2nd International Civil Engineering Conference (ICEC 2020)
Department of Civil Engineering
Federal University of Technology, Minna, Nigeria

Stabilization of Clay Soil Using Cement and Volcanic Ash for Sustainable Pavement Structure

Musa, A.; Alhaji, M. M. & Alhassan, M.
Department of Civil Engineering, Federal University of Technology, Minna
Email: musanature@yahoo.com

ABSTRACT

A residual clay soil was collected at Bako village along Gwagwalada-Garki road in Federal Capital Territory of Nigeria using the method of disturbed sampling. The clay was characterized and microstructural tests including X-ray diffraction (XRD) test, Scanning Electron Microscopy (SEM) test and Electron Dispersive Spectroscopy (EDS) tests were also conducted on the clay soil. The clay was then compacted at Standard Proctor energy level to obtain the maximum dry density (MDD) and optimum moisture content (OMC). Unconfined compressive strength (UCS) tests were then conducted on the natural clay and clay mixed with 0, 2, 4 and 6% cement which are in turn admixed with 0, 3, 6, 9, 12 and 15% volcanic ash (VA) each. Results showed that the clay classified under clay of high plasticity (CH) based on unified soil classification system. The clay also consists majorly of montmorillonite, ankerite, calcium silicide, anorthite, anothoclase and orthoclase minerals. The SEM test revealed flaky nature of the clay with pore spaces. The natural clay specimen compacted at standard proctor energy level mixed with varied composition of VA showed 2.5 times increase in UCS compared to the value of the natural clay. For clay made of 6% cement with varied percentage VA, the UCS increased by 80% compared with UCS of specimen containing 6% cement-0% VA. The optimal VA value for maximum UCS values lies between 6% and 9% VA.

Keywords: Cement, Clay, Stabilization, Sustainability, Volcanic ash.

1. INTRODUCTION

Clay soils constitute major problems in geotechnical engineering compared to other forms of soils. Their particles are normally surrounded by negative charges resulting from the ions around the particles. Soft clay soil has the characteristics of high deformation on application of small loads while stiff unsaturated clay soils have the tendency of large swelling with ingress of water. Therefore, the application of clay soils as foundation soil for structures either suffers excessive deformation on application of load or swells excessively with ingress of water. In most occasions, road pavement structures have been founded on clay soils or clay soil have been used as pavement material due to non-availability of quality pavement materials. In any of these cases, the clay soil will require stabilization to improve its strength and durability.

A lot of stabilization methods ranging from mechanical, chemical and biological forms have been used to stabilize clay soils. Mechanical stabilization entails mixture of two or more soils of different gradation in other to achieve optimal mixture which when compacted will result in to most dense state. Some of the mechanical stabilizations includes the work of Ibrahim (1983) who stabilized black cotton soil with sharp sand found as deposit below the superficial black cotton soil deposit. The mixture was used for the construction of Maiduguri-Gamburu road in north-eastern Nigeria. Another mechanical stabilization is the stabilization of clay soils using non-plastic silt (Alhaji and Sadiku, 2015). The unconfined compressive strength (UCS) was observed to increase from 272 and 770kN/m^2 for British Standard Light (BSL) and British Standard Heavy (BSH) compaction energy levels at 0% replacement to 295 and 795kN/m^2 for BSL and BSH compaction energy level respectively at 10% replacement after which the values reduced to 22 and 60kN/m^2 for BSL and BSH compaction energy levels respectively at 70% replacement. Stabilization of clay soil using cold reclaimed asphalt pavement (RAP) is also a form of mechanical stabilization (Alhaji et al, 2014). The result showed 7.2% increase in UCS and 9.2% increase in California Bearing Ratio (CBR). Mechanically stabilized clay soil using quarry dust was treated with cement kiln dust (Amadi and Osu, 2016). It was observed that curing time affects the strength of the specimen tremendously. The UCS increased from 1.25 to 5.25 times higher than the value of specimen tested immediately after preparation. Some other mechanical forms of stabilization are studies by (Ola, 1981; Louafi and Bahar 2012; Diouf et al 1990) on the mechanical stabilization involving clay soils mixed with sandy soil.

Chemical stabilization entails mixture of chemical substance like cement, lime, or mixture of both, etc to a deficient soil in other to improve its strength and durability. Stabilization of soils using cement or mixture of cement and pozzolana has become a common phenomenon and has yield positive result in many instances. Portland cement alone have been used to stabilize soil for road base (Ismail et al, 2014). Tremendous improvement in strength and durability was recorded with the addition of Portland cement. Some other works include the stabilization of lateritic clay using cement and bagasse ash as pozzolana (Osinubi and Alhaji, 2009), variation of compressive strength of cement-treated marine clay with water content (Tsuchida and Tang, 2015), effect of sodium silicate and promoter on the strength of cement stabilized clay (Ma et al, 2015), cohesive soil stabilized with a mixture of cement and rice husk ash (Prasad et al, 2017), improvement of weak residual soil using cement and rice husk ash (Basha et al, 2005). All these studies recorded higher strength compared to the use of cement alone.

