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GEOTECHNICAL INVESTIGATION OF OSOGBO-IWO ROAD COLLAPSIBLE SOIL'S CLAY FRACTION AND IMPROVEMENT USING BENTONITE

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Abstract — This research investigated the collapsible subgrade soils along Osogbo-Iwo Road in South-Western Nigeria. The road pavement has had a history of incessant differential settlement due to the effect of water on the subgrade material hence the soil's dominant clay mineral was assessed, and an attempt was made to improve the soil with bentonite. Representative soils were taken from three failed sections of the road and their geotechnical characteristics determined in the laboratory. The soil was classified according to American Association of State Highway and Transportation Officials (AASHTO) as A-5 (Silty-sand) and ML group (inorganic silts, fine sands with low plasticity) according to USCS Classification system. The clay fraction (which is 10% of the soil mass) was extracted via sedimentation and centrifugation. From the result of the X-ray diffraction (XRD) and consistency limits tests carried out, Kaolinite was observed to be the dominant mineral of influence. The relatively inert nature of the clay fraction was deduced to be a major contributor to its collapsible nature. Bentonite was added to the soil in the concentrations of 1-3 % respectively. The results showed that the untreated samples gave OMC values of between 11.7-14.97 %, MDD (1644-1453.6) kg/m^3, UCS (61.98-78.01) kPa, Soaked CBR (2-6) % and a Collapse Index (C.I) of 10-12 % which places the soil under a "Severe trouble" category. 1-2 % bentonite gave the best improvement having moved the soil from "severe trouble" category to trouble category.

***Keywords*:** Collapsible soil, clay fraction, collapse potential, bentonite, clay mineral

1.0 INTRODUCTION

Collapsible soils are soils which appear to be strong and stable in their natural state but experience large volumetric decrease on wetting, resulting in large and often unexpected settlements which yields disastrous consequences for structures built on such deposits [1–4]. According to [5] and [6], the mineralogy of the clay minerals, which comprise the majority of the bonding material is one of the key factors in evaluating the collapse behaviour of soils. Clay can be described as a naturally occurring material which is comprised primarily by fine grained materials and is generally plastic at appropriate water content and will harden when fired or dried. Clay minerals are pivotal in the formation of structural bonds in collapsible soils because the primary silt particles in the soil are connected by clay minerals. According to [7] and [8] the saturation of the soil with water softens the clay minerals and destroys the inter-particle bonds between the solid particles thereby producing a large volumetric decrease and a permanent settlement. This shows that the collapse behaviour of a soil depends on the nature of the clay mineral since different clay minerals have varying moisture absorption properties.

Clay minerals may be grouped into three main classes with respect to shrinkage and swelling characteristics: low to very low (e.g. Kaolinite), moderate (e.g. Illite) and high to very high (e.g. montmorillonite) [9]. The most commonly occurring clay minerals are Kaolinite and montmorillonite. Despite having similar structures composed of the same units (i.e., silica tetrahedron and alumina octahedron), they exhibit different swelling and shrinkage properties. In terms of structure, kaolinite is composed of alternate layers of silica tetrahedral and alumina octahedral units while montmorillonite is composed of two silica tetrahedral to every octahedral unit. Due to this structural difference, the engineering properties are significantly different.

Most researches on collapsible soils have analyzed the microstructural characteristics of the bulk sample [10–14] but few researches have been oriented towards the extraction and investigation of the clay in order to have a more comprehensive understanding of the soil's collapse behaviour.

A soil is not susceptible to collapse if its clay fraction exceeds 30 % [5, 15, 16] as shown in Table 1.0. Also, the relative amount of the various clay minerals in the soil affects to a large extent its properties, depending on both the types and amounts of the different clays present. According to [17] the potential severity of soils based on the collapse potential can be classified as shown in Table 2.0. The collapse potential (CP) is then defined as:

$$CP = \frac{\Delta H}{H_o} = \frac{\Delta e_c}{e_0 + 1} x100 \quad (1)$$

Where ΔH is the change in height of the specimen upon flooding, H is the original height of the specimen, Δe is the change in void ratio of the specimen upon flooding and e is the void ratio before flooding. According to [16] the Osogbo-Iwo road soil is a typically silty sand and found to be unsuitable. The soil also has low plasticity index of 10%, low moisture content and low dry density has low relative density of 28.6 % with high void ratio and high porosity which indicate that the soil is weak and compressible. The research was able to establish that the subgrade material was collapsible in nature. However, the clay fraction of the soil was not analyzed and no solution was proffered to the problem. [18] assessed the role of clays on the stability of a collapsible soil in Mosul city. The main results showed that the collapse potential increased continuously for samples compacted at a low unit weight, mixed with the percentages of low plastic clay, while there was a maximum collapse potential occurred at 5 % of highly plastic clay soil. Hence, when a highly plastic clayey soil is used, collapse potential decreases at clay content more than 12 %. However, the clay used in the research was not pure expansive clay (Bentonite) but plastic and non-plastic clay soil excavated from locations in Mosul city.

