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Stabilization of Soft Soil by Incinerated Sewage Sludge Ash from Municipal Wastewater Treatment Plant for Engineering Construction

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ABSTRACT: *Effective Management of Municipal Solid Waste cannot be achieved without involving wastewater treatment plants as they generate a sludge that must be disposed of in an environmentally friendly manner. Therefore, recycling or reusing them are the preferred options for sustainable development. The study presented the use of incinerated sewage sludge ash (ISSA) as a soil stabilizing agent. Oxide compositions were determined by the X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD) and Toxicity Characteristic Leaching Procedure (TCLP). The result showed that ISSA contains Silicon oxide,* SiO_2 *(61.42 %), Aluminum oxide* Al_2O_3 *(23.51 %) and Iron oxide,* Fe_2O_3 *(4.24 %) in high proportion. Clay soil with low to medium plasticity (CL) from an A-7-6 group was replaced with 0 % 3 %, 5 %, 7 % and 10 % ISSA. Test such as California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), Compaction and Atterberg limit were conducted. Soil obtained lowest OMC and highest MDD values both at 7% ash content. PI dramatically reduced at the short extension of curing age from 21 % to 7 % at 10 % ISSA content thereby improving it from category A7 to A2. With 2.25 % at 3 days realized as the maximum value for resistance to loss in strength, durability requirement is satisfied. ISSA effectively raised CBR values of soil from 15.6 % to 19.5 %, 32.6 %, 47.9 % and 46.4 % respectively. 7 % ISSA additive yielded the best result. Therefore, the study concludes that 7 % ISSA additive effectively enhance the strength of soft soils.*

Keywords: Wastewater, Incinerated Sewage Sludge Ash, Toxicity Characteristic Leaching Procedure, Soil Stabilization, California Bearing Ratio, Unconfined Compressive Strength

1. INTRODUCTION

Industrialization leads to rapid improvement in the standards of living. However, it has also resulted in pollution and the generation of solid wastes [1]. Rapid urbanization, climate change, inadequate maintenance of water and water infrastructure and poor solid waste management may lead to water scarcity, water pollution, adverse health effect, and rehabilitation cost that could overwhelm the reliance of cities [2]. It also releases pollutants capable of causing depletion of the ozone layer, global warming and significant rise of ocean level [3].

Waste is a prime and important environmental problem [4]. Presence of waste is an indication that materials are not being utilized efficiently. Valuable resources in the form of matter and energy are lost during waste disposal.

An effective waste management alternative is the need for the hour [1]. Recycling and re-use of waste is the preferred options for sustainable development, rather than incineration or landfilling, but with sewage sludge, this is not straight forward because of perceptions over contaminants, pathogens and its facial origin [5].

Wastewater resulting from poor management of municipal solid waste cannot be discharged into watercourses directly without treatment, as the good quality of water bodies for aquatic lives will be depleted and distracted [6]. Water treatment processes generate a sludge that must be discharged in an environmentally friendly manner [7]. Municipal wastewater is treated in sewage treatment plants also referred to as [8]. Within wastewater treatment plants, sewage sludge represents the residue generated during the primary, the secondary and the tertiary treatment [9].

Sewage sludge refers to the residual, semi-solid material produced as a by-product during sewage treatment [9]. The composition of sewage sludge is dependent on its origin in terms of the type of wastewater treatment, therefore it is variable and unpredictable. Thus, the handling of sewage sludge represents one of the most significant challenges in wastewater management [10]. Sewage sludge treatment by a variety of processes including aerobic digestion, anaerobic digestion, chemical fixation composting, heat drying, air drying, lime stabilization, landfilling, agricultural reuse, sea or surface water disposal and incineration of sewage sludge is the possible key to minimizing the risks in terms of the quantitative occurrence or negative impacts of mentioned components [11]. All these factors play an important role in the decision with regard to ultimate sewage sludge disposal [12].

In recent decades, the disposal of sewage sludge has been an important problem of sewage treatment plants [13]. According to [14], finding cost-effective and innovative solutions while responding to public pressures and stringent environmental quality standards are the challenges facing sludge managers and environmentalist. As a result, the alternative method and techniques of disposal need to be sorted out.

Dealing with soft subgrade or cohesive soil is one of the most major problems faced by geotechnical engineers [15]. Cohesive subgrade soils are expansive clays, characterized by the phenomena of swelling on the absorption of water and shrinkage on drying. These characteristics make them highly problematic when used as foundations for pavement and buildings. Pavement subgrade constructed with soft cohesive soil could evoke significant engineering problems [7].

