➢ *Effects of Lime, Lime-CFA Stabilization on CBR of Expansive Soils*

Lime is a primary binder (Makusa, 2012) and provides an economical way of soil stabilization. Quick lime was used to stabilize clay soil from the study area. The CBR of lime, and lime+CFA stabilized soil data were summarized in tables 9 and 10 , graphically, they are represented in figures 9 . Results of CBR test for the stabilized soil specimens show that the addition of lime improved the CBR of the soil. After stabilization,the results revealed that with increase in lime and lime-CFA contents,there was increase in CBR values. Maximum increase in strength was achieved after 7 days of curing generally with 14 % and 28% of lime, and lime-CFA contents for unsoaked samples respectively. At these percentages, approximately 400-500% and 300-700% increase in strength from additives after modification were achieved for lime and lime-CFA respectively for unsoaked samples. Also, for soaked samples, results also revealed that with increase in lime, and lime-CFA contents, there was increase in CBR values, maximum increase in strength was achieved after 7 days of curing with 6% and 28% lime, and Lime-CFA samples respectively. At these percentages, approximately 100-180% and 100-200% increase in strength from additives after modification was achieved, these values indicate that soaking generally r educed the CBR of all samples. With soaked samples, further increase after 6% lime application did not cause any increase in CBR value. This indicates that the 6% may be considered as the optimum amount of lime needed to achieve pozzolanic reaction with the soil strength. Further Increase in lime content beyond the optimum value results in a marginal decrease in the strength of sample, which may be due to insufficient silica and/or alumina in the soil for pozzolanic reaction(Herrin and Mitchell,1961) .Obviously, quicklime-Coal Fly ash stabilized soils proved to be mechanically stronger. (Figures 9 and 10) reveals the strength of quicklime-fly ash by showing all high points corresponds to CBR of fly ash mixtures ,which indicate a potential to sustain higher bearing loads than only lime-stabilized soil.Obviously,the attainement of this level of improvements is owing to the fact that the clay soil used in this research work is moderately to highly plastic and clay soils from the study area and have a Plasticity index greater than 10 and more than 25 percent of the soil passing the No. 200 (0.075mm) sieve (Solanki, Zaman, & Dean, 2010). These results agree with those reported by (Prasad et al; 2010),(Panjaitan, 2014)(Hussain and Dhar,2019.) Again soils stabilized with fly ash mixes show more increase strength gain long after curing.

SOIL+LIME PERCENTAGES	CBR VALUE	
	UNSOAKED	SOAKED
0	2.3	1.0
2% LIME	431	139
4%LIME	438	141
6% LIME	402	134
8%LIME	404	134
10%LIME	417	139
12%LIME	497	171
14%LIME,	531	182

Table 11: Effects of treatment with lime on CBR of expansive soils from Enugu Shale.

SOIL+ LIME+CFA PERCENTAGES	CBR VALUES %	
	UNSOAKED	SOAKED
0	2.3	1.0
2% LIME,4% CFA	321	107
4%LIME,8% CFA	351	117
6% LIME, 12%CFA	425	142
8%LIME, 16%CFA	520	173
10%LIME,20%CFA	568	189
12%LIME,24%CFA	629	209
14%LIME,28%CFA	698	233

Table 12: Effects of treatment with lime-coal fly ash on CBR of expansive soils from Enugu Shale.

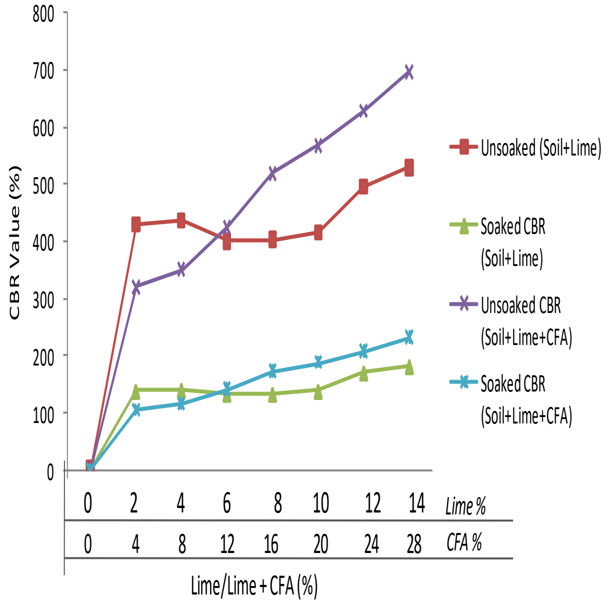

Fig.9: CBR of lime, and lime+CFA stabilized soil from

A recent study by Nnabuihe also established that the optimum lime and lime-fly ash contents needed to effectively treat a soil to reduce swelling and develop increased strength were 6% and 3%:12% respectively while this study agrees with the present study of 6% for lime , but does not agree with 6% and 28% for lime-coal fly ash(Amadi et al.,2021), the slight differences in the optimum lime contents required to achieve pozzolanic reaction with the soil-lime-coal fly ash admixtures may be attributed to the geology of the study areas. The study by Nnabuihe et al.,2021 was carried out on Pre-Santonian sediments (Lokpaukwu and Awgu)which lie within the Abakaliki Basin (Reyment,1965), while the present study was carried out on the Anambra basin (Mamu Formation,Enugu Shale and Nsukka Formation which are Post Santonian deposits. deposits.Again it may also be that soil in the study area benefits more from the extra silica and aluminium contained in the coal fly ash as a smaller amount of 12% was quickly exhausted in the pozzolanic reaction(Amadi et al.,2021)

V. CONCLUSION

- *Some conclusions were deduced from the present study as follows:*

This investigation acknowledges the effective utilization of an industrial waste such as fly ash in conjunction with small amounts of cement and lime as a sustainable civil engineering material.

It is found that the chemical stabilisation effectively increased California bearing ratio results which indicate strength gain of the treated soil, while Atterberg limits showed reduced swelling potential ,however, portland cement provided highly effective clay stabilization, usually with the added benefit of higher strength gain when combined with CFA.

In view of these results and analysis therefore, the two options performed well as stabilization options.

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