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Investigation of Mineralogical and Geotechnical Characteristics of Share-Tsonga Claystones, Northern Bida Basin, Nigeria

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Abstract

The claystones, with varieties of application, can be pivotal to boosting Nigerian economy. The Maastrichtian claystones of Enagi Formation at Share and Tshonga areas, Bida Basin, Nigeria were investigated to determine their mineralogy, geotechnical properties and their industrial applications. X-Ray diffractometry (XRD) and Scanning Electron Microscopy (SEM) were employed to determine their mineralogy. The particle size distribution (PSD), Atterberg limits, permeability and firing characteristics were probed. The claystones contain mainly kaolinite (20%-22%) while the main non-clay mineral is quartz (45%-62%). Other minerals include plagioclase (2%-15%), mica (5-15%), anatase (3%), pyrite (2%) and ilmenite (3%). PSD shows that sand ranges from 22% to 43%, while the clay ranges from 14% to 34% and silt varies from 46 to 56%. The Share claystones are more clayey while the Tsonga's are more sandy. The liquid limits, plastic limit, plastic indices and activity range from 43% to 71%, 17% to 31%, 25% to 40% and 0.6 to 2.0 respectively. The claystones have low to medium expansivity, and medium to high plasticity index which suggest suitability as attenuation layer. The Tsonga claystone has a higher coefficient of permeability of 5.826x 10^{-6}cm/sec than Share's (5.173x10^{-6}cm/sec). The low permeability may suit the claystones as attenuation layer. The firing test shows presence of expansive clays and increased level of mobile iron-bearing minerals with grey to yellow colour. The study concludes that the claytones can be used in paper making, barrier lining, bricks, pottery and ceramics which can add to increasing resource base of Nigeria.

1.0 Introduction

The Bida Basin located in the Middle Belt region of Nigeria has prospect for valuable resources. The claystones have potential to serve as source of revenue if well harnessed [1], because, its availability, diverse application, and short process of treatment have made it very resourceful in most countries [2]. The basin has received more attention lately as Nigerian government attempt to increase her source of revenue and diversify resource base. The Bida Basin has been reported to host about 4km thick of clastic sediments [3], [4]. The basin trends Northwest-Southeast (NW-SE) and it is bordered by Sokoto Basin in the North and by Anambra Basin to the south (Figure 1). The structural configuration of the basin has been described as being controlled by fault system trending NW-SE [5], [6], [7]. The pervasive facies variation across the basin paved way for their subdivision into the northern and southern sub-basins [8], [9], [10]. In the northern sub-basin, [11] documented four stratigraphic horizons which include: the basal Campanian-Maastrichtian Bida Formation (conglomerate, sandstone), Sakpe Formation (Ironstone), Enagi Formation (sandstone, siltstone, claystone) – the formation of interest in this study, and the youngest Batati Formation (Ironstone). Their lateral equivalents in the southern Bida Basin are Lokoja Formation (conglomerate, sandstone), Patti Formation (sandstone, shale, claystone, siltstone and coal – as reported for the first time by [12] and Agbaja Formation (ironstone). [13] worked on stratigraphy of Bida Basin and provided a relationship between sediments in Bida Basin and Anambra Basin (Figure 2).

Clays are very fine-grained sediments that become plastic with increasing moisture, and they become very hard when subjected to intense heat [14], [15]. According to [16], the replacement of muscovite, biotite, and chlorite by kaolinite is the possible process for clay formation. [17] studied clays around Kutigi area in Bida Basin and described the clay as kaolinitic, inorganic, low plasticity and highly pervious. The study of claystones in the Bida Basin have been of interest to researchers such as [18], [17], [19] in recent years, as clay is rated to be a global resource with wide application in Plaster of Paris, paint, ceramics and pharmaceutical industries among others [19]. [20] reported that claystone and shale in southern Bida Basin are kaolinitic with medium compressibility, low permeability and intermediate to high plasticity. Other researchers that have worked and contributed to the study of claystone in Nigeria includes [21], [22], [23], [24]. All have reported sedimentary kaolinitic clay deposits across Nigeria which is typical of humid tropical climate.

[18] reported that claystones from Share are inorganic with medium compressibility, while [25] reported that the claystones from Share-Tsonga axis are of high intensity weathering of felsic provenance and deposited in humid and oxic setting which is also characteristic of tropical climate. As a follow up to the previous studies within the northern Bida Basin and maiden test of Tsonga clays, the present study focuses on further assessment of the properties of the claystones to determine their suitability for economic and development interests. To achieve this, we examined the particle size analysis, mineral composition, physical and geotechnical characteristics, permeability and firing capacity. The geotechnical

appraisal of the claystone in the northern Bida Basin is being reported for the first time. The geotechnical properties of any clay deposit are key to its industrial application.

1.1 Physiographic setting

Share lies within latitude $8^0$48’55.51”N and longitude $4^0$58’40.1”E while Tsonga is located within latitude $9^0$1’09”N and longitude $5^0$9’0.11”E in Kwara state, Nigeria. In Share there are high and lowlands terrain while Tsonga area is generally low lying and it is closer to River Niger. The area is accessible by minor roads. The study area experiences both raining season and dry season annually. The raining season starts from around April till September October while the raining part of the year is dry season. Furthermore, the climatic condition is tropical savannah which is characterized with sparse deciduous trees and shrubs. The rainy season have a good deal of rainfall while during the dry season, there is little or no rainfall.

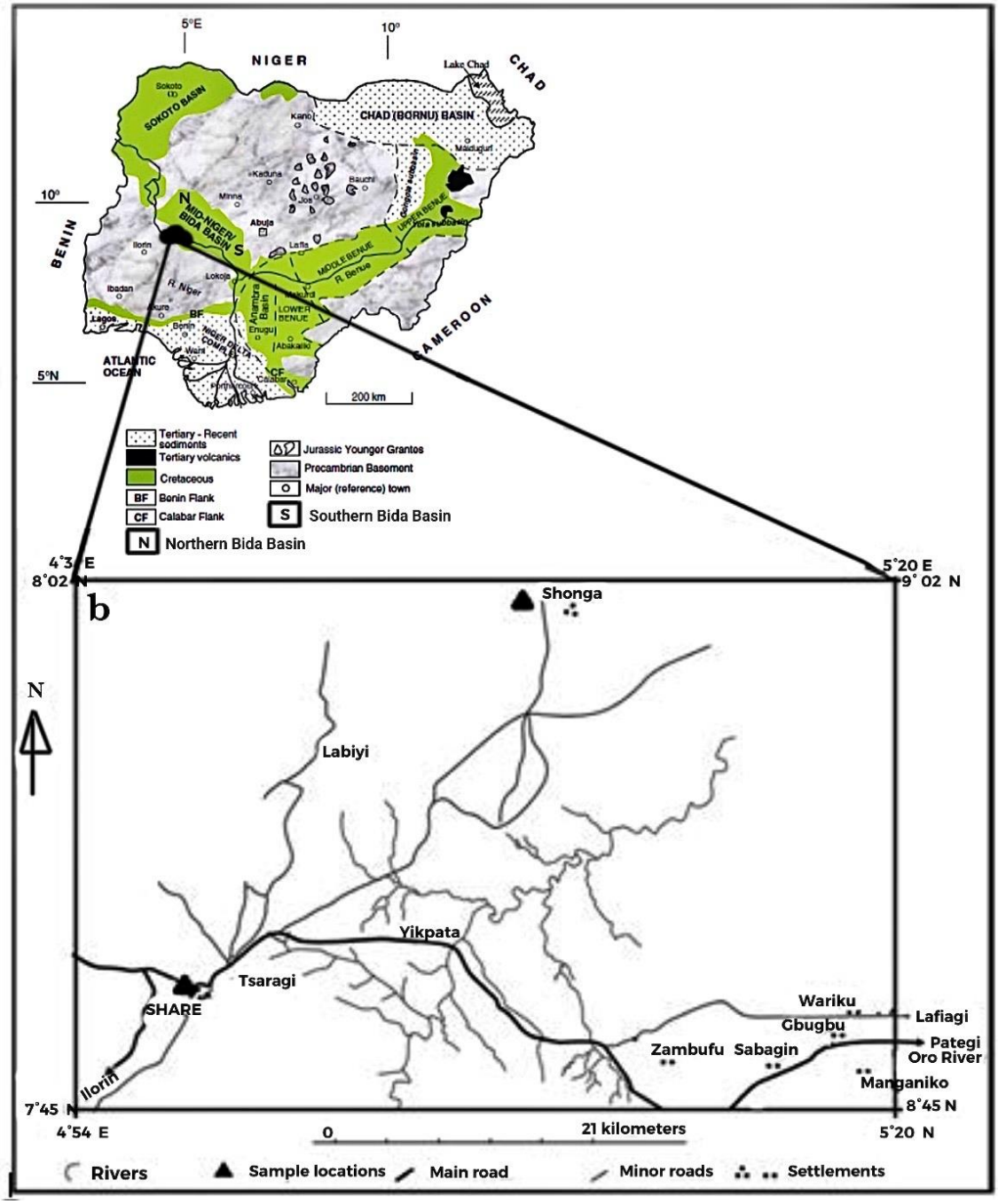


Figure 1: (a) Geological map of Nigeria showing Bida Basin (modified after [26] (b) Map of the study area (boxed area of Fig. 1a) and locations of the investigated outcrops in Share, Tsaragi and Shonga, modified after [27]