Traditionally and widely accepted type of soil stabilization technique use bitumen emulsion as a binding agent for producing road base. However, it is not environmentally friendly and becomes brittle upon drying. Other alternative methods include cement, lime, and chemical stabilization which are quite expensive [16]. Hence cheaper alternatives are needed so as to reduce the cost of soil stabilization and in general the overall cost of construction.

Consequently, the development of techniques to safely reuse and efficiently dispose of sludge is vital to reducing the amount of the sludge generated. Since sludge ash consists of pozzolanic materials, which can be applied in many resource recovery kinds of research, sewage sludge ash is no longer considered as the final product of wastes [17].

This study would focus on some of the issues relevant to achieving practicable and affordable balance in sustainable sludge management by using incinerated sewage sludge ash to solve problems associated with soft subgrade soils and environmental pollution.

2. MATERIALS AND METHOD

2.1 MATERIALS

The materials used within the scope of this study were; Dewatered sludge sample, Cohesive soil, $HN0_3$, Buffer solution, Distilled water and Borax, Test sieve, Mechanical shaker, Drying oven, Tray, Scoop, Brush, Evaporation dish, Soil hydrometer, Measuring cylinders, Stop clock, Glass rod, Thermometer, Chemical reagents, Balance, Corrosion resistant containers, Pallete knives, A flat glass plate, Wash bottle, Cone penetrometer, Metal cups, Metal straight edge, CBR mould, 4.5 kg rammer, Metal tray, Standard Proctor mould, CBR machine, Surcharge weights, Digital pH meter (model no:HI98135), Atomic absorption spectroscopy (model no: HI98135), Beaker, Stove, Spatula, Density bottles, Wash bottle, X-ray diffractometer (SCHIMADZU 6000 MODEL), X-ray fluorescence thermo-scientific (ADVANT'X 1200 MODEL), Herzog vibrating cup miller.

2.2 DEWATERED SLUDGE SAMPLE

Dewatered sewage sludge was obtained from Wupa Wastewater Treatment Plant (W.W.T.P.) in federal capital territory Abuja and transported down to Abubakar Tafawa Balewa University Bauchi (ATBU Bauchi) in plastic bags as in Fig 1 below, serves the city of Abuja, the Capital of the federal republic of Nigeria with an average design flow of 13120 m^3/day), average B.O.D. Load 66,000 kg/day and effluent quality 15/20/10 BOD/TSS/N.

Fig -1: Wupa Wastewater Treatment Plant

The sludge was collected after primary and secondary treatment processes of wastewater treatment were conducted. About 50 kg of dewatered sludge was collected. The sludge obtained were air dried by natural evaporation in an open space to facilitate burning as depicted in Fig. 2. After drying, the sample was incinerated in a brick kiln at about 800°C at the ceramic section of the industrial design department of ATBU Bauchi and then grounded into particles. The grounded sludge was sieved through sieve no. 425 in the soil laboratory of the Civil Engineering Department, Faculty of Engineering and Engineering Technology, ATBU Bauchi. After sieving, about 7.5 kg of sieved sludge was obtained.

Fig -2: Drying of Dewatered Sewage Sludge Sample

2.3 CHARACTERIZATION OF INCINERATED SEWAGE SLUDGE ASH

Tests such as toxicity characteristics leaching procedure (TCLP), X-ray diffraction (XRD), X-ray fluorescence (XRF) were performed to analyze the properties of the ISSA.

2.4 COHESIVE SOIL

A natural occurring cohesive soil was used for the study. The soil sample was obtained from Bauchi metropolis, Bauchi State, Nigeria, at a depth of 1.5 m below the ground level using the method of disturbed sampling. A pH test was conducted according to [18] on cohesive soil. The natural moisture content and specific gravity of untreated cohesive subgrade soil were investigated. Standard laboratory tests were conducted in accordance with specifications outlined in [19] to verify the soil classification and also determine the compaction characteristics of the soil obtained for comparison with the assumptions made for data and subsequent test control.

2.5 ASH SOIL SPECIMEN

The specimens of soil and ash mixture were prepared by adding 0 %, 3 %, 5 %, 7 % and 10 % (in weight percentage) of sludge ash to soft soil. Moreover, in order to investigate the influence of sludge ash on the strength of soft soil, laboratory test such as pH was conducted according to [18] on the ash-soil specimen using a pH meter with model no: HI 98135, Atterberg Limits test in accordance with specifications outlined in [19]. Compaction and CBR test were performed on the samples using the compaction energy stipulated by the West African standard (WAS) while the Unconfined Compressive Strength (UCS) test was conducted in accordance with [19] for natural soil and [20] for the stabilized soil. The resistance to loss in strength (RLS) was calculated using Equations (1) below:

$$\text{Resistance to Loss in Strength} = \frac{\text{Pi}-\text{Pc}}{\text{Pi}} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where:
Pi = UCS of specimen cured for 7 days and soaked for 7 days (kN/m^2)
Pc = UCS of specimen cured for 14 days (kN/m^2)

