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Physico-Chemical and Geotechnical Properties of Greywater-Polluted Soils Treated with Cereal Gruel Supernatant

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ABSTRACT

The present study assessed the impact of Cereal Gruel Supernatant (CGS) on physico-chemical and hydraulic/geotechnical properties of Greywater Contaminated Soils (GCS). The GCSs and Control Soils (CSs) were collected from two sampling locations within Basement Complex geological formation at depths of 0.5, 1.0, and 1.5 m from the surface. The experiment consists of four treatments: CS with no presence of greywater, GCS, CS with 50 ml of CGS, and GCS with 50 ml of CGS. The results of this study showed that the alteration of most analyzed properties on GCSs depend greatly on sampling depth while effect of CGS treatment on properties of GCS is site specific. There is no significant effect of CGS on both Dry Density and Moisture Content of collected GCSs at Eutric Luvisols and Vertic Cambisol locations while impact of CGS on other analyzed soil properties is site dependent. Two-way ANOVA showed that based on sampling depths, there are significant differences at 5% level for most analyzed soil properties except Shear Strength, Organic Matter and Soil Resistivity while no significant difference at 5% level occurred based on soil treatment with CGS. Further investigation is needed to study the trend of alteration of soil properties with sampling depths by various cereal based starchy fermented gruel on GCS at varying concentrations.

Keywords: Basement Complex; Greywater; Physico-chemical; Geotechnical; Cereal gruel supernatant; Soil treatment

INTRODUCTION

Wastewaters are usually produced as end products of certain daily human activities. The volume of wastewater produced by a society as a result of anthropogenic activities depends to some extent on the standard of living, domestic water consumption, pattern of development in a geographical setting, and cultural beliefs of the residents of a particular society (Baharvand & Mansouri Daneshvar, 2019; Schilling & Trånckner, 2020). According to Ghrair et al. (2018), Greywater is defined as wastewater that is generated as water outflows from the bathrooms, kitchens, and laundry excluding the wastewater from toilets. The issue of management of greywater for

alternative uses has not been given proper attention by environmentalists in developing countries of African continent, where improper disposal of wastewater is more rampant (Morel, 2005).
The reuse of greywater attempts to preserve the nearby freshwater source thereby reducing the impact of environmental pollution of shallow aquifers (Al-Hamaeideh & Bino, 2010). Though, the use of greywater for agricultural purposes is well reported (Travis et al., 2008; Al-Hamaiedeh & Bino, 2010, Anwar, 2011, Mohamed et al., 2018), there is insufficient information/data on the geotechnical and physico-chemical characteristics of greywater contaminated soils (Ganiyu et al., 2020). Surfactants, (being major components of detergents and bathing soaps used in laundry and bathtubs) are organic molecules consisting of hydrophilic and hydrophobic groups and have potentials of altering physico-chemical and hydraulic/geotechnical characteristics of soil (Mohamed et al., 2018, Ganiyu et al., 2020). For instance, Mohamed et al. (2018) investigated the changes in soil properties after the irrigation with laundry wastewater. Calabar & Karabash (2015) evaluated the changes in California bearing ratio of sub-base material modified with tire buffings and cement addition. Several researchers have also investigated the use of treated wastewater as mixing water for concrete production (Cebeci & Saatci, 1989; Shekarachi et al., 2012; Kucche et al., 2015)) while Ghrair et al., (2018) evaluated the potential of reused greywater (treated and raw greywaters) in concrete and mortar. However, non-ionic surfactants have also been reported to promote the solubilization of heavy metals while the anionic and cationic surfactants hinder the removal of dissolved heavy metals (Kosobucki et al., 2008; Ren et al., 2014). Surfactants are reported to be useful in bio-acidification process as they assist in increasing the dissolution of substrates by reducing interfacial tension (Ren et al., 2014). Are et al. (2018) reported the application of organic materials for soil amendment as a means of improving physical properties of degraded soil. However; treatment of porous media such as soil with fermented liquids and its associated effects has not been reported.

Fermented cereal gruels and beverages serve as source of Lactic Acid Bacteria (LAB) and yeasts (Nkhata et al., 2018; Adebo et al., 2022; Bouakkaz et al., 2024). The major microorganism found in *Ogi* fermentation is *L.plantarum,* responsible for the production of lactic acid (Adebo et al., 2022, Ohenhen and Ikenebomeh, 2007; Ajayi & Ajenifuja (2024). Studies conducted by Afolayan et al. (2017) revealed that *Omidun* (cereal gruel supernatant (CGS)) obtained from popular acid fermented cereal gruel sediment called *Ogi* in Nigeria had the highest LAB count compared to the cooked Ogi. However, published works on effects of soil microbial isolates dwell more on how to improve increased grain crop yields (Abd El-Ghaniy et al., 2010; Chaudhary et al., 2023). In addition, priobiotic strains have been reported to have potential for the removal of heavy metals from water and soil (Bhakta et al., 2012; Ameen et al., 2020; Hasr Moradi Kargar & Hadizadeh Shirazi, 2020). It has also been reported by Osungbaro (2009) that different varieties of maize exhibit various pasting viscosities and consistencies on the amylograph while the swelling characteristics (thickening) of *Ogi* have been found to be predisposed by fermentation period. For instance, Aminigo & Akingbala (2004) reported that lowering of viscosities in the process of supplementation of fermented cereal foods has effects on the consistency of the gruels prepared there from. Furthermore, Klang et al. (2019) reported that reduction of the swelling capacity on maize-based formulations could be due to its richness in amylase and fermentation process.