Table 1 Classification of Collapsible Soil [5, 15, 16]

Clay Fraction CF (% < 2μm)	Probability of Collapse
5% <CF<15%	High probability
15% <CF<30%	Probability of collapse
CF>30%	No collapse

Table 2 Potential Severity of Collapse [17]

Collapse Potential (%)	Severity of Problem
0-1	No problem
1-5	Moderate trouble
5-10	Trouble
10-20	Severe trouble
>20	Very severe trouble

This research is therefore aimed at analyzing the mineralogical composition of the clay fraction of Osogbo-Iwo Road collapsible soil and the feasibility of improving its geotechnical characteristics using bentonite. Compared to the use of impure clay in [9], a small percentage of bentonite is expected to expand, fill the void spaces of the collapsible soil fabric and reduce its collapse potential.

2.0 MATERIALS AND METHODS

2.1 The Study Area

The soil investigation was carried out under standard laboratory conditions on soil samples which was obtained along 3 different sections of Osogbo -Iwo Road, Osun state. The coordinates of the sample locations are as follows: Location 1 (longitude 7.7936711N and latitude 4.4909929E), Location 2 (Longitude 7.794651N and Latitude 4.4877133E) and Location 3 (Longitude 7.794651N and Latitude 4.48779677E) (Figure 1 and 2) where large quantities of undisturbed and disturbed representative samples were collected at 1.1m below ground surface.

The depth of water to the ground surface at each location is 1.43m, 1.34m and 0.26m respectively All tests were performed in the Geotechnical Laboratory, Civil Engineering Department of the Federal University of Technology, Akure.

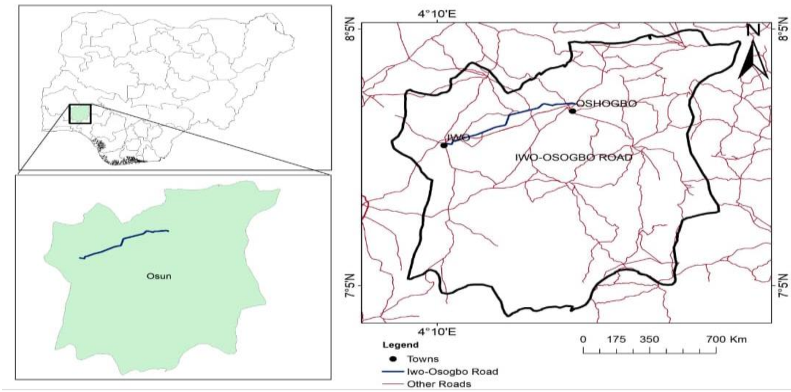

Figure 1 Map of Osun state, south western Nigeria map

Figure 2 Aerial photograph showing Sample locations

2.2 Bentonite

Bentonite is a clay formed as a result of chemical weathering of volcanic ash. It consists predominantly of smectite minerals, usually montmorillonite [$Si_8Al_4O_{20}(OH)_4.nH_2O$] (Fig. 3). Montmorillonite is composed of two silica sheets and one alumina sheet. The structure of the mineral allows water and other polar molecules to enter in between its layers resulting in its high swelling characteristics and shrinkage occurs with the removal of water from its lattice [19]. Commercial grade bentonite was used in this study.

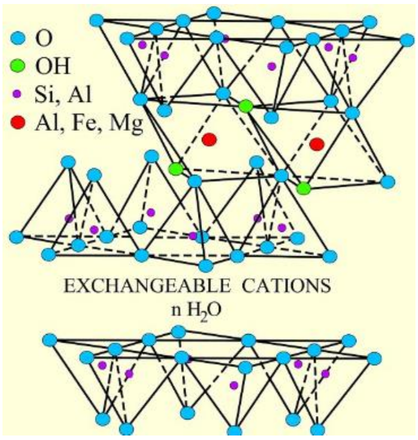

Figure 3 Structure of Montmorillonite [20]

2.3. Experimental Programme

2.3.1 Index Property Tests

The following preliminary tests were conducted on the natural soil to determine the index property. The soils were classified using the American Association of State Highway and Transportation Officials [21] and Unified Soil Classification System (USCS) [22].

The moisture content, liquid limit, plastic limit, linear shrinkage, particle size [23]

According to [24] activity is the ratio of the plasticity index to the percentage of the clay sized fraction. This can be expressed mathematically as equation (2)

$$\boldsymbol{A} = \frac{\boldsymbol{P.I}}{(\%\ \boldsymbol{of\ clay\ size\ fraction})} \tag{2}$$

Where A is activity and P.I is the Plasticity Index.

2.3.2. Compaction Test

West African Standard (WAS) Compaction Test was carried out on both the natural and stabilized samples in accordance with the Nigeria General Specifications [25].

2.3.3. Collapse Index Test

The one dimensional Collapse Index Test of treated and untreated samples was carried out in accordance to the procedures in [26].

2.3.4. Unconfined Compressive Strength (UCS) Test

Unconfined Compressive Strength (UCS) was used to test the ability of the soil samples to withstand failure by compression. This was carried out based on the procedures outlined in [23].

2.3.5. California Bearing Ratio (CBR) Test

The California bearing ratio (CBR) test was carried out on the treated and untreated samples in both soaked and un-soaked conditions in accordance to the procedure in [23].

