Published by
NIGERIAN SOCIETY OF PHYSICAL SCIENCES
Available online @ https://journal.nsps.org.ng/index.php/jnsps

J. Nig. Soc. Phys. Sci. 6 (2024) 1921

Journal of the Nigerian Society of Physical Sciences

Characterization of mine spoils for the reclamation of degraded lands of the Jos-Bukuru tin field, central Nigeria

Sunday Sani Daku[a,*], Ogbonnaya Igwe[b]

[a] *Department of Geology, Faculty of Natural Sciences, University of Jos, Nigeria*
[b] *Department of Geology, Faculty of Physical Sciences, University of Nigeria, Nsukka*

Abstract

Tin mining operations on the Jos Plateau have left a lasting impact on the environment, resulting in derelict land, mine spoils, and over a thousand abandoned mining ponds. These ponds have become potential hazards, endangering unsuspecting members of the public. This study aims to provide a comprehensive geochemical and geotechnical characterization of the mine spoils to assess their suitability for the reclamation and restoration of the degraded mined lands. The geochemical analysis reveals that the mine spoils exhibit a moderate to strong level of acidity, with a pH range of 3.91 to 5.90 (average: 4.85). Furthermore, they display deficiencies in essential nutrients such as phosphorus (average: 0.02%) potassium (average: 0.31%), as well as copper (average: 19.15 ppm). Notably, the mine spoils are enriched in iron (average: 6.31%), manganese (average: 165.15 ppm) and zinc (average: 53.24 ppm). These findings highlight the inadequate presence of both micronutrient and macronutrient elements which are necessary for successful revegetation which is a crucial component of reclamation. Results from the geotechnical tests indicate that the mine spoils possess an average fines content of 56.03%, a mean liquid limit of 38.06%, and a mean plasticity index of 15.52%. Additionally, the average linear shrinkage value is measured at 10%. The average values for maximum dry density (MDD) and optimum moisture content (OMC) are 1.65 g/cm³ and 19%, respectively. The unsoaked California bearing ratio (CBR) averages 34.64%, while the coefficient of permeability for the spoil is approximately 1.24×10^{-3} mm/sec. Furthermore, the spoils average cohesion (C) was measured to be 12.15^0 while the mean angle of internal friction (ϕ) is 30.77 KN/M^2. These results collectively indicate that mechanical and chemical stabilization, involving the use of lime, fly ash, and other soil-stabilizing agents is imperative for the effective reclamation of the degraded lands using the mine spoils. Such measures if adopted and implemented will mitigate the risk of accidents and drowning incidents from mining ponds and other abandoned pits involving unsuspecting members of the public and will contribute to the overall environmental restoration efforts in the Jos-Bukuru Tin Field.

DOI:10.46481/jnsps.2024.1921

Keywords: Degraded lands, Geochemical, Geotechnical, Mine spoils, Reclamation

Article History :
Received: 23 December 2023
Received in revised form: 29 April 2024
Accepted for publication: 15 July 2024
Published: 11 August 2024

Communicated by: Naheem Salawu

1. Introduction

Tin mining began in Jos, Plateau State, Nigeria, in 1904 during the colonial era [1]. Despite its importance to the state and national development, it has had significant environmental impacts leading to the formation of; spoil heaps, gully erosion, sheet erosion, water pollution, river diversion and blockage, mining ponds, and abandoned mine pits [2]. According to Mallo [3], there are currently 1000 mining ponds covering an area of 17 Km^2 in the Jos-Plateau tin fields and it is esti-

*Corresponding Author Tel. No.: +234-803-769-8271.
Email address: dakus@unijos.edu.ng (Sunday Sani Daku)

(a)

(b)

Figure 1. Photograph showing (a) Remnant of the mine spoil (b) Unreclaim Mining Pond close to the collapsed structure at Kwang.

mated that mining activities have devastated about 316km2 of arable land, with only about 13 Km^2 reclaimed. Studies by Adiuku-Brown [4] indicated that between 1980 and 1993, there were 119 accidents in these mining areas, resulting in 106 fatalities. According to recent reports, 33 persons were reportedly killed in Barkin Ladi Local Government Area alone in the past two months as a result of mine site collapse [5]. In addition, there have been several deaths resulting from underground mine (loto) collapse and drowning in mining ponds and pits that have gone unreported.

Mining wastes can have various negative impacts on the environment such as soil erosion, air and water pollution, toxicity, natural disasters, loss of biodiversity and economic decline [6, 7]. Therefore, it is crucial that mineral extraction processes ensure the reclamation of mine lands to make it productive [8]. The Plateau State government intends to restore mining sites as closely as possible to their maximum positive value through reclamation and rehabilitation [3]. For mine spoils to be effectively used for reclamation, it is essential to ascertain their chemical, physical, biological and geotechnical components.

High potential acidity (low pH) significantly affects mine spoil productivity. As rock particles oxidize and weather, pyritic minerals (FeS), if present, convert to sulphuric acid and significantly lower pH. However, Maiti [9] assert that carbonate-bearing minerals (Ca,Mg,(CO_3) tend to raise pH as they weather and dissolve. Vegetation grows most effectively when the pH in a mine spoil is neutral. Therefore, Refs. [10, 11] stated that a mine spoil pH in the range of 6.0 – 7.5 is ideal for forages and other agronomic and horticultural plants. In a mining waste site located in Central Coalfield Limited's (CCL), North Karanpura area in the Ranchi district of Jharkhand State of India, Ref. [12] reported values of pH ranging from 4.9 to 5.3, which indicates the acidic character of the dumps.

In general, overburden mining waste dumps reportedly have low concentrations of three major macronutrients namely; N, P, and K [7, 13]. Some of the important metallic micronutrients that are essential for plant growth are Fe, Mn, Cu, and Zn. Because of the constant weathering of rocks coupled with primary minerals, these micronutrients are present in the soil. When these metals dissolve, they do so in harmful amounts that could slow down plant growth, because they are more soluble in acidic solutions [14–16]. When restoring acidic coal overburden, Maiti and Ghose [12] observed that increasing the pH and organic matter content are crucial for the long-term reclamation of mining overburdens. According to Nicolau [17], Moreno- de las Heras [18] and Hu *et al.* [19] soil for reclamation that contains more than 50% stone should be assessed as being of poor grade. According to Maiti and Saxena [20], the stone composition of overburden dumps from coal mines can range from 80 to 85%. Stone content in overburden dumps was reported by Ref. [12] to range from 35% to 65%, with an average value of 55%. The relative proportions of sand (2.0 - 0.05 mm), silt (0.05 - 0.002 mm), and clay (0.002 mm) sized particles influence the texture of the soil. Sand-like mine spoils are not capable of retaining as much water or minerals as soils with finer textures such as loams and silts [8]. In general, soils with loamy textures have an optimal distribution of particle sizes. Where siltstone spoils predominate, silt-loam textures are frequent [21]. Furthermore, Ref. [21] reported that the maximum percentage of sand and clay needed for reclamation in mined soil at the Singrauli coal field, India, were 66% and 8.6% respectively while Refs. [22, 23] reported that the greatest sand and clay content in mine spoil overburden to be 80% and 11% respectively if it is to be used for reclamation. Sheoran *et al.* [8] recommended that revegetation is the most widely acknowledged and practical method of reclaiming mine wastes to lessen erosion and

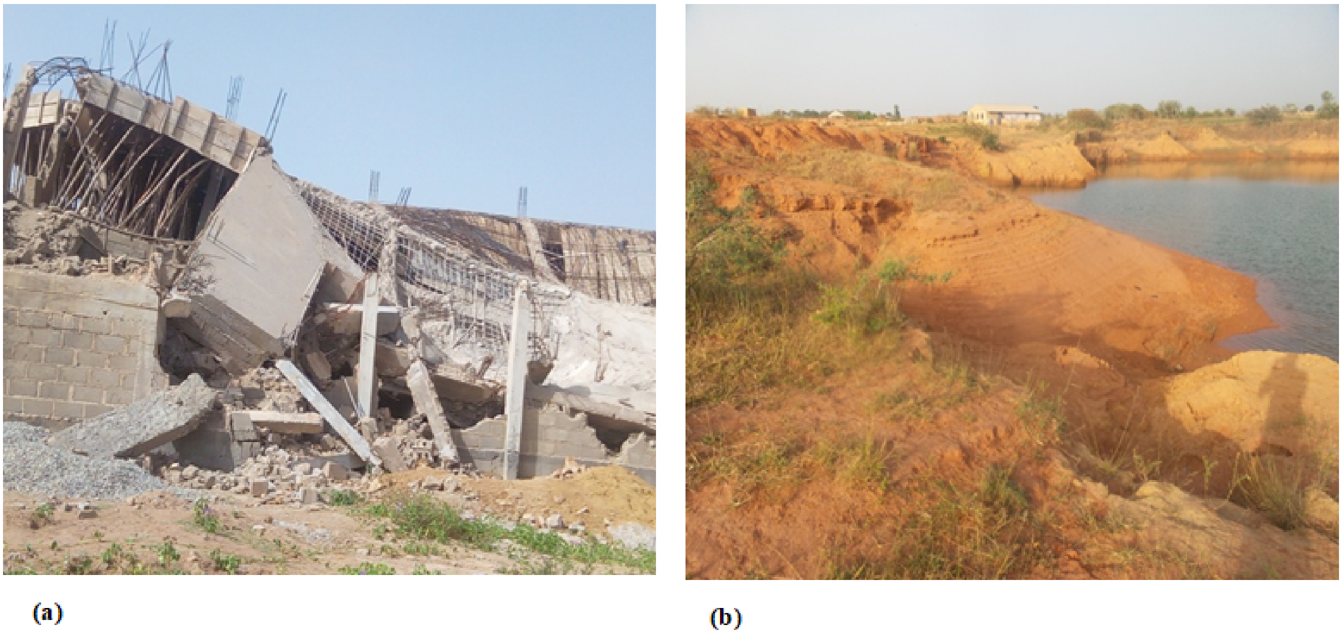

Figure 2. (a) Men reworking the mine spoil for Tin at Rayfield resort (b) Collapsed structure constructed on unstablized reclaimed land at Kwang.

safeguard the soil against deterioration.