In view of the foregoing, the present study was set out to investigate the potential of cereal gruel supernatant (CGS), a readily available cereal based starchy fermented gruel as treatment on improving physico-chemical and geotechnical properties of greywater contaminated soils. The specific objectives were to assess the effect of fermented cereal gruel treatment on physico-chemical and engineering properties of greywater contaminated soils at varying sampling depths, the potential of greywater contaminated soil as suitable aggregate for pavement sub base and base materials and the use of analysis of variance to study the interrelationship among the mean values of analyzed soil properties under different sampling locations and fermented gruel treatment.

MATERIALS AND METHODS

Site Description and Geological Setting

The study was carried out at two different sampling locations (Isolu and Mapo within Abeokuta and Ibadan, respectively) in southwest, Nigeria. The geographical coordinates of the soil sampling points were measured by a GPS and lie within longitude $3^\circ 26' 00''$ and $3^\circ 54' 00''$ and latitude $7^\circ 12' 00''$ and $7^\circ 26' 00''$ (Fig. 1). The two sampling locations fall within the humid/sub humid tropical climate of southwest Nigeria. Residential houses in the two sampling locations are characterized by unhygenic environmental conditions, overcrowded buildings, derelict and makeshift wooden houses with little or no compliance to urban development and planning regulations. Furthermore, houses in the studied locations discharge household wastewaters/sewages into pit latrines while bathroom rich greywater has been coming directly in contact with virgin soils for decades in the two sites. The soil type in Isolu is Typic Palendalf/Eutric Luvisols while that of Mapo is Vertic Eutrudept/Vertic Cambisol (FAO, 2015). The soils in Isolu and Mapo are classified locally as Abeokuta and Egbeda series respectively (Smyth & Montgomery, 1962).

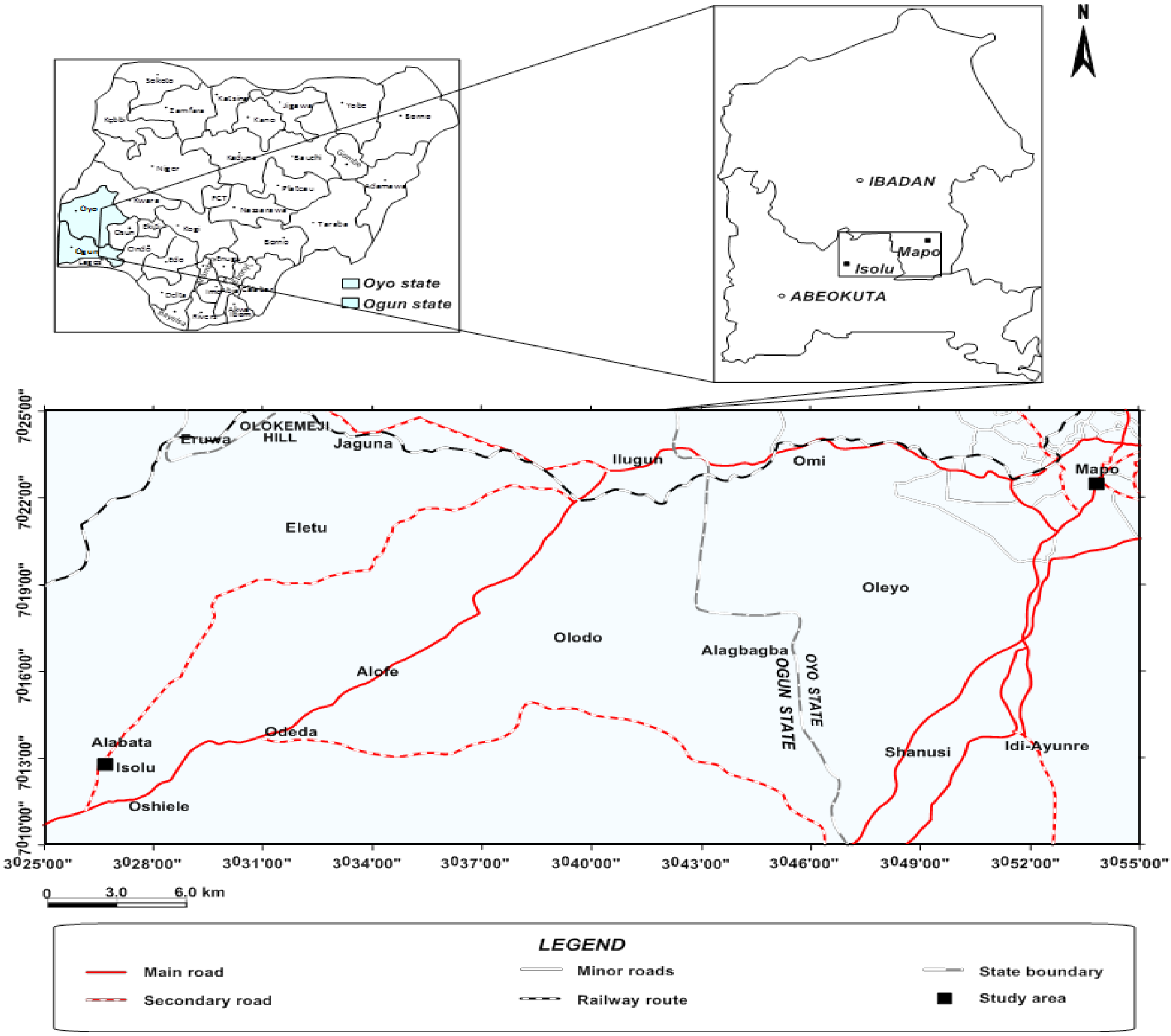

Figure 1: Location Map of the Study Area

Soil Samples Collection and Analytical Methods

Twenty-four (24) soil samples were collected at depths of 0.5, 1.0, and 1.5 m from the surface at the two sampling locations. At each sampling location, two sampling points were created. These were discharge zones of bathroom greywater coming directly from the outlet of bathrooms on the virgin soil and a control site where there is no occurrence of greywater falling on the virgin soil

