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RESEARCH ARTICLE

Investigation of the Impact of Tropical Red Clay Soils' Mineralogical Composition on their Physical and Mechanical Properties– a Case Study Ruaka – Kenya

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Abstract:

Introduction:

Residual soils covering large areas of the earth have been chiefly discovered in the last 30 years in most volcanic tropical and subtropical countries. Understanding their behaviour is essential for various infrastructure developments.

Methods:

The physical and mechanical properties of the soils are affected by their mineralogical composition. There is a need to determine the mineralogical composition of the soils and investigate the impact on properties. This paper presents the results of a laboratory study conducted on red clay soil from Ruaka, a suburb in Kenya, to investigate the effect of mineral and chemical composition on the soil's physical and mechanical properties. Disturbed and undisturbed samples were subjected to different tests such as Atterberg limits, soil classification, consolidation test, X-ray fluorescence, X-ray diffraction and petrology test based on the British Standard soil classification system (1377-1994). The soils were classified as clay with high plasticity, and high clay content varied between 59-79% resulting in mechanical instability of the soil in this site.

Results:

The mineral and chemical analysis indicated the formation of unique minerals like Halloysite, Quartz, Kaolinite, and Mica, which influenced the geotechnical properties of clay. The index properties of clay recorded high values; the moisture content and plastic limit varied between 37- 46% with a slight increase as depth increased; the liquid limit varied between 63-68% with increased depth.

Conclusion:

The average value of maximum dry density was reported as around 1247 kg/m³ with high optimum moisture content, reaching 35.5%. Besides that, the soil had a high void ratio of 1.145 to 1.63, which increased the permeability of the clay to 1.223E-5 cm/s. The properties of red clay soils in more than ten tropical regions in Kenya compared with the soil under study are also presented in this paper.

Keywords: Halloysite, Tropical soils, Chemical, Mineralogical, Composition, Residual soils, Ruaka.

Article History

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1. INTRODUCTION

Residual soils, covering large areas of the earth, have been discovered for the last 30 years in most volcanic tropical and subtropical countries. The soils are mainly formed from the

physical and chemical weathering of the parent rocks and minerals. They are found in the following African countries: Cameroons, Ethiopia, Tanzania, Rwanda, Kenya, Spanish Guinea, and the Canary Islands. Countries in the East African region, such as Kenya, usually experience high rainfall during which red-brown nitosols soil is derived from volcanic rocks of steep slopes. The soils generally have an acidity of pH 4.0 to pH 6.0, particularly in the Murang'a, Nyeri and Nyandarua

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districts of central Kenya and several parts of the Eastern province of Kenya [1]. East Africa includes six distinct climate zones: the Lake equatorial climate, the modified equatorial climate, the Kenya highland sub-tropical climate, the tropical climate, the coastal tropical climate, and the desert and semi-desert climate. Kenya has a subtropical and a coastal tropical climate, which results in a diverse range of tropical red clay soils formed over various igneous (both volcanic and intrusive) rocks.

Geotechnical engineers usually assume that the residual soils conform to preconceived patterns of soil in terms of mechanical behaviour. However, applying concepts from other soil types, such as sedimentary soils, may or may not be relevant to these soils.

Red soil is a type of residual soil and one of the most problematic soils characterized by swelling due to wetting and shrinkage due to the high clay content inherent in its structure [2]. It is very hard when dry; however, it loses this strength when in a wet condition.

The relationship between residual soil structure and engineering qualities does not provide a qualitative explanation for the soil's unusual properties in practice. As a result, the mineralogical composition and structure are usually used to characterize the residual soil [3 - 6]. The unusual properties of some forms of residual soil are attributed to their specific clay minerals, which cause their mechanical and physical properties to be strongly linked to their mineralogy composition [7]. Residual soils' mineralogy composition influences their behaviour more than stress history [8, 9]. Physical and chemical weathering produces particular clay minerals that can control its behaviour. Residual soil, unlike sedimentary soil, does not consider stress history. Therefore, the terms 'normally consolidated' and 'over consolidated' are irrelevant to residual soils.

According to Wesley [6, 8], the residual soils are divided into three main groups (A, B, and C) mentioned in detail by Wesley. (2009) [8]. The current study will focus on group (C) - tropical soil, specifically tropical red clays, categorized under three sub-groups that included the group of residuals characterized by unusual properties. In engineering literature, tropical soils are sometimes described as falling into two broad categories: tropical black and red.

The uniqueness of residual soils has been demonstrated in previous studies. Despite the availability and importance of residual soils, few dedicated efforts have been made to develop a comprehensive document that characterizes their behaviour. This would allow the decision-makers to think accordingly and in time to avoid unanticipated problems. Physical and chemical weathering produces particular clay minerals that can control its behaviour. This type of soil has recently received special attention from researchers due to its unusual behaviour attributed to its remarkable properties. The red soil in this paper was studied in Ruaka, a suburb of a large African city, Nairobi, where relevant data on physical and mechanical properties are lacking. Kenya is one of the developing countries under the pressure of economic development. The country is currently involved in massive infrastructure

expansion projects including the construction of bridges, roads, water supply pipes, underground structures, and other infrastructure throughout the country especially in Nairobi. Therefore, more research on red soils is necessary to meet the requirements of the ever-increasing construction works. This study investigated the effect of the chemical and mineralogy composition of Ruaka soil on its engineering properties. The present study results will inform infrastructure development in the area and the general behaviour of tropical red soils.

2. REVIEW OF PREVIOUS WORKS

The first systematic study of this soil in Kenya was conducted between 1937 and 1945 for the Ruiru Dam site [10]. A large earth dam came to be built in the tropical areas of Kenya. It was observed for the first time that the properties of this residual soil were considerably different from those seen in temperate climate sedimentary clays. The optimum moisture content was around 50%, while the maximum dry density was approximately 72 lb/ft³ (11.53 kN/m³). Therefore, Karl [11] reassessed the integrity of this dam on this soil; the results showed that the abnormal properties were assets rather than liabilities, and the clay did not conform to conventional behaviour. Between 1947 and 1949, another site investigation for Sasumua Dam took place, Halloysisite was a principal constituent, and the soil showed similar properties. Furthermore, the liquid limit was high, the natural moisture content was high, the maximum dry density varied from 65 to 75 lb/ft (10.20 to 11.77kN/m³), and the optimal moisture level was between 55 and 45%. The soil cohesion (*c'*) and the friction angle (ϕ') were generally between 26 and 30 kN/m² and 34°, respectively.

In yet another study, Newill [12]. investigated the properties of two samples of red clay soil, one from Nairobi's Kabete district and the other from a site near the Sasumua Dam, 40 miles northwest of Nairobi; his research highlighted the unusual properties of Kenya's red clay soils and the difficulties in interpreting laboratory tests such as the plasticity and compaction tests. The same conclusion was presented by B. Huat *et al.* [9], Dixon & Robertson [10], and Karl [11] when they studied the red clay soil from Nyeri and Ruiru Dam in Kenya. The soil possessed unusual properties, including excessively high moisture absorption, increased index values and abnormally low Maximum Dry Density (MDD); they attributed these properties to its mineralogy composition and structure.

Several other studies [5, 13 - 16] were carried out to investigate the impact of the mineralogy composition on the physical properties of tropical clay and to obtain further laboratory evidence of the abnormal behaviour of this soil. The comprehensive investigation was launched in 1993 by the Overseas Development Administration for some tropical regions in Kenya and Indonesia [17 - 19]. They observed that the increase in clay content is consistent with the variation in mineralogical composition, which makes tropical soils' mechanical and physical properties unstable. Additionally, these soils can exhibit swelling characteristics in an intermediate weathering stage.

Wesley [6, 8] emphasized that geotechnical engineers

should have open minds about how residual soils may behave and not assume they will conform to preconceived patterns, especially when working with tropical soils. Based on this engineering background, more and more attention has been paid to understanding the behaviour of tropical soils. Further studies [17, 19 - 25] were carried out to determine the behaviour of red clay and to solve practical engineering problems such as the settlement deformation of buildings. More recently, a study by Xue *et al.* [26] in southern China investigated red clay's shear strength and creep behaviour to evaluate red clay's long-term shear strength and deformation when subjected to various structural loading. Their study provided promising results that can help solve the settlement problem in this type of soil.

Although there is a universal need to develop a method for indexing the abnormal properties of tropical soils, conventional index tests, particularly Atterberg limits, remain essential tools for the adequate characterization of these soils [6]. Furthermore, Wesley [6] criticized the argument that soil drying affects the results of Atterberg limits tests, stating that the influence of soil drying on the Atterberg limits is confined to shifting the point on the plasticity chart parallel to the A-line. So, this is insignificant because the only criterion for evaluating the soil is the distance above or below the A-line.

However, Gadzama *et al.* [20] investigated the effect of temperature variation ranging from 25 to 150°C on the geotechnical properties of selected black cotton soils. Their results revealed decreased liquid and plastic limits and increased MDD. There was no increasing effect on Plasticity Index (PI) and Optimum Moisture Content (OMC).

According to Attah & Etim [2], the reaction of clay mineralogy to an elevated temperature significantly impacts its engineering properties in service. Even though their study was conducted on lateritic soils, their results showed a decrease in the Atterberg limit and an increase in MDD, which was consistent with Gadzama *et al.* [20].

In the tropics, soil formation is very varied and frequently complex. Because of its high clay content, it is an expansive soil that offers a considerable engineering problem, necessitating its stabilization before being employed for any engineering applications. As a result, the recent investigations by George *et al.* [21], Hanuma *et al.* [22], Sani *et al.* [23], Osinubi *et al.* [24], and Abner [25] on red clay have contributed to improving its properties. The studies [21 - 25] concluded that such soils, due to their unpredictable behaviour, are unsuitable for engineering construction, emphasizing the need for soil stabilization to enhance engineering properties.

The difficulty and abnormal behaviour would appear when applying 'conventional' soil mechanical concepts regarding sample drying and preparation. Particularly with tests that require remoulding the samples, such as the triaxial test, controlling the optimum moisture content with the MDD

becomes challenging.

The relationship between the mineralogical composition of this soil and its engineering properties is complex and understudied in geotechnical engineering because the properties of this soil are strongly reliant on the weathering condition of the parent rocks, which varies by region. The behaviour of tropical red soil from Ruaka was defined and analyzed using standard testing to determine the usefulness of these tests in the engineering evaluation of tropical red clay soil properties. The results were compared to the chemical, mineralogical, index, and mechanical properties of typical tropical red soils from different tropical climatic regions in Kenya.

3. LOCATION AND GEOLOGY OF STUDY AREA

The soil investigated in this study is red clay soil collected from Ruaka. Ruaka town is located in Ndenkeru Ward, Kiambaa Sub-County, Kiambu County. The suburb is located northwest of Nairobi and is easily accessible *via* the Northern Bypass and Limuru Road (Fig. 1). Ruaka is part of the larger Nairobi Metropolitan Area, with easy access to Kiambu, Limuru, Nairobi, Thika, Kajiado, Machakos, and Muranga Towns [26]. The study area is located between Longitude 36° 48' 0.51", 36° 48' 6", and 36° 48' 10.1", East, and latitudes 1° 12' 33.6", 1° 12' 36.7" and 1° 12' 38.7", South of the Equator which is characterized as having tropical red soils as shown in Fig. (2).

Three boreholes were used for laboratory investigation to characterize the soil of Ruaka with depths of 10.5m, 8.95m, and 8.95m; the investigation could not go more profound due to the presence of rocks that are out of the scope of this study. The subsoil characteristics of each borehole are studied in detail.

The mineralogy and structure of the soil determine the engineering behaviour, which in turn, is dependent on the original rock type and climatic and drainage conditions both during and after weathering. Grain size, unit weight, strength, and compressibility vary significantly due to these parameters.