Rooting depth in mine spoils are constrained by high bulk density, therefore, natural soils that are agriculturally productive should range in bulk density between 1.10 to 1.50 g/cm^3 [12]. However, Rimmer and Younger [24] found a bulk density of up to 1.80 Mgm^{-3} in the soil beneath a grass sward in the United Kingdom making it difficult for effective plant growth. Majority of plant species cannot efficiently extend their roots through high bulk-density mine wastes as plant growth is directly hampered by compacted soil. Thus, rooting constraints, compaction, and poor capacity to retain water, high bulk density, and a lack of micronutrient and macronutrient elements are the main variables restricting mine spoil productivity. Mamata and Amiya [25] emphasized that strategies should take into account textural composition, physicochemical characterization, soil fertility/quality, microbial community structure, soil management practices, and nutrient cycling at least to the level that existed before mining when using mine spoil for reclamation. It is crucial to remember that reclamation aims to lower the risk of water pollution, restore the landscape aesthetics and productivity and stop further deterioration.

The Jos- Bukuru area have been devastated by many years of unregulated mechanized mining of tin and other associated minerals leaving in its wake mine spoils (Figure 1a) and mining ponds (Figure 1b). The degradation of the land has continued unabated through digging and reworking of the mine spoils by artisanal miners (Figure 2a). Furthermore, due to paucity of lands for construction of residential and other infrastructures, some of the yet to be stabilized but reclaimed lands are been utilized for construction which has led to economic losses due to collapse of infrastructures (Figure 2b).

Numerous scholars including Refs. [3, 4, 26, 27] have examined the fatalities, environmental effects and deterioration caused by tin mining on the Jos – Plateau. However, there is no known research output to characterize these materials generated by tin mining activities for use in the reclamation of the degraded lands. Given the growing population and urbanization in the area, it is important to effectively reclaim these derelict lands for appropriate occupation and utilization. This can only be achieved if the soil possessed the requisite geotechnical and geochemical properties so that the incidences of infrastructural collapse due to poor engineering soil properties as well as the inability of the soil to support revegetation due to lack of essential micronutrient and macronutrient elements will not be experienced. Therefore, the geotechnical and geochemical characteristics of the mine spoil is being investigated to determine its suitability or otherwise to reclaim the derelict and degraded lands that has become death trap for mine workers and other unsuspecting members of the public.

2. The study area

The study area is situated between latitude $9^o 40' 00'' - 9^o 55' 00''$N and longitude $8^o 50' 00''$ - $9^o 00' 00''$E and covers an area of four hundred and five (405) square kilometers. It is bordered geographically to the north by Jos North, to the east by Jos East, to the west by Riyom and the south by Mangu and Bokkos Local Government Areas as shown in Figure 3.

Two primary relief systems; the highlands and lowlands with a dendritic drainage pattern, defines the study area (Figure 4).

The geology of the study region is a component of the Jos-Bukuru younger granite Complex, which has been the subject of in-depth investigation by Refs. [28–30]. Biotite-granite, specifically fine-grained biotite granite and porphyritic biotite granite, makes up the majority of the younger granites in the

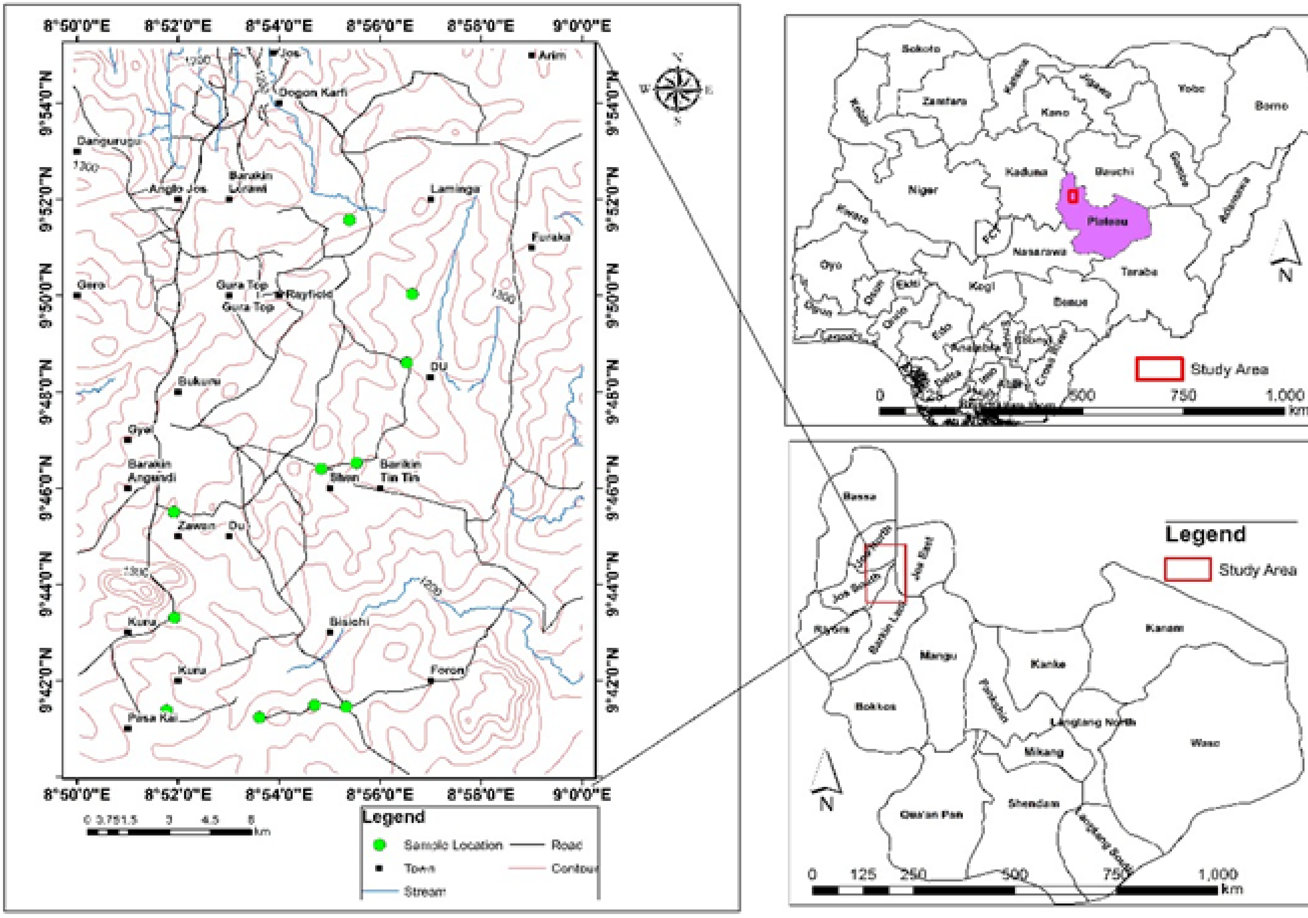

Figure 3. Topographic map of the study area subset from the map of Plateau State.

study area (Figure 5). The younger granites occur in the study area as chains of highlands of variable heights (Figure 6) with fine, medium, coarse grained and porphyritic textures.

3. Materials and Methods

3.1. Sampling

Mine spoil samples were collected from abandoned tin and columbite mine sites within the Jos- Bukuru tin mining fields. The samples were collected following the United States Environmental Protection Agency [31] procedures. To obtain a representative sample of the soil, samples were taken from the different strata of the face of the mine spoil heap. Due to the mine spoils' heterogeneous nature, different soil components were taken from the top, middle, and bottom of the heap. The lumps were then broken and thoroughly mixed to produce a composite sample. For this investigation, a total of 45 samples were gathered and examined. To retain the soil's natural wetness, the soil samples were then gathered into airtight bags (big polythene bags enclosed in sacks). The samples were then taken from the field to the Geology and Soil laboratory of the Department of Civil Engineering at Kaduna Polytechnic for Geotechnical analyses, while a portion was pulverized at the Geochemistry laboratory of the Department of Geology, University of Jos and transported to Bureau Veritas (ACME) laboratory, Vancouver, Canada for Geochemical analyses using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) instrumentation method.