2.3.6. Clay fraction extraction

The bulk sample was oven dried for about 24 hours. After which it was poured on a flat tray and the crumbles broken down into smaller particles after which about 1 part of the silt-clay mixture (< 75µm) was mixed with 10-20 parts of water (Figure 4). 1870 grams of soil passing the No.200 (75µm) sieve was taken as a sample and dispersed in a cylindrical container containing 18700 ml of water. The mixture was thoroughly mixed and left to stand for 8 hours to ensure that all the silt-size particles settled down at the bottom of the container. At the end of the sedimentation period i.e., every 8 hours (9am- 5pm); (5pm- 9am) the top 10cm representing the clay portion was siphoned out using a rubber hose without disturbing the silt material at the bottom. After which the suspended 2µm Clay fraction (sometimes known as the total clay fraction) was decanted. A centrifuge was then used in extracting the clay fraction from the solution (Figure 5).

Figure 4 Gravity Sedimentation

Figure 5 Clay Fraction Extraction Via Centrifugation

2.3.7. X-Ray Diffraction Analysis

X-ray diffraction analysis was carried out on the clay fraction using Air-dried preferred orientation (ADPO). This is to ensure accuracy in mineral identification as other orientations which require heat might alter the mineral structure. The basal spacing of the crystals was used in identifying the clay minerals. This is based on Braggs' equation (3)

$$n\lambda = 2d\sin\theta \quad (3)$$

Where,
λ= the wavelength of a parallel beam of X-rays
θ = angle parallel to the atomic planes
d =distance between parallel atomic planes
This test was carried out at the National Geosciences Research Laboratories, Nigerian Geological Survey Agency, Kaduna.

3.0 RESULTS AND DISCUSSION

3.1 Soil Classification

The grain size curves of the samples from the three sections of the Osogbo-Iwo Road are shown in Figure 6. The grain size distribution revealed that a large component of the soil was silty-fine to medium-fine sand with (11-24.3) % clay acting as binder to bind the particles together. It was deduced that the silt controls the soil's behaviour. The typical range of specific gravity for silty sand is between 2.67 and 2.7 [27]. From the results shown in Table 3, the sample is classified as ML group (inorganic silts, fine sands with low plasticity) according to the unified soil classification system (USCS) and as an A-5 material (silty sand) which is fair -poor in terms of general ratings as a subgrade material according to the AASHTO classification system.

Table 3 Geotechnical properties of the natural/Untreated soils

PARAMETER(S)	LOCATION 1	LOCATION 2	LOCATION 3
Natural moisture content (%)	5	7.5	5.6
Specific Gravity (Gs)	2.68	2.7	2.65
Atterberg limits			
Liquid limit (%)	26.1	26.3	34.1
Plastic limit (%)	16.0	16.5	20.3
Shrinkage limit (%)	11.0	11.5	13.0
Plasticity index (%)	10.1	9.8	13.8
OMC (%)	11.7	14.57	14.97
MDD(KN/m^3)	1644	1489.61	1453.60
CBR *Un-soaked (%)*	10	17	10
CBR *Soaked (%)*	3	6	2
UCS(KN/m^2)	75.92	63.61	71.82
ASSHTO classification	A-5	A-5	A-6
USCS Classification	ML	ML	CL

