International Journal of Advances in Engineering and Management (IJAEM)
Volume 4, Issue 8 Aug. 2022, pp: 936-945 www.ijaem.net ISSN: 2395-5252

Agro waste-Based Binders for the Stabilisation of Tropical Soils

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Submitted: 10-08-2022 Revised: 17-08-2022 Accepted: 20-08-2022

ABSTRACT
Most soils used in construction are sufficiently stiff in the dry state but lose their stiffness when saturated with moisture leading to a reduction in strength and bearing capacity. Consequently, for earth roads, soil stabilisation (typically using Portland cement) is critical to ensure that these roads are sufficiently water-proof and provide all-weather access. Alkali activation, an emerging technology involving the reaction between solid aluminosilicate sources and alkaline solutions for the production of binders, has the potential to serve as the next-generation soil stabilisation mechanism. However, high embodied energies associated with the production of alkali activators may negate the eco-friendly benefits of these binders. This study explores the viability of harnessing alkali activation chemistry for soil stabilisation using agro/industrial wastes as replacements for alkali activators. Source materials were sourced from various parts of the country: wood ash and rice husk ash were sourced from Fursa rice mill, Kano; Kaolin was sourced from Bokkos, Plateau State and various representative soil samples were collected from Abuja and Gombe State. Preliminary characterisation of all source materials was conducted to determine geotechnical properties and mineralogical/elemental oxides composition. Initial trial mixes were performed to determine optimum mix ratios for each source material in developing water-proofing binders. Subsequently, optimised mixes were introduced at varying proportions (0-15% by dry weight of soil) at moisture contents corresponding to the optimum moisture content of respective soils). Strength development within the soil based on each composition was evaluated by determining the unconfined compressive strength of test pieces (in the dry and soaked conditions) after 24hrs and 7 days of room temperature curing. The optimum UCS at both 24hrs and 7 days is from 5-10% additives content with UCS values ranging from 1.3-2.6Mpa for different soil samples. The results from this study show the potential of the reuse of waste materials for developing useful technological solutions in tandem with the global actualisation of a circular economy.

Keywords: Stabilisation, Alkali-activators, Soils, Additives, kaolinite.

I. INTRODUCTION

1.1 Background

Stabilisation has been widely used to enhance the engineering properties of soils, such as strength, compressibility, hydraulic conductivity and density. Additives have been used to modify these soil properties through water-proofing, bonding or a combination of both (Chittoori, 2008). Puppala and Chittoori (2013) classify these additives into three main categories: traditional, non-traditional and by-product stabilisers. The traditional stabilisers include cement, lime, bituminous materials and fly ash; non-traditional stabilisers include polymers, enzymes, and ammonium chloride, while the by-product stabilisers comprise cement kiln dust, iron ore tailings, bagasse ash etc. Amongst these three categories, the traditional stabilisers remain the most widely used for stabilisation (NCHRP 11, 2009). Earth roads provide access to rural areas and are considered to have a high economic impact on society. One of the materials often encountered in earth roads is naturally occurring clay.

These clays pose particular problems to the earth roads as their response to changes in moisture content and the platelet structure of the material frequently causes damage and defects (Tosti et al. 2013), leading to loss of all-weather access in these areas

These soils are sufficiently stiff in the dry state but lose this stiffness when saturated with water resulting in a reduction in strength and bearing capacity with a corresponding increase in compressibility, which may lead to excessive settlement and subsequent failure of the structure (Moayed&Allahyari, 2012).

Recently, various imported non-traditional stabilisers have been actively marketed for use on various construction projects, particularly highway construction within Nigeria. Different brands of nanotechnology-based modifiers have in recent times been imported into Nigeria for use as stabilising agents of tropical soils during construction. The Nigerian Building and Road Research Institute has conducted various tests to ascertain the effect of such products on the engineering properties of tropical soils (NBRRI Report No 32). Results have shown that these stabilisers can significantly improve the strength and permeability of tropical soils.