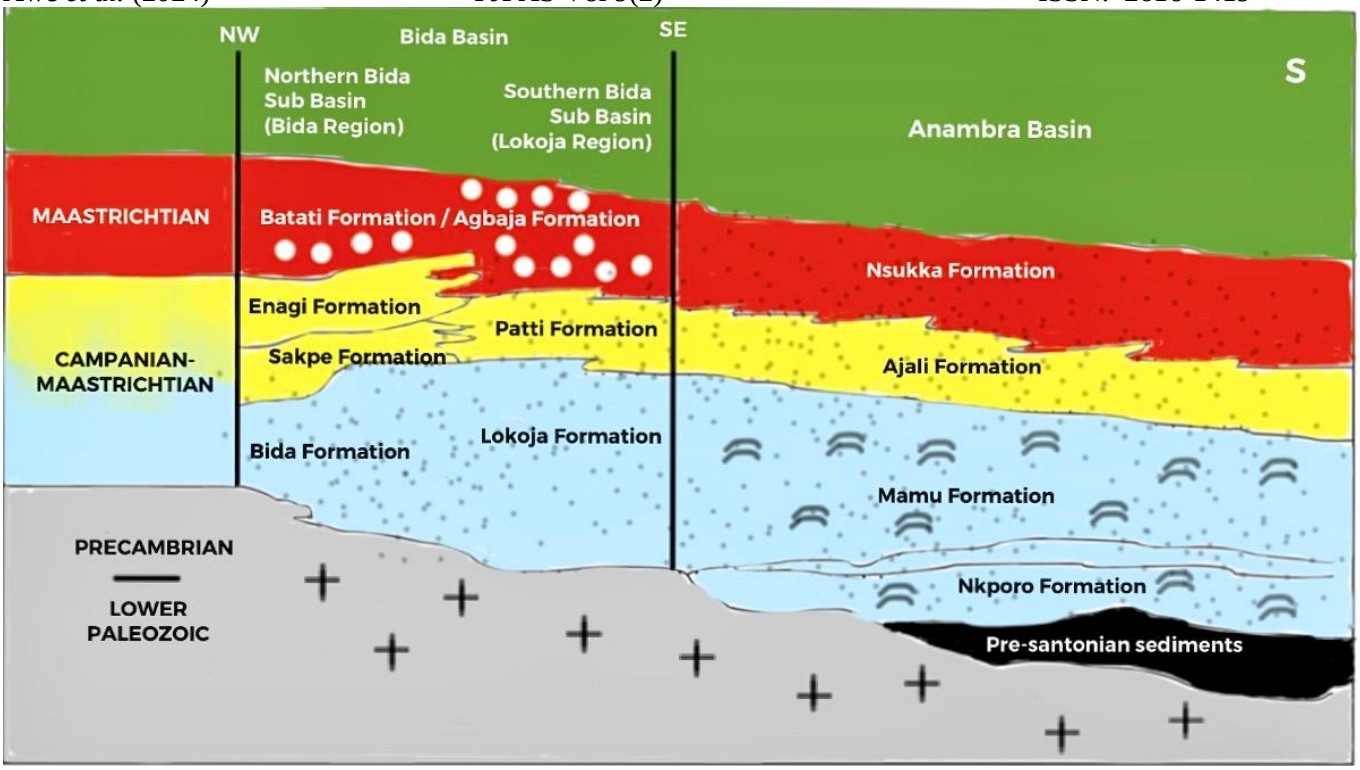


Figure 2: Regional stratigraphic successions in the Bida Basin and their lateral equivalents in the Anambra Basin [13]

2.0 Sampling and Methods

The samples used in this study are cliff surface samples. Three claystone samples were taken at Share and labelled L3G, L4G and L4H. L3G and L4G were taken at the eastern side of the ridge while L4H was taken at the western side. L5G was taken at Tsonga (figure 1b) . The entire sedimentary sections were logged taking cognizance of texture, true thickness and sedimentary structures (Figures 3, 4 and 5). At Share, there is evidence of artisanal mining which allowed ease of sampling (Figure 3b). Selected claystones were subjected to X-Ray diffractometry (XRD) at Department of Geology, University of Free State. The claystones were further subjected to Atterberg limit, permeability, firing analysis and specific gravity at Department of Geology, University of Ilorin, Kwara state, Nigeria.

3.0 Results and Discussion

3.1 Lithologic Profile

The rock units encountered in the study areas include claystone, sandstone, conglomerate, and ironstone. The ironstone is not present at Tsonga, even though the section is capped by highly ferruginized and indurated conglomerate. Generally, the claystone colour varies between white and dirty white (creamy) with random reddish stain probably due to leaching of iron-bearing minerals from overlying iron-rich sandstones. The Share section is about 35metres thick (Figure 3a). The claystone, about 4m thick, occurs at the middle of the section. At this level, prolonged excavation of the clays by artisanal miners created artificial caves (Figure 3b). The

claystone is bounded at the top by ferruginized sandstone and clayey micaceous sandstone at the base. There are evidences of reddish-brown stains in the claystone and the stains were probably imparted by iron bearing minerals percolating through the sandstone into the microfractures within the clays. The claystones are laterally persistent along the east-west (E-W) depositional strike and were sampled at two points (Figure 4, samples L4G and L4H were taken at this section), and at the eastern end of the ridge near Tsaragi. Figure 4 shows the E-W trending claystone bed overlain by ferruginized sandstone. The Agbona ridge is flat topped, with ironstone serving as capping for the entire sequence. At Tshonga, the lithologies also consist dominantly of sandstone, claystone, capped with ferruginous and highly indurated conglomerate (Figure 5).

3.2 Particle Size Distribution (PSD)

The particle size data generated from the investigated clay samples is shown in Table 2. According to classification of [28], L3G - 24% sand, 52% silt and 24% clay; L4G - 22% sand, 57% silt and 21% clay; L4H - 8% sand, 58% silt and 34% clay, and L5G - 43% sand, 43% silt and 14% clay. The plot of percentage passing against particle size (Figure 7) clearly indicate that all the claystone are silt-dominated, therefore described as clayey siltstone. From table 3, the claystone from Share are texturally finer (82%) than the claystone from Tshonga (57%), though they are both silty, while samples from Tshonga have more sand fraction (43%) than Share claystones (18%). The studied claystones seem to be texturally similar to Ilokuno clays [22], and clays from Northern Cameroon [29] considering percentage of fines (clay and silt).

3.3 Mineralogy

The mineral grains in the studied claystone are dominantly angular to sub-angular with few sub-rounded grains indicating probable proximity to the source and less transportation. The XRD diffractograms revealed that the mineral constituents of the claystone are as follows; quartz (L3G-45%, L4H-70% and L5G-62%), kaolinite (L3G-%, L4H-% and L5G-%), plagioclase (L3G-%, L4H-% and L5G-%), anatase (L3G-%, L4H-% and L5G-%), mica (L3G-%, L4H-% and L5G-%), pyrite (L3G-%, L4H-% and L5G-%) and ilmenite (L3G-%, L4H-% and L5G-%) which indicate that the investigated claystone are quartz-dominated (Figures 6ai, 6bi and 6ci). The results show similarity in mineralogical for all the samples (Table 1). The quartz composition of these clays is similar to claystone from Kutigi [17], and also consistent with kaolinitic clay reported by [20] and [29] in the southern part of the basin.