3.2. Geochemical Analyses

Tin mine spoils are chemically heterogeneous containing major, trace (heavy metals), rare and in some cases radioactive elements. Sample splits of 0.25g were analyzed using the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) instrumentation method. The samples were pulverized and split into a representative portion for ultra-trace geochemical multi-acid digestion using HF-HNO_3-$HClO_4$ and HCl. Prepared samples were thoroughly dried using an acid solution of (2:2:1:1) H_2O-HF-$HClO_4$-HNO_3, 50% HCl was then added to the residue, heated using a mixing hot block, and the solutions were transferred to test tubes. For several Cr and Ba minerals, as well as some oxides of Al, Hf, Mn, Sn, Ta, and Zr, this digestion is only partial as there may be some As, Sb, and Au loss due to volatilization during fuming. The analysis was carried out following procedures described by Bureau Veritas Laboratory, Canada (ACME).

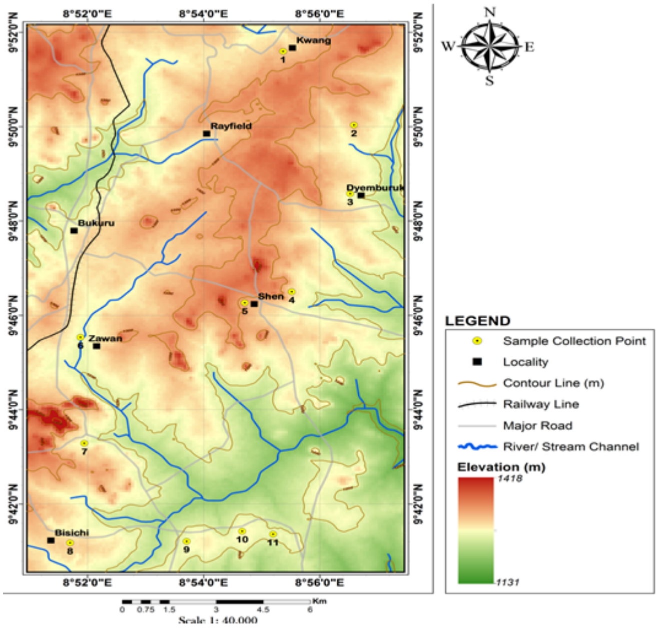

Figure 4. Relief map of the study area showing sampling sites.

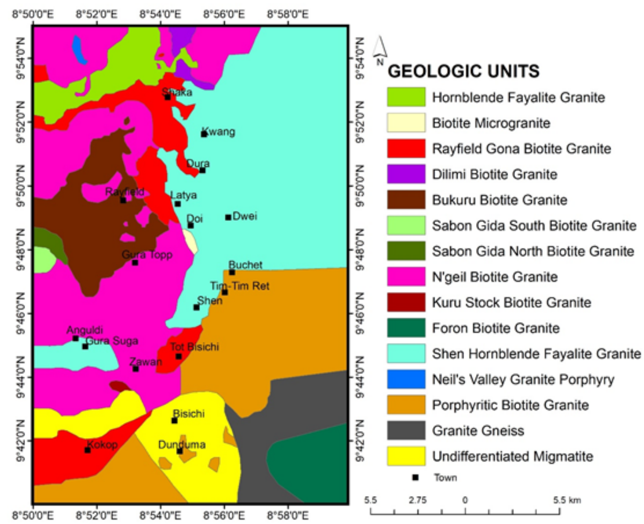

Figure 5. Geologic map of the study area.

The soil samples were pulverized and 20g was placed in a beaker and 10ml of distilled water was added and gently stirred. Following that, the pH of the soil-water mixture was determined using an Apere instrument pH meter. This was carried out in the Geochemistry Laboratory of the University of Jos' Department of Geology. The equipment used for this includes a measuring cylinder, a beaker, a stirrer, distilled water, and a measuring scale.

3.3. Geotechnical Tests

Geotechnical examinations including sieve analysis, Atterberg consistency limits test, compaction, shear strength, permeability, and California bearing ratio (CBR) tests was performed on the samples at the Geology and Soil Laboratory of Kaduna Polytechnic. These analyses were conducted in conformity with British Standard procedures [32] for the Atterberg consistency limits test, compaction, shear strength, permeability and California bearing ratio (CBR) while the hydrometer test was done using the Ref. [33] procedures.

4. Results and Discussion

4.1. Chemical characterization

The chemical composition of the mine spoils as well as the descriptive statistics are presented in Tables 1 and 2 respectively.

4.1.1. Soil pH

The most often utilized indicator of mine soil quality is soil pH, which measures active soil acidity. Mine spoils in the study area have pH values ranging from 3.91– 5.90 with an average of 4.85 as can be seen in Table 1. The lowest value (more acidic) of 3.91 was found in sample SSD 33 located at Gura Topp while the highest value (least acidic) of 5.90 was found in sample SSD 40 situated at Kwang-Hei. This implies that the mine spoils are very strongly acidic to moderately acidic [34]. The acidic nature of these soils had earlier been reported in Refs. [35, 36]. Olowolafe [37] attributed the low pH of the soil to be due to the granitic parent rocks that underlie the Jos- Plateau tin mining area as well the abundance of laterites. Low pH causes hazardous metals (Al, Fe, and Mn) to become more soluble and available, which may inhibit the growth of N-fixing bacteria, plants and prevent the leaching of important elements [35]. The implication of this is that the mine spoil when in contact with water may lead to corrosion of critical infrastructures such as metal pipes that may be buried under it in the course of eventual development of the reclaimed land. Also, plant growth will also be hampered if optimum growth and productivity of the soil is to be expected. By pre-treating the soil with lime, fly ash, and other soil-neutralizing agents, the pH of the soil can be raised thereby reducing the soil corrosive potential and the likelihood of the formation of complex ions which may be detrimental to human health, infrastructure and the environment.

4.1.2. Soil Fertility

Soil fertility is dependent on the availability of plant nutrients and these nutrients are defined by Ref. [38] as chemical components that are generally necessary for plant growth and reproduction. Macronutrients such as C, H, O, N, P, K, Ca, Mg, and S are crucial for plant growth. Although ion antagonism or cation competition caused by an excess of certain elements in the soil might lead to a deficiency in other elements [39]. Micronutrients including B, Cl, Fe, Mn, Cu, Zn, Mo, and Ni are among those that are present in smaller amounts than macronutrients. The constant weathering of rocks mixed with primary minerals is responsible for the availability of these elements in the soil, which are generally significant and necessary for plant growth [7, 13].

The concentration of micronutrients and macronutrients (el-

Table 1. Concentrations of some micronutrient and macronutrient elements and pH of mine spoils in the study area.