However, the process of clay modification using polymers is typically carried out under high-temperature conditions, thereby reducing sustainability. A more recent development that has attracted much interest in the material science world is the geopolymer technology, as it allows for synthesis under ambient conditions. The term 'geopolymer' was coined by a French Scientist, Davidovits in 1979 to classify a group of mineral polymers with SiO_4 and AlO_4 tetrahedra as the structural units (Davidovits, 2011). Basically, geopolymers refer to a class of inorganic polymers that are formed as a result of a reaction between an aluminosilicate source and an alkaline solution. A review of literature has shown that geopolymers are relatively cheap and can be produced from clay minerals (kaolinite, metakaolin), industrial and agricultural waste by-products (rice husk ash, bagasse ash, groundnut husk ash etc.) (Duxson et al. (2007), Zhang et al. (2010); He et al. (2011)).

These precursors are required for the development of geopolymers, and it is expected that with the right mix design, they can be tailored for the stabilisation of earth roads for the provision of water repellent road surfaces, particularly in rural areas. Furthermore, there is the need to develop a new generation of indigenous stabilisers using locally sourced materials to promote in line with the nation's economic recovery growth plan. Therefore, this project seeks to explore the viability of geopolymerisation as the next-generation stabilisation mechanism in the development of earth roads for Nigeria.

The main objective of this research project was to explore the viability of geopolymers for the nano-modification of tropical soils by revealing the fundamental science of the nanoscale geopolymer-clay interactions and hence the soil cementation and stabilisation mechanisms.

II. EXPERIMENTAL INVESTIGATION

2.1 Materials

2.1.1 Soil

The soil used for the study was collected from Gwagwalada, UniAbuja, Giri, Kuje, Jabu(Kubwa), and Waru(Apo) Abuja and Black cotton soil from Gombe State. Preliminary characterisation of all source materials was conducted to determine geotechnical properties as well as mineralogical/elemental oxides composition.

2.1.2 Kaolin

Kaolin (Bokkos white) was sourced from Bokkos, Plateau State. Kaolin was calcined at 650^o C for 90 minutes to obtain an amorphous phase metakaolin and sieved through 600-micron mesh size to increase the surface area and, ultimately, the reaction speed.

2.1.3 Agro waste (Rice husk ash and Wood ash)

Wood ash and rice husk ash were sourced from Fursa rice mill, Kano. They are waste components from the rice milling process. The RHA is pulverised into very fine and porous material having a particle size range of 5-75 micron; the physical properties of RHA largely depend on burning conditions. After the oxidisation process of Rice husk, the RHA was formed, which nearly contains 85-97% of silica. Wood ash was obtained from the combustion of wood.

2.2 Characterisation of Soil samples

2.2.1 Determination of Mineralogical and Elemental Composition of Soils

The mineralogical composition was determined using the X-ray Powder Diffraction method. This is a laboratory-based analytical technique used for the identification of crystalline materials. X-ray powder diffraction is widely used in geology, environmental science, material science, and engineering to rapidly identify unknown crystalline substances (typically in less than 20 minutes).

A small amount of the sample was obtained and ground to a very fine size before analysing it using the Empyrean X-ray Diffractometer Machine. Samples were analysed before and after stabilisation to identify changes in the mineralogical composition as well as identify new phases.

2.2.2 Determination of geotechnical properties of soils

This includes the determination of the geotechnical properties of the soil samples for the

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purpose of identifying and classifying the soils. The samples were tested in accordance with BS 1377:1990 and BS 1377: Part 4: 1990: 3.4 for compaction, respectively.

2.3 Preparation of specimens and testing procedures

Soil samples were pulverised and air-dried. The wood ash sample was diluted in water to obtain leachate (Ca0) with a PH of 11, which served as the alkaline solution 2. Kaolin was calcined at 650C for 90min to obtain metakaolin; specimens were prepared by thoroughly mixing the leachate, Metakaolin, RHA and with the soil sample at different proportions. 0, 24hrs and 7days were selected as curing period to allow for all reactions between the stabilisers and the soil before conducting evaluation tests.