3. RESULTS AND DISCUSSION

3.1 CHARACTERISATION OF INCINERATED SEWAGE SLUDGE ASH

To characterize ISSA, samples were prepared for TCLP. Results obtained from the preliminary analysis of sludge showed that leached metal concentration of sewage sludge ash was much less than those regulation set by the Environmental Protection Agency as shown in Table 1 and thus, the risk of hazardous heavy metals leaching following the use of solidified sewage sludge ash as construction materials may be safely concluded to be quite low. The potential environmental influence of SSA has been studied by several authors analyzing leaching from samples. [21],[12] and [7] all concluded that it was within allowable limits according to all parameters which are in line with the results obtained. Ongoing research has also shown that about 78 – 98 % Cd, Cr, Cu, Ni, Pb, and Zn present in sewage sludge are retained in the ash after incineration; these are however below detectable limit whereas up to 98% of the Hg may be released into the atmosphere with the flue gas [22].

Table -1: Toxicity Characteristics Leaching Procedure (TCLP)

Elements	Test Results (Mg/L)	EPA Standards (Mg/L)
Cd	0.04	1
Cr	0.25	0.5
Cu	1.9	15.00
Fe	2.52	-
Pb	0.64	5
Zn	15.95	25

Fig. 3 shows the XRD pattern of 800°C incinerated sewage sludge ash in this research. According to the XRD patterns, the major components that were identified in sewage sludge ash are quartz (silicon dioxide, SiO_2), and iron oxide (Fe_2O_3), CaO (calcium oxide). The XRD patterns show the peak of the sample at 23.9683°, where it mainly consists of quartz. The intensity at a peak of 23.968° is 466 counts per min. The next peak was at 18.1777° with 112 counts per min, consisting of iron oxide. Meanwhile, the peak at 47.4625° with 73 counts per min. shows that incinerated sewage sludge ash also comprises of calcium oxide which is in line with the findings by [23] using both raw and incinerated SSA as at 600°C and 800°C in the form of powder. This further explains the importance of the incineration process as it increased the amount of some content and lead also to the formation of others.