(100 m from the discharge zones). From the discharge point of greywater, a grid of 2 m by 2 m was identified with the use of a tape measure. The samples were taken using a core sampler; four at each of the corners of the grid, and one in the center, making 5 clusters, which were later mixed together to form a representative sample at each depth. Greywater contaminated soil (GCS) was collected within the greywater discharge zone while control soil sample (CS) was collected from control site at each sampling location. The disturbed soil samples were collected with the aid of soil auger and suitably packed inside a polythene bag and labeled properly for easy identification. Disturbed soil samples collected were used for physico-chemical and geotechnical properties. The soil samples were air dried, gently crushed and sieved with a 2 mm sieve before commencement of analyses. Cylindrical cores (5 cm diameter and 5 cm in height) were also used to take undisturbed soil samples at varying depths for determination of saturated hydraulic conductivity, porosity, and moisture content. Soil samples were collected at different depth in order to assess the trend of variation of analyzed parameters with sampling depth. The collected soil samples were analyzed in the soil physics laboratory of the Institute of Agricultural Research & Training (IAR&T), Moor Plantation, Ibadan, Nigeria.

Another set of GCSs and CSs from the two locations were further treated with 50 ml of Cereal Gruel Supernatant (CGS) and left for a week for chemical reactions to take place between the soil particles and CGS. The soil physico-chemical parameters of interest were particle size distribution, soil pH, organic matter (OM), cation exchange capacity (CEC) and soil resistivity while geotechnical and hydraulic properties are Atterberg limit test (plastic limit (PL) and liquid limit (LL)), Plasticity Index (PI), bearing ratio (BR) and shear strength (SS); porosity, moisture content (MC) and K_{sat} respectively. Particle size distribution was determined by modified Boyoucous hydrometer as described by Gee & Or (2002) with textural classification was done using the USDA textural triangle. A digital pH meter was used to measure pH in water of each soil sample based on ASTM G51-95 (ASTM, 2012) standard while soil MC was determined using the method of weight loss in accordance with ASTM D4959-07 (ASTM, 2007). Soil resistivity was measured using the M.C. miller soil boxes according to the ASTM G57-05 (ASTM, 2005) standard, K_{sat} of core samples was measured using the constant head method based on Reynolds & Elrick (2002) while porosity was calculated as the ratio of pore volume of the test sample to the total volume. The CEC was determined using the ammonium acetate (NH_4OAC) displacement methods of

Jackson (1958) while OM was determined using the $K_2Cr_2O_7 - H_2SO_4$ wet oxidation method as modified by Nelson & Somners (1982). Dry density was calculated using the following relationship:

$$\rho_b = \frac{M_s(g)}{V_b(cm^3)} \tag{1}$$

where ρ_b is the soil dry density (g cm^{-3}); M_s is the mass of oven dried soil (g) and V_b is the volume of the soil (cm^3) ≡ volume of the cylindrical core, where $V_b = \pi r^2 h$; r and h are the internal radius and the height of the cylindrical core.

Atterberg limits test was determined according to ASTM D4318-17E1 (ASTM, 2017) standard while SS was determined according to ASTM D2850-15 (ASTM, 2015) standard. BR was determined based on ASTM D1883-16 (ASTM, 2016) standard.

Statistical Analysis

Analysis of variance (ANOVA) was performed on the soil data in order to assess the significance of all analyzed parameters based on sampling depths and amendments. ANOVA was performed to determine if the selected soil physic-chemical and geotechnical properties varied significantly with respect to varying depths and soil treatment. The results of ANOVA were presented as mean ± standard deviation where the means were separated at the $p \leq 0.05$ level of significance.

RESULTS AND DISCUSSION

Physico-chemical and Hydraulic Properties

The results of physico-chemical properties of the collected control soils, GCSs, treated CSs and treated GCSs at the two sampling locations are presented in Table 1.

Table 1: Results of Physico-chemical properties of collected and treated soil samples at the two locations