4. MATERIALS AND METHODS

Undisturbed and Disturbed soil samples were extracted from three boreholes, as shown in Fig. (3), at various depths (8.95m and 10.5m). The basic properties obtained from these undisturbed and undisturbed soil samples were determined using a variety of tests. A light excavator with a 100 mm diameter and 500mm long cylindrical corer was pushed into the soil to the desired depth to extract the undisturbed soil (U100) sample; this static push method prevents the corer from rotating, resulting in high-quality samples (Figs. 4 and 5). Disturbed samples were collected using a drill and stored in plastic containers. The samples are then sent to the laboratory in sealed containers to preserve their natural moisture contents, preparing them for subsequent laboratory analysis.



Fig. (1). The location of the area of study (Ruaka).

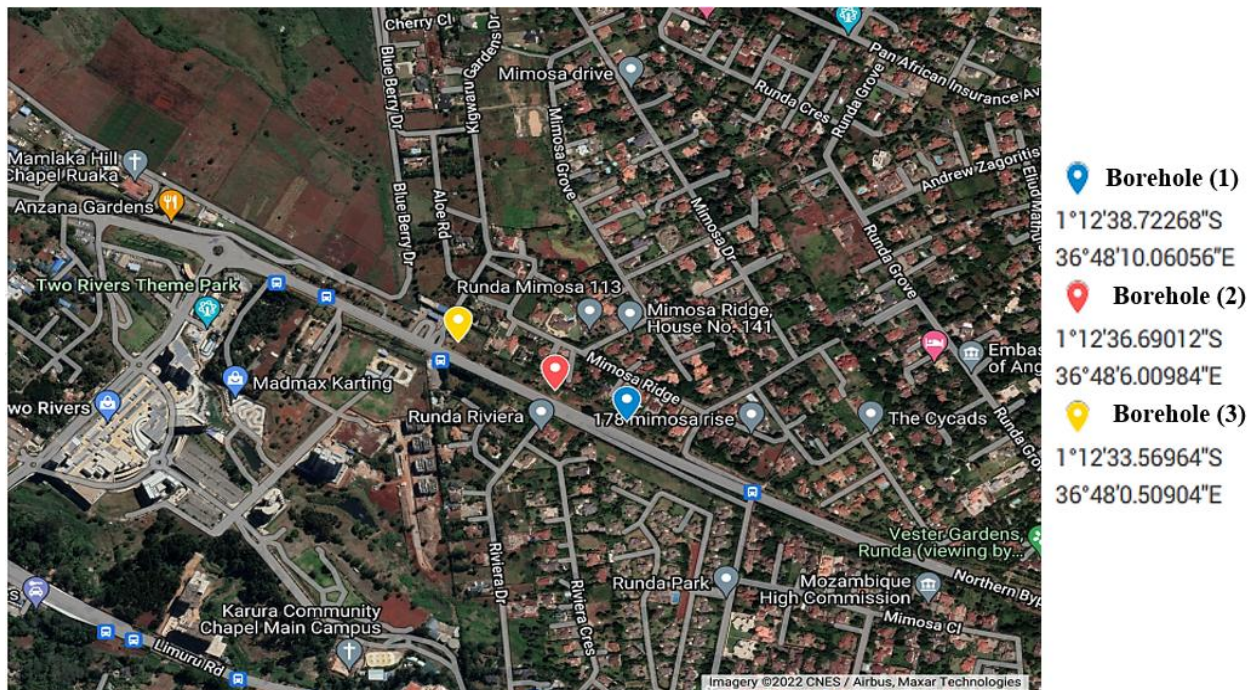


Fig. (2). Location of sample site (three boreholes).



Fig. (3). Soil sample collections, including disturbed sample (right) and undisturbed sample (left).



Fig. (4). Apparatus used during geotechnical drilling.



Fig. (5). Extruding the undisturbed samples.

The collected soil samples were subjected to two laboratory tests: soil classification tests (moisture content, Atterberg limits, specific gravity, and particle size distribution)

and soil strength tests (standard proctor compaction and consolidation tests). After that, the samples were fully air-dried, and the lumps were pulverized and sieved for different tests performed using the British Standards, as summarized in Table 1. The chemical and mineralogical composition tests were also carried out to determine the characteristics of this soil and their impact on the physical and mechanical properties.

Table 1. Summary of engineering laboratory tests and relevant standards.

Test	Standard
Natural Moisture Content	BS1377-2 [27]
Atterberg Limits ((Falling Cone) and Linear Shrinkage	BS1377-2 [27]
Particle Size Distribution (wet sieving) Particle Size Distribution (hydrometer)	BS1377-2 [27]
Particle Density / Specific Gravity	BS1377-2 [27]
Consolidation - oedometer test	BS1377-5 [28]
Compaction – Proctor Effort	BS1377-4 [29]

5. RESULTS AND DISCUSSION

5.1. Microstructure of Ruaka Clay

5.1.1. Petrology Test

Petrology refers to the scientific study of rocks focusing on their composition, texture, structure, occurrence, distribution, and origin. It assesses the physicochemical conditions and geologic processes. This test is also concerned with the three major types of rocks: igneous, metamorphic, and sedimentary.

The analyses were performed from three groups of samples from different depths categorized as Group 1, Group 2, and Group 3, respectively. These three groups of samples were prepared, dried, and hardened by heating at 105°C and subjected to a petrological analysis. Group 1 soil represents weathered clay soil with minute Quartz grains; Group 2 are these soils that showed red loam soil. The structure is argillaceous material, rich in organic and porous cementing materials. Finally, Group 3 was characterized by highly weathered aluminosilicate minerals due to alteration of the parent rock, making its behaviour seems like weathered red loam soil; the soil had Pyrite as a trace element. The microscope images are displayed in Fig. (6(a-c)), which describes the microstructure composition of each group.

5.1.2. X-Ray Fluorescence and X-Ray Diffraction Analyses

The chemical and mineral compositions in Ruaka's soils were determined using the standard chemical and mineral tests X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD), respectively. Several disturbed samples from Ruaka soil were subjected to chemical and mineral analyses to investigate the chemical and mineral composition of the tropical red soils in the study area. The clay of Ruaka had a nearly identical concentration of primary oxides (CaO, Fe₂O₃, FeO, MgO, Al₂O₃, SiO₂). As listed in Table 2, the Ruaka soil contains high amounts of Al₂O₃, SiO₂, and Fe, among other chemical components, indicating Halloysitic soil behaviour.

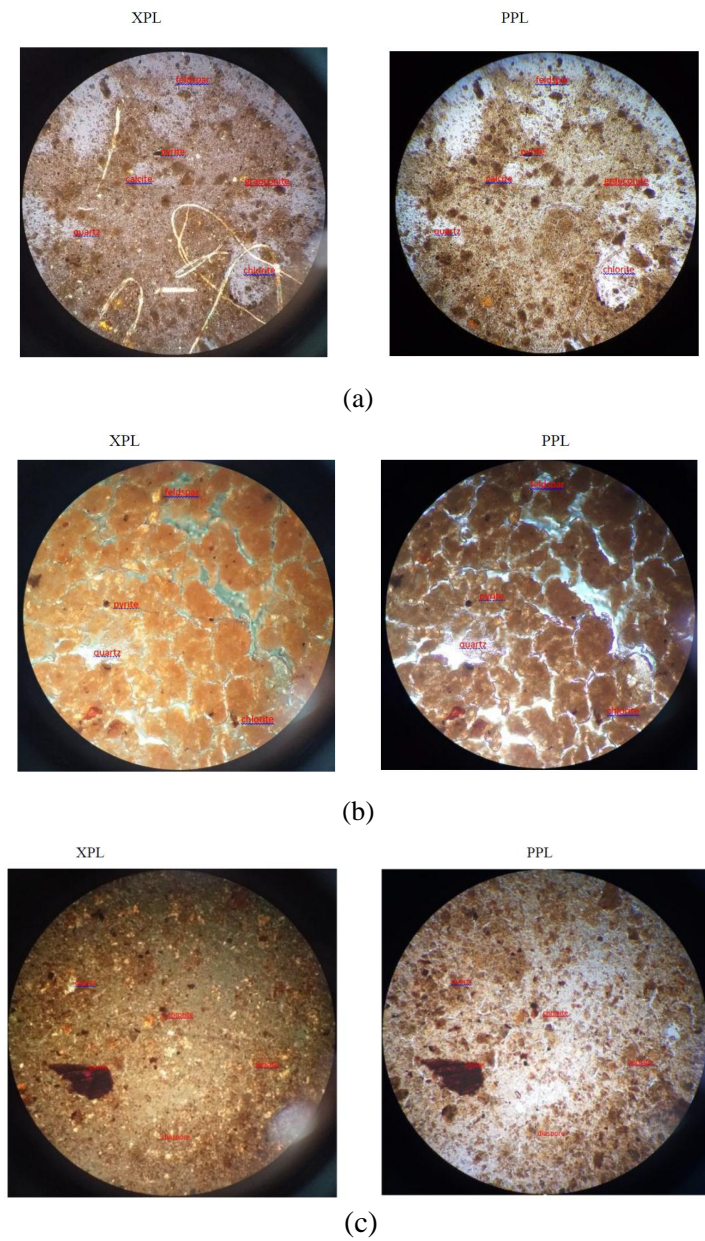


Fig. (6). Petrographic view: (a) Group1 (b) Group 2 (c) Group 3.

Table 2. The chemical composition of Ruaka soils from the XRF test.

Elements	%
Aluminium oxide, Al_2O_3	34.47
Silica oxide, SiO_2	45.76
Potassium oxide, K_2O	0.509
Calcium oxide, CaO	0.034
Titanium oxide, TiO	1.652
Manganese, Mn	0.467
Iron oxide, Fe_2O_3	16.387
Zirconium, Zr	0.225
Niobium, Nb	0.076
Yttrium, Y	0.022
Rubidium, Rb	0.012

(Table 2) contd.....

Elements	%
Zinc, Zn	0.02
Nickel, Ni	0.009
Copper, Cu	0.004
Molybdenum, Mo	0.003
Cerium, Ce	0.308
Thorium, Th	0.015
Thallium, TL	0.011
Lead, Pb	0.009

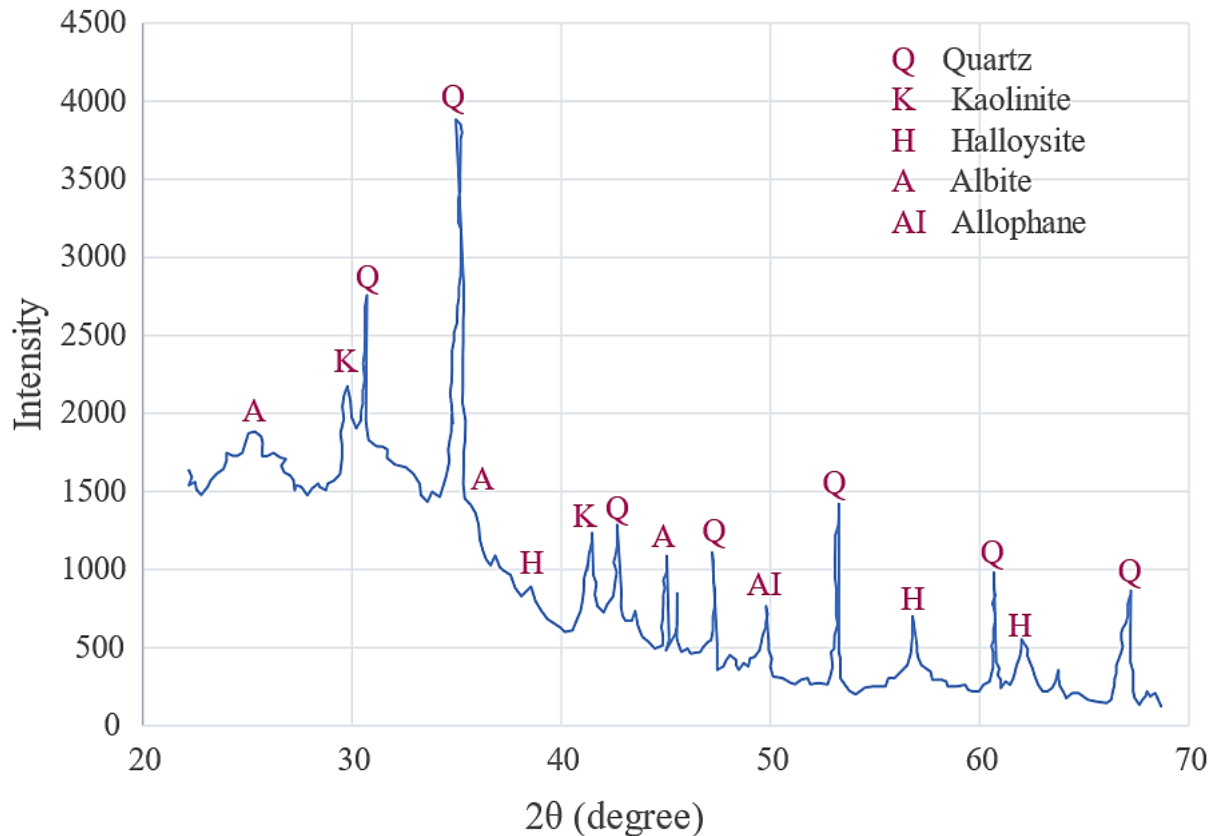


Fig. (7). XRD pattern of the Ruaka soils.