The common biological stabilization in use is the application of enzymes for improvement of soils. The work by (Khan and Taha, 2015; Sahoo and Sridevi, 2018; Muguda and Nagaraj, 2019; Rao and Hanuma, 2019; Somireddy, 2019; Renjith et al, 2017) are indication of the potential of enzymes as soil stabilizers. Volcanic ash are products from volcanic eruptions and are deposited around the vents of the eruption epicenter. A lot of studies on the engineering use of volcanic ash have been carried out in Indonesia and some other countries in Africa. However, little or no study have been done on the volcanic ash found around the recent volcanic eruptions in Jos Plateau area of Nigeria. This research is intended to evaluate the effect of volcanic ash in Jos Plateau on the engineering properties of cement stabilized clay soil.

1.1 STABILIZATION OF SOILS USING VOLCANIC ASH

Clay soil has been stabilized with varied composition of cement, lime, volcanic ash and a combination of these chemicals (Hossain et al, 2006). Compaction, unconfined compressive strength, split tensile strength, modulus of elasticity and California bearing ratio tests were used as evaluation criteria to determine the effect of these chemicals on the strength and durability of the clay soil. It was concluded that the stabilized clay using these chemicals can be employed in various constructions including road pavements and low-cost housings. Hossain and Moi (2011) worked on the effect of cement kiln dust and volcanic ash on the strength and durability of clay soils. Compaction, unconfined compressive strength, split tensile strength, modulus of elasticity and CBR tests were used to determine the effect of cement kiln dust and volcanic ash on the strength and durability of clay soils. It was concluded that stabilization of clay using these chemicals can result to sustainability in construction industries.

A deposit of volcanic ash was characterized, classified and utilized as a soil stabilization material in Indonesia (Rifa'i et al, 2013). It was observed that addition of volcanic ash and curing of the specimen for 14 days increased the engineering properties of the soft clay, decrease liquid limit and increased the bearing capacity of the clay. 35% volcanic ash and 5% lime was observed to be the optimum mixture required for maximum strength. A volcanic ash that resulted from volcanic eruption on Mountain Merapi, admixed with lime was used to treat clay soil (Rifa'i and Yasufuku, 2014). The study revealed that volcanic ash and lime decreased the fine fraction of the clay, decreased the consistency limit to non-plastic soil, decrease the swelling potential and increased the bearing capacity of the clay. 35% volcanic ash and 9% lime was observed to be the optimum mixture for maximum strength. Volcanic ash obtained from Kelud admixed with lime was used to treat clay soil (Latif et al, 2016). Addition of lime and volcanic ash resulted to decrease in consistency limits and increase the grain size of the clay particles. 20%, 22%, 25%, 27% and 30% volcanic ash admixed with 5% lime each was observed to be the optimum mixture for maximum geotechnical improvement. Latif et al (2016) worked on the chemical characterization of some volcanic ash deposits in Indonesia considering the morphology and mineralogy. X-ray diffraction (XRD) and Scanning Electron Microscopy (SEM) tests were used as evaluation criteria to determine the mineralogy and morphology of some selected volcanic ash deposits. The study showed that Merapi volcanic ash is a form of fibrous glassy particles with elongated particles, Sinabung volcanic ash shows berry-like glass particles with angular blocky forms while Kelud volcanic ash texture is sponge-like glass.

A clay soil which classified as clay of low plasticity (CL) according to unified soil classification (USCS) system and A-7-6 according to American Association of State Highway and Transportation Officers (AASHTO) classification system was treated with a mixture of 2% gypsum and varied composition of volcanic ash (Roesyanto et al, 2017). CBR and UCS tests were used as evaluation criteria to determine effect of volcanic ash on gypsum treated clay soil. The UCS increased from 1.4kg/cm^2 for clay soil without additive to 2.79kg/cm^2 for clay treated with 2% gypsum and 10% volcanic ash. The soaked CBR however, increased from 4.44% for clay without additive to 9.07% for the clay treated with 2% gypsum and 9% volcanic ash. Quick lime and volcanic ash have been used to stabilize clay soil with CBR as evaluation criteria (Hastuty et al, 2017). The result showed that the liquid limit reduced from 29.88% to 11.33% on application of 4% quick lime and 24% volcanic ash. The maximum CBR of 9.01% was observed at 4% quick lime and 8% volcanic ash.

A clay soil which classified under clay of low plasticity (CL) according to USCS was treated with 4% volcanic ash and varied composition of sugarcane bagasse ash (Hastuty et al, 2017). The UCS increased from 1.38kg/cm^2 to 5.1kg/cm^2 at optimal mixture of 4% volcanic ash and 10% sugarcane bagasse ash. The maximum CBR value of 13.91% was recorded at optimal mixture of 4% volcanic ash and 4% sugarcane bagasse ash. Cheng and Huang (2019) worked on the stabilization of black cotton soil with lime (0-9%), volcanic ash (0-25%) and their combinations. It was reported that black cotton soil (BCS) stabilized with a combination of lime and volcanic ash yields higher CBR and UCS when compared with single stabilizer. BCS stabilized with 3% lime and 15% volcanic ash meets the requirement for use as base course material for roads.