Description of the site	**% sand**	**% silt**	**% clay**	**pH in H_2O**	**OM (g/kg)**	**CEC (cmol/kg)**	**Soil resistivity (ohm cm)**
0.5 m Control Mapo Ib	74.22	12.86	12.92	9.32	0.81	2.87	6.25
1.0 m Control Mapo Ib	66.22	12.86	20.92	8.31	0.81	0.99	6.25
1.5 m Control Mapo Ib	60.22	8.86	30.92	5.21	0.56	0.37	4.31
0.5 m Control Mapo 2	73.29	13.26	13.45	9.49	0.84	2.85	6.45
1.0 m Control Mapo 2	65.29	13.26	21.45	8.45	0.84	0.99	6.45
1.5 m Control Mapo 2	59.29	9.26	31.45	5.36	0.59	0.37	4.50
0.5 m GCS Mapo Ib	74.68	12.86	12.46	9.38	0.81	3.35	6.25
1.0 m GCS Mapo Ib	67.68	13.86	18.46	9.16	0.88	1.25	6.74
1.5 m GCS Mapo Ib	60.68	10.86	28.46	6.43	0.69	0.48	5.28
0.5 m GCS Ib 2	73.56	12.99	13.45	9.33	0.82	2.87	6.31
1.0 m GCS Mapo 2	66.56	15.99	21.45	10.39	1.01	1.42	7.77
1.5 m GCS Mapo 2	59.56	11.99	31.45	6.97	0.76	0.44	5.83
0.5 m Control Isolu	71.68	8.86	19.46	6.20	0.56	1.23	4.31
1.0 m Control Isolu	59.68	14.86	25.46	8.66	0.94	0.66	7.22
1.5 m Control Isolu	53.68	12.86	33.46	6.74	0.81	0.35	6.25
0.5 m Control Isolu 2	72.03	7.52	20.45	5.29	0.48	1.10	3.66
1.0 m Control Isolu 2	60.03	14.52	25.45	8.51	0.92	0.59	7.06
1.5 m Control Isolu 2	54.03	13.52	32.45	7.13	0.86	0.37	6.57
0.5 m GCS Isolu	72.22	9.86	17.92	6.95	0.62	1.40	4.79
1.0 m GCS Isolu	58.22	14.86	26.92	8.45	0.94	0.55	7.22
1.5 m GCS Isolu	52.22	12.86	34.92	6.56	0.81	0.31	6.25
0.5 m GCS Isolu 2	73.22	15.33	11.45	10.96	0.97	3.86	7.45
1.0 m GCS Isolu 2	66.22	7.33	26.45	4.74	0.46	0.57	3.56
1.5 m GCS Isolu 2	52.22	12.33	35.45	6.29	0.78	0.28	5.99

*Note: Description with 2 at the front denotes soil treated with CGS

From Table 1, addition of CGS treatment to CS and GCS for each sampling depth at Ibadan location resulted in slight reduction in percent sand content but slight increase in percent silt. Similar increase in silt content of silty clay soil with the addition of glutinous rice slurry was also reported by Yue et al. (2021). However, for soil samples collected at Isolu location, treatment with CGS leads to slight rise in % sand in CS at all sampling depths, but only at 0.5 and 1.0 m depths for Isolu GCS. The addition of CGS to both CS and GCS samples at Ibadan resulted in slight increase in % clay at each sampling depth. The clear increase in clay content in the treated CS and treated GCS at Ibadan was probably due to the decomposition of the mineral component of the soil (Yue et al., 2021). However, at Isolu sampling location, the percent clay in GCS reduced following the application of CGS at 0.5 and 1.0 m sampling depths. Treatment of collected soil samples at Ibadan (Vertic Cambisol) with CGS did not alter the pH status of either CS or GCS. This is an indication that buffering capacity of soil in Ibadan is noticeable and follows clear trend at each sample depth. This concurs with reported rise in soil buffering ability of the soil treated with biochar by Yue et al. (2021). Furthermore, likely higher soil buffering capacity in Ibadan soil might be due to increase in OM at each sample depth on application of CGS. In addition, slight increas in clay particles with the addition of CGS to both CS and GCS at Ibadan was also noticed at each depth. However, addition of CGS to Isolu GCS leads to alteration in soil pH status at sampling depths 0.5 and 1.0 m (see Table 1). In addition, there is no clear trend of variation of pH, OM and % clay in treated CS and amended GCS relative to CS and GCS at Isolu area. According to pH permissible limit set for mixing water for concrete, the pHs of Isolu GCS at all sampling depths fall within the pH limit of 6 – 9 (CCCA, 2007; EPA, 2012). There is slight increase in OM under the CGS treatment of both CS and GCS at Ibadan location. However, the alteration in OM due to the addition of CGS to CS and GCSs at Isolu location did not follow clear trends. There is no noticeable effect on CEC values of both GCSs and CSs at Ibadan location following the application of CGS at all sampling depths. However, addition of CGS treatment to Isolu CSs resulted in slight reduction of their CEC values at 0.5 and 1.0 m depths when compared with CEC values of untreated CS. The CEC value of treated GCS at 0.5 m depth increased significantly over that of untreated GCS but slightly increased at 1.0 m depth at Eutric Luvisols location. Compared to the initial porosity values of untreated CS and GCS at Ibadan, the addition of CGS treatment to both CS and GCS did not result in any alteration of porosity values at all sampling depths. However, there is reduction in porosity values for treated Isolu GCS at sampling depths 0.5 and