From Table 2, a significant percentage of 'free' iron oxide (16.40%) was observed in the Ruaka clay, which might be responsible for their clustering since iron oxide is known to behave as a cementing agent [30]. The XRD investigation revealed that the dominant clay minerals in Ruaka's soil were Quartz, kaolinite, and Halloysite, with a fraction of Allophane, and albite, as shown in Fig. (7).

Temperature, drainage, and topography have reduced the in-place rocks to residual soils ranging from clays to sandy silts and silty sands, grading into saprolite and partially weathered rocks as depth increases, which are controlled by the minerals

in its clay [4, 16, 17, 31]. Quartz is resistant to chemical disintegration during weathering, whereas feldspar and Mica are primarily converted into clay minerals.

5.2. Physical Properties

5.2.1. Moisture Content and Atterberg Limits

The tests were performed on the natural and heated soils according to the procedure outlined in BS 1377: Part 2: 1990 [27]. Table 3 summarises the values of moisture content (MC) and Atterberg limits (plastic limit (PL), Liquid limit (LL), and plasticity index (PI) in the initial state for the samples; Fig. (8) shows the MC distribution with depth.

Table 3. The index properties of Ruaka soil.

Borehole	Depth	PL	LL	PI	In-MC
BH01	3.5	36	63.55	27.6	37.5
	6.5	44.4	67.45	23.1	43.7
	7.5	50	67.8	17.8	44.35
BH02	2	40.8	63.4	22.6	41.92
	3.5	50	62.6	12.6	45.50
	5.5	44.8	63.4	18.6	48.32
BH03	3	45.5	62.21	16.7	31.87
	4.5	40	65	20	34.48
	6	37.9	67	29.1	45.64

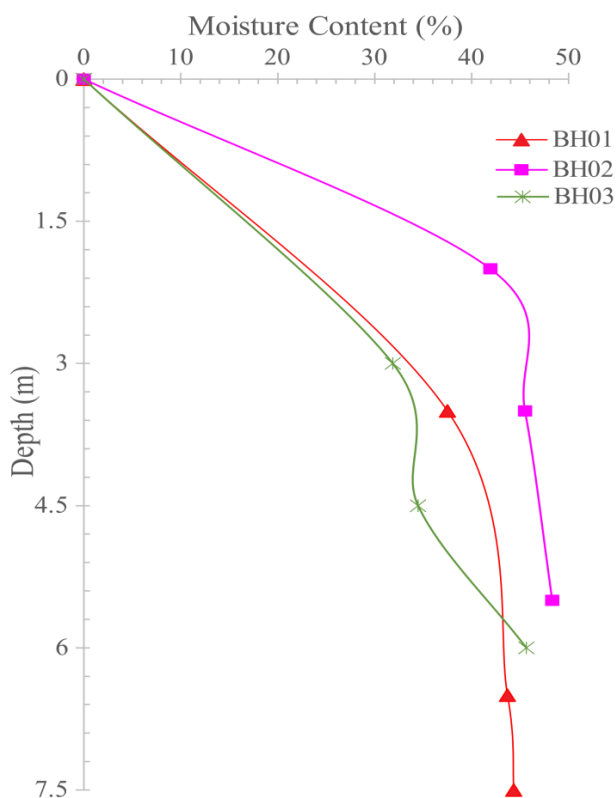


Fig. (8). The variation in initial water content with depth.

Twelve block samples were collected from three boreholes with depths ranging from 3m to 9m. The site investigation revealed that the structure of this soil is susceptible to drying. As a result, the testing was done as close to the natural moisture content MC. So, when drying was required, it was achieved through air-drying or oven drying at a maximum temperature of 105°C.

The initial MC for tropical red clay from Ruaka was high. The trend showed a slight increase in the water content with the depth, which is consistent with what has been reported in earlier studies [3, 10, 11, 32 - 35] regarding this soil's abnormal behaviour. In contrast, Abner [2] found a decrease in the Atterberg limits and an increase in MDD while studying the effect of temperature on red clay. The initial MC values converged significantly with the PL values. The trend of the

water content distribution for BH01 and BH03 seems to be similar, whilst the trend of BH02 was at the upper bound of that trend.

Fig. (9) shows the profile of the Atterberg limits with depth. The LL was determined using the Cone penetrometer test, (Fig. 10), the preferred method for the Casagrande test. The laboratory results in Table 3 indicated that both LL and PL values at different depths in each borehole showed slight variations. However, the trend in BH02 showed a slight increase in the values of LL and PL than other boreholes. The reasoning behind some of these findings is that the capacity of a clay particle to hold exchangeable metal ions is determined by the size of the diffused double layer and the dipolar water attracted to that layer.

For analyzing and defining the residual soils, Atterberg limits are a helpful tool. However, these limits should not be considered separately. The emphasis was placed on the plasticity chart, which is a valuable indicator of its engineering properties. The soil profiles appeared non-uniform at 2m and deeper up to 7.5m, as evidenced by a downward increase in index characteristics (MC and Atterberg limits) with depth. However, these results seem to be different from what has been reported by Northmore *et al.* [17], who investigated the soil in three locations in central Kenya northwest of Nairobi at 7.9m. Their findings revealed that index properties were homogeneous across sites, with no identifiable trend with depth, which confirms that the behaviour of this soil is unpredictable as it depends mainly on the mineral composition of the soil in the particular region.

5.2.2. Specific Gravity

The specific gravity or particle density, G_s , was determined using the Pyknometer method, (Fig. 11) following BS 1377-2 (1990). The particle densities of the samples were unusual for clay soil, ranging between 2.30 and 2.55 and lower than those reported for residual soils in previous studies [4, 5, 8, 35 - 37], which could be attributable to the proportion of organic matter inherent in its parent rocks. On the other hand, some of the samples had anomalous values such as 2.94 and 2.21, which agreed with [14, 18, 38] that tropical soils could have unusually high, or unusually low soil characterized by highly variable particle densities. Northmore *et al.* [17] investigated various samples from some tropical regions in Kenya, and they found a broader range of G_s , ranging from 2.67 to 2.95.

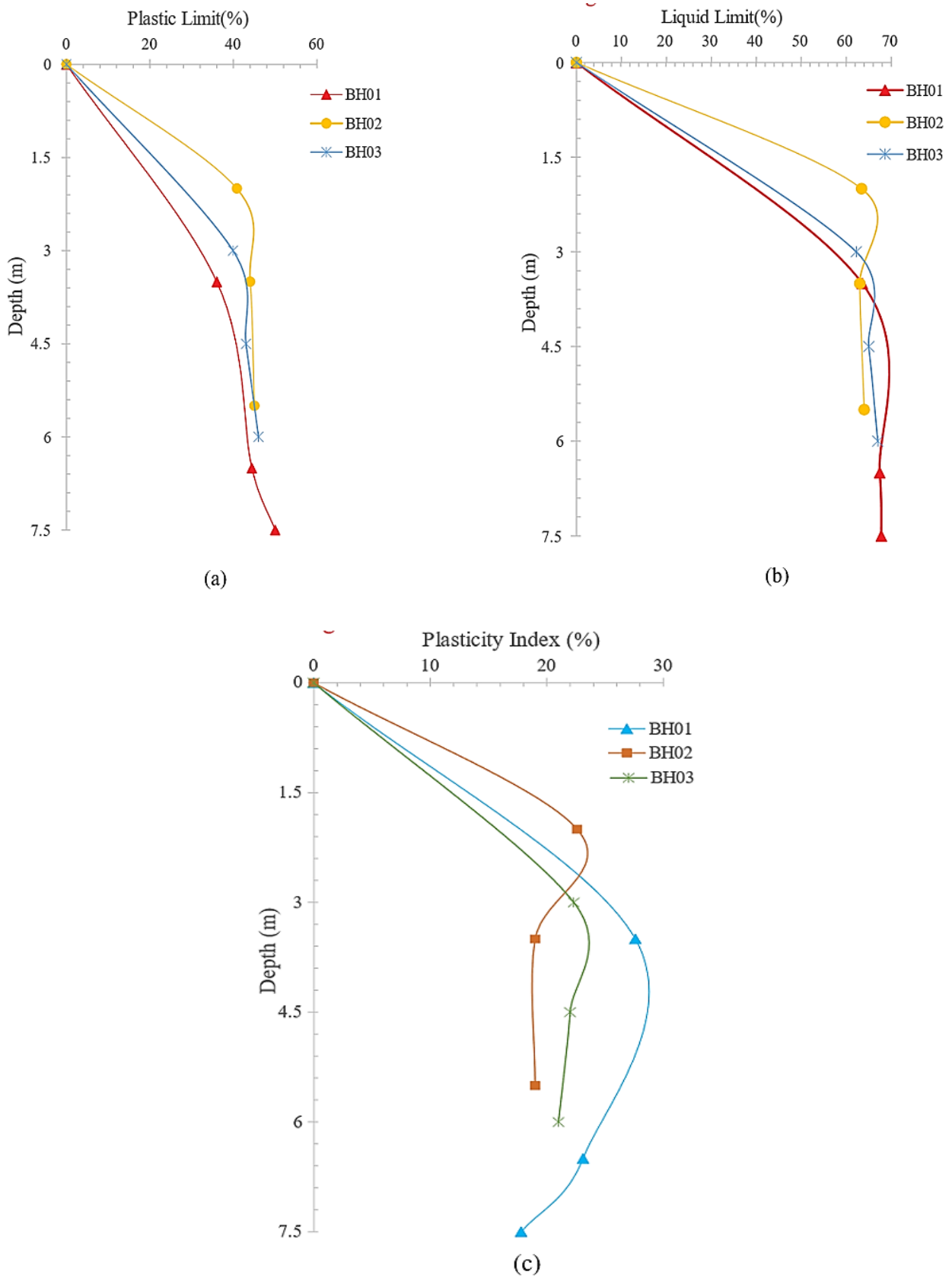


Fig. (9). The variation of Atterberg limits with depth: (a) variation in plastic limit, (b) variation in liquid limit, (c) variation in plasticity index.



Fig. (10). Cone penetrometer test for Atterberg limits – Ruaka soil.



Fig. (11). Preparation of the samples for the particle density test (Pyknometer).

The main factor that affects the G_s of Ruaka soils is the presence of clay minerals with low particle density, such as kaolinite which has a particle density that varies between 2.2 and 2.6. Another factor contributing to reducing the G_s of Ruaka soil was oven drying of samples. Furthermore, the previous research [12, 17, 33] discovered that hydrated minerals such as Halloysite usually lost little inter-layer moisture after oven drying, resulting in a reduction in the G_s of soil.