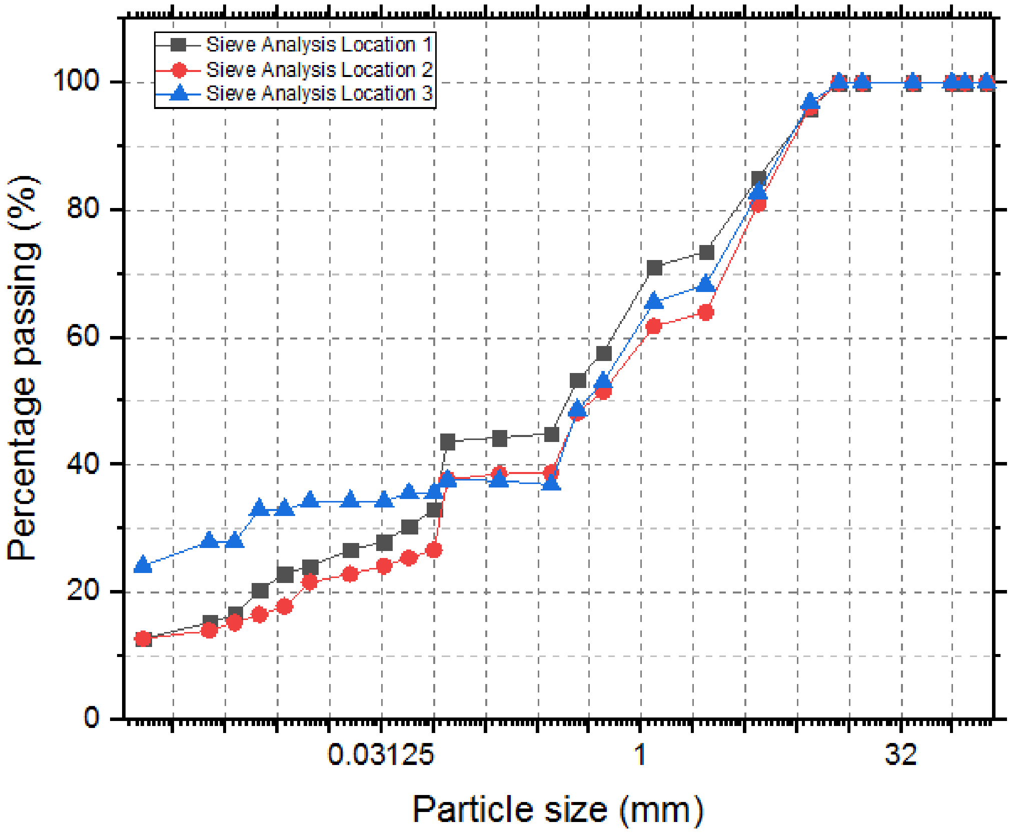

Figure 6 Grainsize distribution of location (1-3) samples

3.2 Clay Mineral Identification

3.2.1 X-Ray Diffraction Results of The Clay Fraction

From the XRD results (Figure 7), location 1 sample's clay fraction comprised majorly of Kaolinite with some traces of quartz. Kaolinite was observed at the following d-spacing's in the chart: 7.08501Ǻ, 3.55105Ǻ, 3.32442 Ǻ, 1.60166 Ǻ, 1.54026Ǻ, while quartz was observed at 1.48709 Ǻ. For location 2, the clay fraction was also found to be dominated by Kaolinite. However, it also contained some amount of Quartz. Kaolinite was observed at the following d-spacing's 7.15164 Å, 4.45035 Å, 4.45081 Å, 3.56183 Å, 3.34350 Å, 2.33937 Å, 1.7021 Å, 1.66667 Å, and 1.32987 while Quartz was observed at (3.34350 Å, 2.56061 Å, 2.49721 Å, 2.38183 Å, 1.56591 Å and 1.49030 Å. While for Location 3 samples, the clay fraction also comprised of Kaolinite and Quartz. Kaolinite was observed at the following d-spacing's 7.16208 Å, 4.4844 Å, 4.14244 Å, 3.56880Å, 3.34109 Å, 2.68368 Å, 2.49614 Å, 1.78736 Å, 1.48996 Å while Quartz was observed at the following d-spacing's: 1.66525 Å, 1.54061 Å, 1.30951.

Using semi-quantitative analysis as described by [28] the approximate percentages of minerals in the clay fraction are shown in the Table 4.

Table 4 Percentages of clay minerals in the clay fraction

Samples	Kaolinite (%)	Quartz (%)
Location 1	94%	6%
Location 2	85%	15%
Location 3	92%	8%

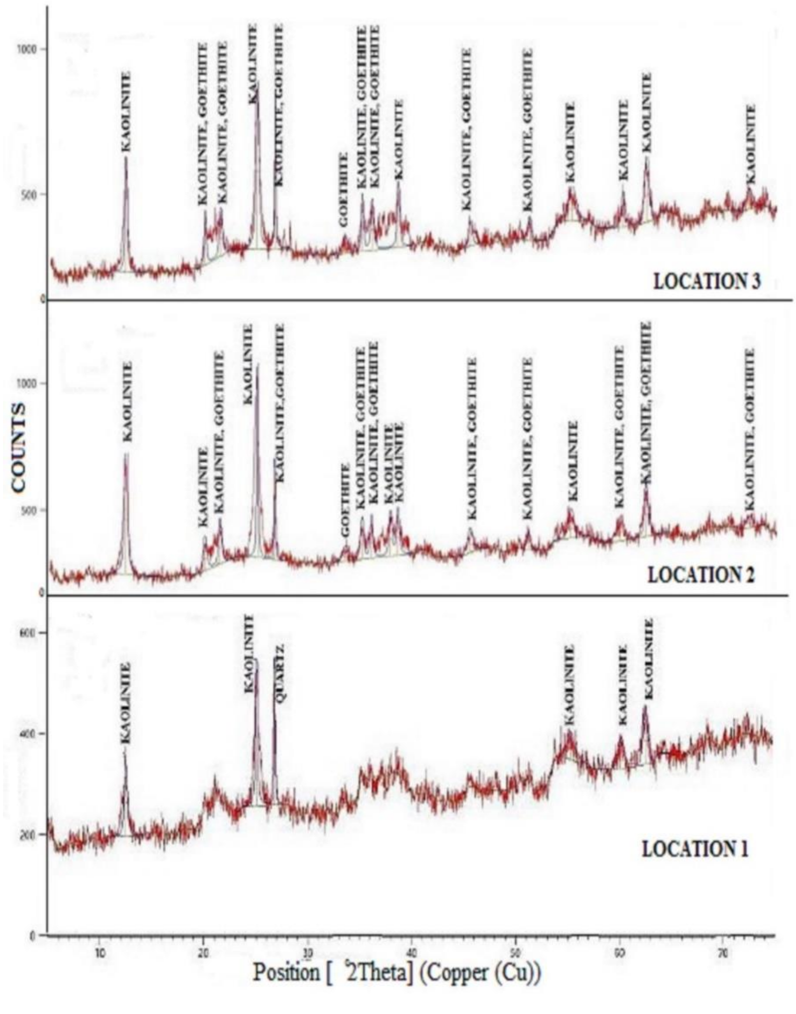

Figure 7 X-Ray Diffraction Results of the Location (1-3) Clay Fraction

3.3. Atterberg Limits Test Results

Table 5 Atterberg limits for the Location (1-3) Clay fraction sample

Parameter	Location 1	Location 2	Location 3
Liquid limit (%)	62.5	63.0	71.7
Plastic limit (%)	39.4	33.6	37.3
Shrinkage limit (%)	11.0	14.3	12.9
Plasticity Index (%)	23.1	29.4	34.4
Activity	0.23	0.29	0.34