III. RESULTS AND DISCUSSION

3.1 Characterisation of Soil samples

The geotechnical properties of the soil samples are presented in Table 1, carried out based on BS 1377 parts 2&4, while the mineralogical and elemental composition of each sample, as determined by the XRD and XRF, respectively, are presented in Tables 2 and 3. As observed in Table 1, the geotechnical properties of the soils indicate that the soils were predominantly clayey soils or clayey sands based on the USCS soil classification system. However, mineralogical compositions indicate soils comprise a wide range of minerals despite similar soil classifications. All soils comprised varying quantities of quartz and kaolinite, indicating geologic origins as showed in table 2. The elemental composition of soil samples asshown in table 3, composed of majorly Silica, Alumina and iron oxides ($Si0_2$, Fe_20_3 and Al_20_3), and loss on ignition ranges from 14.6-18.0, respectively.

Sample Location		Giri	Kubwa	Uni. Abj.	Ccecc	Wuye	Gwag.	Kuje Jamul	Apo	Kuje Kuch
Particle Size Distribution	Gravel	0	10	20	10	10	34	0	0	0
	Sand	28	42	20	35	50	42	46	3	30
	Silt	44	20	20	20	24	17	22	97	30
	Clay	28	28	40	35	16	7	32		40
Atterberg Limits	LL	42.00	45.20	48.40	48.20	35.50	25.90	35.40	98	42.20
	PL	15.58	24.51	26.12	22.60	20.78	11.10	20.74	24	19.24
	LS	9.69	9.55	-	11.31	9.38	11.31	8.19	21	11.90
	PI	26.42	20.69	22.28	25.60	14.72	14.80	14.66	74	22.96
Compaction	MDD	1.70	1.62	1.62	1.68	1.76	1.96	1.74		1.56
	OMC	17.60	22.60	22.00	20.00	16.60	11.20	17.60		22.40
Soil Classification		CL	SC	CL	CL	CL	SC	SC	CH	CL

Table 1: Geotechnical properties of soil

Table 2: Mineralogical composition of samples

	Quartz	Kaolinite	Illite	Muscovite	Hematite	Goethite	Montmorillonite	Rutile
Gwags	■	■				■		
Giri	■	■	■					
BCS	■	■					■	■
Kuje Kuchikau	■	■		■	■			
Wuye	■	■	■		■			
Kuje Jamul	■	■	■		■			
Apo (Waru)	■	■		■				

Table 3: Elemental composition of samples

Location/ Borrow Pit	Fe_2O_3	SiO_2	Al_2O_3	MgO	CaO	K_2O	TiO_2	MnO	Na_2O	LOI
Kuje Jamul	13.7	45.5	21.6	0.1	0.1	1.0	0.8	0.1	0.1	15.7
Wuye	14.1	46.0	19.6	0.6	1.6	0.1	1.2	0.0	0.2	15.7
Apo	10.2	44.5	24.2	0.9	2.1	0.2	1.0	0.1	0.1	16.8
KujeKuchikau	12.7	46.8	23.1	0.8	0.8	0.1	1.1	0.1	0.1	15.4
Gwagwalada	7.1	50.0	18.6	0.1	0.3	2.0	1.7	0.1	1.0	18.0
Giri	6.6	58.8	15.0	0.0	1.9	0.1	1.7	0.3	1.1	14.6

3.2 Characterisation of Agrowastes

Table 4 presents the elemental oxide composition of the major elemental oxides in wood ash, rice husk ash, and metakaolin. As observed, the primary oxide composition in RHA was silica, whilst wood ash comprised primarily of Calcium Oxide. On the other hand, the composition of metakaolin was primarily alumina and silica oxides, respectively. Based on prior work, these compositions were ideal for the alkali activation process.

Table 4: Elemental Oxide Composition for metakaolin and agro wastes.