SAMPLE ID	Mo	Cu	Zn	Ni	Mn	Fe	Ca	P	Mg	K	pH
SSD 1	4.10	18.00	160	28.6	197	6.61	0.04	0.026	0.06	0.17	5.31
SSD 2	5.50	21.00	97	38.6	247	5.64	0.05	0.019	0.1	0.41	4.72
SSD 3	5.00	26.90	35	33.9	194	10.50	<0.01	0.027	0.03	0.1	4.95
SSD 4	7.60	40.90	34	46.2	337	13.19	0.04	0.039	0.09	0.24	4.91
SSD 5	5.00	44.90	45	46.5	202	10.51	0.07	0.029	0.09	0.28	5.48
SSD 6	7.60	34.60	50	39.1	362	6.77	0.04	0.029	0.08	0.25	4.15
SSD 7	11.20	32.40	56	30.5	191	8.41	0.03	0.028	0.09	0.58	4.74
SSD 8	7.10	22.90	101	23.3	395	10.61	0.04	0.02	0.12	0.38	4.98
SSD 9	12.80	18.30	53	23.1	213	9.44	0.03	0.035	0.05	0.21	5.57
SSD 10	3.40	10.10	42	15.3	191	3.68	0.03	0.016	0.06	0.42	4.84
SSD 11	5.60	8.20	68	16.7	76	3.19	0.02	0.008	0.04	0.18	5.00
SSD 12	8.10	21.60	121	20.1	321	5.70	0.05	0.019	0.08	0.81	5.40
SSD 13	6.20	9.00	26	12.4	64	3.80	<0.01	0.019	0.02	0.05	4.84
SSD 14	4.90	9.50	26	16	61	3.02	<0.01	0.017	0.02	0.07	4.42
SSD 15	10.80	16.10	32	21.3	113	7.91	0.02	0.023	0.03	0.08	5.03
SSD 16	21.50	12.90	44	22.2	107	6.64	<0.01	0.024	0.02	0.06	4.18
SSD 17	2.30	18.30	59	25.9	126	3.57	0.07	0.02	0.08	0.22	5.54
SSD 18	5.60	24.60	52	35.3	154	9.01	0.07	0.026	0.09	0.26	5.77
SSD 19	2.60	5.00	38	8.8	53	1.42	<0.01	0.011	0.01	0.05	4.03
SSD 20	4.50	18.50	46	33.6	176	8.58	0.05	0.026	0.11	0.71	4.95
SSD 21	2.60	19.30	40	36.9	106	3.75	0.07	0.016	0.1	0.37	4.70
SSD 22	1.60	11.20	35	23.7	90	2.28	0.06	0.012	0.09	0.5	4.78
SSD 23	7.30	24.60	51	29.3	124	8.89	0.03	0.025	0.07	0.36	4.87
SSD 24	8.90	24.70	59	42.8	209	10.31	0.05	0.026	0.09	0.25	4.98
SSD 25	2.30	12.60	46	20.1	90	2.61	0.06	0.013	0.07	0.35	5.28
SSD 26	8.40	14.90	42	26.3	111	6.13	0.02	0.018	0.05	0.27	4.90
SSD 27	6.70	18.90	68	26.9	125	5.59	0.05	0.022	0.07	0.23	4.93
SSD 28	2.80	20.70	39	33.4	148	5.05	0.07	0.016	0.1	0.35	5.04
SSD 29	3.20	16.40	47	27.7	124	3.63	0.04	0.016	0.08	0.34	4.35
SSD 30	5.10	20.60	77	39.3	151	6.00	0.08	0.02	0.1	0.27	5.36
SSD 31	3.80	21.20	39	40.2	296	6.80	0.07	0.023	0.12	0.55	4.95
SSD 32	8.40	22.10	45	48.7	151	7.23	0.05	0.026	0.07	0.17	5.03
SSD 33	7.80	28.70	30	38.6	187	8.86	<0.01	0.024	0.04	0.09	3.91
SSD 34	13.80	11.00	55	35.4	107	5.94	0.02	0.029	0.03	0.08	4.80
SSD 35	4.10	11.90	42	15.8	118	3.51	0.03	0.01	0.06	0.54	4.45
SSD 36	7.20	26.40	82	31.6	187	10.40	0.04	0.028	0.06	0.22	4.63
SSD 37	6.20	17.60	58	25.1	122	7.20	0.02	0.024	0.06	0.29	4.99
SSD 38	2.00	18.50	30	40.5	114	3.92	0.05	0.014	0.09	0.27	4.97
SSD 39	1.80	20.70	76	42.6	234	4.24	0.22	0.024	0.29	1.67	4.53
SSD 40	2.80	18.60	56	29.1	118	4.19	0.09	0.026	0.1	0.6	5.90
SSD 41	4.40	17.50	29	28.9	168	5.04	0.03	0.021	0.06	0.19	4.40
SSD 42	11.30	20.50	42	28.1	182	11.75	0.02	0.028	0.04	0.11	4.59
SSD 43	2.90	7.20	26	10.8	61	2.03	0.01	0.015	0.02	0.08	4.23
SSD 44	7.30	11.30	53	21.4	107	6.67	0.02	0.031	0.03	0.11	4.30
SSD 45	4.70	11.30	44	17.2	222	3.67	0.04	0.017	0.06	0.31	4.70

The micronutrients are measured in Parts per million (ppm) while the macronutrients are measured in percentages (%).

ements) in the mine spoils is presented in Table 1 and are as follows; Mo (1.60 – 21.50 ppm with an average of 6.19 ppm), Cu (5.00 – 44.90 ppm with an average of 19.15 ppm), Zn (26.00 – 160 ppm with an average of 53.24ppm), Ni (8.80 – 48.70 ppm with an average of 28.84 ppm), Mn (53.00- 395 ppm with average of 165.15ppm), P (0.01 – 0.04% with an average of 0.02%) and K (0.05 – 1.67% with an average value of 0.31%), Fe (1.42 – 13.19% with an average of 6.31%), Ca (0.01 – 0.22 with an average of 0.04%,) and Mg (0.01- 0.29 with an average of 0.071%). For optimum plant growth, these elements are

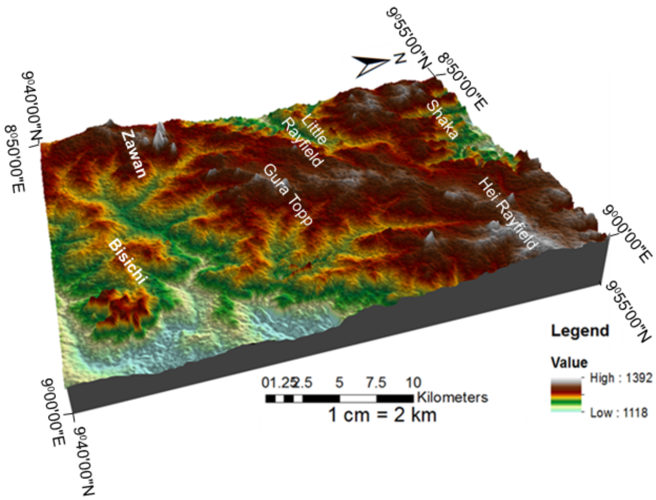

Figure 6. Digital elevation model of the study Area.

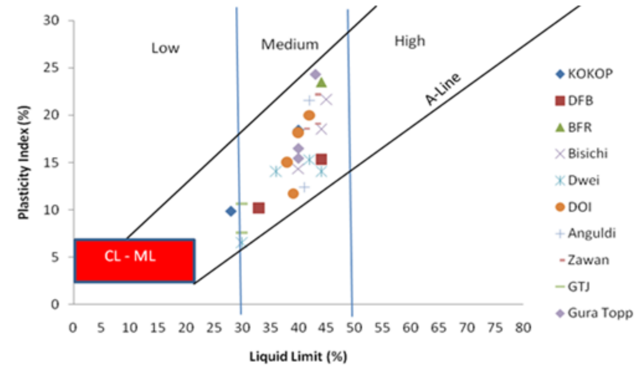

Figure 7. Plasticity chart of soil in the study area.

required in certain concentrations as proposed by Jensen *et al.* [39]. Table 2 below compares the measured concentration of the essential micronutrient and macronutrient elements in the mine spoils with the proposed standards.

The concentration of macronutrient and micronutrient elements of the mine spoils compared with the adequate concentration required by green plants for optimum growth, shows that the soils are enriched in Fe, Mn, Mo, Ni and Zn but deficient in Ca, Mg, P, K and other micronutrients. The high degree of lateralization may be the cause of the high Fe concentration as well as low pH values of the soil. The descriptive statistics of the elements reported in Table 3 indicate that there is no widespread enrichment or deficiency of these (Mn, Mo, Ni, Zn, Ca, Mg, P and K) elements. This supports the findings of Ref. [40], who found shortages in micronutrients such as B, Cu, and Zn as well as exchangeable K and Mg in some soils derived from biotite granites of the Jos Plateau. The shortages of these elements can be attributed to crop removal, leaching, erosion, and the acidic character of majority of the soil. These metals can dissolve in acidic solutions to generate harmful complex concentrations of the elements that may impede plant growth [12, 14–16]. This suggests that to use these soils (mine spoils) for reclamation and subsequently revegetate the land, the fertility of the soil will need to be improved for optimum plant growth and productivity.

4.2. *Geotechnical Characterization*

The geotechnical results for ease of description and discussion are divided into index properties and strength properties.

4.2.1. *Index Properties*

Soil's index properties reveal how soil will behave qualitatively under different kinds of loads. These properties include particle size distribution, liquid limit, Plastic limit and linear shrinkage as summarized and presented in Table 4.

4.2.2. *Atterberg Limits*

The Casagrande plasticity chart (Figure 7), which includes the A-line, is crucial for classifying soils [41]. The liquid limit, plastic limit, plasticity index and linear shrinkage values of the investigated soils ranged from 0 –55%, 18.18–33.33%, 6.47–24.29% and 5.00 – 13.57% respectively. While the average values for the linear shrinkage, plasticity index, plastic limit, and liquid limit are respectively, 38.06%, 15.52%, 15.52%, and 10.33%. The three soil properties of particle size distribution, liquid limit, and plasticity index are then used to categorize the examined soil samples into CL (low plasticity), CI (medium plasticity), and CH (high plasticity). According to Casagrande's chart (Figure 7), all forty-five (45) of the soil samples that were examined are clays of medium or intermediate plasticity.