5.2.3. Particle Size Distribution

The particle size distributions of the samples were determined using a combination of wet sieving and hydrometer analysis following the standard BS1377-2 [27]. The mechanical or sieve analysis on oven drying samples was

performed to determine the distribution of the coarser, larger-sized particles. The remainder ($\leq 0.075\text{mm}$) is determined by a sedimentation technique that assumes that the soil particles in aqueous suspension obey Stokes' Law which provides a smooth curve and complete gradation profile of coarser soils, Fig. (12). When the soil sample is dispersed in water, the particles settle at different rates depending on their shape, size, and weight, as shown in Fig. (13). To avoid the effect of the dispersing agent on the particle size distribution results, Sodium Hexametaphosphate was used as a dispersing agent at a concentration of 2g/litre.



Fig. (12). Sieve analysis (left) and hydrometer test (right).



Fig. (13). Prepare the samples for the hydrometer test.

The grading curves of samples from various depths and boreholes are shown in Fig. (14), and the percentages of fine particles in Ruaka's soil are listed in Table 4.

Table 4. Average range of various grain size fractions for Ruaka soils.

Borehole	Samples	Ruaka		
		Fine fractions		
		Clay %	Silt %	Sand %
BH01	S1	59	40	1
	S2	67	31	2
BH02	S1	77	22.9	0.1
	S2	78	21.9	0.1

(Table 4) contd....

Borehole	Samples	Ruaka		
		Fine fractions		
		Clay %	Silt %	Sand %
BH03	S1	66	33.9	0.1
	S2	79	21	0

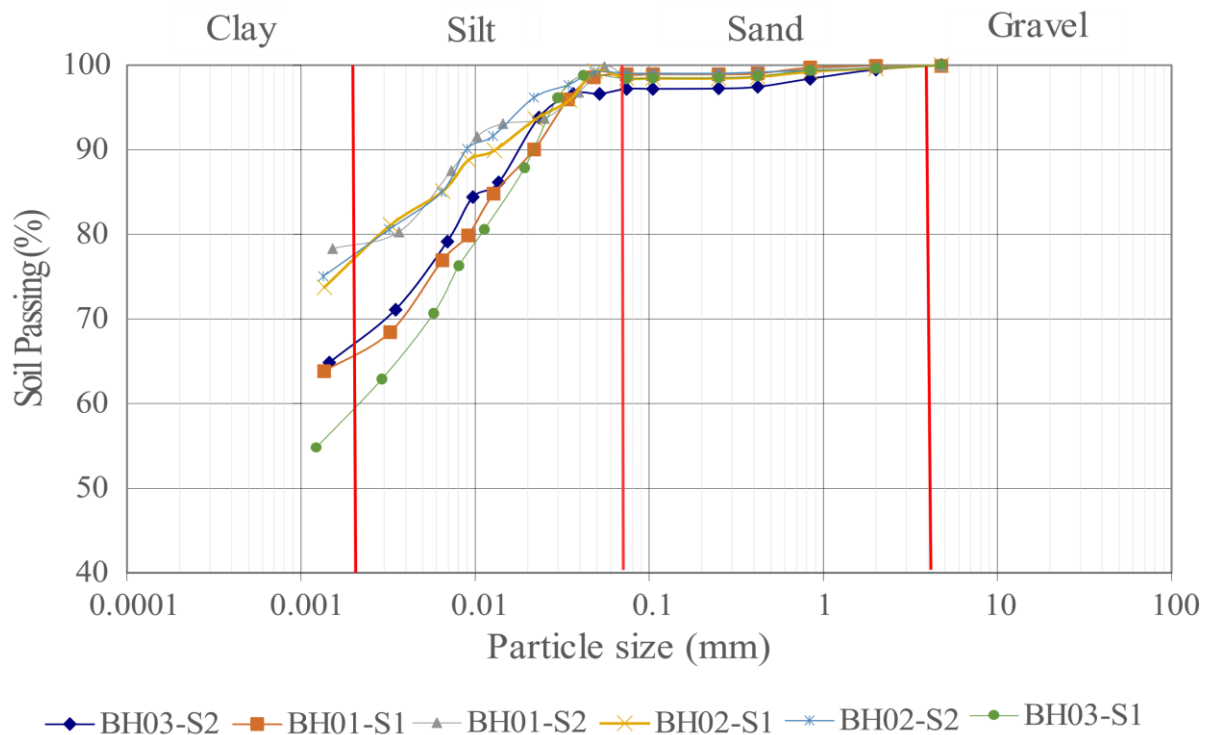


Fig. (14). The particle size distribution curves for Ruaka soil.

Although the analysis included soil from various boreholes and depths, the trends of grading curves exhibited strikingly similar behaviour. According to the BS system, the soils are classified as clay with high plasticity (CH), with a high percentage of clay and silt ranging from 59-79% and 21-40%, respectively. These results support the findings of Abner [2], who reported that soil exposure to elevated temperature leads to clay minerals and water evaporation reactions. Temperature variation decreases the particle size in sandy soil, whereas in clayey soil, the particle size increases as a result of the accumulation of clay fraction [2]

It is noteworthy that problems arise in residual soils when attempting to relate the classification boundaries to LL or PL separately, as in all soil classification systems. As a result, by combining the effects of PL and LL, the plasticity chart becomes a robust criterion for analyzing the behaviour of residual soils. The high values of LL, PL, MC, void ratio, and a significant percentage of clay were contributed to the soil of Ruaka being located below line A, as shown in Fig. (15). This location was consistent with the tropical zone identified by

Dixon & Robertson [10] for the tropical soil in Kenya in Fig. (16).

Wesley [8] improved the plasticity chart by combining subdivision lines relevant to the mineralogical composition of residual soils and attempting to concentrate on the abnormal minerals in clay soil. Moon [40] later validated the Wesley [8] graph using more current data from a range of Halloysite-dominated zones.

It is evident from the Wesley graph in Fig. (17) that the soil in Ruaka tends to be halloysitic soil, which was also supported by XRD and XRF analysis. This could explain some of the unusual characteristics of Ruaka soil, such as its high percentage of plasticity and clay content. Northmore *et al.* [17] found that in most tropical red soils, particularly those containing the hydrated form of Halloysite ($A_1O_2 \cdot 2SiO_2 \cdot 4H_2O$), oven drying cannot remove the initial MC from the soil altogether. As a result, soil plasticity increases, resulting in apparently high MC. However, the breakdown of soil structure and the subsequent increase in clay content may also explain the rise in soil index values.

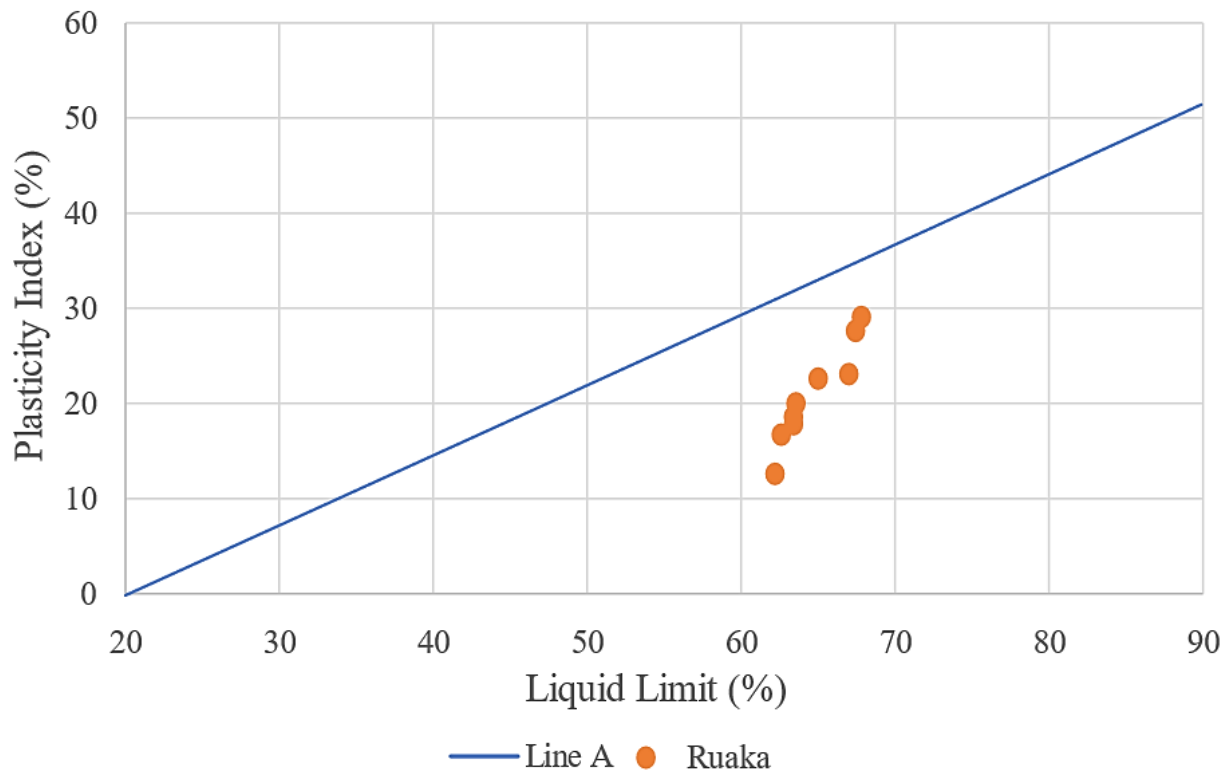


Fig. (15). The plasticity chart of Ruaka soils.

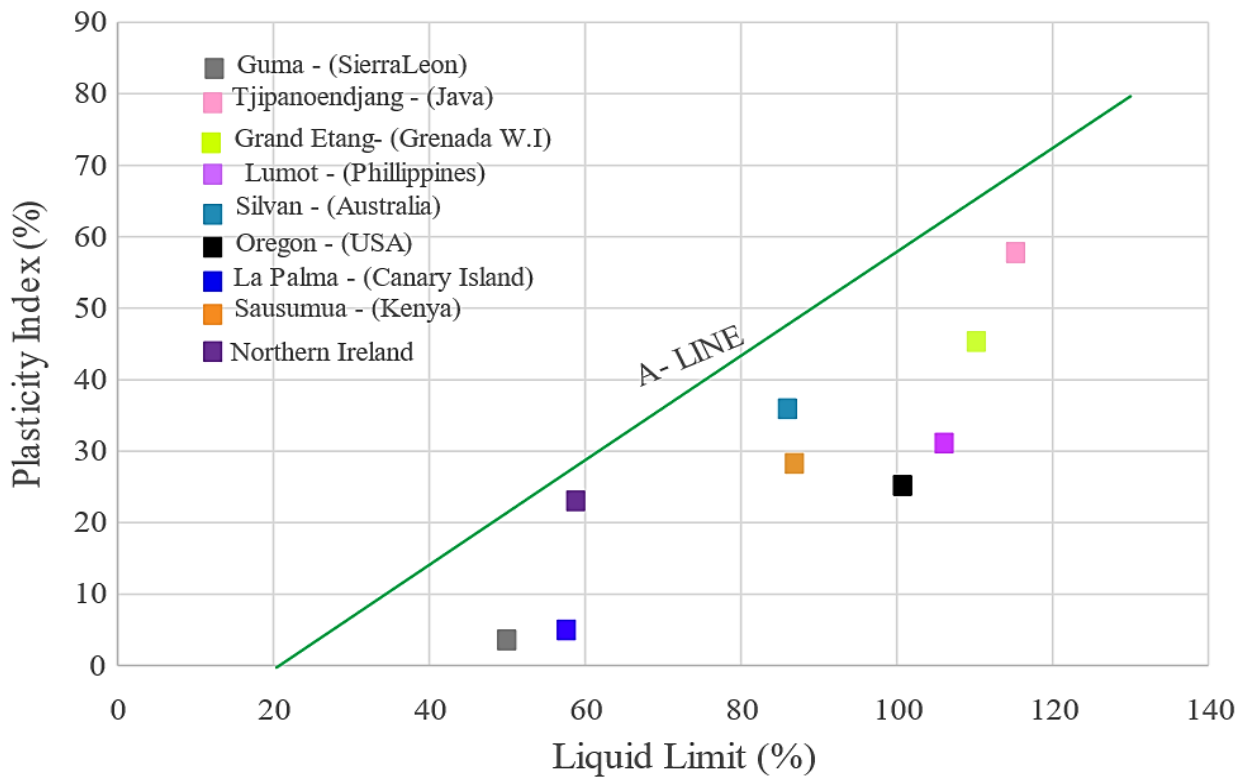


Fig. (16). The chart of Atterberg limits for the tropics zone in Kenya by Dixon & Robertson [10].