According to [32] and [33], the dominant sharp diffractogram peaks indicate moderate to well crystalline mineral components in the clays. Kaolinite does not impact the mechanical and physical characteristics of the claystones [34], because it is rarely chemically active, unlike other clay minerals [35]. The presence of kaolin may also indicate near surface, freely draining environment [38], because it can be derived from primary minerals through dissolution process of primary minerals such as feldspars, biotite, and muscovite, under humid and temperate prevalent climatic conditions [37]. The process of kaolinitization requires intensive weathering

under warm to tropical temperatures and high rates of fresh water percolation through feldspar and other minerals in [38] and [39]. The mineralogical data is well corroborated with the SEM data presented in 6aii, 6bii and 6cii respectively. The kaolinites usually show planar morphologies like the other kaolin minerals [37]. The platy grains of kaolinite are well shown in figure 6cii. This well-crystallized kaolinite is considered to have formed in the primary kaolin via strong and prolonged tropical weathering, where the platy crystals of kaolinite are a bit broken in the sedimentary clay [40]. The dark spots in the SEM images are the void spaces or matrix. Hence, porosity is better in L4G and L4H compared to L5G via electron micrograph while permeability in L4H appears better than L3G. The kaolinite in some cases form part of the matrix sequel to weathering. The pores are dominantly intergranular pores and micropores. Also, the fineness of grains increases from L4H, through L3G to L5G via SEM images.

3.4 Atterberg limits

Atterberg limits test according to [41], was used to determine the physical properties of claystone which is an important factor for engineering design. The result of the Atterberg limit test is presented in **T**able 4. L4H with highest moisture content of 19% has the highest liquid limit (LL) of 71% and highest plastic limit of 31%. L4G with moisture content of 10% has liquid limit of 51% and plastic limit (PL) of 26%. According to [42] classification, L3G and L5G have intermediate plasticity (43% and 48% LL respectively), L4G has high plasticity (51% LL), while L4H has very high plasticity (71% LL). This suggests that the claystone from Share vary in physical properties. The higher the moisture content, the higher the liquid limit and the plasticity. The very high plasticity in L4H is not unconnected with its rich clay content of 34% compared to other samples. [18] suggested that claystones from southern Bida Basin are kaolinitic based on [43] who proposed that plasticity limit of kaolinite is usually not greater than 40% and this tend to distinguish them from halloysites and other clays. Coincidentally, claystone from study (northern Bida Basin) have PL below 40% thereby consolidating their kaolinitic mineralogy. The claystone from Share and Tshonga under investigation have plastic limits ranging from 17% to 36%. The Share clay (L4H) with highest plasticity index (PI) of 40% and highest moisture content of 19% may be due to its fineness as proposed by [44] and [45]. The Atterberg limit plots above A-line shows they are inorganic and also according to [46], clays with specific gravity less than 4.0 can be termed inorganic which is consistent with the specific gravity properties of the studied claystones. Atterberg plot of plastic index against liquid limit (Figure 9) revealed that L4H has a high plasticity while L4G has high plasticity. L3G and L5G have intermediate plasticity which further revealed variation in physical properties of the claystones. It is worthy of note that plasticity increases with increase in clay fraction as likely volume change and expansivity of clay may be due to volume of clay minerals. L5G has tendency for low expansion, L4G and L3G – medium expansion, while L4H – has possibility of high expansion [48] - Figure 10). Generally, as the clay fraction increases, the plasticity and activity/expansivity of the clay also increases. Table 5 shows Atterberg attributes of the studied claystones are similar to most previously studied clays in Nigeria and beyond.

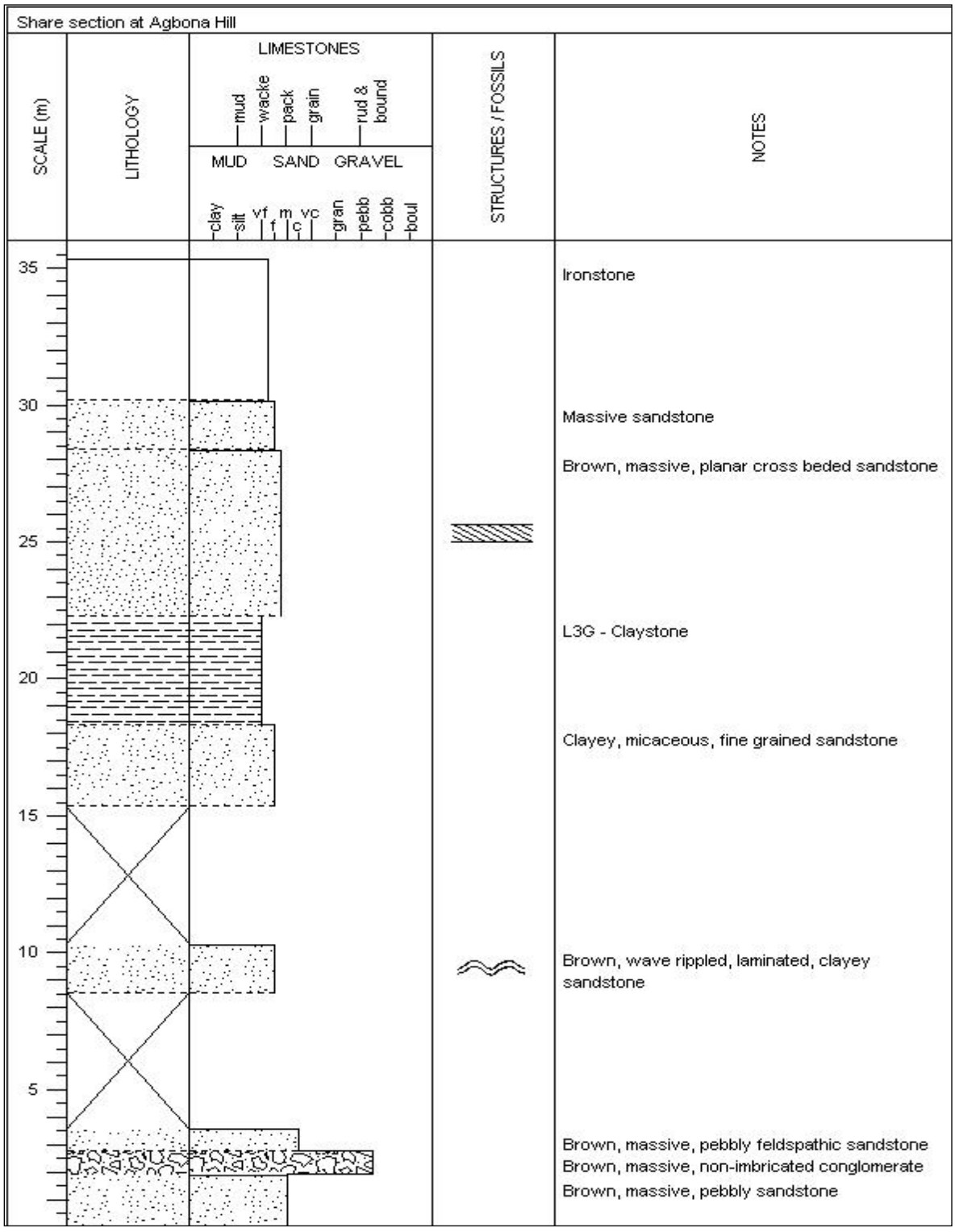


Figure 3a: Lithologic section at Share (latitude: 8º 49' 28.9", longitude.: 4º 58' 24.6", Elevation at the top: 310m, scale: 1cm represents 2m). L3G was taken at eastern side of the ridge while L4G and L4H were taken at the western side of the ridge. The claystone (about 4m thick even though

the thickness varies across the ridge) is sandwiched between sandstone beds. The thick overburden (about 13m) may be a challenge for its exploitation



Figure 3b: Claystone (bordered by black line) at Share artificial claystone cave. The claystone is bounded above my ferruginized sandstone and below by micaceous sandstone**.**



Figure 4: Claystone (CST) bed sandwiched between sandstone (SST) beds. Ironstones (IRS) are transported from the top of the ridge downslope