1.0 m. From this study, the minimum and maximum porosity values were observed in Ibadan GCS at depth 0.5 m and Isolu GCS at 1.5 m depth, respectively. Furthermore, there is decrease in porosity values of Ibadan GCS for each sample depth compared to that of CS whereas the porosity of Isolu GCS increased slightly with respect to CS porosity values at 1.0 and 1.5 m depths. This may be due to the amount or quantity of greywater discharge in Isolu area. The increase in soil porosity with depth concurs with similar rise in porosity value at lower range (volume) of greywater concentration as reported by Faisal Anwar (2021). He reported that soil porosity has relation with concentration of greywater in a particular area. Similarly the increase in soil porosity of GCS at these two sampling depths (1.0 and 1.5 m) in Isolu area may also be due to reduction in CEC values of Isolu GCS over that of CS at these two sampling depths. This may be due to the fact that clay mineralogy and CEC of clay fraction present inevitably vary among soils (Lambooy, 1984). The range of DD values also follow this trend. Maximum porosity (47.92%) in Isolu GCS at 1.5 m depth might be due to reduction of surface tension at this depth (Peng et al., 2017). Similar maximum mean porosity value in mixed surfactant polluted soil was also reported by Ganiyu et al. (2022) in their investigation of physico-chemical and thermal characteristics of mineral and vegetable oils-contaminated soil in Abeokuta, southwest Nigeria. The soil resistivity values for Isolu and Ibadan soil samples ranged from 3.56 to 7.45 ohmcm and from 4.31 to 7.77 ohmcm, respectively. The soil resistivity values for GCSs and CSs at both locations fall below 10.00 ohmcm. Soil resistivity values at 0.5 and 1.0 m depths remain constant for untreated and treated CSs at Ibadan while addition of CGS to Ibadan GCS results in slight increment of soil resistivity values at all sampling depths. However, addition of 50 ml CGS to Isolu CS resulted in reduction of soil resistivity values at 0.5 and 1.0 m depths while the reduction of SR occurred at 1.0 and 1.5 m depths for treated Isolu GCS. As regards to GCS at the two study areas, lowest SR (3.56 ohmcm) was recorded for Isolu GCS at 1.0 m depth while highest SR (7.77 ohmcm) was observed in Ibadan GCS at 1.0 m depth. The lowest SR found in Isolu GCS at 1.0 m depth could be due to enhancement of soil washing by surfactant (detergent) at this particular depth (Ji et al., 2021).

Hydro- geotechnical Properties

The results of soil hydro-geotechnical analyses carried out on the collected and treated soil samples at the two sampling locations are presented in Table 2.

Table 2: Results of Hydro-geotechnical properties of untreated and treated soil samples at the two locations

Description of the site	DD (Mg m^{-3})	Porosity (%)	MC m^3 m^{-3}	Ksat (cm/hr)	Liquid Limit	Plastic Limit	Plasticity Index	Shear Strength kN/m^2	Bearing Ratio (%)
0.5 m Control Mapo Ib	1.58	40.38	0.087	1.31	17.2	13.7	3.5	151.61	3.82
1.0 m Control Mapo Ib	1.49	43.77	0.093	0.45	22..5	17.9	4.6	150.82	6.18
1.5 m Control Mapo Ib	1.42	46.42	0.98	0.17	26.5	21.1	5.4	104.46	6.30
0.5 m Control Mapo 2	1.58	40.38	0.088	1.30	17.8	14.2	3.6	156.18	4.10
1.0 m Control Mapo 2	1.49	43.77	0.94	0.45	23.1	18.4	4.7	156.19	6.54
1.5 m Control Mapo 2	1.42	46.42	0.099	0.17	27.1	21.6	5.5	109.17	6.70
0.5 m GCS Mapo Ib	1.59	40.00	0.083	1.53	16.9	13.4	3.4	151.70	3.68
1.0 m GCS Mapo Ib	1.51	43.02	0.089	0.57	21.5	17.2	4.4	163.50	5.88
1.5 m GCS Mapo Ib	1.44	45.66	0.097	0.22	26.2	20.9	5.3	128.04	7.11
0.5 m GCS Mapo 2	1.58	40.38	0.083	1.31	17.6	14.0	3.6	153.15	4.02
1.0 m GCS Mapo 2	1.51	43.02	0.091	0.65	22.3	17.8	4.5	188.52	6.41
1.5 m GCS Mapo 2	1.43	46.04	0.098	0.20	27.0	21.5	5.5	141.36	7.84
0.5 m Control Isolu	1.52	42.64	0.084	0.56	18.9	15.0	3.8	105.43	3.96
1.0 m Control Isolu	1.45	45.28	0.096	0.30	26.9	21.4	5.5	175.19	8.70
1.5 m Control Isolu	1.40	47.17	0.107	0.16	30.9	24.6	6.3	151.70	9.89
0.5 m Control Isolu 2	1.51	43.02	0.090	0.50	18.6	14.8	3.8	88.66	3.54
1.0 m Control Isolu 2	1.44	45.66	0.096	0.27	26.6	21.2	5.7	171.19	8.50
1.5 m Control Isolu 2	1.40	47.17	0.109	0.17	30.6	24.4	6.5	159.40	10.09
0.5 m GCS Isolu	1.52	42.64	0.083	0.64	18.5	14.7	3.8	116.25	4.06
1.0 m GCS Isolu	1.43	46.04	0.094	0.25	27.9	22.2	5.4	175.19	9.20
1.5 m GCS Isolu	1.38	47.92	0.109	0.14	31.9	25.4	6.2	151.58	10.32
0.5 m GCS Isolu 2	1.60	39.62	0.082	1.76	17.9	14.2	3.6	180.74	4.04
1.0 m GCS Isolu 2	1.46	44.91	0.086	0.26	22.5	17.9	4.6	86.42	4.46
1.5 m GCS Isolu 2	1.38	47.92	0.110	0.13	31.9	25.4	6.5	145.37	10.05