2. EXPERIMENTAL MATERIALS AND METHOD

2.1 MATERIALS

The materials used for this research includes clay soil, cement, volcanic ash and distilled water. The clay was collected from Bako village, a site proposed for T. Y. Danjuma University along Gwagwalada-Garki road. The clay soil was collected at depth of between 0.5m – 1.5m using the method of disturbed sampling. The clay soil was then air-dried and pulverized according to the method highlighted in part 1 of BS1377 (1992). The cement used was a Portland cement purchased locally in a commercial market and kept in a dried place to avoid moisturization of the cement. The volcanic ash used was collected from Keran Swap hill in Mangu Local Government of Plateau State, Nigeria. This area experience one of the most recent volcanic activities in Nigeria and revealed the ash to have solidified in to rocky forms. The solidified volcanic ash was then repulverised and sieved through BS sieve 0.075mm before used for stabilization. The distilled water was purchased from a medical shop opposite General Hospital, Minna, Niger State, Nigeria. These materials are shown in figure 1.

Figure 1: (a) Clay soil; (b) Unpulverized volcanic ash; (c) Pulverized volcanic ash

2.2 METHODS

The air-dried clay soil sample was characterized through the determination of its index properties in Civil Engineering Laboratory, Federal University of Technology, Minna, Nigeria, using the method highlighted in BS 1377 (1992). X-Ray Diffraction (XRD) and X-Ray fluorescence (XRF) tests were also carried out on the clay soil. The tests were conducted in Ithemba Laboratory, Somerset West, South Africa and Electron Microscope Unit, University of Western Cape, Cape Town, South Africa. Phase characterization of the minerals and estimate of the average crystallite size of the various synthesized materials were conducted on a Bruker AXS D8 XRD system.

Scanning Electron Microscopy (SEM) test was also carried out by placing 0.05 mg of the synthesized materials, sprinkled on a sample holder, covered with carbon adhesive tape and wire sputter coated with Au-Pd using Quorum T15OT for 5 minutes prior to analysis. The sputter coated samples were characterized using Zeiss Auriga HRSEM. The SEM, which visualizes morphology and microstructure of the synthesized products were analyzed using Zeiss Auriga HRSEM. This was carried out to determine the structure of the mineral particles contained in the clay. The clay was then mixed with 0, 2, 4 and 6% cement which in turn is mixed with 0, 3, 6, 9, 12 and 15% volcanic ash each as shown in table 1. The idea behind 15% maximum volcanic ash is derived from the works of () whose optimal percentage of volcanic ash used for soil stabilization ranges from 4% to 9%. The clay soil and clay mixed with varied proportions of cement and volcanic ash were compacted at standard proctor compaction energy level to obtain the maximum dry density (MDD) and optimum moisture content (OMC) of the mixtures. The predetermined MDD and OMC were then used to prepare specimen for UCS test.

The UCS specimen of 76mm diameter and 76mm height was molded at standard proctor compaction energy level. The specimen was wax-cured for 7, 14, 28, 60 and 90 days before UCS test as shown in figure 2. The test was carried out in Civil Engineering Department, Federal University of Technology, Minna at speed of 1.2mm/min.

3. RESULTS AND DISCUSSIONS

The results of the experiments are hereby presented and discussed.

3.1 INDEX PROPERTIES TESTS

Table 1: Mixtures of cement and volcanic ash

Cement (%)	VA (%)
0.0	0.0
	3.0
	6.0
	9.0
	12.0
	15.0
2.0	0.0
	3.0
	6.0
	9.0
	12.0
	15.0
4.0	0.0
	3.0
	6.0
	9.0
	12.0
	15.0
6.0	0.0
	3.0
	6.0
	9.0
	12.0
	15.0

The result of the index properties of the clay soil is shown on table 2 while the grain size analysis graph of the clay is presented in figure 3. From table 2, the clay classified as A-7-6 according to AASHTO soil classification system and clay of high plasticity (CH) according to Unified Soil Classification System. This is an indication that the clay cannot be used as material for road pavement structure and cannot also be used to support pavement structures. It therefore requires stabilization to improve its strength and durability. Figure 3 revealed very high composition (52%) of clay sized particles with gap-gradedness between 63% to 82% at grain size of 0.06 to 0.07mm. This can create pores within the clay mass which can further reduce the strength of the molded clay.

3.2 MICROSTRUCTURAL ANALYSIS OF THE CLAY SOIL

The result of the microstructural analysis of the clay soil are shown from XRD, SEM and EDS results are as shown in figures 4, 5 and 6.

Result of Scanning Electron Microscopy (SEM) and Electron Dispersion Spectroscopy (EDS) are shown in Figures 5 and 6. The EDS result showed 24.9% carbon, 39.8% oxygen, 0.76% magnesium, 9.8% Aluminium, 17.4% silicon, 0.59% potassium, 0.54% calcium, 0.36% titanium and 5.6% iron. The silicon-aluminium ratio of 1.78 confirms the presence of montmorillonite mineral. The SEM image of the soil, remolded at Standard Proctor compaction energy level (Figure 4), revealed occasional presence of air voids (as highlighted in the figure) and dense fabric of flecky clay particles similar to those

Figure 2: Unconfined compressive strength test

reported by Zang *et al.* (2013), Jaiswal and Lal (2016) and Abdullah *et al.* (2017).

Figure 4 present result of XRD test on the clay soil. The result indicates the presence of substantial composition of minerals, including montmorillonite, ankerite, calcium silicide, anorthite, anothoclase and orthoclase minerals. The presence of a peak at 8.96^0 also confirms the presence of montmorillonite mineral (Sharma et al, 2012). These are both primary and secondary minerals. Montmorillonite minerals can increase activity, and hence the consistency of the clay soil. The MDD and OMC of the clay soil, compacted at Standard Proctor energy level was observed to be 1.634 g/cm^3 and 18.5% respectively.