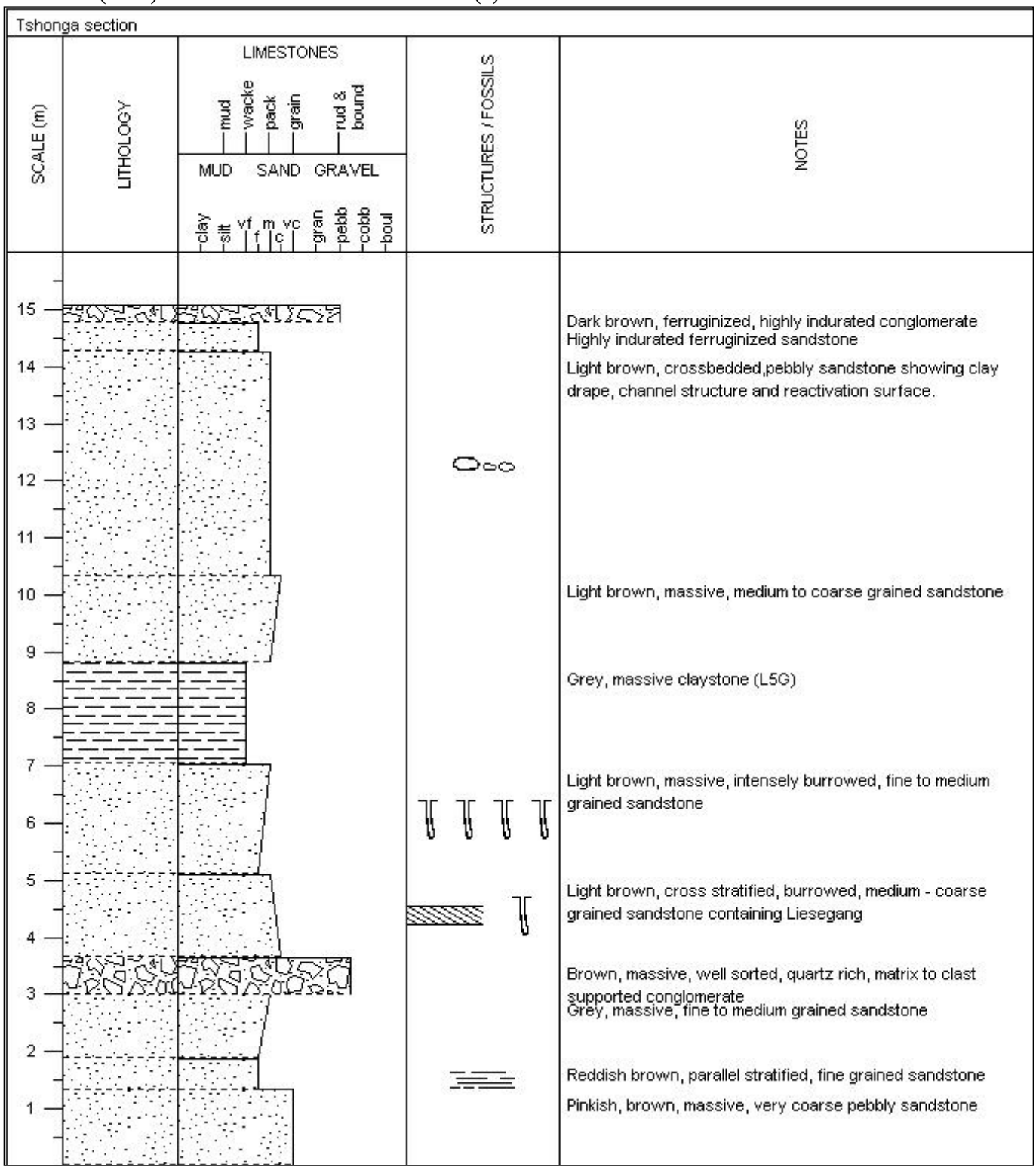


Figure 5: Lithologic section at Tshonga, GPS coordinates: N9^0 01$^{'}$ 85.8$^{"}$, 5^0 08$^{'}$ 48.1$^{"}$. Elevation at the top: 101 m. Just like Share Ridge, the claystone at Tsonga is sandwiched between beds of sandstone**.**

Table 2: Particle size analysis result

	Dry Sieve Analysis (% Pass.)									Hydrometer (% pass.)	
	3.35mm	2.00mm	1.18mm	600 µm	425µm	300µm	212µm	150µm	63µm	0.01	0.001
L3G	100	100	100	100	99	99	98	92	77	24	18
L4G	100	100	100	99	99	98	97	90	80	27	18
L4H	100	100	100	99	99	98	98	97	93	34	24
L5G	100	100	99	95	91	86	83	70	59	18	13

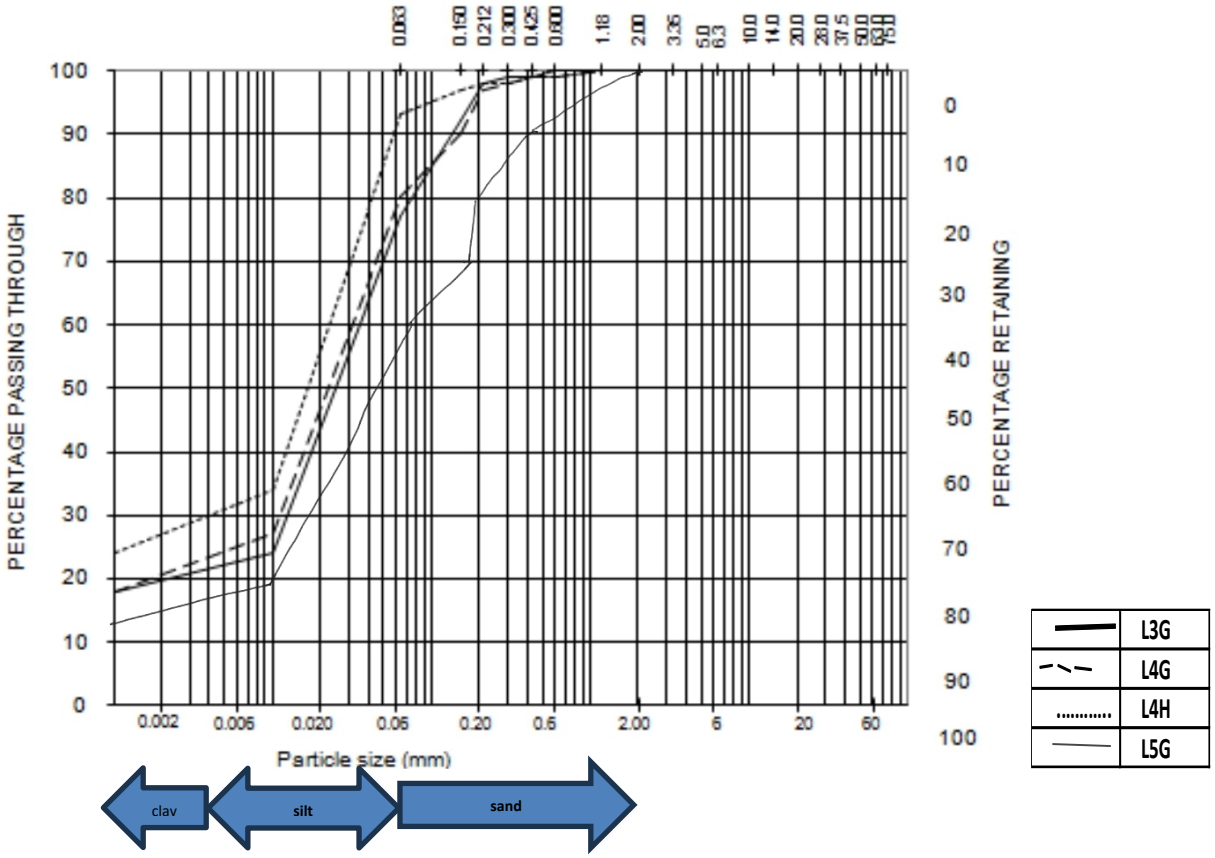


Figure 7: Grain size analysis plot for L3G, L4G, L4H and L5G

Table 3: Comparison of average PSD data with previous work on clays

	Current Study (Average)			B			
	Share	**Tshonga**	**A**	**Ara**	**Ijero**	**Ilukuno**	**C**
Clay (%)	25.3	14.0	12.1	49.7	24.1	32.8	32.8
Silt (%)	56.7	43.0	16.8	16.6	22.8	65.2	44.1
Sand (%)	18.0	43.0	66.9	31.5	51.6	2.0	21.8
Gravel	-	-	4.2	2.2	1.5	-	-

A – [30]; B – [21]; C – [31]