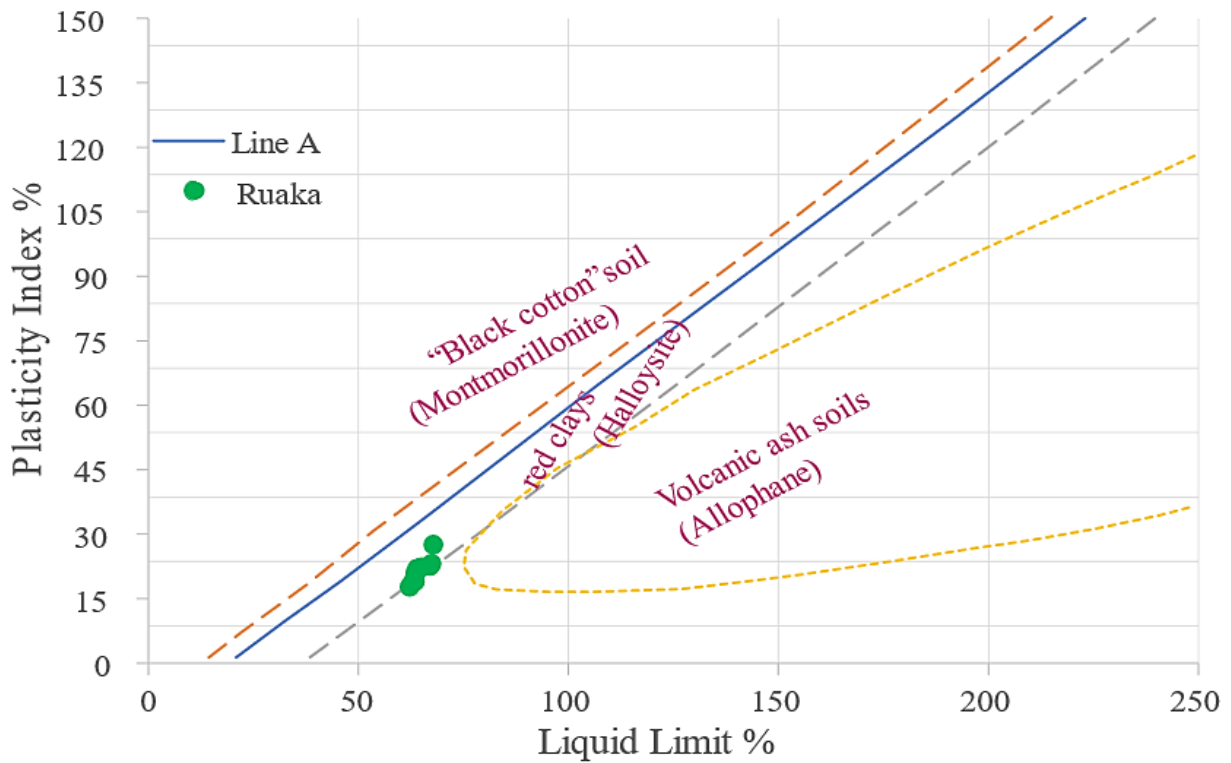


Fig. (17). The zone of Ruaka soil in the plasticity chart of [8].

5.2.4. Activity

The PI and the percentage of clay were used to assess the clay activity for Ruaka samples. The plasticity indexes of the samples were plotted against the clay content using Skempton [39] linear relationship based on the calculated PI and clay content. From Fig. (18), according to Skempton [39] categorization, the clay activity of the soils under investigation ranged from 0.41 to 0.63. Akalu [37]. found a range of activity values of 0.11 to 0.7 with an average value of 0.37 when investigating the engineering properties of red soil in western Addis Ababa that was rich in kaolinite. As evidenced by XRD analysis for the samples of Ruaka, Quartz, kaolinite, Halloysite, and Mica were the dominant minerals in Ruaka clay and have all been low activity minerals [8], if not wholly

inactive, such as Quartz. According to Skempton [39], there is a strong correlation between the activity, mineralogy, and clay's geological history, as presented in Table 5.

5.3. The Properties of Ruaka to other Tropics Regions in Kenya

According to Northmore *et al.* [17], when different soils are grouped or classified based on the plasticity chart, any other soil with the same in situ structural state could be embedded into that zone. Subsequently, it will behave similarly to the soils within that group. As a result, similar behaviour and mineralogical composition can be expected for Ruaka soils compared to clay soils in temperate climates. Table 6 summarises the properties of 12 different regions in Kenya compared to the properties of Ruaka.

Table 5. The activity of some clay minerals [39]

Mineral	Activity
Quartz	0.0
Calcite	0.18
Mica (muscovite)	0.23
Kaolinite	(0.33 - 0.46)
Illite	0.90
Na-montmorillonite	7.2

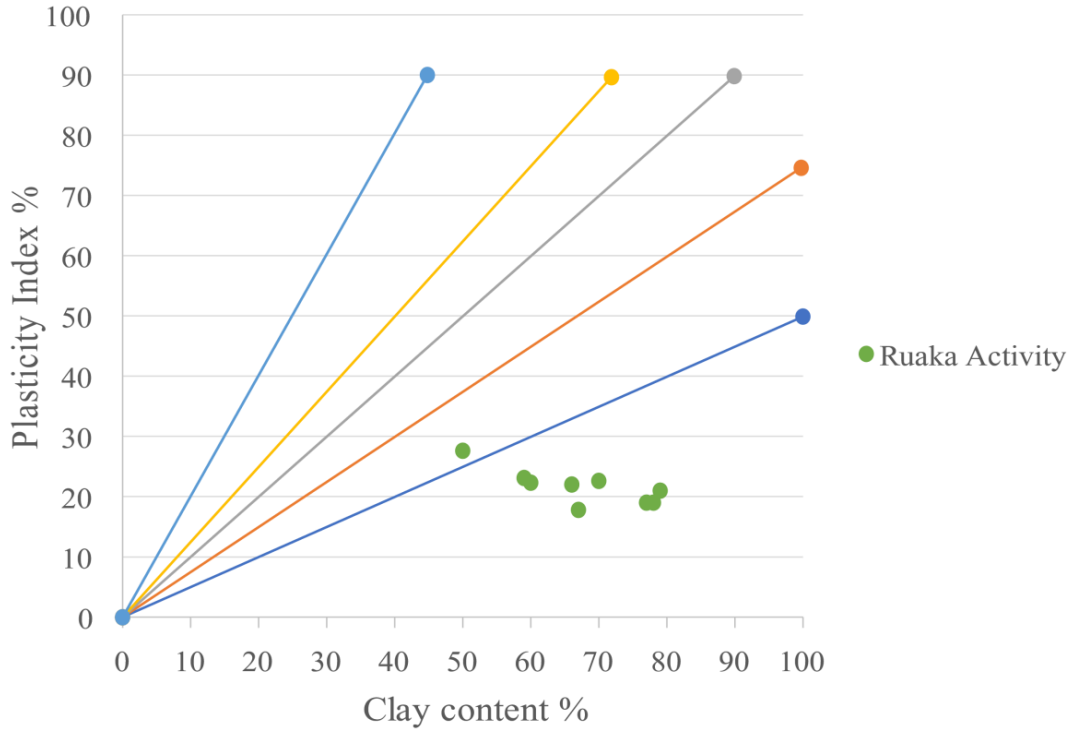


Fig. (18). The clay activity [39].

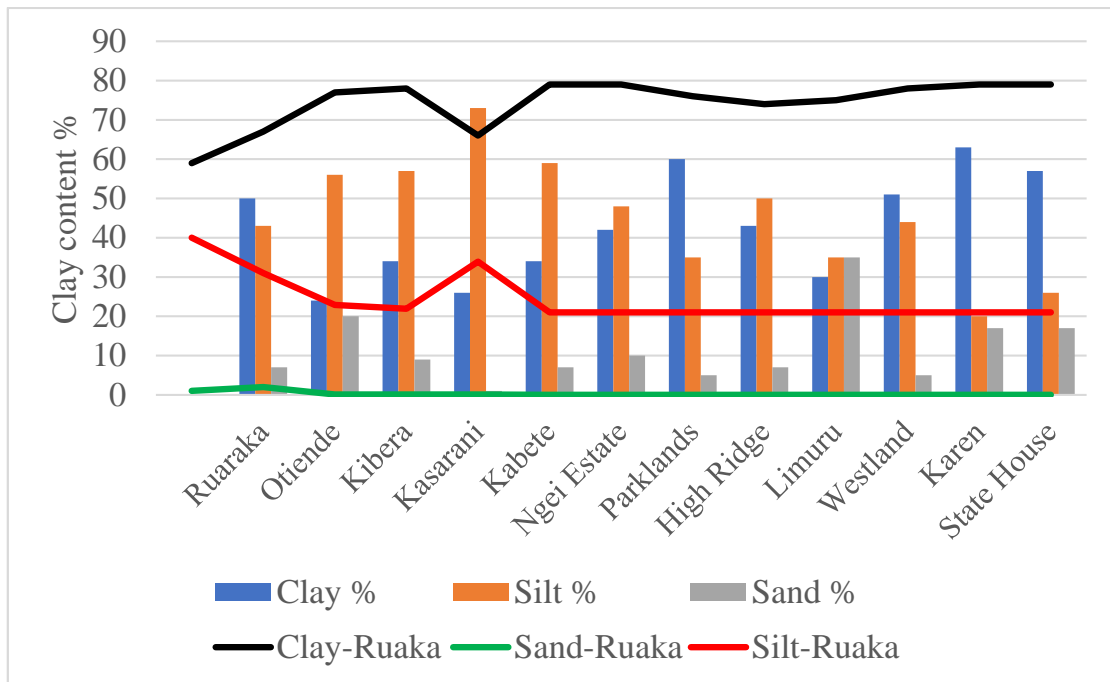


Fig. (19). The comparison of Ruaka fine particles contents and different regions in Kenya.

According to Fig. (19), the soil in Ruaka has a higher proportion of clay-sized grains than soil in other regions. As a result of the increased presence of clay particles, samples from this soil appear to have higher plasticity. In contrast, the percentages of clay and silt in soils from other locations varied

slightly. The PL and Plasticity Index of Ruaka soils showed a good agreement with the Atterberge limits of other regions detailed in Fig. (20a,b). The LL of Ruaka was slightly higher in a few points and almost homogeneous in all areas in Fig. (20c). However, Ruaka soil had a higher clay concentration

than other regions in the analysis. The findings of Northmore *et al.* [17] were validated by Fig. (21) since the soils of Ruaka, and other regions were in the same group and thus behaved

similarly. So, understanding the behaviour of a specific group of soils aids in predicting the behaviour of a new type of soil in the same zone.