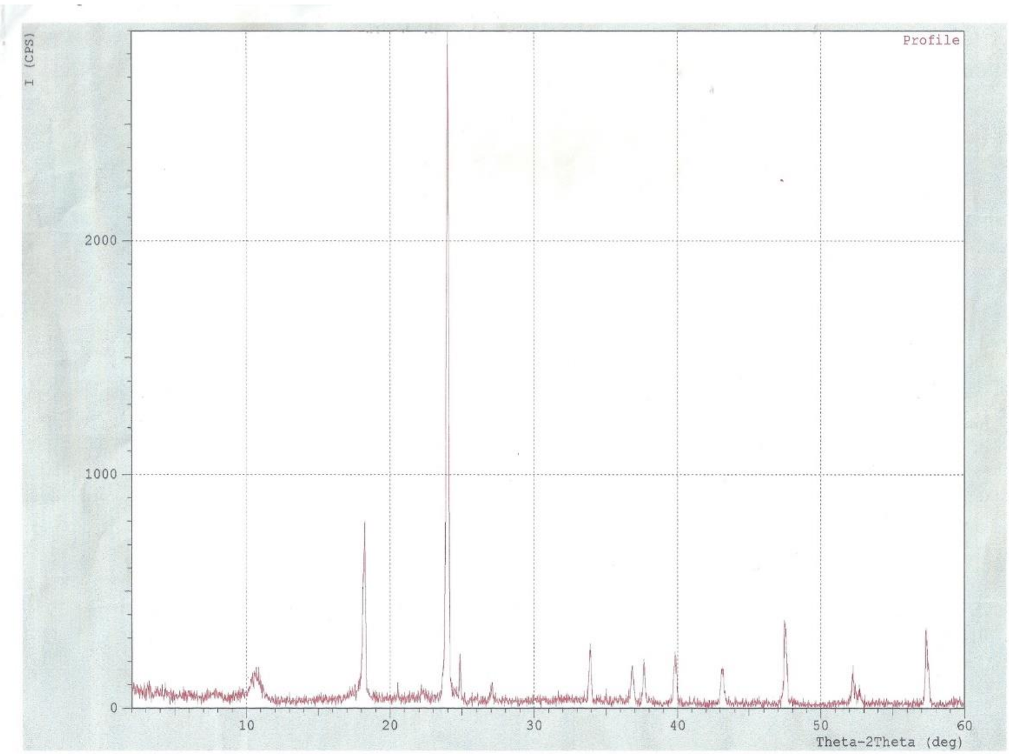

Fig -3: XRD pattern for incinerated sewage sludge ash

Test results obtained from XRF analysis showed that the main components of ISSA were Si, Al, and Fe as shown in Table 2 below. These were related to the three main oxides SiO_2, Al_2O_3, and Fe_2O_3, that were used to carry out a pozzolanic reaction [21]. This indicates that ISSA can carry out pozzolanic reaction with the aluminosilicates contained in fine particles of cohesive soil over a long period of time [7]. In general, the more calcium present in oxides for materials used as stabilizers, the quicker the pozzolanic reaction. CaO in ISSA used for this study was about 3.34%. This implied that the sewage sludge ash could be applied to improve the properties of cohesive soil. [24] compared XRF results for sludge ash and fly ash and found out that the combined amount of SiO_2, Al_2O_3, and Fe_2O_3, which were the main pozzolanas found were 88 % in sewage sludge ash and 75 % in fly ash. In this study, the combined amount was found to be 89.17 %. This indicated that the sewage sludge ash used has the potential to replace fly ash which is currently widely used in applications to improve engineering properties of cohesive soil.

Table -2: XRF Test Result for Oxide Content in ISSA

S/No	ELEMENTAL OXIDES	% COMPOSITION DARK BROWN SEWAGE SLUDGE
1	SiO_2	61.42
2	$Al2O_3$	23.51
3	Ti_2O	0.24
4	Fe_2O_3	4.24
5	K_2O	1.51
6	MgO	0.18
7	Na_2O	0.11
8	MnO	0.02
9	CaO	3.34
10	SnO	1.68

11	NiO	0.12
12	ZnO	0.18
13	Cr_2O_3	0.21
14	S	0.33
15	P_2O_5	0.79
16	PbO	0.15
17	M_OO_2	0.10
18	Zr_2O	0.01
19	V_2O_5	0.27
20	SrO_2	0.12
21	CdO	0.23
22	CuO	0.04
23	Nb_2O	0.05

Analyzing the results obtained from preparation and incineration of sludge ash, it can be concluded that incineration of sewage sludge at 800 °C reduces its volume to less than 50 %, which is a feasible solution to the land disposal problems. Besides that, incineration removed the organic compound and increases the composition of oxide element. Also, ISSA is a potential cement replacement as the major oxide of sewage sludge ash $SiO_2, Al_2O_3,$ Fe_2O_3 and CaO are similar to the Portland Cement based composites where it is the primary component found in the cement clinker.

3.2 PRELIMINARY INVESTIGATIONS ON COHESIVE SOIL

The results for the preliminary test on cohesive soft soil presented in Table 3 showed that the soil is reddish brown in color. From the grain size distribution in Fig. 4, it can be seen that the soil clay content was about 78 % (i.e 78 % of the material passed through sieve no. 200). According to the highway manual specification [25], the clay content for both sub-grade and sub-base and base materials must not exceed 35 %. This high clay content could be responsible for the instability of road pavement. The natural moisture content of the soil also observed was 16 %. It was suggested by Oyelami and Alimi [26] that, samples with high moisture content such as this are not suitable for road construction because it suggests a possible interaction of subgrade and sub-base soils with water from the numerous fractures which would increase the wettability of the soils. This condition is expected to greatly reduce the shear strengths of soil and therefore causes the incessant failure of the overlying pavements.