Atterberg limits and clay content are combined into one parameter to determine the "activity" of clay in the soil [42]. Ratio of the plasticity index and percentage of clay-sized fraction in the soil as shown in Table 4 gives a measure of clay activity which determines the likelihood of the soil to exhibit colloidal behavior and also gives an indication to the mineralogy of clays present in the soils. Fundamentally, the physicochemical qualities of the various constituent minerals and the relative amounts in which they are present influence the properties of clay soils. Activity numbers less than 0.75 indicate that the mineral is inactive, 0.75-1.25 is normal, and larger than 1.25 is active [42]. Activity values between 1 and 2 correlate to illite, activity greater than 2 corresponds to montmorillonite, and activity less than 1 refers to kaolinite. The investigated soils have an average clay activity of 0.90 and ranges from 0.19 to 3.66. Kaolinite and illite have non- expansive lattices, whereas that of montmorillonite is expansive [43]. This is because montmorillonite is characterized by a three-lattice structure that is capable of swelling and shrinking due to its cation exchange properties. The results of the soil investigation shows that kaolinite make up (73.33%) and illite (17.77%) of the clay minerals in the soils and this is found in Kop- Kop, Dunduma, Bisichi, Dwei, one location in Zawan, Gura- Topp, parts of Dura, Anguldi, Kwang and Rayfield. Montmorillonite (8.88%) was also found in some of the soil samples examined, notably in Zawan, parts of Dura

Table 2. Concentration of macronutrient and micronutrient elements in green plants (after Jensen *et al*, 2010) compared with the measured concentration in the mine spoil of the study area.

	Adequate concentration (ppm)	Measured average concentration (ppm)
Macronutrients		
Ca	5000	400
Mg	2000	700
P	2000	210
K	10,000	3,130
Micronutrients		
Cu	100	19.15
Fe	6	6.30
Mn	100	165
Mo	0.1	6.19
Ni	0.05	28.84
Zn	20	53.24

The concentration of some elements measured in percentage was converted to ppm using a factor of 10,000. Also, macronutrients such as N, O, C, H and S are not listed and Cl and B were not investigated.

Table 3. Descriptive statistics of micronutrient and macronutrient element concentration.

	Minimum	Maximum	Mean	Std. Deviation
Mo	1.60	21.50	6.1956	3.79719
Cu	5.00	44.90	19.1578	8.34208
Zn	26.00	160.00	53.2444	26.02635
Ni	8.80	48.70	28.8400	10.13974
Mn	53.00	395.00	165.1556	80.71131
Fe	1.42	13.19	6.3087	2.89756
Ca	0.01	0.22	0.0485	0.03438
P	0.01	0.04	0.0219	0.00665
Mg	0.01	0.29	0.0716	0.04441
K	0.05	1.67	0.3133	0.27428
Ph	3.91	5.90	4.8529	0.44753

and Anguldi. When these soils, particularly those containing kaolinite and illite are used for reclamation and for construction purposes, the incidences of swelling and shrinking leading to structural settlement and collapse may not be experienced, especially when appropriately compacted. However, the same cannot be said of the samples containing montmorillonite.

4.2.3. Grain size distribution

Grain size analysis is important in determining the strength as well as the particle size distribution of soils for engineering purposes [44]. The grain size analyses show that the percentage of clays, silts, sand and gravel ranged from 5.31– 69.66%, 16.90–53.07%, 0.99–58.45%, and 2.10–22.80% while the average composition of clay, silt, sand and gravel is 25.70%, 30.32%, 41.06% and 8.96% respectively. However, the percentage fines (Silt and Clay) range from 28.78 – 99.901% with an average of 56.03%. The clay distribution map is shown in Figure 8. The high clay and silt content of the soil makes it good for mine-out areas to be reclaimed, especially if the reclaimed land is to be planted with new vegetation [8]. This is because of the ability of silt and clay to retain water which is highly needed for plant growth and productivity. Also, reclamation and subsequent occupation of the degraded lands will

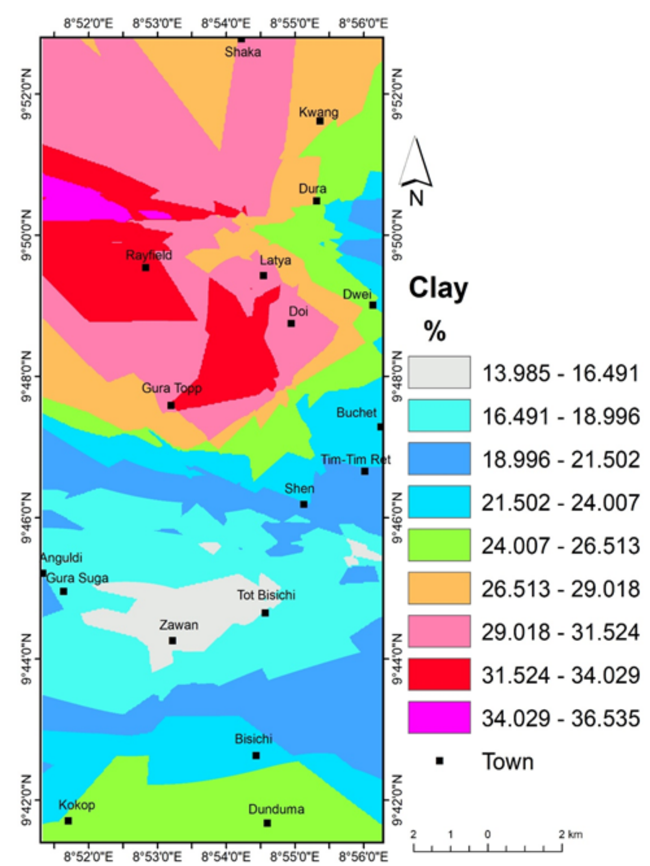

Figure 8. Distribution map of clay content in samples of the study area.

Table 4. Summary of index engineering properties of mine spoils in the study area.

Sample ID	LL (%)	PL (%)	PI (%)	LS (%)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Fine (%)	Activity	Clay type
SSD 1	28	18.18	9.82	7.86	10.5	35.48	33.23	20.79	54.02	0.47	Kaolinite
SSD 2	40	21.58	18.42	10.71	-	19.51	29.16	51.33	80.49	0.35	Kaolinite
SSD 3	44	28.72	15.28	11.43	22.8	30.1	30.65	16.45	47.1	0.92	Kaolinite
SSD 4	33	22.88	10.12	10.00	9.2	27.05	25.91	37.84	63.75	0.26	Kaolinite
SSD 5	44	20.49	23.51	10.71	-	36.1	21.83	42.07	63.9	0.55	Kaolinite
SSD 6	45	23.37	21.63	11.43	-	35.34	43.92	20.74	64.66	1.04	lllite
SSD 7	40	25.66	14.34	11.43	5.6	34.57	30.5	29.33	59.83	0.48	Kaolinite
SSD 8	44	25.54	18.46	11.43	3.69	44.06	28.75	23.50	52.25	0.78	Kaolinite
SSD 9	37	22.47	14.53	7.14	21.89	49.33	20.13	8.65	28.78	1.67	lllite
SSD10	30	23.08	6.92	5.00	20.38	50.82	18.48	10.32	28.8	0.67	Kaolinite
SSD11	55	33.33	21.67	11.43	10.23	50.21	24.61	14.95	39.56	1.44	Illite
SSD12	30	20.94	9.06	9.29	9.1	47.82	27.35	15.73	43.08	0.57	Kaolinite
SSD13	36	21.98	14.02	10.00	4.89	53.77	26.86	14.37	41.23	0.97	Kaolinite
SSD14	42	26.68	15.32	10.71	2.49	49.1	21.86	26.55	48.41	0.57	Kaolinite
SSD15	30	23.53	6.47	10.00	-	49.78	20.47	29.75	50.22	0.21	Kaolinite
SSD16	44	30	14	11.43	2.1	53.55	17.47	26.46	43.93	0.52	Kaolinite
SSD17	40	21.89	18.11	10.71	-	29.79	44.75	25.46	70.21	0.71	Kaolinite
SSD18	39	27.27	11.73	10.71	-	32.08	42.31	25.61	67.92	0.41	Kaolinite
SSD19	38	23.02	14.98	10.71	5.3	58.45	25.99	10.26	36.25	1.46	lllite
SSD20	42	21.98	20.02	10.71	-	25.19	29.73	45.08	74.81	0.44	Kaolinite
SSD21	30	20.34	9.66	9.29	-	26.7	53.07	20.23	73.3	0.477	Kaolinite
SSD22	42	20.42	21.58	10.71	-	41.7	47.63	10.67	58.3	2.02	Montmorillonite
SSD23	41	28.58	12.42	11.43	-	42.27	46.92	10.81	57.73	1.14	lllite
SSD24	43	20.87	22.13	11.43	-	43.86	50.11	6.03	56.14	3.66	Montmorillonite
SSD25	43	23.90	19.10	11.43	-	47.33	47.36	5.31	52.67	3.59	Montmorillonite
SSD26	41	22.42	18.58	10.71	12.36	56.5	19	12.14	31.14	1.53	lllite
SSD27	30	22.47	7.53	9.29	-	38.36	27.71	33.93	61.64	0.22	Kaolinite
SSD28	30	19.41	10.59	8.57	-	33.06	31.12	35.82	66.94	0.29	Kaolinite
SSD29	40	23.54	16.46	10.71	2.46	50.94	24.93	21.24	46.17	0.77	Kaolinite
SSD30	40	24.57	15.43	11.43	-	33.31	21.99	44.70	66.69	0.34	Kaolinite
SSD31	43	18.71	24.29	12.14	-	43.62	22.99	33.89	56.88	0.71	Kaolinite
SSD32	29	18.75	10.25	6.43	-	46.59	16.9	36.51	53.41	0.28	Kaolinite
SSD33	40	20.61	19.39	10.71	-	29.24	19.02	51.74	70.76	0.37	Kaolinite
SSD34	48	23.81	24.19	13.57	-	15.22	23.56	61.22	84.78	0.39	Kaolinite
SSD35	41	21.05	19.95	10.71	-	49.98	29.28	20.74	50.02	0.96	Kaolinite
SSD36	39	21.89	17.11	10.00	-	33.64	41.43	24.93	66.36	0.68	Kaolinite
SSD37	38	20.83	17.17	9.29	-	48.95	24.02	27.03	51.05	0.63	Kaolinite
SSD38	41	25	16	11.43	-	49.12	25.2	25.68	50.88	0.62	Kaolinite
SSD39	35	21.64	13.36	10.00	-	0.99	29.35	69.66	99.01	0.19	Kaolinite
SSD40	42	27.78	14.22	10.71	-	49.27	28.3	44.58	72.88	0.31	Kaolinite
SSD41	31	20.69	10.31	10.00	-	46.8	34.41	18.79	53.2	0.54	Kaolinite
SSD42	40	23.81	16.19	10.71	4.1	51.31	38.32	6.27	44.59	2.58	Montmorillonite
SSD43	31	21.24	9.76	10.00	5.26	57.61	31.02	6.11	37.13	1.59	Illite
SSD44	47	25.66	21.34	11.43	-	49.87	38.8	11.33	50.13	1.88	lllite
SSD45	35	21.89	13.11	10.00	-	49.57	28.2	22.23	50.43	0.58	Kaolinite