From the index properties results shown in table 5, the liquid limit of the clay fraction extracted from all the samples were between 62.5 -71.7 which is not very high in comparison with expansive clays like montmorillonite [29, 30]. The same trend was observed for both the plasticity index and the shrinkage limit which are in the range of 11-12 and 23-34 respectively. These values do not indicate the high presence of expansive clay minerals in the soil's clay fraction. According to [31], the Atterberg limits of clay minerals increases with decreasing particle size. i.e., the plastic limit of attapulgite > montmorillonite > illite > kaolinite, the liquid limit of Na-Montmorillonite > Illite > kaolinite and that the plasticity index of attapulgite>illite>kaolinite. The shrinkage limit would probably be more i.e., Montmorillonite> attapulgite > illite> kaolinite.

According to the results obtained by Click or tap here to enter text.[28], the Iowa collapsible soils, a soil whose clay fraction consists mostly of illite and montmorillonite (medium to high plasticity clay) do not tend to collapse or exhibits relatively little collapse on wetting compared to kaolinite (a low plasticity clay) . This statement was also supported by [32], who stated that soils which have montmorillonite as a dominant mineral can swell easily and this closes the pores in the soil (therefore preventing collapse). In this research, the clay fraction of the Osogbo-Iwo Road soil was deduced to have kaolinite as the dominant mineral in the soil's clay fraction. This shows a low plasticity clay with poor bonding characteristics [33]. It contains a relatively small amount of clay which acts as a binder in the clay mineral skeleton, which greatly contributes to the collapsible nature of the soil.

3.4 Effects of The Additives on The Soil's Compaction Characteristics

Table 6 Compaction Characteristics of Treated and Untreated Soil

S/n	Sample	Parameter(s)	Location 1	Location 2	Location 3
1	Control	OMC (%)	11.7	14.57	14.97
		MDD (kg/m^3)	1409.88	1348.65	1409.88
2	1% Bentonite + Soil	OMC (%)	12.02	15.10	12.50
		MDD (kg/m^3)	1502.61	1460.23	1535.11
3	2% Bentonite + Soil	OMC (%)	12.92	12.50	12.60
		MDD (kg/m^3)	1538.26	1567.23	1497.76
4	3% Bentonite + Soil	OMC (%)	15.20	14.0	11.5
		MDD (kg/m^3)	1566.23	1533.34	1483.54

As shown Table 6, the effect of the addition of bentonite on the compaction characteristics of the samples varied from one location to the other. The samples were wetted for 8 hours before compaction. There was an increase in the OMC with increase in bentonite concentration values in location 1 and 2 from 12-15.1 % and 15.1-14 % respectively. However, a decrease of 12.5-11.5 % was observed for location 3 samples. With the addition of bentonite, increase in the MDD values was observed in location 1 and location 2 samples i.e., 1502.61-1566.23 Kg/m^3 and 1460.23-1533.34 Kg/m^3 at 3% bentonite respectively. However, a decrease was recorded for location 3 samples 1535.11-1483.54 Kg/m^3. In general, bentonite addition didn't produce a consistent effect on the OMC and MDD values of the soil.

3.5 Effects of The Additives On The Unconfined Compressive Strength

From Figures 8-10, all the untreated samples gave relative low strength results with location 1 sample having the lowest strength value of 61.58 kPa and location 2 sample having the highest strength value of 82.61 kPa. The addition of 2% bentonite gave the best improvement in both sample 1 and 3 while 1% was observed to give the best results in the location sample. The highest strength value recorded on the location 1 sample (143.59 kPa) and the lowest value recorded on the location 3 sample (133.35 kPa). The increase in strength observed in the samples can be attributed to the filling of the soil mineral skeleton with bentonite. The bentonite also behaves like a binder in the soil matrix. This makes the soil more compact and hence increases its strength. The denser the soil, the lesser its susceptibility to collapse [34–36].