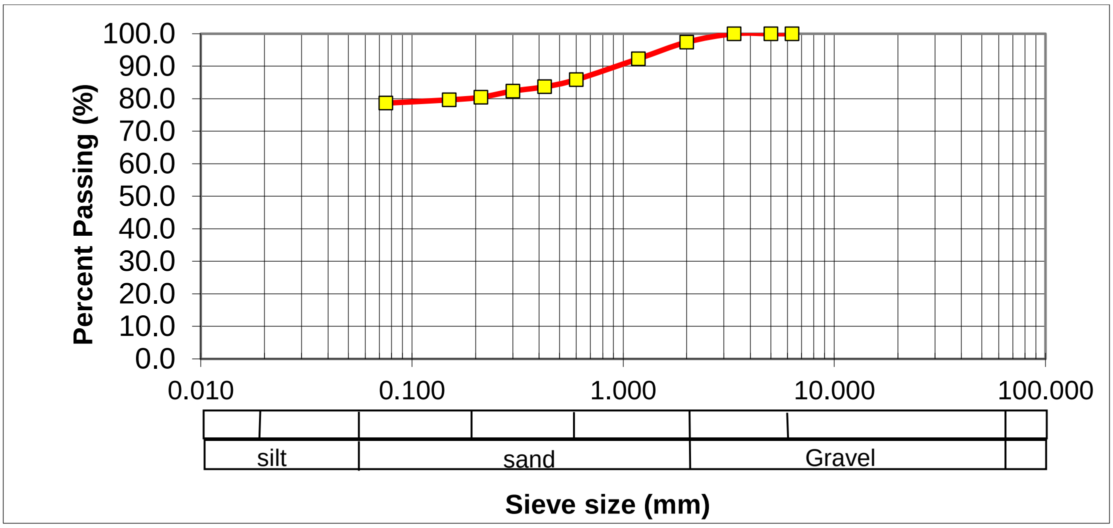

Fig 4: Particle size distribution curve

The liquid limit and plastic limit of the soil were 45 % and 23 % respectively. As outlined in [19], Liquid limits of 40 – 60 % and above are typical of clay soils while values of 25 – 50 % are typical of silty soils.

Soils with liquid limits <30 % are considered to be of low plasticity and compressibility. Those between 30% and 50% exhibit medium plasticity. Those with liquid limits >50 % exhibit high plasticity and compressibility. It follows that the sample falls within medium plasticity and based on high plasticity figures, the soils are expected to exhibit high swelling potentials and high shrinkage.

The soil was classified as A-7-6 using the American Association of State Highway Transportation Officials (AASHTO) soil classification system and CL using the Unified Soil Classification System (USCS). According to AASHTO classification of soil samples for highway, A-1 and A-2 soils are excellent and good soils for highway with percentage passing sieve No. 200 not more than 35 % while A-3 to A-7 soils are fair to poor soils with percentage passing sieve No. 200 greater than 35 %. Based on this, the soil was classified as poor soil for both sub-grades. The California bearing ratio of the untreated soil was found to be 15.6 % which can be said that the soil yielded fair CBR value. This deficiency could be attributed to the high amount of clay present in the soil or ingress of water into the soil. The average specific gravity obtained was found to be 2.56 which further classified the soil as an inorganic clay.

Table -3: Properties of Untreated Soil Sample

Test	**Result**
Percentage passing sieve no. 200 Natural moisture content	78% 16.20%
Liquid limit (LL)	45%
Plastic limit (PL)	23%
Plasticity index (PI)	22%
Optimum moisture content	16%
Maximum dry density(MDD)	1.58 mg/m^3
pH	6.77
Color	Reddish Brown
California bearing ratio	15.60%
Specific gravity	2.6
Soil classification:	
1. AASHTO	A-7-6
2. USCS	CL

3.3 ANALYSIS OF ASH-SOIL SPECIMEN

3.3.1 ATTERBERG LIMIT

In this study, atterberg limit test was carried out to determine the plastic limit (PL) and liquid limit (LL) of soil based on [27]. Besides that, the plasticity index of the soil was also measured to classify it [28]. The effect of the ISSA on the Atterberg's limits of the soil sample is illustrated in Fig. 5. Plastic indices for sludge ash-soil specimens were reduced dramatically at the short extension of curing age. As seen on the figure, the plasticity index of 0 % sludge ash additive (i.e untreated soil) was found to be 22 %. However, it began to decline at 3 %, 5 %, 7 % and 10 % sludge ash additive to 19 %, 15 %, 9 % and 7 % respectively. This behavior implies that the engineering characteristics of cohesive soil have improved from category A7 to A2 and that the plasticity index of the soil has changed from medium to low plastic soil. From the AASHTO soil classification of soil samples for highway, A-1 and A-2 soils are considered excellent and good soils for highway construction. Thus, this result indicates that the additive of ISSA could improve the engineering characteristics of soft soil from poor to good subgrade soil.