LL= Liquid Limit; PL= Plastic Limit; Plasticity Index; LS=Linear Shrinkage

entail provision of critical infrastructure such as roads. Therefore, the mine spoils were evaluated and the data compared to stipulated standards for road construction. Three samples located at Tot Bisichi, Shen, Zawan and Hei-Rayfield meet the Federal Ministry of Works and Housing (FMWH) in Ref. [45] requirement of ≥35% fines for soils to be used as subgrade or sub-base in road construction. The high proportion of fines can be attributed to the weathering of feldspars from granitic parent rocks present in the study area.

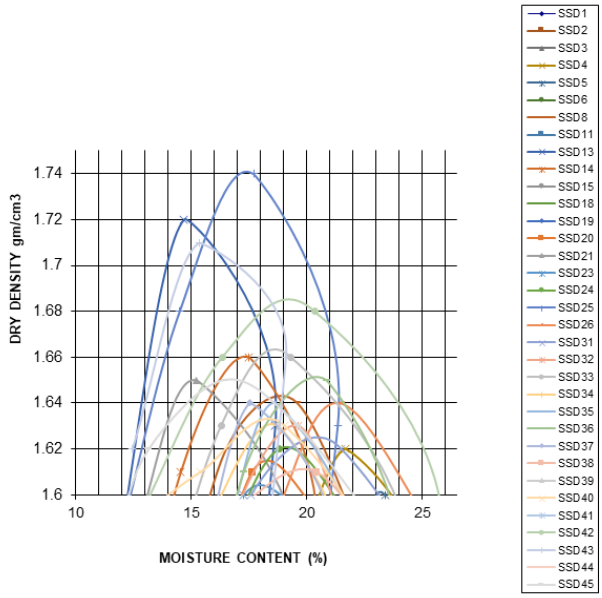

Figure 9. Stacked compaction curve of soil samples with low MDD and high OMC.

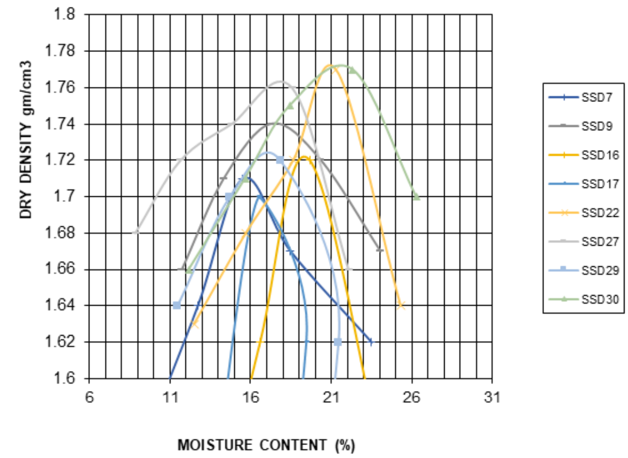

Figure 10. Stacked compaction curve of soil samples with medium MDD and medium OMC.

4.3. *Engineering Properties*

Engineering parameters of soils that can be used to characterize soil's engineering behavior include Compaction, California Bearing Ratio (CBR), shear strength, and permeability. A summary of these properties is presented in Table 5.

4.3.1. *Compaction*

To avoid harmful consolidation under applied stress, soils for construction must be compacted to attend high degree of density [46]. The soils in the study region had a maximum dry density (MDD) that ranged from 1.47 to 1.88 g/cm^3 at an optimum moisture content (OMC) of 10.30 to 24.49%. The compaction curves of the investigated soils have been divided into those of low MDD with high OMC, medium MDD with medium OMC and high MDD with low OMC as shown in Figures 9, 10, and 11.

It can be observed from Figure 9 that most of the soil samples have low maximum dry density (MDD) and high optimum water content (OMC), followed by those with both medium MDD and OMC (Figure 10) and the least samples have high MDD and low OMC (Figure 11). Thirteen (13) representing 28.88% of the samples, exhibit MDD values above the Federal Ministry of Works and Housing (FMWH) [45] minimum value of 1.70 g/cm3, which is required for construction purposes. These samples are located in Bisichi, Doi, Shen, Buchet, Anguldi, Dwei, Zawan,Gura Topp and Hei Rayfield. Unless the soils samples with low MDD and high OMC and those with both medium MDD and OMC are adequately compacted and stabilized to reduce voids, increase strength, and decrease permeability, it is likely that the mine spoils will exhibit low bearing capacities and eventually will not be able to function effectively as construction materials due to their low maximum dry density and optimum moisture content.

This further implies that the soil must be compacted above the MDD and OMC values if it is to provide the best strength, prevent water infiltration, and distribute structural stresses uniformly into the pavement components. The soil will however, support plant development and soil microorganism activity if the degraded lands and mining ponds are to be reclaimed and revegetated because excessive compaction directly inhibits plant growth [8].

4.4. *California Bearing Ratio (CBR)*

The strength of the subgrade of a road or other paved area, as well as the materials used in its construction, are measured by the California Bearing Ratio (CBR) [46]. Infrastructures like roads are essential for the environment and a necessary tool for socio-economic growth and development, therefore, the CBR of the mine spoil was assessed to determine its suitability for use as subgrade or sub-base material if roads are to be constructed on or with the mine soil in the future. The results of the unsoaked California Bearing Ratio (CBR) ranged from 20.20–60.72% with an average of 34.64%. All the soil samples analyzed have CBR values greater than the ≥ 15% recommended for highway subgrade soil material for road construction and none meet the ≥ 80% for use as sub-base road material specified by the Federal Ministry of Works and Housing [45]. If these soils are to be utilized as a sub-base material for road construction, they must be subjected to improvement strategies to acquire the required strength, otherwise the road will experience rapid deterioration leading to economic losses. However, the mine spoils will serve excellently as foundation (subgrade) materials for roads.

4.4.1. *Direct Shear Strength*

One of the most crucial engineering characteristics of soil is shear strength, since it is necessary whenever a structure depends on the soil's shearing resistance [47]. The tested soil's

Table 5. Summary of engineering properties of soils in the study area.