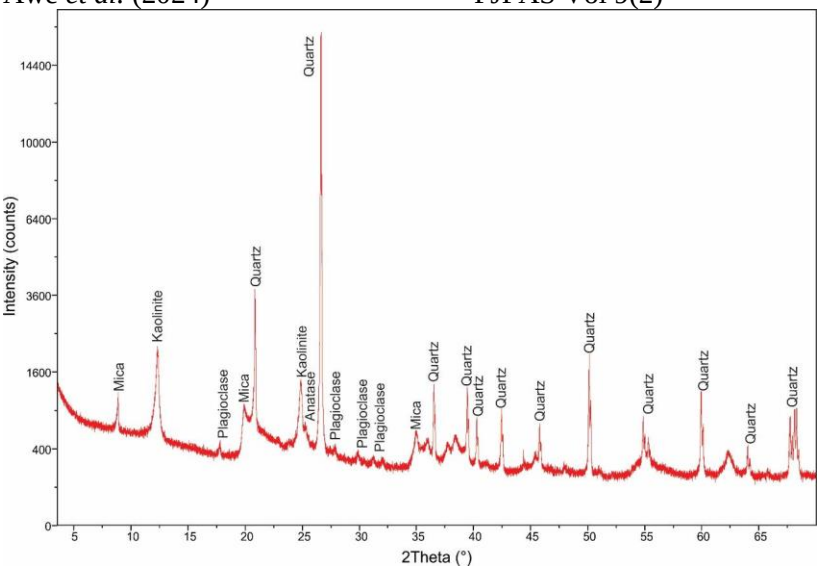


Figure 6ai: X-ray diffractogram for L3G

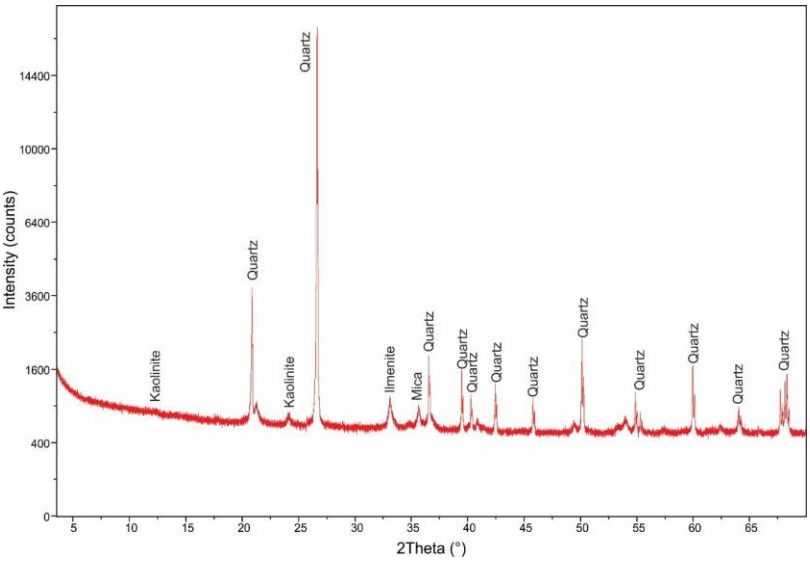


Figure 6bi: X-ray diffractogram for L4H

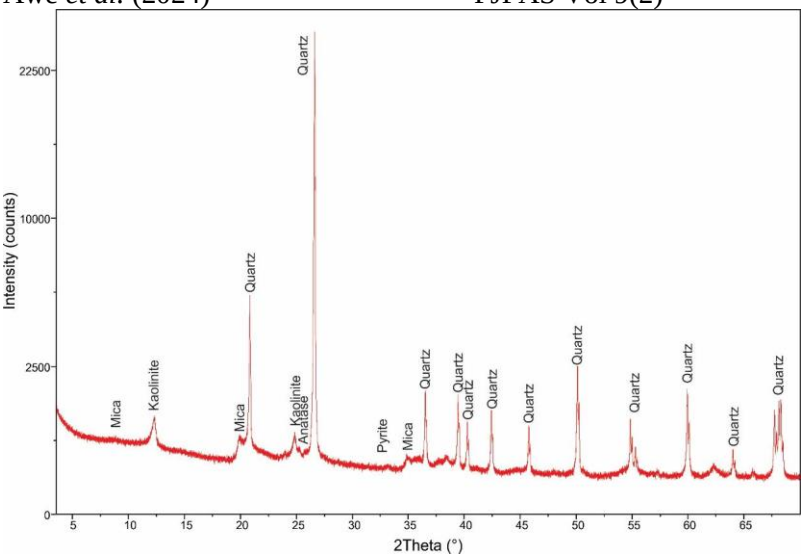


Figure 6ci: X-ray diffractogram for L5G

Table 1: Percentages of minerals present from X-ray diffractogram

	Mineral	**%**			**Mineral**	**%**			**Mineral**	**%**
L3G	Quartz	45		**L4H**	Quartz	70		**L5G**	Quartz	62
	Mica	15			Mica	5			Mica	13
	Kaolinite	22			Kaolinite	20			Kaolinite	20
	Plagioclase	15			Ilmenite	5			Pyrite	2
	Anatase	3							Anatase	3

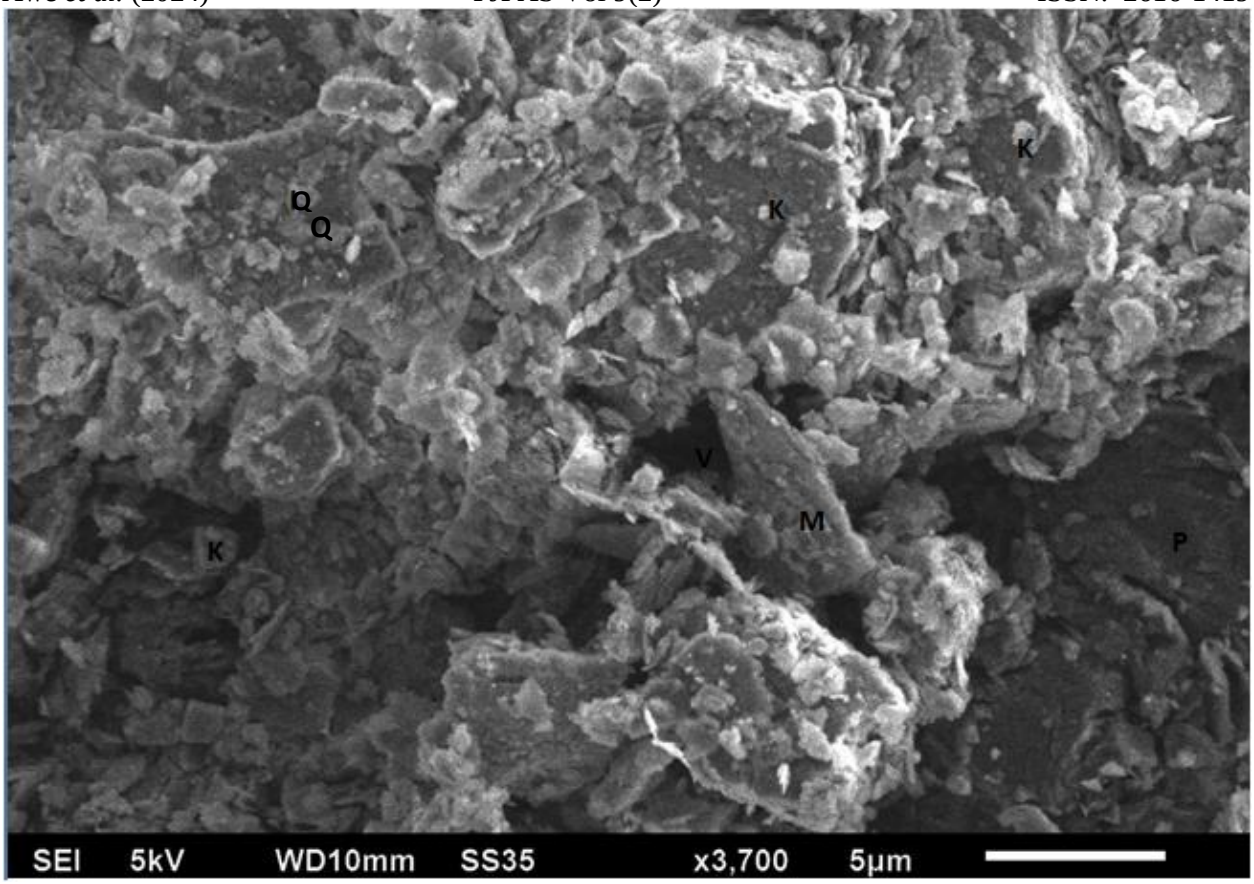


Figure 6aii: SEM image of L3G showing crystalline quartz (Q), mica (M), pore space (P) and kaolinite (K)