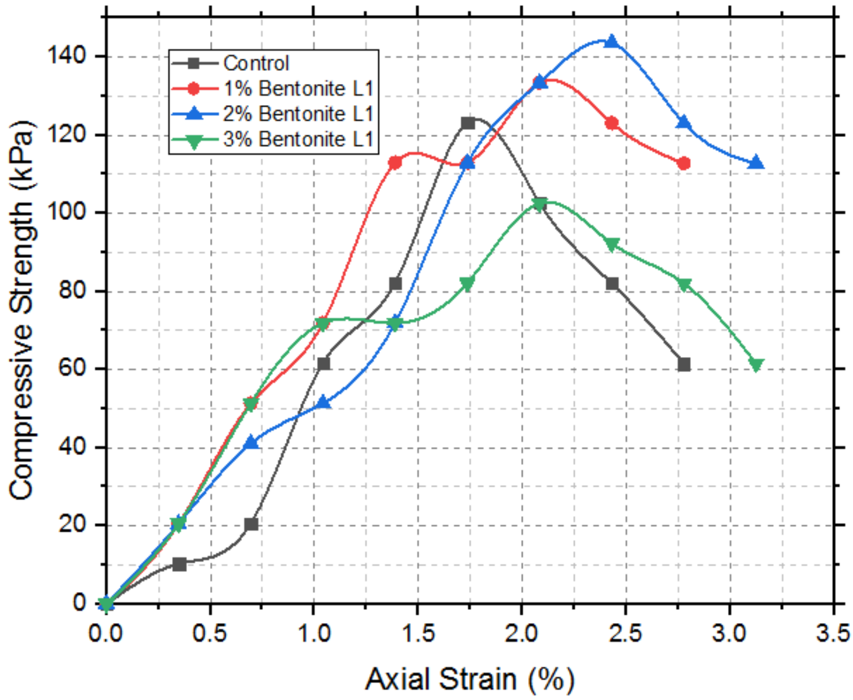

Figure 8 Bentonite stabilized samples (L1)

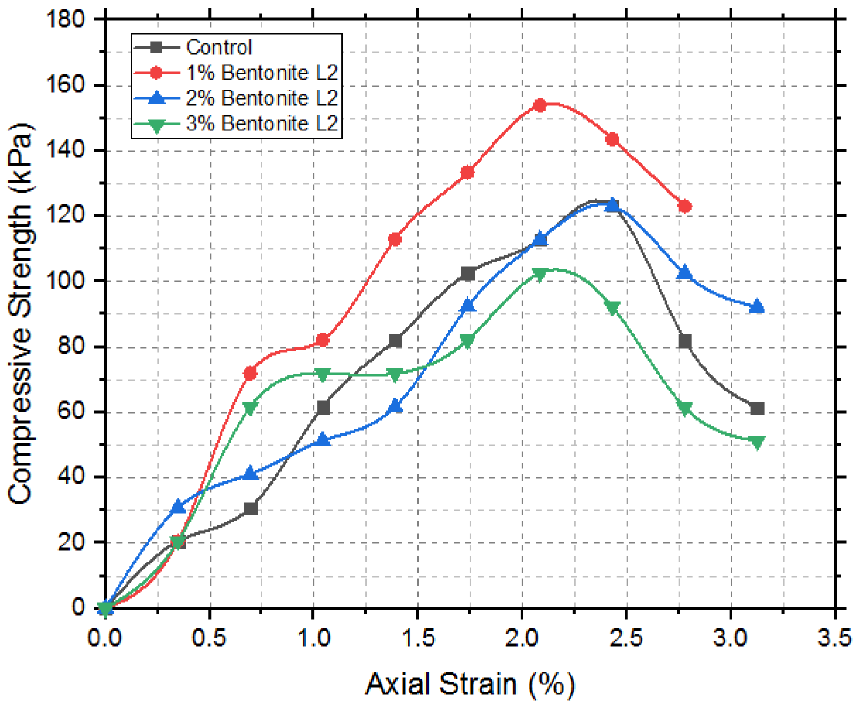

Figure 9 Bentonite stabilized samples (L2)

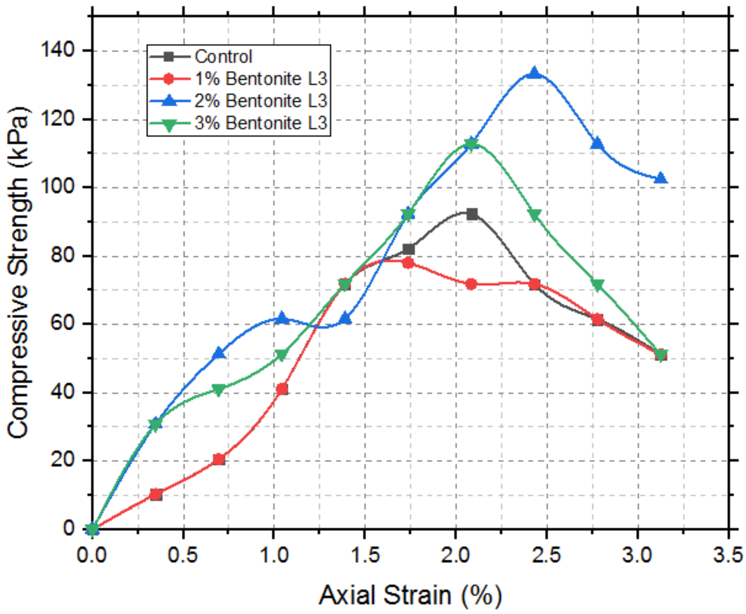

Figure 10 Bentonite stabilized samples (L3)

3.6 Effect of Bentonite On The Collapse Potential Of The Samples

From Figure 11-13, the Collapse Index for the untreated samples were found to range between 9-12 % and these fall under the "severe trouble" category according to [17] (Table 2). The additives generally improved the soil samples by reducing their collapse potential. For instance, 2% Bentonite addition gave an improvement of 30-33.3 % and reduced the collapse potential of the soil from 9-12 % to between 6-8 %, this moves the soil from a "severe trouble" category to a "trouble" category.