Table 2: Summary of Index Properties of the clay

Description	**Quantity**
Sand	18.4
Silt	28.9
Clay	53.0
Liquid limit	64.3
Plasticity Index	35.9
Specific Gravity	2.66
MDD (Standard Proctor compaction)	1.634
OMC (Standard Proctor compaction)	24.5
AASHTO soil classification	A-7-6
Unified Soil classification	CH

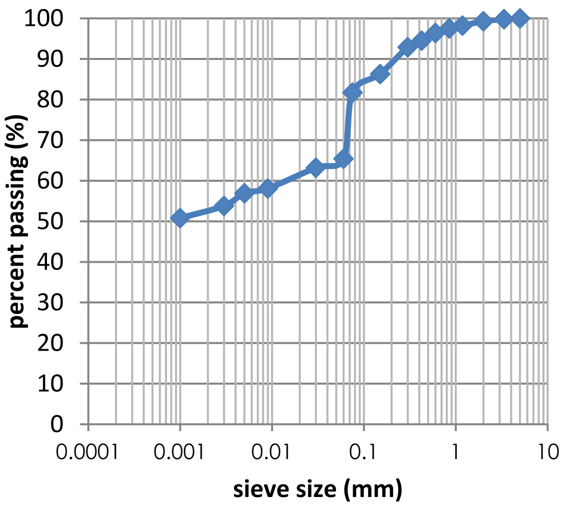


Figure 3: Grain size analysis of clay

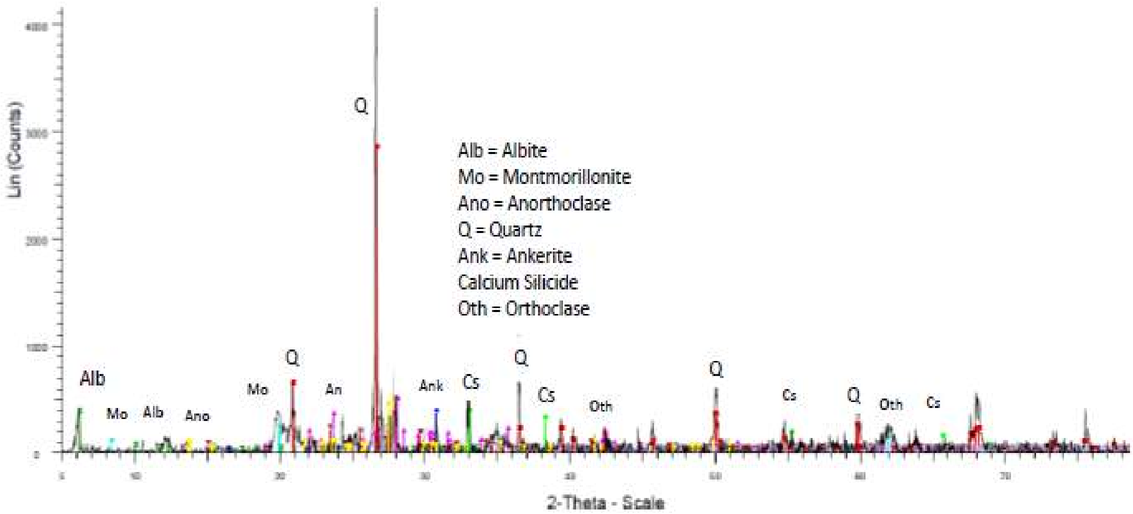


Figure 4: Graph of XRD Result

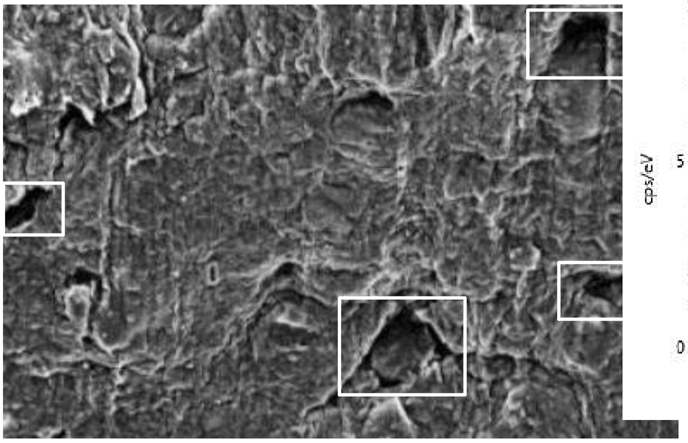


Figure 5 Result of SEM Test

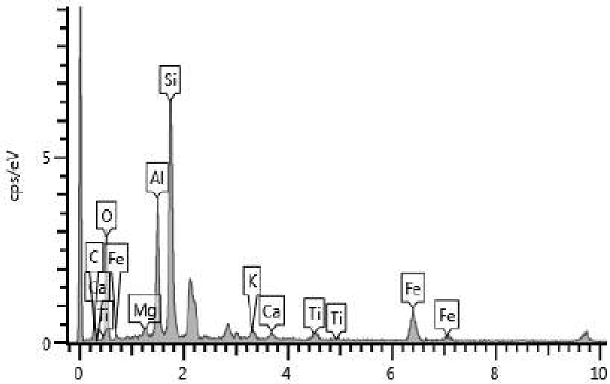
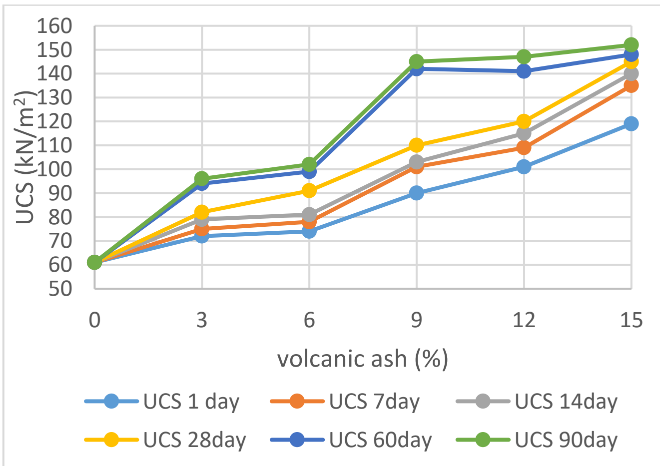


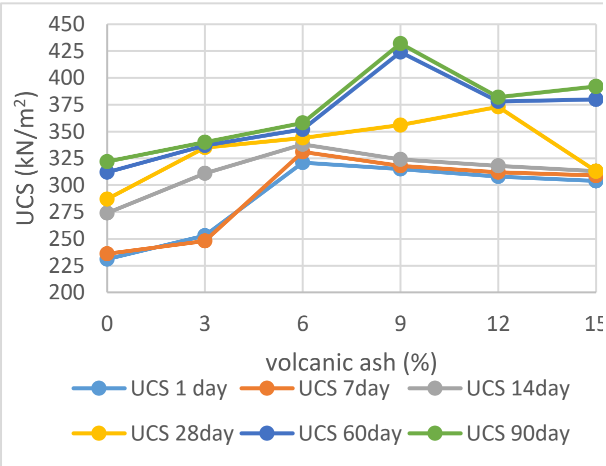
Figure 6: Result of EDS test