% Composition of Oxides	RHA	WA	MK
SiO_2	97.3	Nd	63.4
Al_2O_3	Nd	Nd	30.6
Fe_2O_3	0.35	0.9	0.64
CaO	O.6	93.61	Nd

Figure 5 a,b&cpresents XRD patterns obtained from wood ash, rice husk ash and metakaolin respectively.However, from the representation it alsorevealed the absence of clear defined peaks in wood ash composition, which indicate primary amorphous nature. Similarly, XRD patterns of rice husk ash indicate the amorphous nature of silica which is a desirable quality required to ensure a high level of reactivity during the alkali activation process.

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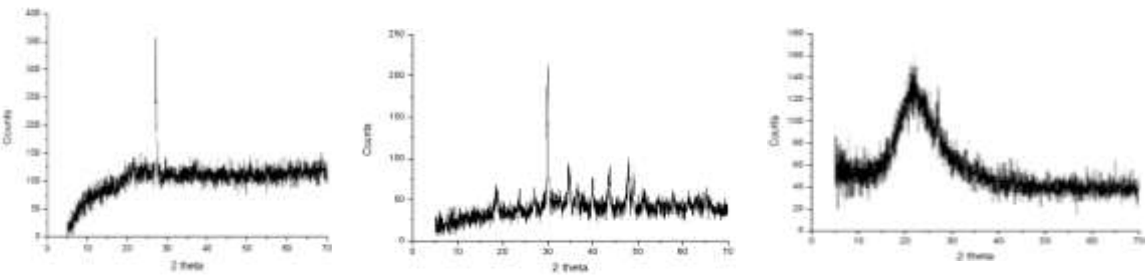


(a) Wood ash (b) Metakaolin (c) Rice husk ash

Figure 5: XRD patterns obtained from wood ash, rice husk ash and metakaolin

3.3 Effect of Alkali activated agro wastes on the properties of soil

The effect of alkali-activated agro wastes on the soil properties was determined with respect to its density, unconfined compressive strength and water absorption. The results are discussed below:

3.3.1 Unconfined Compressive Strength

Fig. 6 below shows the result of unconfined compressive strength against additives content for samples tested at 24hrs based on BS 1377-1990-7. This was conducted to ascertain the time dependence of reaction and its impact on the strength properties of soils. For the majority of soils, the initial inclusion of additives results in an increase in unconfined compressive strength and subsequent reduction with an increase in additive contents. A similar trend of strength behaviour was reported by (Alhassan, 2008) and(Arvind K. et al. 2015). The decrease in the UCS values after the addition of 10% additives, as shown in figure 6, may be due to the formation of weak bonds between the soil and the cementitious compounds formed. Maximum improvement of these soils (Giri, Gwagwalada, Wuye and Kuje Kuchikau) can be observed at additive content of 5%; whereas optimum content for Kubwa and Apo soils can be observed at 10% additive content. This suggests that a higher quantity of additives is required to obtain optimum results for these groups of soils. On the other hand, the inclusion of additives in Kuje Jamul soils results in an initial slight increase in the compressive strength of soils with subsequent reduction with an increase in additive contents. This suggests that soil improvement for this group of soils may not be achieved through alkali-activated agro wastes. For all soils tested, it was observed that strength values obtained with additive content of 15% were comparable to strength obtained with untreated soils suggesting that at this content, the benefit of soil improvement with alkali-activated agro wastes was not achieved. However, the degree of soil improvement varied for different soil types, with soils from Giri demonstrating the highest strength improvement after 24hrs testing.