	Shear Strength Test			Compaction Characteristics			
Sample ID	C (KN/M^2)	ϕ (^{0})	ϒ (KN/M^3)	MDD (g/cm^3)	OMC(%)	CBR (%)	Permeability (mm/Sec)
SSD 1	31	14	18.42	1.52	20.28	59.82	$1.29x10^{-3}$
SSD 2	31	13	19.55	1.56	21.71	48.94	$1.80x10^{-3}$
SSD 3	28	15	14.99	1.51	21.38	37.33	$9.95x10^{-4}$
SSD 4	11	18	17.86	1.62	21.66	29.46	$8.52x10^{-4}$
SSD 5	30	15	17.76	1.6	21.74	24.17	$1.35x10^{-3}$
SSD 6	30	14	15.92	1.5	24.17	43.23	$9.34x10^{-4}$
SSD 7	30	14	20.01	1.71	15.51	27.72	$8.62x10^{-4}$
SSD 8	14	19	18.38	1.64	19.58	24.05	$8.90x10^{-4}$
SSD 9	47	10	18.54	1.74	17.28	22.85	$1.08x10^{-3}$
SSD 10	29	15	18.11	1.82	14.19	30.66	$8.99x10^{-4}$
SSD 11	29	13	20.6	1.53	24.49	26.45	$1.05x10^{-3}$
SSD 12	18	18	17.27	1.84	16.52	26.81	$8.66x10^{-3}$
SSD 13	31	15	17.75	1.72	14.69	27.05	$1.35x10^{-3}$
SSD 14	43	13	17.94	1.66	17.5	20.2	$8.28x10^{-4}$
SSD 15	40	12	18.76	1.58	19.93	32.59	$1.10x10^{-3}$
SSD 16	11	15	18.64	1.72	19.66	48.13	$7.48x10^{-4}$
SSD 17	30	10	18.76	1.70	16.46	28.86	$1.08x10^{-3}$
SSD 18	20	12	20.43	1.56	19.7	39.14	$8.59x10^{-4}$
SSD 19	32	10	19.93	1.56	16.26	24.65	$1.09x10^{-3}$
SSD 20	27	10	17.51	1.61	17.63	36.07	$1.07x10^{-3}$
SSD 21	30	11	16.92	1.65	15.22	24.89	$8.18x10^{-4}$
SSD 22	23	11	19.36	1.77	21.3	26.33	$7.36x10^{-4}$
SSD 23	34	10	19.02	1.60	17.28	25.73	$1.12x10^{-3}$
SSD 24	38	10	17.6	1.62	18.8	48.82	$9.53x10^{-4}$
SSD 25	28	11	18.35	1.74	17.7	34.75	$8.32x10^{-4}$
SSD 26	40	10	17.78	1.64	21.48	32.59	$8.62x10^{-4}$
SSD 27	40	10	18.47	1.76	18.6	41.3	$1.20x10^{-3}$
SSD 28	14	14	17.86	1.88	20.06	23.45	$8.49x10^{-4}$
SSD 29	25	10	18.1	1.72	17.8	47.13	$1.62x10^{-3}$
SSD 30	33	10	17.68	1.77	22.33	44.67	$1.28x10^{-3}$
SSD 31	33	10	19.3	1.62	21.48	47.86	$1.14x10^{-3}$
SSD 32	30	10	19.53	1.63	19.64	26.69	$7.52x10^{-4}$
SSD 33	30	11	19.12	1.66	19.29	29.28	$1.29x10^{-3}$
SSD 34	43	9	15.68	1.63	18.73	60.72	$1.28x10^{-3}$
SSD 35	40	10	19.69	1.64	18.55	34.87	$8.60x10^{-4}$
SSD 36	20	12	16.87	1.65	20.85	51.46	$1.29x10^{-3}$
SSD 37	12	15	18.67	1.64	17.53	33.07	$1.28x10^{-3}$
SSD 38	42	15	18.26	1.61	20.41	28.98	$8.24x10^{-4}$
SSD 39	44	10	18.31	1.47	16.77	42.75	$1.40x10^{-3}$
SSD 40	41	10	18.62	1.63	19.02	35.83	$1.25x10^{-3}$
SSD 41	32	11	18.02	1.59	18.81	34.27	$1.73x10^{-3}$
SSD 42	44	9	20.19	1.68	20.34	31.56	$8.60x10^{-4}$
SSD 43	30	11	19.8	1.71	15.33	27.72	$1.30x10^{-3}$
SSD 44	49	10	18.21	1.59	20.56	35.29	$7.64x10^{-4}$
SSD 45	28	12	20.15	1.65	16.45	30.72	$8.67x10^{-4}$

cohesion (C) ranged from 11 to 49 KN/M^2, whereas the angle of internal friction (ϕ) ranged from 9 to 19°. The areas with very low (9- 13^0) angle of internal friction are; Tot Bisischi, Kop–Kop, Tim -Tim ret, Dwei, Doi, Gura -Suga, Anguldi, Zawan, Gura – Top, Latya, Anguldi, Rayfield, Kwang, Hei and Dura. These values demonstrate that the soils (mine spoil) in the study area have low bearing capacity when considered in isolation and cannot withstand greater vertical loads without undergoing excessive deformation or settlement due to their low angle of internal friction values [48, 49]. However, the relatively high

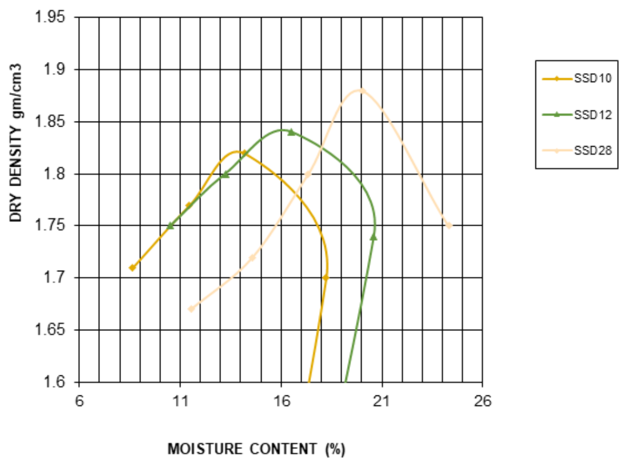

Figure 11. Stacked compaction curve of soil samples with high MDD and low OMC.

values of cohesion may act as additional force that will hold the particles together thereby increasing the resistance to deformation under applied stress and enhancing the stability of the mine spoils. Consequently, this will reduce the incidences of soil erosion and infrastructural collapse when these materials are used for reclamation and construction of massive engineering structures.

4.4.2. Permeability

The coefficient of permeability for the soils ranged from 1.05 x 10^{-3} – 9.95 x 10^{-4} mm/s with an average value of 1.24x10^{-3} mm/s. According to Igwe *et al.* [50], this suggests that the soil is silt to clay and can be categorized as medium to low permeability soil. Zhao *et al.* [51] posited that soils with hydraulic conductivity (k) less than 10^{-4}cm/s (10^{-3}mm/s) are considered to have low permeability. This implies that the mine spoil is inadequately ventilated and has the potential to obstruct the movement and supply of vital nutrients to plant roots as well as the growth of beneficial nitrogen-fixing organisms, which will result in poor plant growth and development when use to restore the degraded mined land. However, due to the poor permeability of the mine spoil, it can be utilized for reclamation as water won't easily seep into the soil and harm the structures built on it.

5. Conclusion

The mine spoils of the Jos- Bukuru tin field has been investigated for the purpose of reclamation of the degraded land caused by many years of unregulated mining of tin and other associated minerals on the Jos - Plateau. The spoils are strongly to moderately acidic and has the potential of retarding the growth and productivity of plants and may also corrode some critical metal infrastructure such as pipes that may be buried underneath the spoils in the future. Some micronutrients and macronutrients that are required for revegetation, which is crucial for the reclamation of degraded areas, are deficient in the soils. The spoil will need to be made more fertile in order for plants to flourish and produce at their best. Kaolinite and illite of intermediate plasticity are the two main clay minerals in the mine wastes, easily compacted, and are also not known to expand or contract when in contact with water. Thus, using these materials for reclamation may not have detrimental effects on geotechnical stability through swelling and shrinking. However, demonstrated by the strength tests (compaction, California bearing ratio, permeability and shear strength), the angle of internal friction, maximum dry density and optimum moisture content need to be enhanced through soil stabilization and strength improvement procedures.

Acknowledgement

The work reported in this paper is a component of an ongoing Ph.D research of the corresponding author at the Department of Geology, University of Nigeria, Nsukka. The main author wishes to sincerely acknowledge the Academic Staff Union of Universities (ASUU) for the grant in support of doctoral thesis offered to me.

References

[1] B. W. Hodder, "Tin mining on the Jos Plateau Nigeria", Economic Geography **35** (1959) 109. https://doi.org/10.2307/142394.

[2] A. O. Omotehinse & B. D. Ako, "The environmental implications of solid mineral mining in Nigeria with a special focus on tin in Jos and coal in Enugu", Journal of sustainable mining **18** (2019) 18. https://doi.org/10.1016/j.jsm.2018.12.001.

[3] S. J. Mallo, *Minerals and Mining on the Jos Plateau*, ACON Publishers, Jos, Nigeria, 2007, pp. 139–152. https://www.scirp.org/reference/referencespapers?referenceid=1484069

[4] M. E. Adiuku-Brown, "The dangers of abandoned mined ponds and lotto on the Jos Plateau", Journal of Environmental Sciences **3** (1999) 258. https://www.researchgate.net/publication/45072354_The_Dangers_Posed_by_the_Abandoned_Mine_Ponds_and_Lotto_Mines_on_the_Jos_Plateau.

[5] J. Abraham, "33 killed in Jos mining site collapse, association say", Punch.com. https://punchng.com/33-killed-in-jos-mining-site-collapse-association-says/ (accessed October 10, 2023).

[6] M. H. Wong, "Ecological restoration of mine-degraded soils, with emphasis on metal-contaminated soils" Chemosphere **50** (2003) 775. https://doi.org/10.1016/s0045-6535(02)00232-1.

[7] A. S. Sheoran, V. Sheoran & P. Poonia, "Rehabilitation of mine-degraded land by Metallophytes", Mining Engineers Journal **10** (2008) 11. https://www.researchgate.net/publication/281422861_Rehabilitation_of_mine_degraded_land_by_metallophytes.