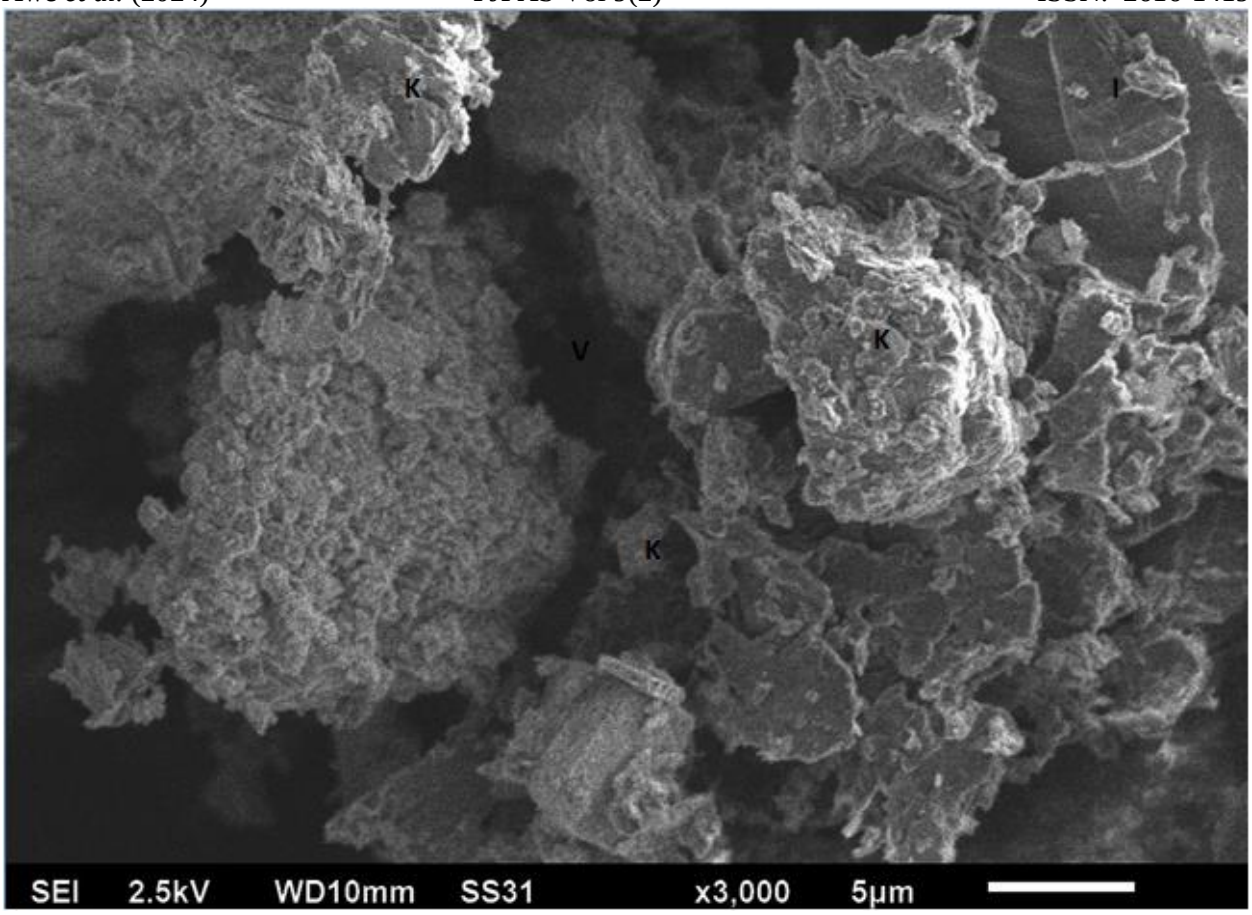


Figure 6bii: SEM Image of L4H with presence of nodular texture suggesting percolating iron-rich minerals and possible permeability

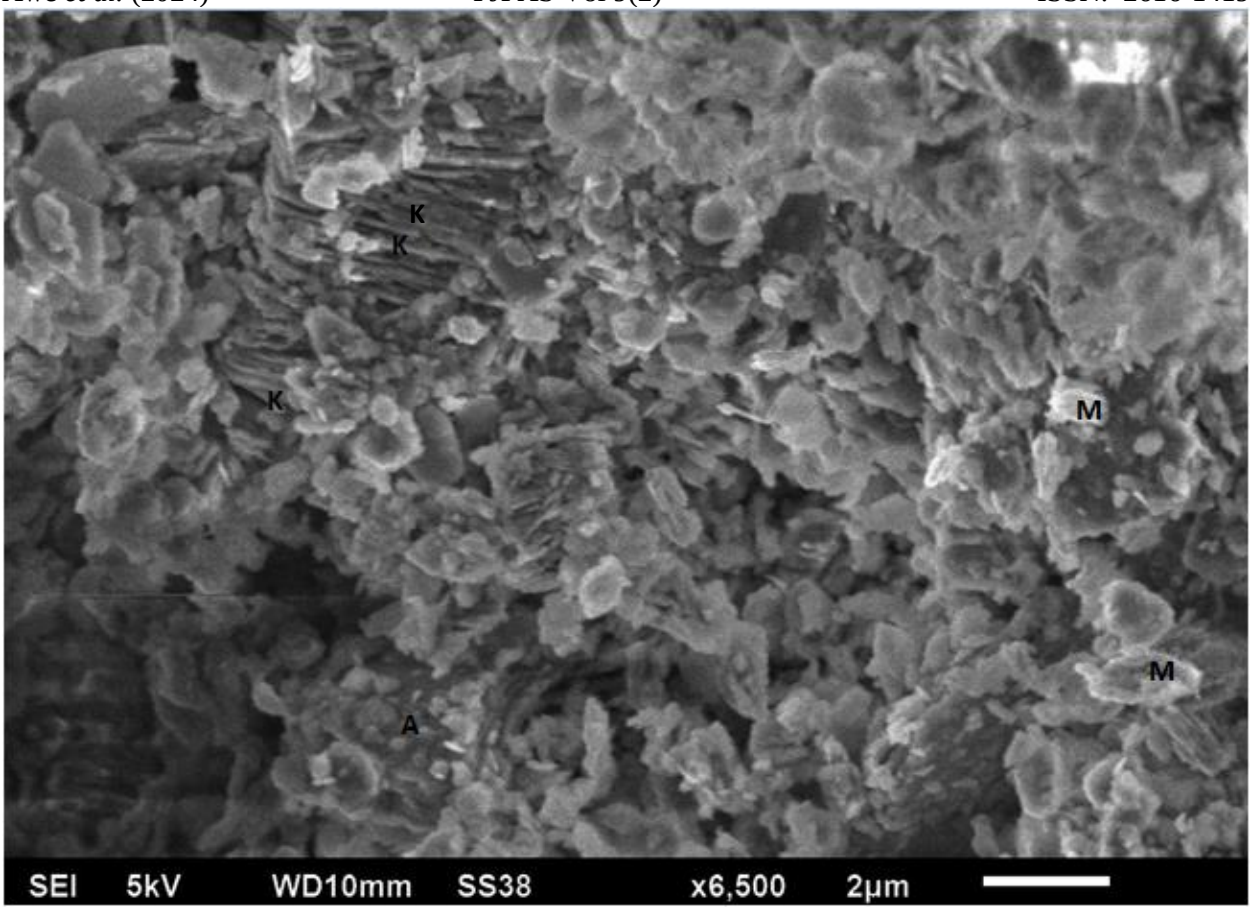


Figure 6cii: SEM Image of L5G showing presence of kaolinite (k) and Mica (m)

K-kaolinite, M-Mica, A-Anatase, I-Ilmenite, P-Plagioclase, V-Void space

Table 4: Atterberg limit test result and moisture content

	Bulk Density (mg/m3)	**Dry Density (mg/m3)**	**Moisture content**	**Liquid Limit (%)**	**Plastic Limit (%)**	**Plastic Index (%)**
L3 G	1.44	1.42	2	43	17	26
L4 G	1.55	1.4	10	51	26	25
L4 H	1.46	1.23	19	71	31	40
L5 G	1.64	1.59	4	48	19	29

Table 5: Comparison of average Atterberg limit result of different clays

	Current Study							F				
	Share	**Tshonga**	**A**	**B**	**C**	**D**	**E**	**Ara**	**Ijero**	**Ilukuno**	**G**	**H**
LL	55	48	21	51.8	63.6	52.6	49.83	45.1	29.7	56.1	66.8	46.9
PL	24.7	19	15.5	32.4	28.25	27.6	21.1	23.2	16.8	-	34.5	30.4
PI	30.3	29	5.6	19.4	35.3	25	28.73	21.9	12.9	-	32.3	16.5

A – [17], B – [22], C – [23], D – [48], E – [30], F – [21], G – [31], H – [49]

3.5 Density and Permeability

Samples L4G and L4H have high moisture contents MCs (10% and 19% respectively – **Table** 3) compared to L3G and L5G (2% and 4%) respectively. These claystones have higher moisture content compared to most clay from south-west Nigeria (maximum moisture content of 2.59%) according to [50]. Conversely, average MC of 19.8% was reported for Erusu clays south-west Nigeria [30]. The high moisture content of the studied claystone (Table 4) may account for wider differences in their bulk densities and corresponding dry densities, and this may also indicate higher porosity and permeability. The bulk densities of the analyzed claystone (1.44 to 1.64 mg/m^3) which conforms to findings of [18].