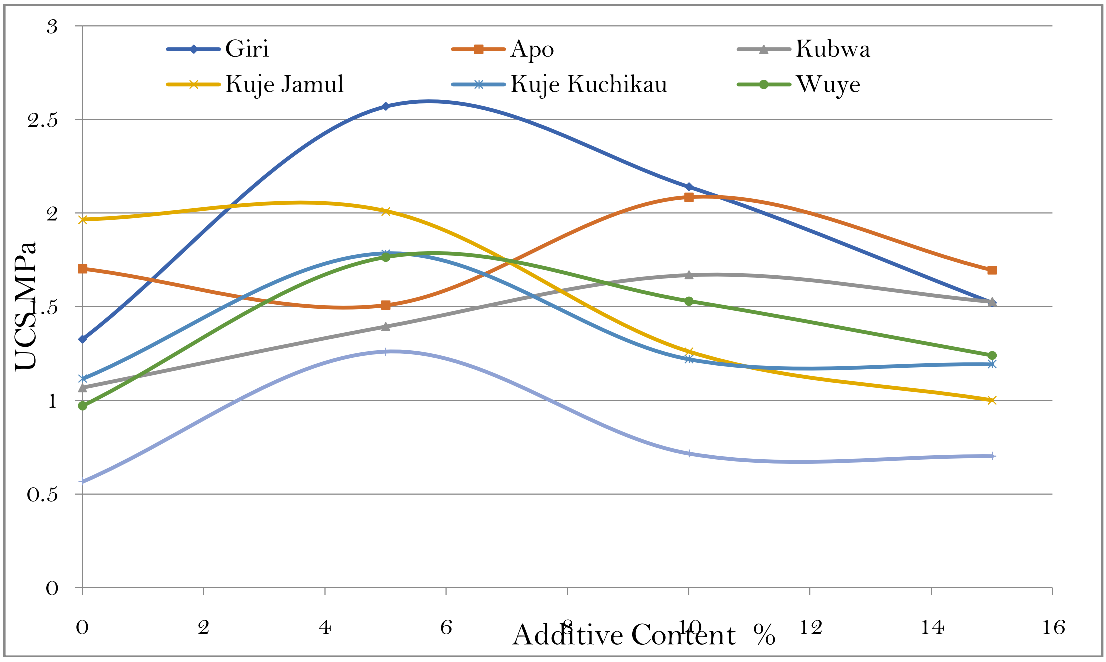


Figure 6: Variation of unconfined compressive strength with additive content tested after 24hrs

The strength values of soils tested after 7 days showed a similar trend observed with soils tested after 24hrs. Optimum values were obtained between 5-10% additive content for most soils.

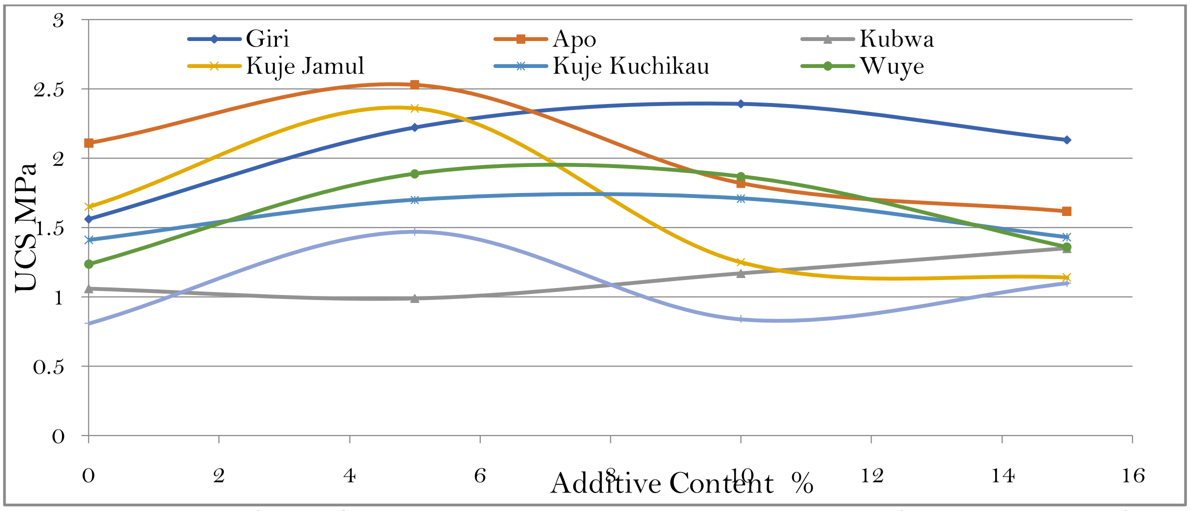
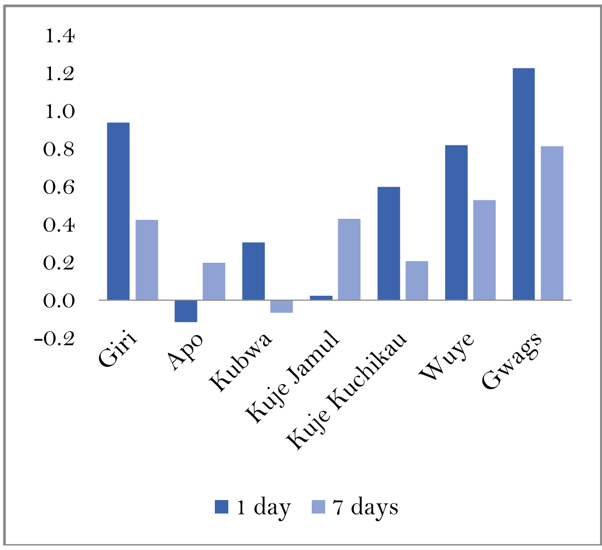