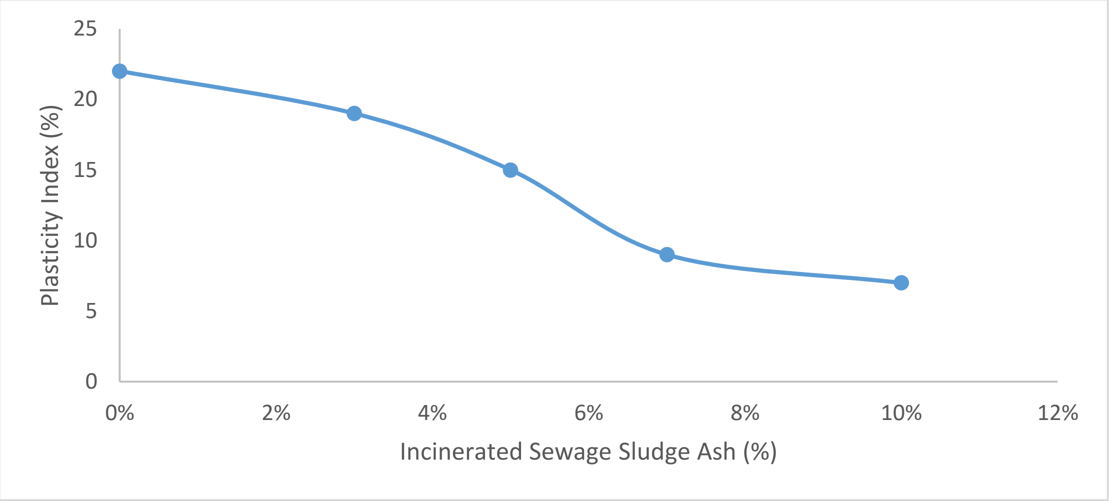

Fig -5: Plasticity Index

3.3.2 COMPACTION CHARACTERISTICS

Soil-ISSA specimens were prepared by mixing the desired proportions of potable water, soil, and ISSA. The percentages of ISSA used in the study ranged from 0 to 10 % by weight of dry soil. The mixtures were thoroughly mixed in a tray to obtain a uniform color as described by [29]. The moisture-density relationships of the soil samples for various percentages of ISSA added were compacted using WAS compaction energies. Maximum Dry Density and OMC of the soil sample with 0 % ISSA were found to be 16 % and 1.58 mg/m^3 respectively. However, as depicted in Fig. 6, an addition of 3 %, 5 %, 7 % ISSA increased the MDD and caused a reduction in the OMC which is in agreement with [30].

According to Bello [31], samples characterized by a high value of dry density and low moisture content are best suitable as sub-grade materials. As suggested by [32], increase in dry density and reduction in moisture content observed was due to the fact that ISSA has higher unit weight and its specific surface area is smaller than that of the soil samples. MDD was also increased due to the fact that the fine particle of the ISSA filled the pores within the soil sample causing it to be more compact and denser. Further addition of ISSA beyond 7 % (i.e. at 10 % of ash additive) lessened the MDD. This result can be attributed to sludge ash as either filled with clods or filling pores among soil particles as ash content increased beyond 7 %. Thus, [33] have earlier reported that, when the amount of sludge ash additive reached the maximum level, soil particles in per unit volume of sludge are formed from condensed clods. The highest value for MDD observed from all samples was 1.68 mg/m^3 at 7 % sludge ash additive. In general, the trends of the compaction curves shown in the plot is one of increasing MDD values with the corresponding decrease in OMC as more sludge ash was added. The adjustment in the composition of the stabilized mixtures reflected in changes for both MDD and OMC [34].