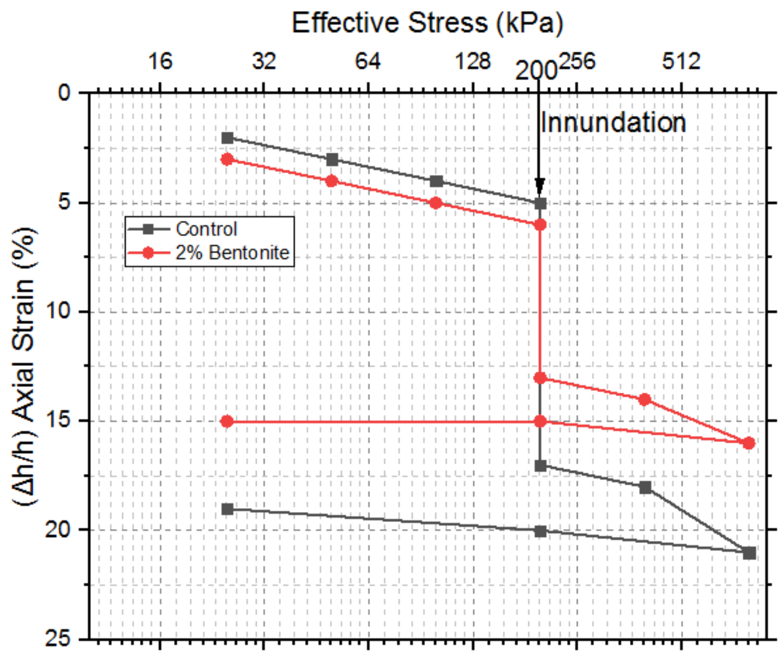

Figure 11 Bentonite stabilized samples (Location 1)

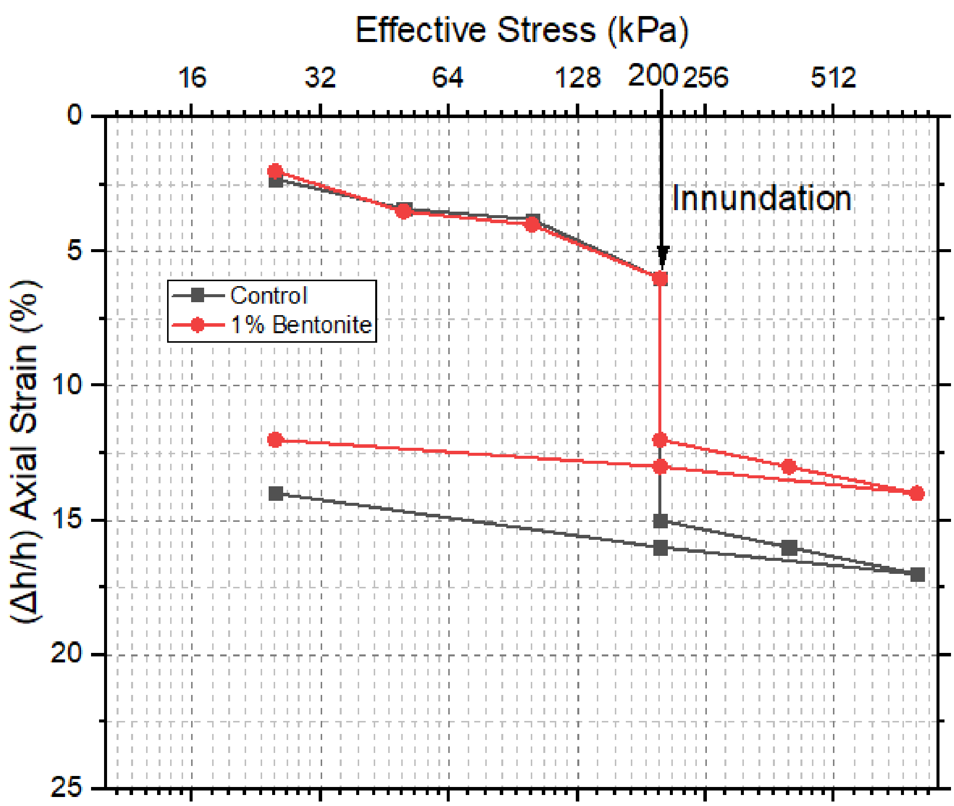

Figure 12 Bentonite stabilized samples (Location 2)