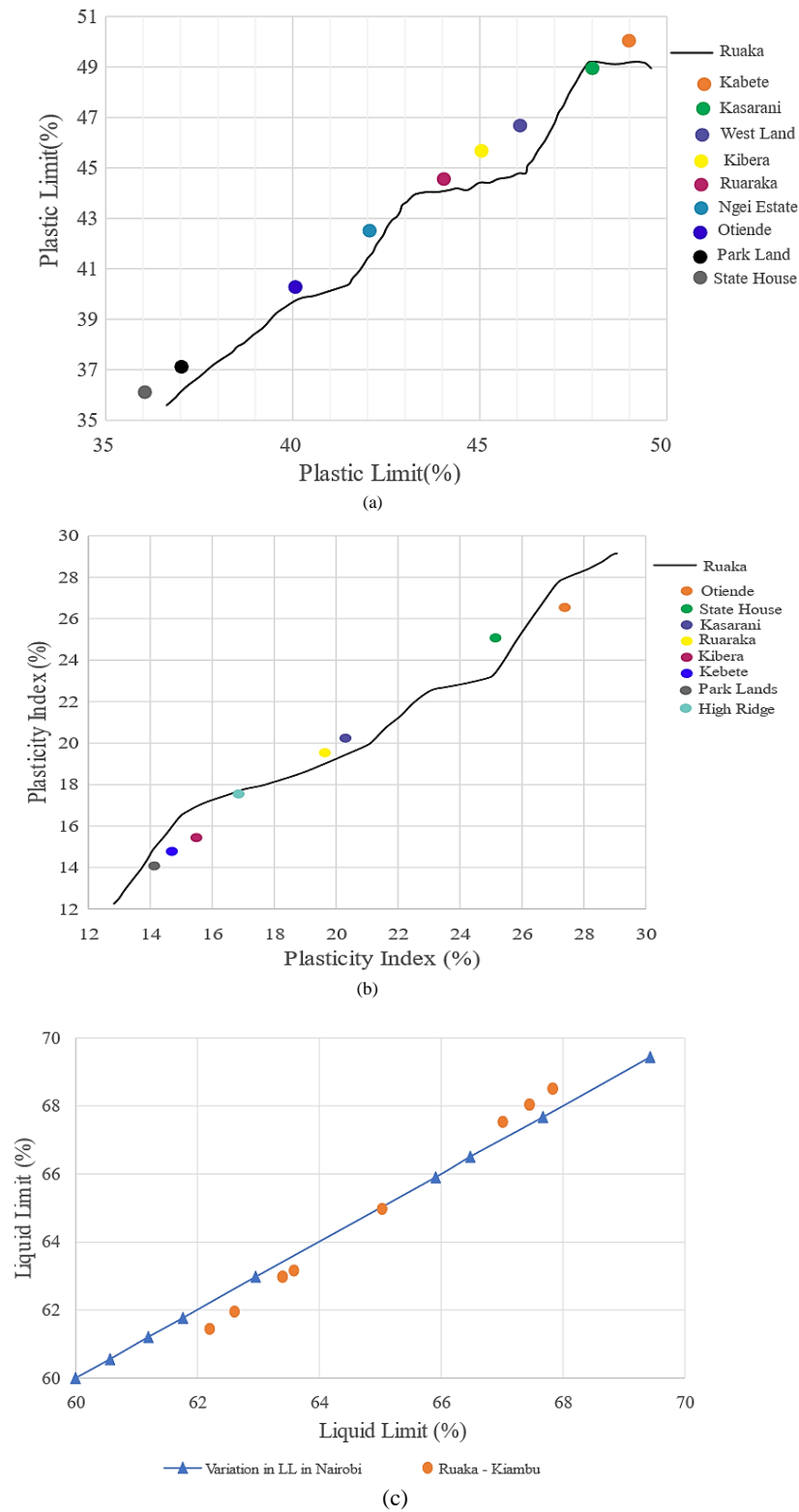


Fig. (20). The variation in index properties between Nairobi and Kiambu (Ruaka): (a) Plastic limit variation (b) Plasticity index variation (c) Liquid limit variation.

Table 6. The index properties of various regions in Kenya.

No	Location	Clay %	Silt %	Sand %	Atterberg Limits (%)			Specific Gravity	Compaction		Cc
					LL	PL	PI		MDD KN/m3	OMC	
1	Ruaraka	50	43	7	55	37	18	2.65	13.4	30.5	—
2	Otiende	24	56	20	66	33	33	2.7	14.2	28.3	0.332
3	Kibera	34	57	9	57	38	19	2.64	13.2	32.4	—
4	Kasarani	26	73	1	55	30	25	2.68	13.6	29.7	0.45
5	Kabete	34	59	7	60	42	18	2.66	13.6	36.5	0.43
6	Ngei Estate	42	48	10	71	35	36	2.66	13.6	31.5	0.365
7	Parklands	60	35	5	56	41	15	2.61	13.6	32.6	0.235
8	High Ridge	43	50	7	58	41	17	2.69	13.4	32	0.294
9	Limuru	30	35	35	65	39	26	2.66	14.1	29.4	0.15
10	Westland	51	44	5	65	39	26	2.65	13.6	32	—
11	Karen	63	20	17	68	35	33	2.65	—	—	0.11
12	State House	57	26	17	55	29	26	2.62	—	—	0.255

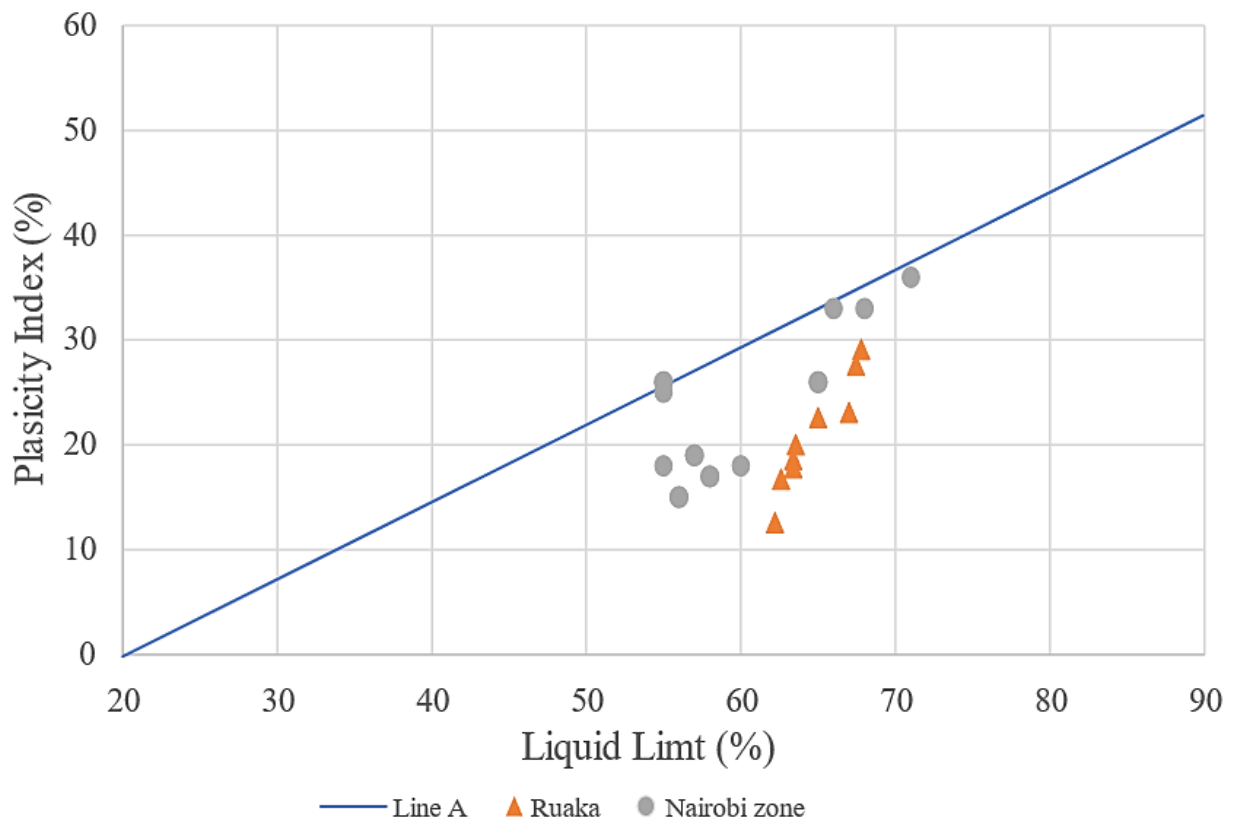


Fig. (21). The plasticity chart of Ruaka soils and other regions.

5.4. Mechanical Properties

The mechanical properties of a number of samples from the study area were carried out in the laboratory according to British Standards Institution [29], BS1377:Part 5:1990 [28], which included the consolidation (oedometer test), standard Proctor test, and permeability test. These properties were then

linked to the soil type and its chemical and mineralogy composition.

The bulk density and void ratio were calculated using particle density (in situ) for the samples in their natural state. The analysis of results in Fig. (22a-c) indicated that BH02 and BH03 had high convergence properties, while BH01 had slight differences.

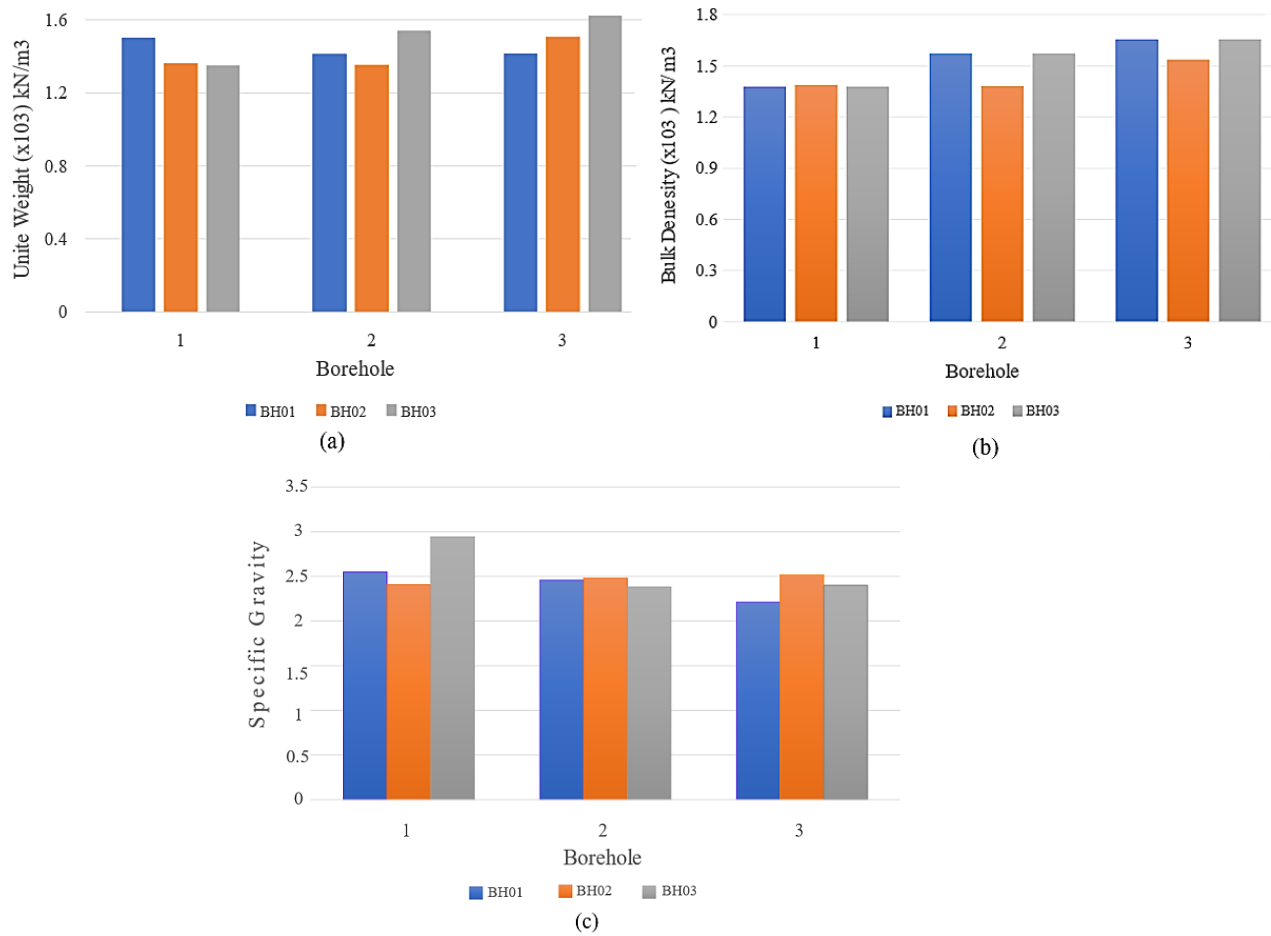


Fig. (22). Physical properties of Ruaka soil: (a) The unit weight (b) Bulk density (c) Specific gravity.