Figure 7: Variation of unconfined compressive strength with additive content for samples tested after 7 days

Consequently, the comparison is made between strength values obtained at 24 hrs and 7 days for additive content of 5 and 10% to evaluate the time dependence of the strengthening reactions. A comparison of the degree of improvement relative to untreated soils is presented in Figure 8. Figure 8 shows that the highest degree of improvement was obtained with Giri and Gwagwalada soils which were observed when samples were tested after 24hr. However, testing of these samples after 7 days indicated a degree of loss in soil strength.



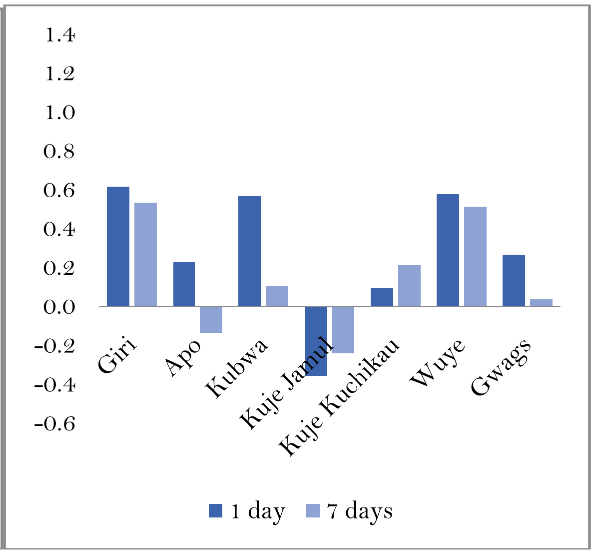


Figure 8: Comparison of soil improvement relative to untreated samples for samples containing (a) 5% additive content and (b) 10% additive content.

Apo soils show the least improvement with the inclusion of additives, whilst Kuje Jamul soils present a time dependence of soil improvement using alkali-activated agro wastes.

3.3.2 Density

Figures 9 and 10 show the variation of density of soil samples with additive content for samples tested after different curing periods. For all testing periods, it can be observed that the inclusion of agro wastes results in the reduction of the density of soil samples. This trend is expected as the replacement of soils with higher specific gravities with agro wastes in the form of ash would result in the reduction of mass of samples with an attendant effect on the density of samples. However, it is observed that this trend is not observed with Giri soils tested at 24hrs, where inclusion of additive (5-10%) into the soils results in a significant increase in density, indicating the possibility of reactions resulting in the formation of new products with higher density. This further explains the increase in compressive strength observed in these samples.