From Table 4, the claystone samples have very low permeability (10^{-6} cm/s), according to standard, which is mostly described as a boundary between pervious and impervious materials. [29] also reported dominantly low permeability for claystones in the southern part of the basin. However, the claystones do not conform to the requirement as an isolation barrier for clay-rich material, according to [51] and [52], who all unanimously stipulated that clay materials should have permeability of 1.0×10^{-7} cm/s, to be used as a single liner or isolation barrier. Also, according to [53], order of 10^{-6} cm/s for the studied claystone shows they have optimum permeability as an attenuation layer.

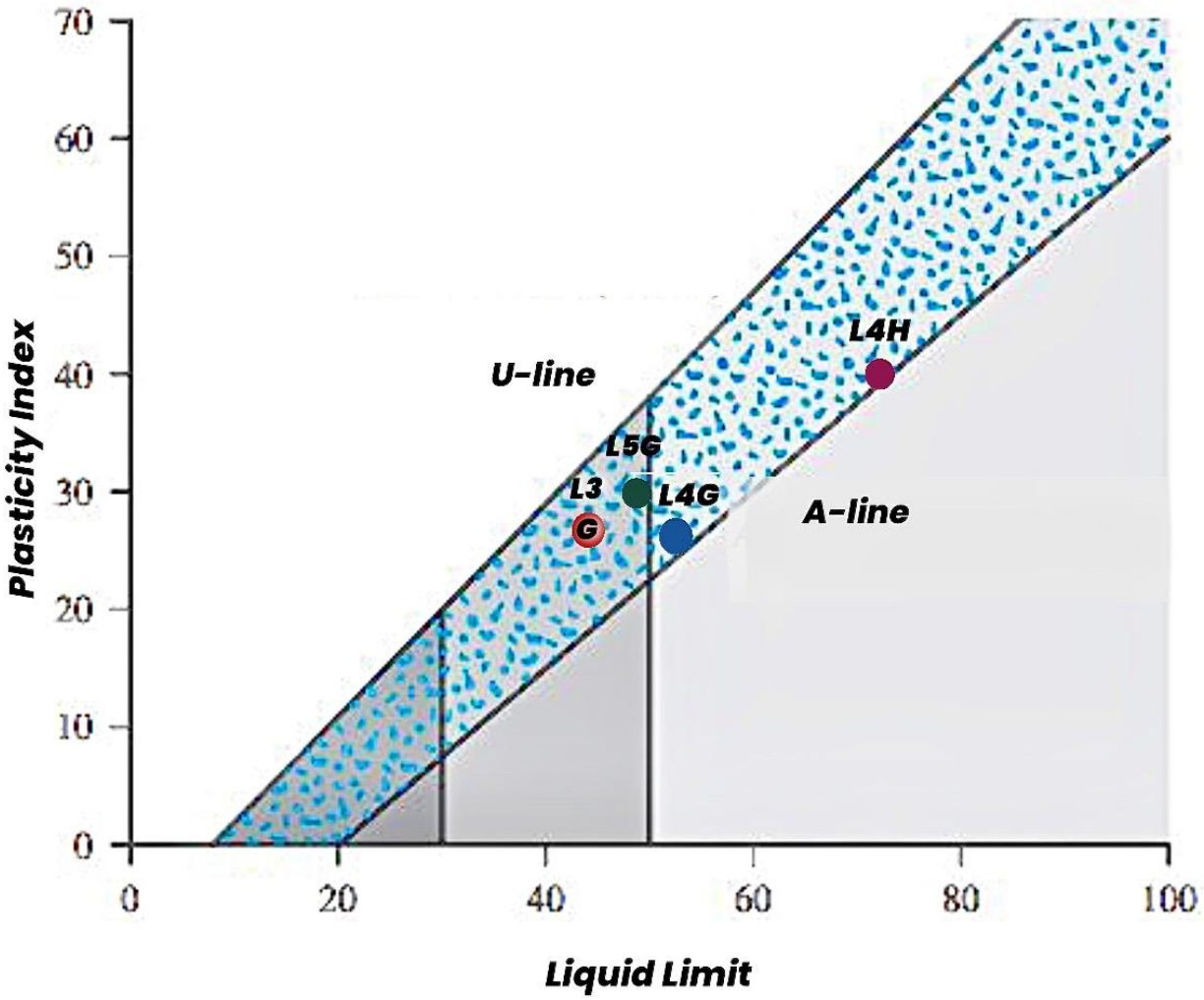


Figure 9: Casagrande chart classification of the samples (after [54])
LP – Low plasticity, IP – Intermediate Plasticity, HP – High Plasticity, VHP – Very High Plasticity

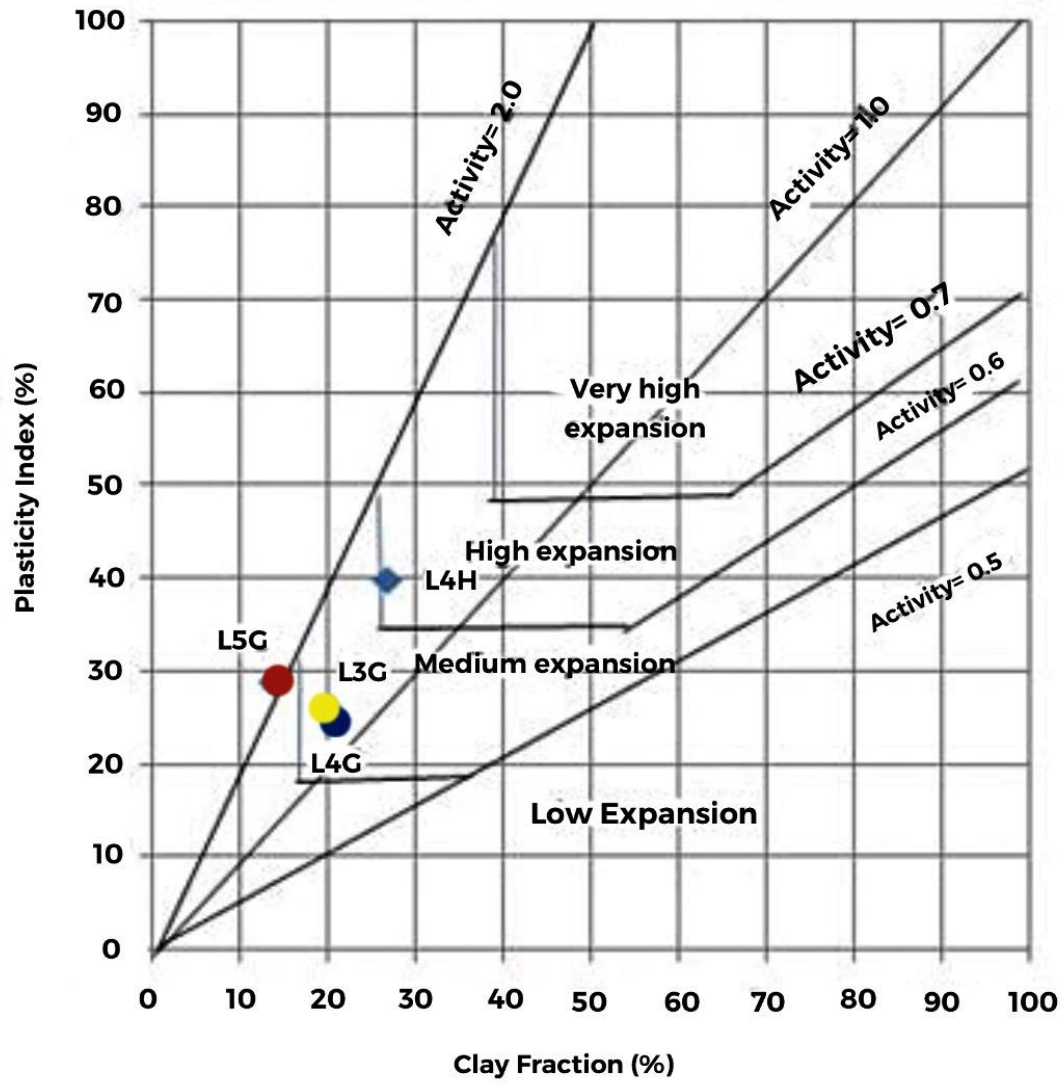


Figure 10: Degree of soil expansion in (after [47])