3.3 EFFECT OF VOLCANIC ASH ON CEMENT STABILIZED CLAY

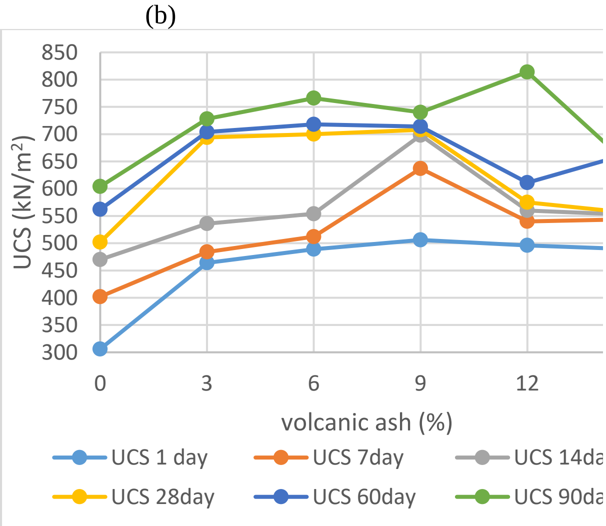
The effect of UCS with varied composition of volcanic ash (VA) for 0, 2, 4 and 6 percentages of cement is shown in figures 7a, 7b, 7c and 7d respectively. Variation of UCS with varied percentage of VA and 0% cement is shown in figure 7a. The result revealed continuous increase in UCS with increase in VA. The values increased from 61kN/m^2 at 0% volcanic ash to 96, 102, 145, 147 and 152kN/m^2 at 3, 6, 9, 12 and 15% VA respectively. Addition of 15% VA therefore represent 2.5 times increase in UCS of the clay.



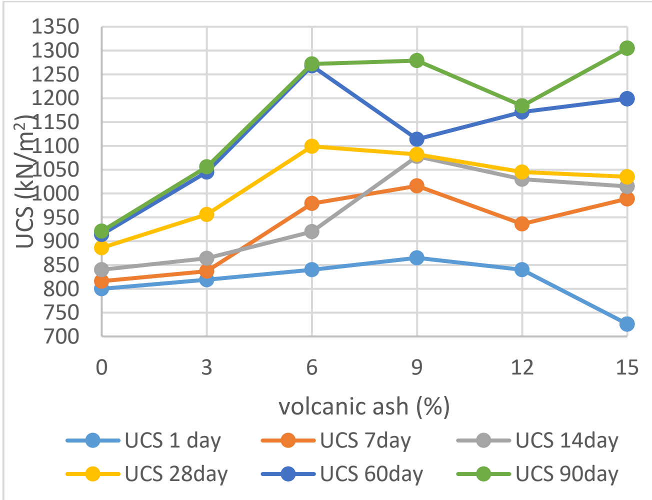
(a)



(b)



(c)