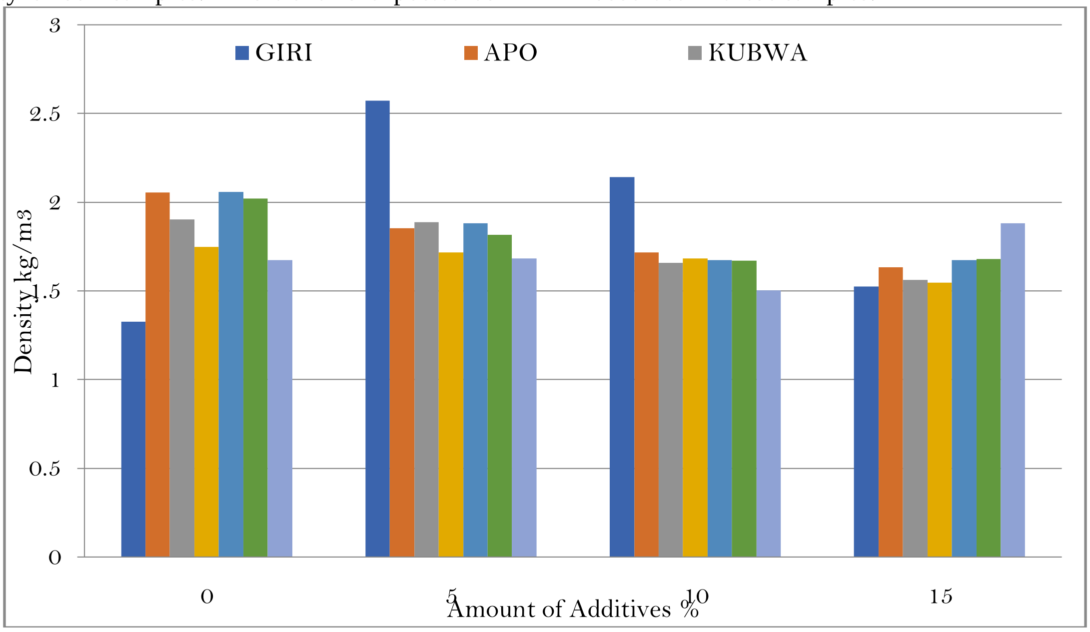


Figure 9: Variation of density with additive content for samples tested after 24hrs

Typically, the density of compacted earth has been correlated to compressive strength for earthen materials in various studies. (NBRRI Report No. 38), however, the drop in density observed with test specimens in this study does not correlate with strength values obtained, indicating that the strength observed may not be attributed to the compact nature of soils but may be attributed to alkali activation compounds produced.

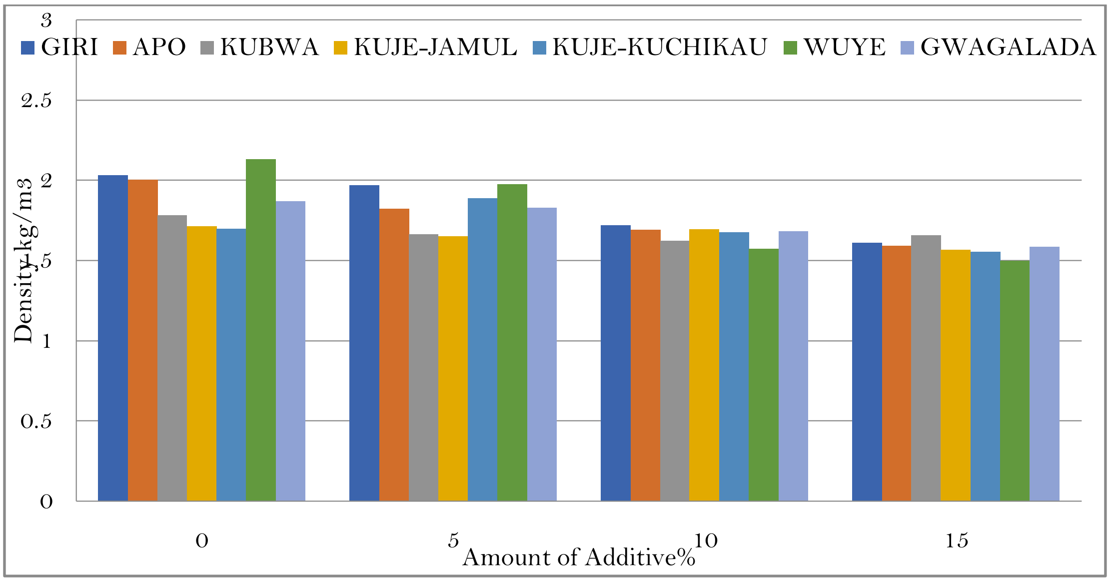


Figure 10: Variation of density with additive content for samples tested after 7 days