Based on the similarity of the physical properties of the Ruaka soil, the samples were combined and divided into three main groups: Group01 (G01) up to 3.5m, Group02 (G02) up to 6m, and Group03 (G03) up to 7.5m and were sufficient to describe the general behaviour of the Ruaka soil. Furthermore, this reduced the number of samples and laboratory tests, particularly in oedometer tests and the standard proctor test, which helped avoid error and confusion when interpreting the results.

5.4.1. Compaction Test

A series of compaction tests were carried out on the three groups of soils using the Proctor apparatus according to the British Standards Institution [29]; British Standard Light (BSL) or Standard Proctor compaction test was used. The tests involved compacting the soil into three layers, each receiving 25 blows from a 2.5kg rammer falling through a height of 300mm. The blows were uniformly distributed over the surface of each layer during compaction. Individual data and the best fit curve were displayed for moisture content versus dry density. The values of the MDD and OMC obtained from the compaction tests are shown in Table 7 and Figs. (23 and 24).

Table 7. Maximum dry density and optimum moisture content.

Borehole	MDD (kg/m ³)	OMC (%)
Group01	1280	36
Group02	1278	36
Group03	1181	34.5

Compared to usual tropical clay soils in Kenya, which have been documented by earlier researchers [5, 35, 37, 40, 41], values of MDD of Ruaka were low, and values of OMC were high, as shown in Fig. (23) and Table 7. The data of Ruaka were closely grouped on a plot of moisture content versus dry density, with OMC of 35% and MDD around 1.2 Mg/m³, which is consistent with the findings by Northmore *et al.* [40], who reported MDD of approximately 1.2 Mg/m³ and OMC about 45% when investigating typical tropical clay soil in Kenya.

Coleman *et al.* [42] reported maximum dry density for the Nyeri region in Kenya at around 1313.6 kg/m³, and the optimum moisture content was 36% which is correspondingly high. However, the value reported for red clay was low compared with average clay soils.

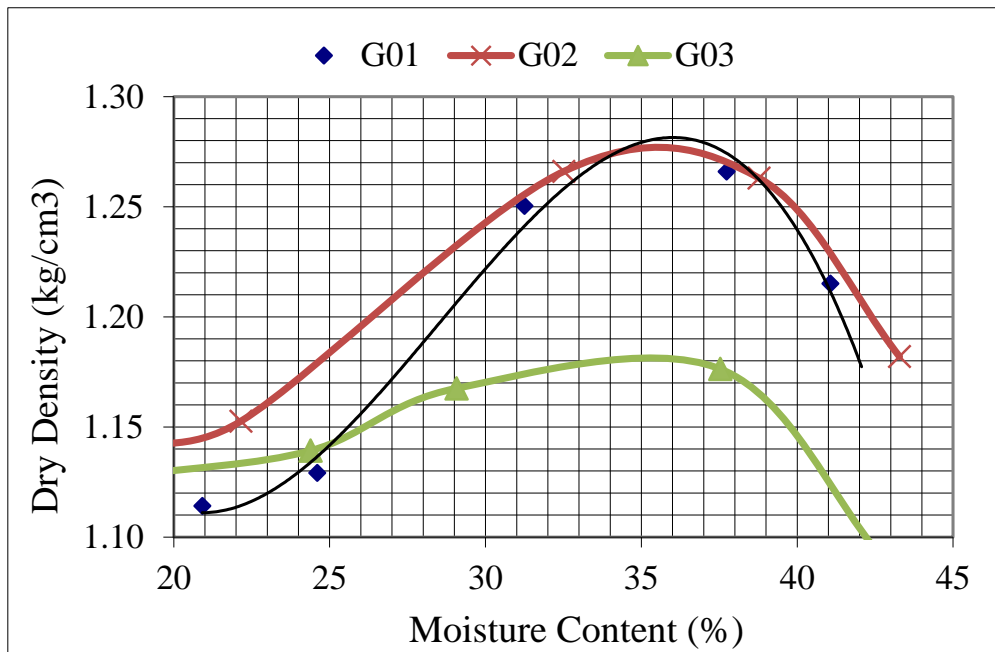


Fig. (23). Compaction curves of Ruaka soils.



Fig. (24). Preparation of the sample for the consolidation test.

Dixon & Robertson [10], reported optimum moisture content of approximately 50% and maximum dry density of about 72 lb/ft³ (1153.4 kg/m³) and 65 to 75 lb/ft³ with optimum moisture content ranging from 55% to 45% for Ruiru, and Sasumua Dams in Kenya, respectively. However, on the other hand, the high or low density is related to changes in soil lithology.

5.4.2. Consolidation Test (Oedometer Test)

The consolidation tests were carried out according to BS: 1377: Part 5: 1990 [28] on a number of undisturbed samples (U100) from each group. The samples were extruded from the tubes into the ring of consolidation and used directly by 6cm diameter and 2cm height, (Fig. 24). A laboratory experiment, 1-D consolidation was carried out by oedometer test by applying the standard loads of 100, 200, 400, 800, 1600, and 3200 Kp, (Fig. 25). The load increments were kept for at least 24 h or until the pore pressure was entirely dissipated.



Fig. (25). Standard loads in consolidation test.

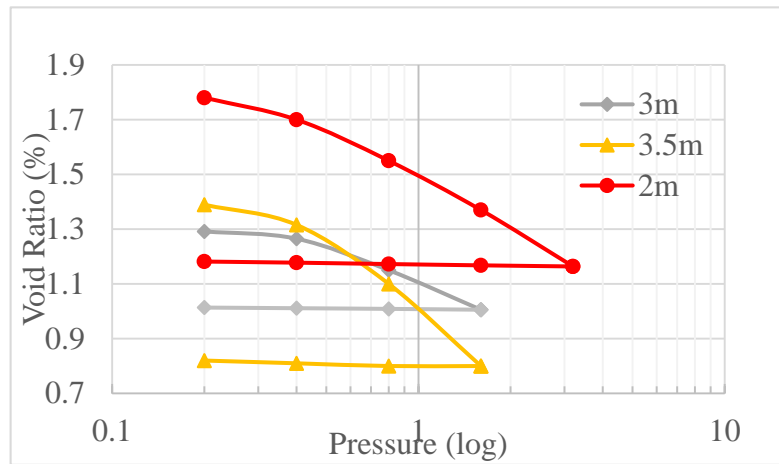
It is noteworthy that higher density values were recorded when determined from oedometer specimens, with average differences ranging between 14, 18, and 23% for G01, G02, and G03, respectively. The oedometer ring preparation process was most likely the cause for this slight increase in sample density.

The initial undisturbed void ratios ranged between 1.145 and 1.63, which was lower than the void ratio reported by Northmore *et al.* [40]. In their study, void ratios of Indonesian and Kenyan soils ranged from 1.14 to 5.36 and 0.92 to 3.47, respectively, and had high natural moisture contents (greater than 150% in some samples), indicating the presence of Allophane in both cases. In the case of Ruaka, on the other hand, the hydrate Halloysite was dominant.

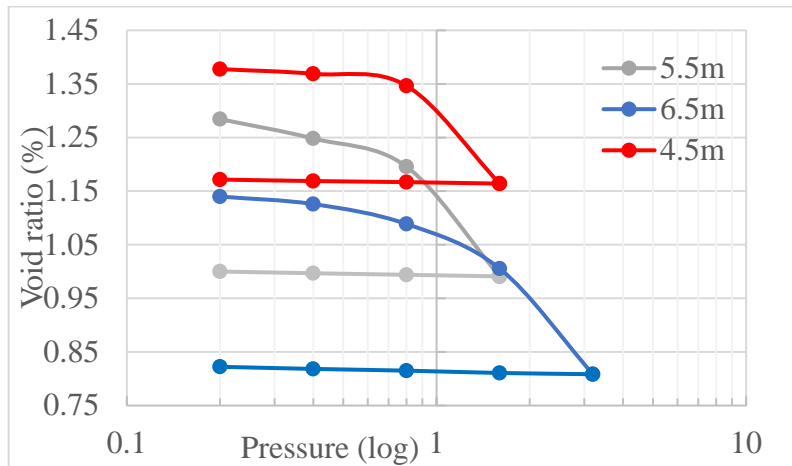
Based on the computed void ratios at the end of each load stage, all load stages are usually merged into a single graph of void ratio as a function of the logarithm of the effective

pressure, as shown in Fig. (26). The values of the compression index C_c generated from the logarithmic plot of void ratio and

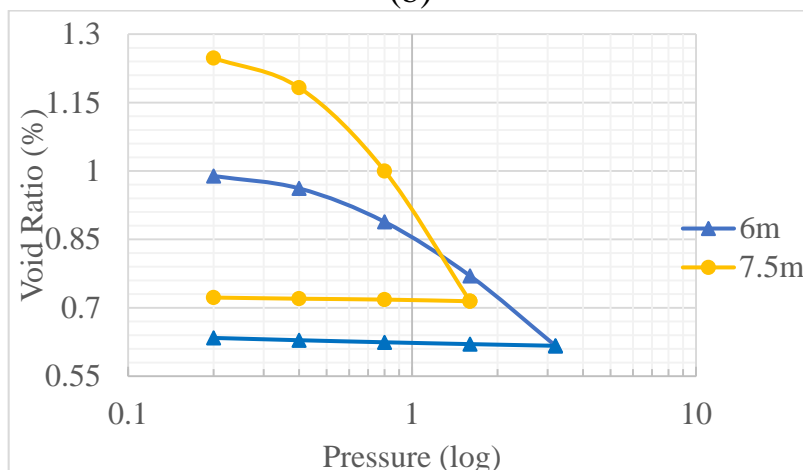
effective pressure to indicate the settlement magnitude are detailed in Table 8.



(a)



(b)



(c)

Fig. (26). The variation in void ratio versus log applied load during oedometer testing with the depth: (a) G01 (b) G02 (c) G03.

Table 8. Values of compression index for the three boreholes of Ruaka soils.

Borehole	Depth (mm)	Compression index, Cc
G01	3.5	0.35
	3	0.29
	2	0.21
G02	6.5	0.45
	5.5	0.3
	4.5	0.25
G03	6	0.17
	7.5	0.27

As the applied pressure increases with depth, the rate of void ratio decreases, increasing Cc values.

The Ruaka soil had high values of void ratio and the degree of saturation which ranged between (1.21- 1.82) and (69- 99) %, respectively. The permeability ranged between (1.223E-5 – 2.464E0-6) cm/s, which was explained because Halloysite occurs in materials with a loose, open structure generated during the depositional and weathering processes resulting in a high porosity and the void ratio [43].

CONCLUSION

This study was designed to investigate the effect of mineral and chemical composition on soils' physical and mechanical properties for the red clay soils selected from Ruaka, Kenya. The investigation showed that the soils' microstructures, chemical, and mineral composition for tropical residual soils, particularly those formed from volcanic rocks, have a distinct mineralogical composition that governs their behaviour and makes them unpredictable. Therefore, working with this soil type might prove more challenging for civil engineering applications. Based on the laboratory findings, the following conclusions are drawn:

- According to XRD analysis, the most abundant minerals in Ruaka clay were Quartz, kaolinite, Halloysite, and Mica. The chemical testing revealed high concentrations of Al_2O_3 and SiO_2 ; the analysis also revealed the presence of a cementing agent represented by free iron oxide, which has a significant amount (16.40%) in the chemical composition.
- The structure and physical properties of tropical red clays may be altered by the mineralogical composition of these soils and partial air-drying at ambient laboratory temperatures. Some of these changes are not reversed when the soil is re-mixed with water. These structural changes can be seen in the index properties such as Atterberg limits, particle size, and particle density (Gs) tests.
- The preliminary tests for the samples in their natural state (in situ) showed a high convergence in their properties (the unit weight, the specific gravity, and the bulk density). However, Ruaka soils showed a high Liquid Limit between 63-68% which increased with increasing depth, and high moisture content varied between 37- 46% convergence with their plastic limit

with a slight increase as depth increased. Other soil properties, such as clay content, increased, ranging from 59 to 79%.