Table 6: Summary of laboratory test results on permeability test

Sample Nos.	Moisture content MC (%)	Bulk density γ_b(Mg/m^3)	Specific Gravity (Gs)	Void Ratio (e)	Porosity (n%)	Coefficient of Permeability K_{av} cm/sec
L5G	21.6	2.018	2.59	0.560	35.9	5.826 X 10^{-6}
L3G	25.3	1.957	2.59	0.659	39.7	5.173 X 10^{-6}

Table 7: Result of firing test

	200^{0}C	400^{0}C	600^{0}C	800^{0}C	1000^{0}C	1200^{0}C
L3G	Pale Yellow	Pale Yellow	Pale Yellow	Light Yellow	Light Yellow	Light Yellow
L5G	Light Grey	Light Grey	Light Grey	Light Grey	Light Grey	Light Grey

3.7 Resource Potential of the claystones

Clays are widely used for ceramic purpose among other diverse applications. The presence of quartz alongside the clay minerals may have great influence on the clay usage. Due to high sand and silt contents compared to clay fraction, the studied claystones are similar to Erusu clays as reported by [30], hence these claystones can be used in brick making to give high strength. According to [43], the plastic limits and corresponding plastic indices for samples L3G, L4G and L5G allow them to be suitable for use in bricks and pottery. The high liquid limit and plasticity index may lead to structural damage, hence the claystones may not be suitable for construction). Conversely the moderate to slightly high plasticity may permit molding of the clays for pottery and ceramics [55]. It was stipulated that the liquid limit of clay used for barrier lining should be less than 90% [56]. The determined liquid limits of the studied claystones are less than 90%, therefore, they are expected to exhibit low hydraulic conductivity. Hence, they may be suitable for use as barrier lining which can prevent migration of leachate. Studies have shown that materials to be used as barrier in landfills should have minimum liquid limit of 20% [57]. The results of the liquid limit were more than 20% but less than 90%. Also, for materials to be used as barrier material in landfills, a minimum plasticity index of 7% is required [52], [51]. Plasticity index of less than 65% was recommended by [56]. The result of the plasticity indices is greater than 7% and less 65%. The result conforms to the findings of [52] and [51]. Therefore, the clay can be used as a landfill barrier. Kaolinite is also non-reactive when in contact with chemicals. According to [58], [57], [42], kaolinite rich clay tends to perform effectively as barrier material. [59], [58] stated that the combination of kaolinite and illite will serve best as barrier material because they perform containment function and attenuation of contaminants. The studied clays meet the clay mineralogy requirement for landfill barrier since they have higher kaolinite contents.

The permeability (hydraulic conductivity) is an important parameter in the design of waste disposal facilities involving burial in the natural clay deposits or the use of clay liners in underground reservoirs, low permeable materials are used in landfill as barriers [60]. The mineralogy of the barrier liner is another factor which helps to determine the shrinkage and swelling potential of the barrier material [22]. The presence of unreactive kaolin in the claystone and relatively low permeability may support their use as barrier liner. Also, materials for use as barrier liner should have at least 30% of fines, [51], [52], and clay content greater than 10% [56]. The studied claystones meet the aforementioned criteria for liner.

Furthermore, the non-or slightly expandable (as shown in Figure 10 – medium expansion) claystones may exhibit yellow colour on firing probably due to Fe^{2+} oxidation or presence of Fe_2O_3 [61] shown by L3G (Table 7). Variation in Fe content may influence tonality, and iron oxide variation of these claystone, according to [25], varies from 0.98% to 22.85% hence, the claystone can be used for fine ceramics owing to bright colour displayed at high temperature. Other proposed applications of the claystones are shown on Winkler's diagram using particle size data. Tshonga clay L5G will be suitable for solid bricks owing to high sand content. L4G will be good for vertically perforated bricks while L3G and L4H do not fall in any defined zone on Winkler's diagram. These

two clays (L3G and L4H) can be mixed or treated for them to fall into Winkler zone.

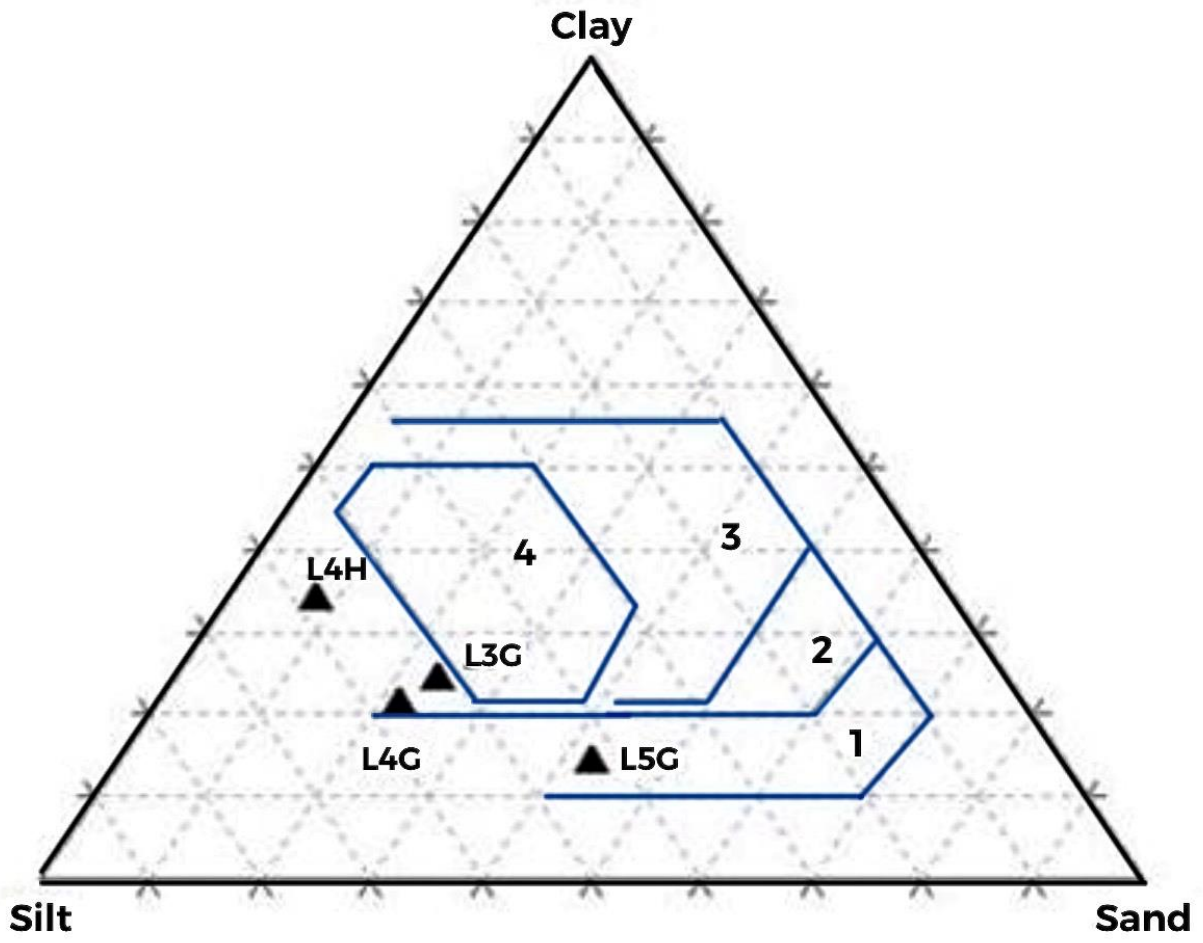


Figure 11: Ternary plot of particle size distribution (after Winkler, 1954)
1– Solid bricks, 2 – vertically perforated bricks, 3 – Roof tiles and light weight blocks, 4 – Hollow bricks

4. Conclusions

The Enagi claystones are siliceous and kaolinitic with high silt particle contents. The claystones vary in physical properties, \and colour. They are likely product of very intense weathering under humid condition. The claystones have low-medium expansivity and low permeability. The clay can be used for pottery, brick making, and landfill barriers. The clays may be suitable for other construction as well as ceramic purposes with further processing to reduce the quartz content.

Declarations

Ethics approval and consent to participate

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Consent for publication

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Author's contribution

AA participated in the field work, interpreted the data and wrote the paper. OO participated in the field work, conceived and designed the experiments, wrote the paper and revised the manuscript**.** SA interpreted the data and wrote the paper. AA participated in the field work and interpreted data. All authors approved the final draft of the manuscript.

Conflict of interest

There is no conflict of interest among the authors

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