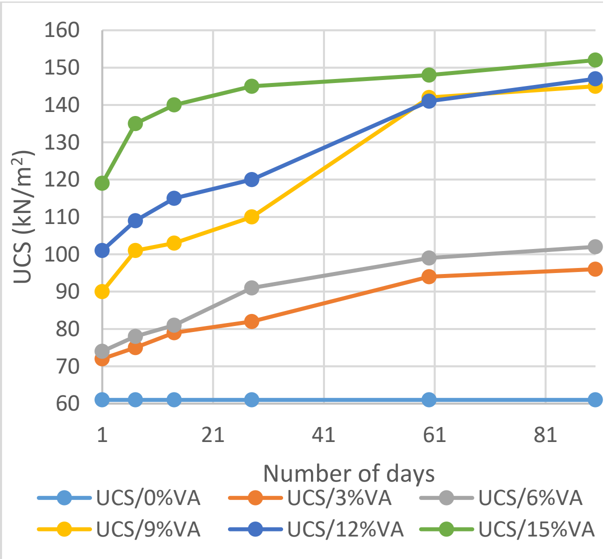
(d)

Figure 7: Variation of UCS with volcanic ash for (a) 0% cement, (b) 2% cement, (c) 4% cement, (d) 6% cement

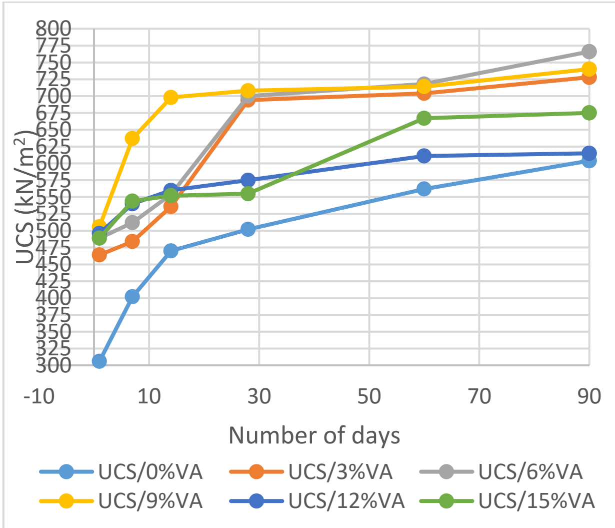
The optimal percentage VA to give the maximum strength occur between 6% and 9% for 2% cement, 4% cement and 6% cement. However, composition with 6% cement occasionally gives optimal strength at 15% VA composition. It can therefore be inferred that higher percentages of cement results to higher optimal VA to give the higher strength. For 2% cement after 28 days of curing, the UCS increased from 287kN/m2 at 0% VA to maximum of 356kN/m2 at 9% VA after which the values reduced to 313kN/m2 at 15% VA. The increase must have resulted from the reaction between the silica contained in the VA and calcium oxide present in cement to form cementitious calcium silicate hydrate (CSH). The reduction observed beyond 9% VA is probably due to higher byproduct of calcium hydroxide which form unreactive whitish solids that reduces the strength of the specimen.

3.4 EFFECT OF CURING TIME ON CEMENT AND VOLCANIC STABILIZATION OF CLAY

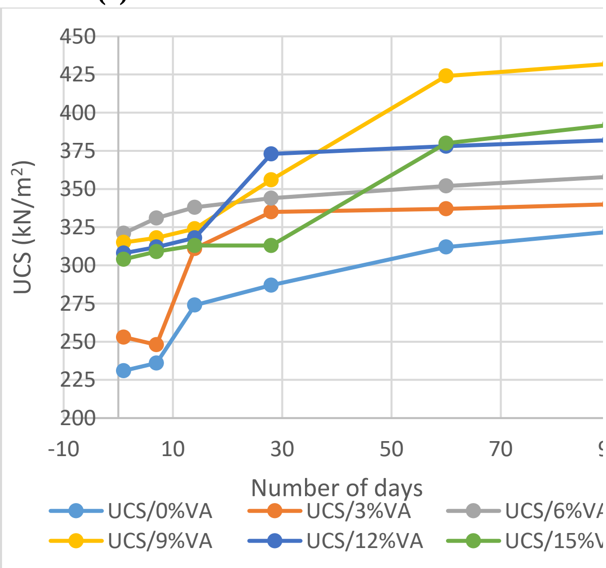
The effect of curing time on the UCS of VA stabilized clay soil at varied cement compositions are shown in figures 8a, 8b, 8c and 8d for 0, 2, 4 and 6% cement respectively. For 0% cement shown in figure 8a,



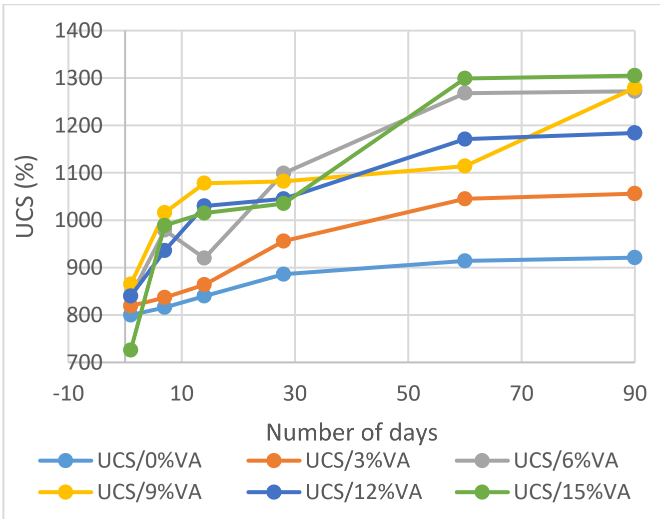
(a)