- Ruaka clay was found to have a high void ratio of 1.145 to 1.63, with saturation values ranging from 69 to 99%. This increased permeability and lowered MDD by an average of 1247 kg/m³ with 35.5% OMC.
- The presence of kaolinite, Quartz, and oven drying of hydrated Halloysite significantly reduces the specific gravity (Gs) values.
- A good positive relation was observed from the oedometer test between the void ratio, e, and the compression index, Cc, with increased pressure and depth. However, the high amount of clay content made this soil mechanically unstable.
- Compared to the other nearby regions with the same tropical soil features in Kenya, Ruaka clay showed a higher fraction of clay-sized grains, which appear to have higher plasticity; however, Atterberg limits revealed a good agreement with the trend of other regions. This type of correlation is highly recommended because understanding the behaviour of a specific group of soils aids in predicting the behaviour of a new type of soil within that zone.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The authors confirm that the data supporting the findings of this study are available within the manuscript.

FUNDING

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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Declared none.

REFERENCES

- [1] W.M. Ngecu, C.M. Nyamai, and G. Erima, "The extent and significance of massmovements in Eastern Africa: Case studies of some major landslides in Uganda and Kenya", *Environ. Geol.*, vol. 46, no. 8, pp. 1123-1133, 2004. [<http://dx.doi.org/10.1007/s00254-004-1116-y>]
- [2] I.C. Attah, and R.K. Etim, "Experimental investigation on the effects of elevated temperature on geotechnical behaviour of tropical residual soils", *SN Appl. Sci.*, vol. 2, no. 3, p. 370, 2020. [<http://dx.doi.org/10.1007/s42452-020-2149-x>]
- [3] L. Kong, and A. Guo, "Analysis of engineering properties of red clay during drying process", *GeoFlorida*, vol. 41095, no. 11, pp. 301-306, 2010. [[http://dx.doi.org/10.1061/41095\(365\)27](http://dx.doi.org/10.1061/41095(365)27)]
- [4] G. E. Brink, Engineering geological evaluation of transported tropical red soils., Thesis (PhD), University of Pretoria, 2015.
- [5] B.K. Sahu, and F.S. Atibu, "Problems of red coffee soils in Kenya", *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, vol. 26, no. 3-4, p. A116, 1989.

- [6] [\[http://dx.doi.org/10.1016/0148-9062\(89\)92057-3\]](http://dx.doi.org/10.1016/0148-9062(89)92057-3)
L. Wesley, *Geotechnical Engineering in Residual Soils.*, John Wiley & Sons, 2010.
[<http://dx.doi.org/10.1002/9780470943113>]
- [7] Y. Muceku, and P. Lazo, "The chemical-mineralogical composition and their effect on physical and mechanical properties of cohesive soils in tirana area, Albania", *Fresenius Environ. Bull.*, vol. 22, no. 10, pp. 3006-3015, 2013.
- [8] L. Wesley, "Behaviour and geotechnical properties of residual soils and allophane clays", *Obras Proy.*, vol. 6, pp. 5-10, 2009.
- [9] B.B. Huat, and D.G. Toll, *Handbook of Tropical Residual Soils Engineering*, CRC Press, 2012.
- [10] H.H. Dixon, and R.H.S. Robertson, "Some engineering experiences in tropical soils", *Q. J. Eng. Geol.*, vol. 3, no. 3, pp. 137-150, 1970.
[<http://dx.doi.org/10.1144/GSL.QJEG.1970.003.03.01>]
- [11] T. Karl, "Design and performance of the sasumua dam", *Angew. Chemie Int. Ed.*, vol. 6, no. 11, pp. 951-952, 1958.
- [12] D. Newill, "A laboratory investigation of two red clays from Kenya", *Geotechnique*, vol. 11, no. 4, pp. 302-318, 1961.
[<http://dx.doi.org/10.1680/geot.1961.11.4.302>]
- [13] G. West, and M.J. Dumbleton, "The mineralogy of tropical weathering illustrated by some west Malaysian soils", *Q. J. Eng. Geol.*, vol. 3, no. 1, pp. 25-40, 1970.
[<http://dx.doi.org/10.1144/GSL.QJEG.1970.003.01.02>]
- [14] T. R. Forbes, *Ferrallitic and ferruginous tropical soils of West Africa*, Cornell University, 1973.
- [15] S.T. Benavides, *Mineralogical and chemical characteristics of some soils of the Amazonia of Colombia.*, PhD Thesis, Graduate Faculty of North Carolina State University at Raleigh, 1973.
- [16] Y. Muceku, and P. Lazo, "The chemical-mineralogical composition and their effect in physical and mechanical properties of cohesive soils in Tirana area, Albania", *Fresenius Environ. Bull. Ger.*, vol. 22, pp. 306-315, 2013.
- [17] K.J. Northmore, M.G. Culshaw, P.R.N. Hobbs, J.R. Hallam, and D.C. Entwisle, "Engineering geology of tropical red clay soils", *UK Br. Geol. Surv.*, p. 158, 1992.
- [18] J.R. Hallam, and K.J. Northmore, "Geotechnical borehole sampling of tropical red clay soil", *Br. Geol. Surv.*, p. 114, 1993.
- [19] M.G. Culshaw, P.R.N. Hobbs, and K.J. Northmore, "Engineering geology of tropical red clay soils: Manual sampling methods", *Br. Geol. Surv. Tech. Report, WN*, vol. 93, no. 14, p. 22, 1992.
- [20] E.W. Gadzama, I. Nuhu, and P. Yohanna, "Influence of temperature on the engineering properties of selected tropical black clays", *Arab. J. Sci. Eng.*, vol. 42, no. 9, pp. 3829-3838, 2017.
[<http://dx.doi.org/10.1007/s13369-017-2485-3>]
- [21] R. George, "Desiccation effect of compacted tropical black clay treated with concrete waste", *Leonardo Elect. J. Pract. Technol.*, vol. 33, pp. 69-88, 2018.
- [22] K.N.V.K. Hanuma, D.S.V. Prasad, C. Engineering, B.V.C.E. College, and M. Tech, "A study on stabilization of black cotton soil and red soil by using heat treatment method", *Int. Res. J. Eng. Technol.*, vol. 4, no. 6, pp. 779-782, 2017.
- [23] J.E. Sani, R.K. Etim, and A. Joseph, "Compaction behaviour of lateritic soil-calcium chloride mixtures", *Geotech. Geol. Eng.*, vol. 37, no. 4, pp. 2343-2362, 2019.
[<http://dx.doi.org/10.1007/s10706-018-00760-6>]
- [24] K.J. Osinubi, F. ASCE, A.M.A.A.O. Eberemu, P. Yohanna, and R.K. Etim, "Reliability estimate of the compaction characteristics of iron ore tailings treated tropical black clay as road pavement sub-base material", *Cca*, vol. 2015, pp. 144-154, 2016.
- [25] N.M. Abner, Investigation of the engineering properties of compressed earth blocks made from red coffee soil stabilized with a mixture of cassava peel ash and sugarcane bagasse ash., Thesis, Technical University of Kenya, 2019.
- [26] K. County, D. Abuya, M. Oyugi, and E. Oyaro, "Management of the effects of land use changes on urban infrastructure capacity: A case study of Ruaka Town, Kiambu County, Kenya", *Civil and Environmental Research*, vol. 8, no. 4, pp. 158-190, 2019.
[<http://dx.doi.org/10.7176/CER/11-7-03>]
- [27] BS1377-2, *BS 1377-2 Methods of Test for Soils for Civil Engineering Purposes-Part 2 Classification tests*, no. 1, 1991. Available from:
<https://www.bsigroup.com/en-GB/standards/bs-1377-2/>
- [28] BS1377-5, "British standard methods of test for soils for civil engineering purposes part 5. compressibility, permeability and durability tests methodes", *Br. Stand.*, no. 1, 1991. Available from:
<https://www.bsigroup.com/en-GB/standards/bs-1377-2/>
- [29] BS1377-4, "BS 1377-4:1990 Methods of test for soils for civil engineering purposes. Part 4: Compaction-related tests", *Br. Stand.*, no. 4, p. 70, 1991. Available from:
<https://www.bsigroup.com/en-GB/standards/bs-1377-2/>
- [30] A.G. Davis, N. Birch, and R.J. Chandler, "Classification tests on African red clays and Keuper Marl", *Q. J. Eng. Geol.*, vol. 1, no. 3, pp. 207-209, 1968.
[<http://dx.doi.org/10.1144/GSL.QJEG.1968.001.03.06>]
- [31] B.B. Huat, D.G. Toll, and A. Prasad, *Handbook of tropical residual soils engineering.*, 2012.
[<http://dx.doi.org/10.1201/b12302>]
- [32] F.J. Gichaga, F.S. Atibu, and B.K. Sahu, "Horizontal and vertical movements of red clay highway embankments", In: *Second International Conference on Case Histories in Geotechnical Engineering, June 1-5, 1988, Kenya*, 1988, p. 25.
- [33] G. Brink, "A brief overview of the typical engineering characteristics of tropical red soils", *Eng. Geol. Soc. Territ.*, vol. 6, pp. 211-214, 2015.
[http://dx.doi.org/10.1007/978-3-319-09060-3_33]
- [34] B. BK. Huat, G.S. Sew, and F.H. Ali, *Tropical Residual Soils Engineering*, Taylor & Francis Group Plc.: London, UK, 2009.
- [35] D.A. Bruggemann, and J.D. Gosden, "The performance of Thika Dam, Kenya", In: *Longterm Benefits and Performance of Dams - Proceedings of the 13th Conference of the British Dam Society and the ICOLD European Club Meeting held at the University of 32 Kent, Canterbury, UK from 22 to 26 June*, Thika Dam, Kenya, 2004, pp. 421-432.
- [36] O.O. Olofinyo, O.F. Olabode, and I.O. Fatoyinbo, "Engineering properties of residual soils in part of Southwestern Nigeria: Implication for road foundation", *SN Applied Sciences*, vol. 1, no. 5, p. 507, 2019.
[<http://dx.doi.org/10.1007/s42452-019-0515-3>]
- [37] M. Akalu, Engineering Characteristics of Red Soil: A Case from Western Addis Ababa, Master Thesis, Addis Ababa University, 2017.
- [38] J.E. Sani, P. Yohanna, K.R. Etim, J.K. Osinubi, and O.A. Eberemu, "Reliability evaluation of optimum moisture content of tropical black clay treated with locust bean waste ash as road pavement sub-base material", *Geotech. Geol. Eng.*, vol. 35, no. 5, pp. 2421-2431, 2017.
[<http://dx.doi.org/10.1007/s10706-017-0256-2>]
- [39] A.W. Skempton, *Selected Papers on Soil Mechanics*, Thomas Telford, 1984.
- [40] K.J. Northmore, M.G. Culshaw, P.R.N. Hobbs, J.R. Hallam, and D.C. Entwisle, "Engineering geology of tropical red clay soils: Summary finding and their application for engineering purposes", *Tech. Report, Br. Geol. Surv.*, pp. 1-88, 1992.
- [41] P. Smart, "Structure of a red clay soil from Nyeri, Kenya", *Q. J. Eng. Geol.*, vol. 6, no. 2, pp. 129-139, 1973.
[<http://dx.doi.org/10.1144/GSL.QJEG.1973.006.02.01>]
- [42] J.D. Coleman, D.M. Farrar, and A.D. Marsh, "The moisture characteristics, composition and structural analysis of a red clay soil from Nyeri, Kenya", *Geotechnique*, vol. 14, no. 3, pp. 262-276, 1964.
[<http://dx.doi.org/10.1680/geot.1964.14.3.262>]
- [43] V. Moon, "Halloysite behaving badly: Geomechanics and slope behaviour of halloysite-rich soils", *Clay Miner.*, vol. 51, no. 3, pp. 517-528, 2016.
[<http://dx.doi.org/10.1180/claymin.2016.051.3.09>]