*Note: Description with 2 at the front denotes treated soil with CGS

Table 2 shows that K_{sat} value of Ibadan GCS at 0.5 m depth clearly reduced following the addition of CGS treatment. Addition of CGS to Ibadan CS revealed no noticeable effect on K_{sat} values while there is fluctuation in K_{sat} values for treated Ibadan GCSs. When compared with the initial values of K_{sat} in untreated CS at Isolu location, addition of CGS treatment leads to reduction of K_{sat} at both 0.5 and 1.0 m depths. However, addition of CGS to Isolu GCS resulted in significant increase of K_{sat} at 0.5 m depth. It must be noted that the lowest K_{sat} value (0.13 cm/hr) was noticed in treated Isolu GCS (with highest value of MC (0.110 m^3 m^{-3}) at 1.5 m depth while the highest value of K_{sat} (lowest MC value (0.082m^3 m^{-3}) was also noticed in treated Isolu GCS at 0.5 m depth. When considering the values of K_{sat} in GCSs and CSs at the two study areas, it was observed that K_{sat} values of Ibadan GCS at each sample depth were higher than their corresponding values in CS (Table 2). This could be due to the fact that detergents can lessening soil moisture retention by altering the surface tension of water as well as the contact angle between the solid and liquid phases (Karagunduz et al., 2015). However, the reverse is the case in the trend of variation of K_{sat} in Isolu GCS at each depth relative to CS (Table 2). This is in agreement with the assertion by some scientists that detergent solution support in abatement of K_{sat} (Peng et al., 2017; Sarabi & Sepaskhah, 2013). Nevertheless, it must be noted that the disparities in K_{sat} due to the use of detergents are both limited and contentious (Peng et al., 2017; Ganiyu et al., 2022).

The collected raw CS, GCS, treated CS and treated GCS at 0.5 and 1.0 m sampling depths in Ibadan sampling location had LL values within the permissible limit of <25% for suitable aggregates for base and sub-base courses. At Isolu location, raw CS, raw GCS, and treated CS collected at 0.5 m depth had LL values within the specification of ASTM D1241-00 (2000) and AASHTO M147 (2008). However, addition of CGS to Isolu GCS allowed LL values at 0.5 and 1.0 m depths to be within the specification limit for sub-base materials. It must however be emphasized that state like Colorado allows LL values up to 35% (Colorado, 2010; Osouli et al., 2017). All the collected raw soil samples (CS and GCS) as well as treated soil samples at the two locations had PL values that lie within the safe recommended values of 50% maximum for sub-base and base materials. From Table 2, the degree of plasticity of all the analyzed soil samples (raw and treated CS, raw and treated GCS) at the two sampling locations belong to low plastic soil with PI < 7.0 (Mohamed et al., 2018). According to the standard specification of PI values for aggregates used in base and sub- base courses, the CS, GCS, treated CS, and treated GCS for each sampling depth at Ibadan had PI values < 6% and thus suitable as aggregates for base and sub-base materials (ASTM D1241-00, 2000). However, at Isolu location, CS, GCS, treated CS, and treated GCS at 0.5 and 1.0 m depths pass the specification limit of PI< 6%. It should be noted that improved plasticity performance arose with the addition of CGS to GCS in Isolu area at sampling depths 0.5 and 1.0 m (the PI was reduced from 3.8 to 3.6 and 5.4 to 4.6, respectively) (Table 2). However, an improved plasticity behavior was reported for lime-treated kaolin in contrast to its values in glutinous rice slurry amended soil by Hoo et al. (2024). The DD values ranged from 1.38 to 1.60 mg/m^3 in collected soil samples at Isolu while it ranged from 1.43 to 1.59 mg/m^3 in Ibadan soil samples. The lowest values of DD for collected GCS, CS, treated GCS, and treated CS at each of the two locations were found at 1.5 m depth. Application of CGS treatment elevates the DD values of Isolu GCS. However, the DD values almost remain unchanged for amended GCS at Ibadan. Highest value of DD was obtained in treated Isolu GCS at 0.5 m depth (with sandy loam (SL) texture and lowest MC). This agrees with finding of Shifa and Thomas (2017) that reported highest DD occurred at lowest MC. The addition of CGS treatment did not affect the DD values of both GCS and CS at Ibadan sampling location. The shear strength (SS) in kN/m^2 for Eutric Luvisols soils ranged from 86.4 to 180.7 kN/m^2 and from 104.5 to 188.5 kN/m^2 for Vertic Cambisol soil samples. The lowest value of SS was found in treated Isolu GCS at 1.0 m depth while highest value of SS was found in treated Ibadan GCS at 1.0 m depth. Addition of CGS to both CSs and GCSs collected from Ibadan location led to increase in SS values at all the sampling depths when compared with SS values of untreated CS and GCS. This result is in agreement with similar increase in SS for soil samples treated with glutinous rice slurry by Yue et al. (2021). This is also an indication that addition of CGS to soil at Ibadan is more suitable for shallow engineering structures as it enhanced SS under low stress conditions (Yue et al., 2021). There is reduction in SS values at 0.5 m and 1.0 m sampling depths for CS treated with CGS at Isolu sampling location. However, addition of CGS to Isolu GCS resulted in higher SS value only at 0.5 m depth. The BR values for GCS and CS at both locations increase with depths (Table 2). Compared to initial BR values of CS and GCS at Ibadan, addition of CGS treatment resulted in slight increase of BR value for each sampling depth. This might be due to more enhancement in the activity of microorganism at Ibadan study area, leading to more microbially induced carbonate precipitation on polluted soil (Yue et al., 2021). It could also be due to relatively more presence of amylose/amylopectin (main starch molecules) that can cement soil particles into aggregates, thus improved mechanical features of Ibadan GCS (Yue et al., 2021; Patrón et al., 2024). However, application of CGS treatment led to reduction in BR values of treated Isolu CS at 0.5 and 1.0 m depths. There is significant reduction in BR value of treated Isolu GCS at 1.0 m sampling depth. The MC of Isolu soil samples in m^3m^{-3} ranged between 0.082 and 0.110 while it varies from 0.083 to 0.099 for Ibadan soil samples. It should be noted that addition of CGS to CS and GCS at both sampling locations resulted in little or no change in MC. Figures 2a and 2b show the impact of CGS treatment on values of analyzed properties in collected soil samples (CS and GCS).