3.3.3 Resistance to Moisture

The major drawback of using soils as a construction material is their high-water absorption characteristics which affect the overall performance of the blocks in terms of durability. Hence, the addition of various additives is basically to improve its strength properties and reduce the rate of water absorption. Water absorption is a function of clay, and a high rate of water absorption results in swelling of clay fractions which leads to a loss of strength over time. In this study, treated samples were immersed in water to ascertain the nature of water-proofing associated with this stabilisation mechanism. Total immersion of samples in water for 24hrs showed varying behaviour for different soils: at 10-15% additive content, soil samples from Giri, Wuye, Apo and Kubwa partially disintegrated in water, whereas soils from Kuje Jamul, Kuje Kuchikau and Gwagwalada completely disintegrated in water at all additive contents. This suggests that a higher degree of reaction and consequent soil improvement based on alkali-activated agro waste was obtained with the former soils.

3.3.4 Effect of Mineralogy of soils

The mineralogical composition of the soils obtained using X-Ray Diffraction (XRD) analysis shows that all soil samples consist of varying proportions of quartz and kaolinite with the presence of other clay minerals, including illite, muscovite and montmorillonite. Some soils also contained traces of hematite and goethite. The presence of quartz in all soils suggests that they were formed from a parent rock which was predominantly felsic. These rocks contain quartz and have higher silica and lower iron contents. Kaolinite is a 1:1 two-layered clay mineral with a low shrink-swell capacity and a low cation exchange capacity. One layer of the mineral consists of an alumina octahedral sheet that shares a common plane of oxygen atoms, and repeating layers of the mineral are bonded by a hydrogen bond (Das, 2006). Kaolinite has high chemical stability and a low expansion coefficient. Kaolinite is a hydrous silicate of aluminium with a low expansion coefficient and is one of the most important industrial elements used for bricks, ceramics, and many other applications. Research has shown that the hardening of clay cement mixtures involves alteration of clay mineral structures resulting in the formation of secondary cementitious materials in addition to the hydrolysis and hydration of the cement (Herzog & Mitchell, 1963).

It is well known that geotechnical properties are strongly affected by the amount and types of minerals present in it, as demonstrated in previous studies with cement stabilisation (Ojo et al. 2016). However, with alkali-activated binders as stabilisers, no clear correlation between the degree of stabilisation and the mineralogical composition of soils can be observed. This suggests that other soil parameters such as particle size distribution or plasticity of soils may control the behaviour of the alkali activation mechanism.

IV. CONCLUSIONS AND RECOMMENDATIONS

The objective of the study was to explore the viability of producing binders for all-weather access earth roads using agro/industrial wastes to harness the alkali activation process for soil stabilisation. Alkali activation, which is an emerging technology that involves the reaction between solid aluminosilicate sources and alkaline solutions for the production of binders, has the potential to serve as the next-generation soil stabilisation mechanism. However, high embodied energies associated with the production of alkali activators may negate the eco-friendly benefits of these binders. This study sought to explore the viability of harnessing alkali activation chemistry for soil stabilisation using agro/industrial wastes as replacements for synthetic alkali activators.

From the investigation conducted, the following conclusion can be drawn:

- The study has demonstrated the feasibility of total replacement of synthetic alkali activators with agro wastes in the alkali activation process
- The inclusion of binder content significantly modified the strength of some soils by up to 95% and improved water resistance; minimal strength gain was observed with other soils.
- Soil type was a significant variable in the strength development, indicating that soil type is key in adopting this stabilisation mechanism.
- Some soils demonstrated a time dependence of the alkali activation process as the strength significantly improved after 7days of curing
- Post hoc comparisons show that 5-10% binder content significantly modified the untreated soils. Therefore, this optimum binder content is recommended for applications.

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