(c)



(b)



(d)

Figure 8: Variation of UCS with curing days for (a) 0% cement, (b) 2% cement, (c) 4% cement, (d) 6% cement

The strength for 0% VA was observed to be constant at 61kN/m2 throughout the duration of curing. Addition of 3% VA gave gradual increase in UCS from 72kN/m^2 after 1day curing to 96kN/m^2 after 90 days of curing which represents 25% increase in strength. At 0% cement and 15% VA, the UCS increased from 119kN/m^2 after 1day curing to 152kN/m^2 after 90 days curing which also represents 28% increase in UCS. This increase in strength must have resulted from the reaction between silica contained in VA and the ions surrounding the clay minerals. Figure 8b showed the variation in UCS with addition of VA at 2% cement. Addition of 9% VA was observed to stand out with UCS increasing from 315kN/m^2 after 1day curing to 432kN/m^2 after 90 days curing which represents 37% increase in strength of the clay.

The maximum strength obtained on addition of 6% cement with varied composition of VA occurred at 15% VA which gave UCS of 726kN/m^2 after 1day curing to 1305kN/m^2 after 90 days curing which represents 80% increase in strength of the clay.

Figure 8a which deals with addition of VA without cement and revealed gentle slope or gentle rate of increase in strength with increase in curing days except for 15% VA which gave high rate of increase in strength during the first 28 days of curing after which the slope flattened. Figures 8b, 8c and 8d which composes of 2%, 4% and 6% cements with varied compositions of VA, all showed faster rate of strength increase from 1 to 28 days after which the slope flattened out.

4. CONCLUSIONS

From the experiment and analysis carried out in this study, the following conclusions can be drawn:

The clay soil studied falls under clay of high plasticity (CH) based on Unified Soil Classification System (USCS) which cannot be used in its natural state for any component of flexible pavement structure.

Microstructural analysis of the clay using XRD and SEM revealed that the clay consists of both primary and secondary minerals including montmorillonite. The SEM showed the morphology of the compacted clay as flaky in nature with pore spaces.

Maximum UCS of 1305kN/m2 which satisfy a soil material to be used as subbase material for flexible pavement structures. This was achieved at 6% cement and 15% volcanic ash.

The optimal VA required for effective stabilization of clay soil lies between 6 to 9% for clays with lower cement content and 9 to 12% for clay with higher cement contents.

The UCS obtained for clay stabilized with VA only increased by 2.5 times the strength of the natural clay while the UCS at 6% cement increased by 80% at 15% VA addition.

The VA obtained from Keran Swap hill in Mangu Local Government of Plateau State can be used to stabilize clay soil in conjunction with cement for sustainable flexible pavement structure.

REFERENCES

Abdullah, H. H., Shahin, M. A., and Sarker, P. 2017. Stabilization of Clay with Fly-Ash Geopolymer Incoporating GGBFS. Proceedings of the Second World Congress on Civil, Structural and Environmental Engineering (CSEE 17), Barcelona, Spain, ICGRE141-1 – ICGRE141-8.

Alhaji, M. M., Jibrin, R., Etsuworo, N. M. and Alhassan, M. (2014), Stabilization of A-6 Lateritic Soil Using Cold Reclaimed Asphalt Pavement, International Journal of Engineering and Technology, 4 (1), 52-57,

Amadi, A. A. and Osu, A. S. (2018), Effect of Curing Time on Strength Development in Black Cotton Soil – Quarry Fines Composite Stabilized with Cement Kiln Dust (CDK), Journal of King Saud University – Engineering Sciences, 30 (4), 305-312

Basha, E. A., Hashim, R., Mahmud, H. B. and Muntohar, A. S. (2005), Stabilization of Residual Soil with Rice Husk Ash and Cement, Construction and Building Materials, 19, 448-453,

Cheng, Y. and Huang, X. (2019), Effect of Mineral Additives on the Behavior of an Expansive Soil for Use in Highway Subgrade Soil, Applied Sciences, 9(30), 1-14,

Diouf, B., Skidmore, E. I., Layton, J. B., Hagen, L. J. and Kansas, M. (1990), Stabilizing Fine Sand by Adding Clay: Laboratory Wing Tunnel Study, Soil Technology, 3, 21-31,

Hastuty, I. P., Sofyan, T. A. and Roesyanto (2017), The Influence of Using Quick lime and Volcanic Ash as Stabilizing Materials in Clay Viewed from CBR Value, AIP Conference Proceedings, 1903, 1-7,

Hastuty, I. P., Roesyanto, and Ramadhany, G. (2017), The Stability of Clay Using Volcanic Ash of Mount Sinabung North

Sumatera and Sugarcane Bagasse Ash with CBR and UCT Value, MATEC Web of Conferences, 138, 1-8,

Hossain, K. M. A., Lachemi, M. and Easa, A. (2006), Characteristics of Volcanic Ash and Natural Lime Based Stabilized Clay Soils, Canadian Journal of Civil Engineering, 33, 1455-1458,