Figure 2.0a: Soil physico-chemical properties as affected by CGS treatment on CS and GCS

Figure 2.0b: Soil hydro-geotechnical properties as affected by CGS treatment on CS and GCS

Results of Statistical Analyses

Table 3 shows the ANOVA results based on sampling depths and cereal gruel treatment. From the ANOVA Table 3, there is significant differences in % sand, % clay, soil pH, CEC, porosity, MC, K_{sat}, ALs, PI, and BR at 5% level ($p<0.05$) based on depth of sampling. However, the differences in all analyzed parameters upon treatment with CGS were not significant at 5% level ($p<0.05$). For the two study locations (as shown in Table 4), the mean % clay, porosity, MC, PL, LL, PI, and BR increased from 0.5 m to 1.5 m depth. However, the mean values of soil properties such as % sand, DD, K_{sat}, pH, and CEC decreased from 0.5 m depth to 1.5 m depth. Similar significant changes in % sand and % clay with soil depth were also reported by Gul et al. (2011). They discovered that sand particles decreased while clay content increased with increasing soil depth. A similar increase in soil MC with depth was also obtained by Okiotor et al. (2019) in their analysis of geotechnical properties of Ajali sandstone in southeastern part of Nigeria. The reduction of CEC with increase in depth obtained in this study concurs with similar observation by Alhaji et al. (2020). However, the reduction in DD with increase in sampling depth obtained in this study is in contrast with increase in DD with increase in depth reported by Alhaji et al. (2020) for soils under gneiss basement complex in north-central part of Nigeria. It should be noted that highest mean values of ALs and PI were recorded at 1.5 m depths for treated Isolu GCS while the lowest values of ALs and PI were observed at 0.5 m depth for Ibadan GCS. However, highest values of porosity, % clay, and MC at 1.5 m depth were observed in Isolu GCS while least values of % clay, porosity, and MC were noticed in treated Isolu GCS at 0.5 m depth. The recorded values for DD, K_{sat}, soil pH and CEC for treated Isolu GCS were significantly higher at 0.5 m depth than at other sampling depths. However, untreated Ibadan GCS had significantly higher value of % sand at 0.5 m depth.

Table 3: ANOVA results for analyzed soil parameters

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Depth	Sand	1111.583	2	555.792	36.038	.000
	Silt	17.583	2	8.792	1.151	.349
	Clay	1125.250	2	562.625	32.699	.000
	dry density	.092	2	.046	32.852	.000
	Porosity	131.370	2	65.685	32.886	.000
	MC	.001	2	.001	30.068	.000

	hydraulic conductivity	3.875	2	1.937	18.466	.000
	Liquid Limit	494.298	2	247.149	35.540	.000
	Plastic Limit	315.901	2	157.950	36.300	.000
	Plasticity index	20.606	2	10.303	35.174	.000
	Soil resistivity	4.151	2	2.076	1.151	.349
	pH	21.618	2	10.809	3.485	.064
	Organic matter	.070	2	.035	1.149	.349
	Shear strength	2409.137	2	1204.568	1.138	.353
	Bearing ratio	89.044	2	44.522	16.423	.000
	CEC	18.631	2	9.315	18.521	.000
Soil Type	Sand	5.172	3	1.724	.112	.952
	Silt	3.152	3	1.051	.138	.936
	Clay	14.326	3	4.775	.278	.841
	dry density	.001	3	.000	.335	.800
	Porosity	2.010	3	.670	.335	.800
	MC	6.617E-005	3	2.206E-005	.969	.439
	hydraulic conductivity	.220	3	.073	.699	.570
	Liquid Limit	2.090	3	.697	.100	.958
	Plastic Limit	1.388	3	.463	.106	.955
	Plasticity index	.088	3	.029	.100	.958
	Soil resistivity	.734	3	.245	.136	.937
	pH	2.266	3	.755	.243	.864
	Organic matter	.012	3	.004	.132	.939
	Shear strength	438.695	3	146.232	.138	.935
	Bearing ratio	1.078	3	.359	.132	.939
	CEC	1.051	3	.350	.696	.572
Depth * Soil Type	Sand	15.750	6	2.625	.170	.980
	Silt	24.750	6	4.125	.540	.768
	Clay	11.750	6	1.958	.114	.993
	dry density	.002	6	.000	.187	.975
	Porosity	2.239	6	.373	.187	.975
	MC	4.458E-005	6	7.431E-006	.327	.910
	hydraulic conductivity	.303	6	.050	.481	.810
	Liquid Limit	7.203	6	1.200	.173	.979
	Plastic Limit	4.526	6	.754	.173	.979
	Plasticity index	.331	6	.055	.188	.974
	Soil resistivity	5.841	6	.973	.540	.769
	pH	9.000	6	1.500	.484	.808
	Organic matter	.101	6	.017	.552	.760