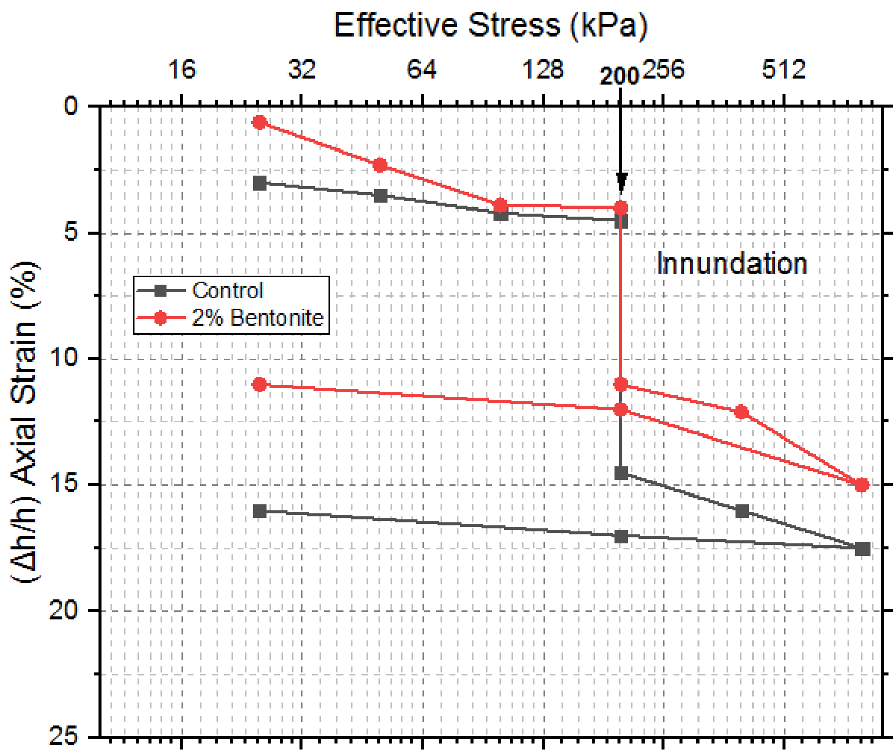

Figure 13 Bentonite stabilized samples (Location 3)

3.7 Effect of Bentonite on The CBR Strength

Figure 14 shows the result of the CBR test conducted on the optima samples in the three locations. The CBR values for the untreated samples gave very strong indications that the soil has high collapse tendencies. This was deduced from the massive reduction in strength of 64.70-80 % on soaking in water. The addition of 2 % bentonite to soils in sample locations 1 and 3 gave unsoaked CBR values of 13 and 16 respectively. On wetting these values reduced to 6 and 9 in each case. Also, the addition of 1 % bentonite to sample gave unsoaked and soaked CBR values of 20 and 10 respectively. The Bentonite treated samples, which gave an apparent strength improvement was found to experience a decrease in strength when soaked. Though, the addition of bentonite of bentonite resulted in the increase in the compressive strength of the soil due to its ability to fill the voids in the soil and adjust its gradation [2, 3, 38]. However due to the inherent nature of bentonite as an expansive material, some of this strength was lost on wetting [34]. Nevertheless, compared to the initial state of the soil, the improvement in the soil's engineering properties is quite significant.

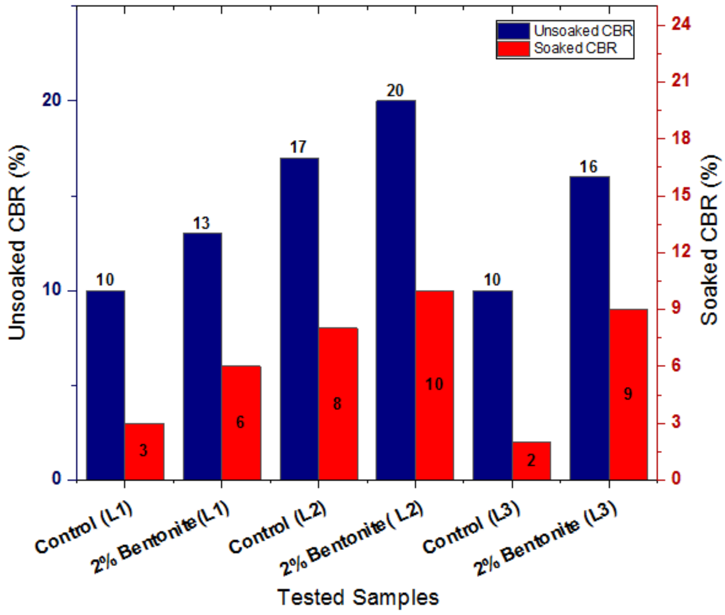

Figure 14 Bentonite stabilized soil samples (L1-L3)

4.0 CONCLUSION

The following conclusions were drawn from the research:

1. The results of the grain size distribution, consistency limits and X-ray diffraction tests revealed Kaolinite to be the dominant mineral of influence in the soil's clay fraction.
2. The inert nature of the kaolinite mineral in the soil among other factors was deduced to greatly contribute to the collapsible nature of the subgrade material since clay acts as the primary binding medium in the soil mineral skeleton.
3. 1-2% Bentonite was deduced to give optimal results. Though it didn't completely correct the collapse problem, it moved the collapse potential of the soil from "Severe trouble" category to a "trouble category".

Conflict of Interests

The authors declare that there are no conflict of interests regarding the publication of this paper.

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