Hossain, K. M. A and Moi, L. (2011), Some Engineering Properties of Stabilized Clay Soils Incorporating Natural Pozzolans and Industrial Wastes, Construction and Building Materials, 25, 3495-3501,

Ibrahim, A. (1983), "Black Cotton Soil in Road Pavement Design, Construction and Performance" In: Tropical Soils of Nigeria in Engineering Practice, Edited by Ola, S. A., Pp 260-278

Ismail, A., Baghini, M. S., Karim, M. R., Shokri, F., Al-mansoba, R. A., Firoozi, A. A. and Firoozi, A. A. (2014), Laboratory Investigation on the Strength Characteristics of Cement-Treated Base, Applied Mechanics and Materials, 507, 353-360,

Jaiswal, M. and Lai, B. 2016. Impact of Rice Husk Ash on Soil Stability (Including Micro Level Investigation). Indian Journal of Science and Technology, 9(30), 1-7.

Khan, T. A. and Taha, M. R. (2015), Effect of Three Bioenzymes on Compaction, Consistency Limits and Strength Characteristics of a Sedimentary Residual Soil, Advances in Material Science and Engineering, 2015, 1-9,

Latif, D. O., Rifa'I, A. and Suryolelono, K. B. (2016), Chemical Characterization of Volcanic Ash in Indonesia for Soil Stabilization: Mophology and Mineral Content, International Journal of GEOMATE, 11 (26), 2606-2610

Latif, D. O., Rifa'I, A. and Suryolelono, K. B. (2016), Effect of Kelud Volcanic Ash Utilization on the Physical Properties as Stabilizer Material for Soil Stabilization, Electronic Journal of Geotechnical Engineering, 21 (04) 1679-1687,

Louafi, B. and Bahar, R. (2012), SAND: An Additive for Stabilization of Swelling Clay Soils, International Journal of Geosciences, 3, 719-725

Ma, C., Qin, Z., Zhuang, Y., Chen, L. and Chen, B. (2015), Influence of Sodium Silicate and Promoters on Unconfined Compressive Strength of Portland Cement-Stabilized Clay, Soils and Foundations, 55(5), 1222-1232,

Muguda, S. and Nagaraj, H. B. (2019), Effect of Enzymes on Plasticity and Strength Characteristics of an Earthen Construction Material, International Journal of Geo-Engineering, 10(2), 1-14,

Ola, S. A. (1981), Stabilization of Maiduguri Black Cotton Soils of Nigeria with Sand, BULLETIN of the International Association of Engineering Geology (24), 145-150

Prasad, D., Borthakur, N. and Das, S. (2017), Effect of Rice Husk Ash and Cement Mixtures on Engineering Properties of Cohesive Soil, Workshop on Sustanable Geotechnics, IIT Kanpur, India, 1-4

Rao, G. V. R. and Hanuma, P. (2019), An Experimental Study on Stabilization of Soils by Using Bio-Enzymes, International Journal of Trend in Scientific Research and Development, 3(5), 651-654

Renjith, R., Robert, D., Fuller, A., Setunge, S., O'Donnell, B. and Nucifora, R. (2017), Enzyme Based Soil Stabilization for Unpaved Road Construction, MATEC Web of Conferences, EACEF, 138, 1-10

Rifai, A., Yasufuku, N. and Omine, K. (2013), Characterization and Effective Utilization of Volcanic Ash for Soil Improvement, Applied Mechanics and Materials, 248, 292-297,

Rifa'I, A. and Yasufuku, N. (2014), Effect of Volcanic Ash Utilization as Substitution Material for Soil Stabilization in View Point of Geo-Engineering, Ground Improvement and Geosynthetic, 238, 138-147,

Roesyanto, Iskandar, R., Hastuty, I. P. and Lubis, A. I. U. (2018), A Study of the Effectiveness of the Use of Gypsum and Volcanic Ash Against the Stability of Clay Soil in Terms of UCT and CBR values, IOP Conference Series-Material Science and Engineering, 309, 1-7,

Sahoo, S. and Sridevi, G. (2018), Soil Stabilization Using Bioenzyme, International Journal of Pure and Applied Mathematics, 118(24), 1-10,

Sharma, N. K., Swain, S. K. and Sahoo, U. C. (2012), Stabilization of Clay Soils with Fly Ash and Lime: A Micro Level Investigation, Geotechnical and Geological Engineering, pp 1-9

Somireddy, G. (2019), Stabilization of Soil Using Bio-Enzyme (TERRAZYME), International Journal of Management, Technology and Engineering, ix(1), 3339-3347,

Tsuchida, T. and Tang, Y. Z. (2015), Estimation of Compressive Strength of Cement-Treated Marine Clays with Different Initial Water Contents, Soils and Foundations, 52 (2), 359-374

Zhang, M., Guo, H., El-Korchi, T., Zhang, G. and Tao, M. 2013. Experimental Feasibiity Study of Geopolymer as the Next-generation Soil Stabilizer. Construction and Building Materials, 47, 1468-1478.

Abdullah, H. H., Shahin, M. A., and Sarker, P. (2017). Stabilization of Clay with Fly-Ash Geopolymer Incoporating GGBFS. Proceedings of the Second World Congress on Civil, Structural and Environmental Engineering (CSEE 17), Barcelona, Spain, ICGRE141-1 – ICGRE141-8.