	Shear strength	3415.615	6	569.269	.538	.770
	Bearing ratio	6.206	6	1.034	.382	.877
	CEC	1.457	6	.243	.483	.809
Error	Sand	185.070	12	15.422		
	Silt	91.635	12	7.636		
	Clay	206.475	12	17.206		
	dry density	.017	12	.001		
	Porosity	23.968	12	1.997		
	MC	.000	12	2.275E-005		
	hydraulic conductivity	1.259	12	.105		
	Liquid Limit	83.450	12	6.954		
	Plastic Limit	52.215	12	4.351		
	Plasticity index	3.515	12	.293		
	Soil resistivity	21.631	12	1.803		
	pH	37.221	12	3.102		
	Organic matter	.365	12	.030		
	Shear strength	12704.800	12	1058.733		
	Bearing ratio	32.532	12	2.711		
	CEC	6.036	12	.503		
Total	CEC	63.483	24			
	Sand	1317.575	23			
	Silt	137.120	23			
	Clay	1357.800	23			
	dry density	.112	23			
	Porosity	159.588	23			
	MC	.002	23			
	hydraulic conductivity	5.656	23			
	Liquid Limit	587.040	23			
	Plastic Limit	374.030	23			
	Plasticity index	24.540	23			
	Soil resistivity	32.357	23			
	pH	70.105	23			
	Organic matter	.548	23			
	Shear strength	18968.247	23			
	Bearing ratio	128.859	23			
	CEC	27.174	23			

Table 4: Results of ANOVA (mean separation) based on soil depth

Parameters	Soil depth at 0.5 m	Soil depth at 1.0 m	Soil depth at 1.5 m
% Sand	73.11 ± 1.0655^{a}	63.74 ± 3.7587^{b}	56.49 ± 3.7635^{c}
% Clay	15.20 ± 3.5051^{a}	22.82 ± 3.7265^{b}	31.95 ± 2.6550^{c}
Dry density (Mg m^{-3})	1.56 ± 0.0367^{a}	1.47 ± 0.0315^{b}	1.41 ± 0.0223^{c}
Porosity (%)	41.13 ± 1.3824^{a}	44.43 ± 1.1895^{b}	46.84 ± 0.8397^{c}
MC (**m^3 m^{-3}**)	0.085 ± 0.0029^{a}	0.092 ± 0.0035^{b}	0.103 ± 0.0058^{c}
Ksat **(cm/hr)**	1.11 ± 0.4796^{a}	0.40 ± 0.1537^{b}	0.17 ± 0.0293^{b}
Liquid Limit (%)	17.93 ± 0.7005^{a}	24.16 ± 2.5247^{b}	29.01 ± 2.5267^{c}
Plastic Limit (%)	14.25 ± 0.5555^{a}	19.25 ± 1.9928^{b}	23.11 ± 2.0060^{c}
Plasticity index (%)	3.64 ± 0.1506^{a}	4.93 ± 0.5175^{b}	5.90 ± 0.5210^{c}
Ph	8.37 ± 1.9646^{a}	8.33 ± 1.6032^{a}	6.34 ± 0.7048^{b}
Bearing ratio (%)	3.90 ± 0.2027^{a}	6.98 ± 1.6439^{b}	8.54 ± 1.7160^{b}
CEC (cmol/kg)	2.44 ± 1.0504^{a}	0.88 ± 0.3360^{b}	0.37 ± 0.0645^{b}

*Values show mean ± standard deviation. Values along the same row with the same superscript are not significantly different at 5% (p>0.05) level.

CONCLUSIONS

The study assessed the impact of fermented CGS treatment on observed soil properties of GCSs at various sampling depths in two locations within Basement Complex formation. Laboratory soil analyses were performed on GCS, CS, treated GCS and treated CS to assess alteration of selected soil properties. The results showed that alteration of selected soil geotechnical/hydraulic and physico-chemical properties on both CS and GCS depends greatly on depth. The effect of CGS treatment on analyzed samples altered soil properties on different scales. For example, the CGS treatment had no significant effects on DD and MC at both locations while other analyzed properties are site specific. According to pH permissible limit set for mixing water for concrete, the pHs of Isolu GCSs at all sampling depths fall within the pH limit of 6 – 9. The highest and lowest values of K_{sat} and CEC were noticed in treated Isolu GCS at 0.5 and 1.5 m depths respectively. All the collected raw soil samples (CS and GCS) as well as treated soil samples at the two locations had PL values that lie within the safe recommended values of 50% maximum for sub-base and base materials. Furthermore, the degree of plasticity of all the collected soil samples (raw and treated CS, raw and treated GCS) at the two locations indicates their low plastic nature. ANOVA result revealed no significant differences in the mean values of all analyzed parameters based on soil treatment while most of the analyzed parameters except SS, soil resistivity, and OM content varied significantly at 5% level based on sampling depths. There should be a further study to evaluate the effects of other starchy fermented gruels treatments at varying concentrations on soil properties at various sampling depths.

Conflict of Interest

The authors declare that they have no conflicts of interest.

Authors' contribution

All authors contributed to the study's conception and design. Soil sample collection and preparation, as well as analyses, were performed by Saheed Adekunle Ganiyu, Oluwaseun Tolutope Olurin, and Michael Olugbenga Olobadola. The first draft of the manuscript was written by Saheed Adekunle Ganiyu, and all authors commented on previous versions. All authors read and approved the final manuscript.

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