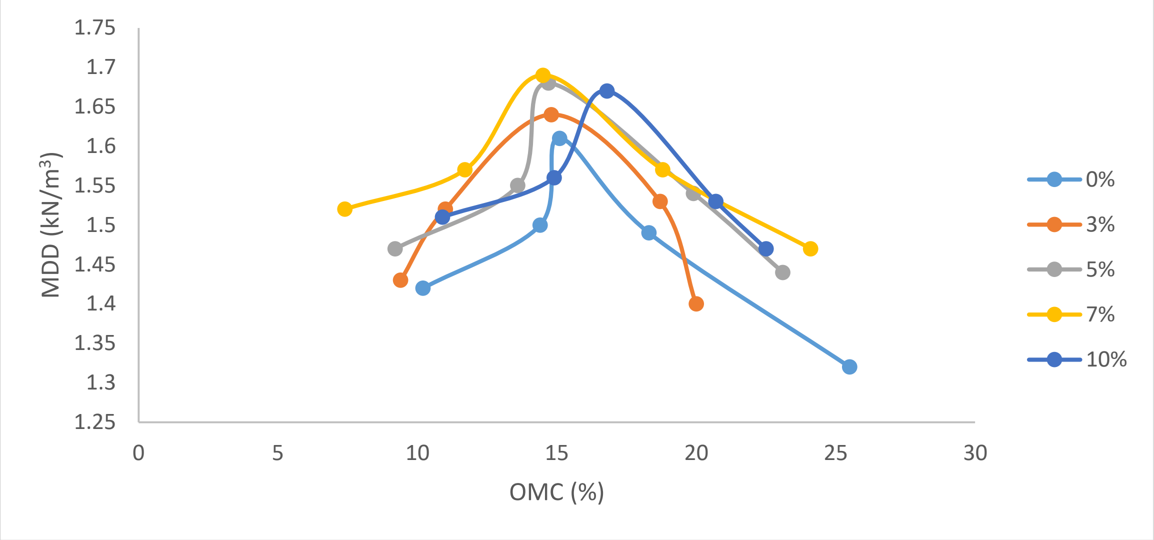

Fig -6: Compaction tests for sludge ash-soil specimens

3.3.3 CALIFORNIA BEARING RATIO (CBR)

CBR test is a familiar test widely used in design to evaluate the strength of soils for base and sub-base applications [29]. In this study, the CBR test was conducted with the West African Standard compaction energy. Results indicated that when the proportion of sludge ash increased in ash-soil samples, CBR values rose as shown in Fig. 7. CBR value of the treated samples increased at a higher percentage of ISSA content. At 3 %, 5 %, 7 % and 10 % ash additive, CBR values rose to 19.5 %, 32.6 %, 47.9 % and 46.4 % respectively. Based on the results obtained it is safe to say that ISSA additive can improve conditions of subgrade soil efficiently with an increased amount of ash added which is in agreement with [7],[32]. This strength increase could be due to the cementing property of the ash, ability of the ash to alter the absorbed water films, increased cohesion with the cementing agent (i.e sludge ash) and adding internal friction. Furthermore, [25] specifies CBR values as 15 % minimum for use as subgrade soil material. It can be seen from the plot that ISSA additive of 7 % yielded maximum results followed by 10 % both of which are classified as excellent subgrades for road construction as they are greater than the required values in the specification. An increase in the CBR value would significantly reduce the total thickness of the pavement [35].

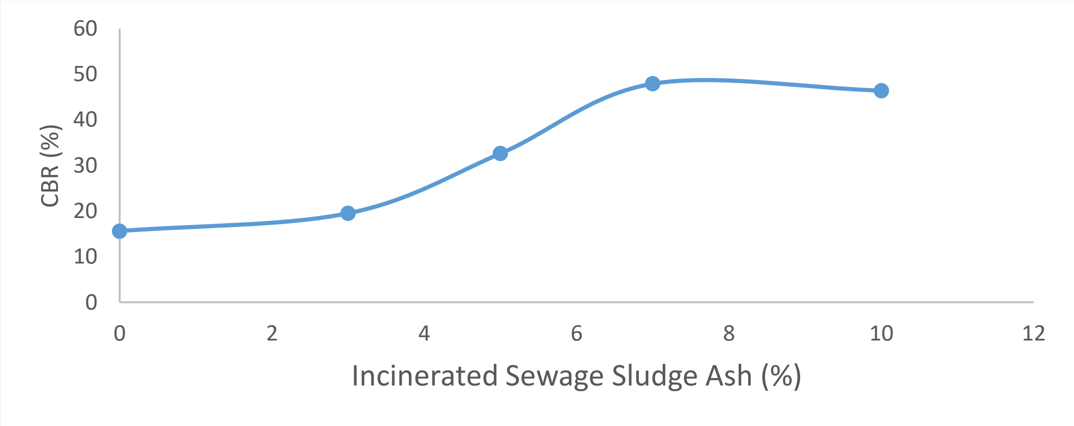

Fig -7: CBR curve for various Percentages of ISSA addition

3.3.4 UNCONFINED COMPRESSIVE STRENGTH

Strength characteristics of soils treated with ISSA as stabilizers are crucial as the structure of such materials evolve with time due to continuing pozzolanic reactions [36]. To illustrate the variation of unconfined compressive strength in this study, the soft soil sample was treated at 3, 5, 7 and 10 % ISSA additive. Fig. 8 shows the unconfined compressive strength result plot for untreated and treated soft soil samples at 7, 14, 28 and 7+7 curing days. The control sample was cured for the days as stated earlier where continual increment was observed at all curing periods except for 7+7 curing days.

The variation of UCS with various percentages of ISSA after compacting the samples at OMC for 7 days, showed that there was a significant improvement in the compressive strength after curing at all the incremental levels. However, the peak 7-day UCS value of 753 kN/m^2 was recorded at 10 % ISSA while the UCS value of 420 kN/m^2 was obtained at 0 % ISSA. The increased strength for treated soil sample with various percentage of ISSA for 7 days ranged between 0.75 to 0.79 times higher compared to untreated soil. When cured for 14 days, the strength increased by 0.47 to 0.56 times higher than the original soil. It is interesting to note that, the increment in the strength of 14 days curing time is a bit lower compared to 7 days curing time. At 28 days, the incremental range was from 0.22 to 0.29 times higher than the untreated soil. However, it was lower than the 14 days curing. After the 7+7 days curing, strength of 207 kN/m^2 was realized for the untreated sample while 253 kN/m^2, 272 kN/m^2, 293 kN/m^2 and 304 kN/m^2 for the treated samples at 3 %, 5 %, 7 % and 10 % ISSA additive. Thus, the incremental range was from 0.22 to 0.47 times higher than the untreated soil.

The significant increase in the ISSA content improved the UCS further. This is because increased ISSA percentage lead to the higher wetness absorption that took place, resulting in less moisture content. As more water is required, loss in strength of soft soil occur. It was observed that the treated soil with ISSA have better strength compared to untreated soil and now evident from the graph that up to the addition of 10 % ISSA, there was an increment in compressive strength.

Increase in UCS was proportional to the increase of ash admixture at the longer extension of curing ages. In this study, ISSA possessed the same pozzolanic properties as fly ash and acted as a stabilizer to control the swelling force of soft soil.

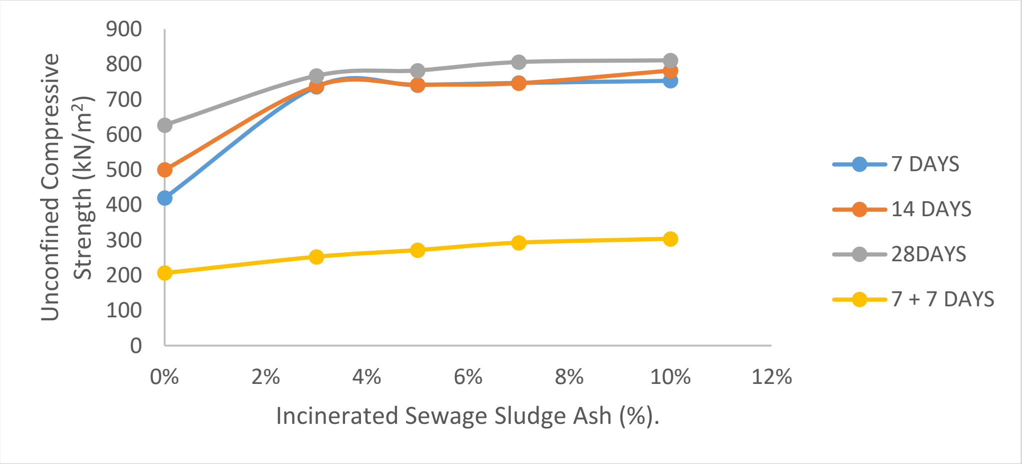

Fig -8: Unconfined Compressive Strength as a function of ISSA content

3.3.5 RESISTANCE TO LOSS IN STRENGTH

It was observed from the results that the reduction in UCS value was less at higher ISSA content. This was due to the formation of more pozzolanic material [29] at higher ISSA content as they were much available for reaction to take place. Table 4 shows that the resistance to loss in strength increased with the increase in ISSA content at all curing periods. Thus, the durability required for the stabilized soil as stipulated by [20] was also satisfied. This is because the resistance to loss in strength in all the specimens never exceeded the maximum 20 % allowable loss in strength by comparing the unconfined compressive strength of 14-days old cured specimen with the unconfined compressive strength of 7 days curing and 7 days soaking in water.

Table -4: Resistance to the loss in strength

Sewage sludge ash content (%)	14 DAYS kN/m^2	7 + 7 DAYS kN/m^2	Resistance to the loss in strength (%)
3	738	227	2.25
5	742	272	1.73
7	746	293	1.55
10	782	304	1.57

4. CONCLUSION

As recycling or reusing the sludge are the preferred options for sustainable development, the study presented the use of ISSA as a soil stabilizing agent and to serve as safe and most economical sludge disposal ways smeans. Hence, the following deductions were drawn:

MDD and OMC of the soil sample with 0 % ISSA were found to be 16% and 1.58 mg/m^3 respectively. The result of the treated sample revealed that MDD increased and caused a reduction in OMC as sludge ash content increased up to 7 % by weight. CBR value at 0 % ISSA additive was found to be 15.6 %. At 7 % ash additive, CBR value of 47.9 % yielded maximum results which classified it as an excellent subgrade for road construction. Plasticity index of 0 % sludge ash additive was found to be 22 %. However it began to decline at 3 %, 5 %, 7 % and 10 % ISSA additive to 19 %, 15 %, 9 % and 7 % respectively. This behavior implies that the soil has improved from category A7 to A2 and that the PI changed from medium to low plastic soil.

The variation of UCS with various percentages of ISSA at OMC for 7 days showed that there was a significant improvement in the compressive strength after curing at all the incremental levels. However, as 420 kN/m^2 was obtained at 0 % ISSA for UCS, the peak 7-day UCS value of 753 kN/m^2 was recorded at 10 % ISSA. Resistance to the loss in strength (RLS) increased with the increase in ISSA content at all curing periods and durability requirement for the stabilized soil was satisfied. This is because RLS in all the specimens never exceeded the maximum 20 % allowable by comparing the UCS of 14 days old cured specimen with that of 7 days curing and 7 days soaking in water. 7% ISSA by weight of the soil is recommended to be considered for use, as it caused a significant improvement in the engineering properties of the soft soil.

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