[8] V. Sheoran, A. S. Sheoran, & P. Poonia, "Soil reclamation of abandoned mine land by revegetation: a review", International Journal of Soil, Sediment and Water **3** (2010) 13. http://scholarworks.umass.edu/intljssw/vol3/iss2/13.

[9] S. K. Maiti, "Moef report, an assessment of overburden dump rehabilitation technologies adopted in CCL, NCL, MCL, and SECL mines" (2003). (Grant no. J-15012/38/98-IA IIM).

[10] M. J. Gitt & D. J. Dollhopf "Coal waste reclamation using automated weathering to predict lime requirements" Journal of Environmental Quality **20** (1991) 285. https://doi.org/10.2134/jeq1991.00472425002000010046x.

[11] A. B. Gould, J. W. Hendrix & R. S. Ferriss, "Relationship of mycorrhizal activity to time following reclamation of surface mine land in western Kentucky I Propagule and spore population densities", Canadian Journal Botany **74** (1996) 247. https://doi.org/10.1139/b96-030.

[12] S. K. Maiti & M. K. Ghose, "Ecological restoration of acidic coal mine overburden dumps- an Indian case study", Land Contamination and Reclamation **13** (2005) 361. http://dx.doi.org/10.2462/09670513.637.

[13] N. J. Coppin & A. D. Bradshaw, *The establishment of vegetation in quarries and open-pit non-metal mines*, Mining Journal Books, London, United Kingdom, 1982, pp. 1–112. https://search.worldcat.org/title/quarry-reclamation-establishment-of-vegetation-in-quarries-and-open-pit-non-metal-mines/oclc/9257310.

[14] R. L. Donahue, R. W. Miller &, J. C. Shickluna *Soils: an introduction to soils and plant growth*, Englewood Cliffs (N.J.): Prentice-Hall, c1983 (5th ed.) Prentice-Hall, 1983, pp. 1–234. http://lib.ugent.be/catalog/rug01:000099533.

[15] C. Poschenrieder & J. Barcelo "Phytoremediation: principles and perspectives", Contribution to Science **2** (2003) 333. https://www.researchgate.net/publication/28076724_Phytoremediation_Principles_and_perspectives.

[16] M. Das & S. K. Maiti, "Metal mine waste and phytoremediation: a review", Asian Journal of Water, Environment and Pollution **4** (2007) 169. https://content.iospress.com/articles/asian-journal-of-water-environment-and-pollution/ajw4-1-19.

[17] J. M. Nicolau, "Runoff generation and routing in a Mediterranean-continental environment: the Teruel coalfield, Spain", Hydrological Processes **16** (2002) 631. https://doi.org/10.1002/hyp.308.

[18] M. Moreno-de las Heras, J.M. Nicolau, & M.T. Espigares, "Vegetation succession in reclaimed coal mining sloped in a Mediterranean-dry environment", Ecological Engineering **34** (2008) 168. https://doi.org/10.1016/j.ecoleng.2008.07.017.

[19] Z. Hu, R. D. Caudle & S. K. Chong, "Evaluation of farmland reclamation effectiveness based on reclaimed mine properties", International Journal of Surface Mining Reclamation and Environment **6** (1992) 129. https://doi.org/10.1080/09208119208944327.

[20] S. K. Maiti & N. C. Saxena "Biological reclamation of coal mine spoils without topsoil: an amendment study with domestic raw sewage and grass-legumes mixture", International Journal of Surface Mining, Reclamation and Environment **12** (1998) 87. https://doi.org/10.1080/09208118908944028.

[21] M.K. Ghose, "Soil conservation for rehabilitation and revegetation of mine-degraded Land", TIDEE – TERI Information Digest on Energy and Environment **4** (2005) 137. https://www.osti.gov/etdeweb/biblio/20638669.

[22] A. N. Singh, A. S. Raghubanahi & J. S. Singh, "Impact of native tree plantations on mine spoil in a dry tropical environment" Forest Ecol. Management **187** (2004) 49. https://doi.org/10.1016/S0378-1127(03)00309-8.

[23] A. N. Singh & J. S. Singh, "Experiments on ecological restoration of coal mine spoil using native trees in a dry tropical environment, India: a synthesis", New Forests **31** (2006) 25. https://doi.org/10.1007/s11056-004-6795-4.

[24] L. D. Rimmer & A. Younger, "Land reclamation after coal-mining operations" In: *Contaminated Land and its Reclamation*, Hester, R.E., Harrison, R.M. (Eds), Thomas Telford, London, 1997, pp. 73-90. https://doi.org/10.1039/9781847550637-00073.

[25] P. Mamata & K. P. Amiya, "Assessment of physicochemical properties influencing mine spoils genesis in chronosequence iron mine overburden spoil and implications of soil quality", International journal of current microbiology and applied science **4** (2015) 1096. https://www.ijcmas.com/vol-4-6/Mamata%20Pasayat%20and%20Amiya%20Kumar%20Patel.pdf.

[26] D. D. Dabi & J. L. Nyagba, "An Alternative Approach to Reclamation of Mine Lands on the Jos Plateau", Nigeria Journal of Environmental Sciences **3** (1999) 245. https://www.researchgate.net/publication/45072352.

[27] S. J. Mallo & H. N. Wazoh, "Reclamation of Abandoned mine-out Areas of Bukuru Rayfield", IOSR International journal Environmental Science, Toxicology and food technology **8** (2014) 32. http://dx.doi.org/10.9790/2402-08212534.

[28] J. D. Falconer, *The Geology and Geography of Northern Nigeria*, Macmillan: London, UK, 1911, pp. 147–154. https://searchworks.stanford.edu/view/1132648.

[29] J. D. Falconer "The Geology of the Plateau Tin Fields", Bull. Geol. Surv. Nigeria **1** (1921) 477. https://doi.org/10.1017/S0016756800109343.

[30] W. N. Macleod, D. C. Turner & E. P. Wright, *The geology of the Jos plateau : explanation of 1:100,000 sheets nos. 147, 148, 168, 169, 189 and 190*, General Geology Geol. Surv. of Nigeria, Lagos, Nigeria, 1971, pp. 109–110. https://nla.gov.au/nla.cat-vn216693.

[31] US, EPA *Environmental Response Team. Standard Operating Procedures*, USA, 2012, pp. 1-13. https://archive.epa.gov/region9/toxic/web/pdf/epa-ert-soil-sop-2012.pdf.

[32] British Standard 1377 Part 2 "Standard Methods of testing soils for civil engineering", British Standard Institution, London (1990). https://webstore.ansi.org/standards/bsi/bs13771990-1314235?.

[33] ASTM D (6913)- 04, "Standard methods for particle size distribution (Gradation) of soils using sieve analysis", ASTM international, West Conshohocken **04** (2009) 34. https://webstore.ansi.org/standards/astm/astmd691304.

[34] R. C. Bruce & G. E. Rayment, *Analytical methods and interpretations used by the agricultural chemistry branch for soil and land use surveys*, Queensland Dept. of Primary Industries, Brisbane, 1982, pp. 1–10. https://geoscience.data.qld.gov.au/data/report/cr042276.

[35] T. J. K. Ideriah & S. A. Abere, "Physico-chemical properties and selected heavy metals in tin mine spoils around Jos, Plateau State", International Journal of Environmental and Agricultural Research **3** (2017) 59. http://dx.doi.org/10.25125/agriculture-journal-IJOEAR-AUG-2017-8.

[36] A. O. Owolabi, Z. O. Opafunso & L. Lajide,"Geochemical evaluation of waste and soil samples around cassiterite mine sites in Plateau State, Nigeria", International Journal of Science and Technology **6** (2017) 808. https://www.researchgate.net/publication/329144056.

[37] E. A. Olowolafe, "Soil Parent material and properties in two separate catchment areas on the Jos Plateau, Nigeria", Geo. J. **56** (2002) 201. https://doi.org/10.1023/A:1025158121610.

[38] A. V. Barker & D. J. Pilbeam, *Handbook of plant nutrition*, CRC press, Boca Raton, 2007, pp. 3–18. https://doi.org/10.1201/b18458.

[39] R. Jensen, S. F. Wolf, S. Brake & F. W. Bekker, "Chemical element concentration in black locust (Robinia Pseudoaccacia L.) and green ash (Fraxinus Pennylvanica Marsh.) leaves at the reclaimed green valley coal mine, Indiana, U.S.A", Environmental Earth Sci. **60** (2010) 1391. http://dx.doi.org/10.1007/s12665-009-0275-2.

[40] E. A. Olowolafe & J. E. Dung," Soils derived from biotite granite on the Jos – Plateau, Nigeria:nTheir nutrient status and management for sustainable agriculture", Resource and conservation recycling **29** (2000) 231. https://doi.org/10.1016/S0921-3449(00)00043-4.

[41] A. Casagrande, "Classification and identification of soils", Transactions of the American Society of Civil Engineers **113** (1947) 783. https://doi.org/10.1061/TACEAT.0006109.

[42] A. W. Skempton, *The colloidal "activity" of clays* In: Proceedings of 3rd international conference of soil mechanics, Zurich, 1953, pp. 57–61. https://www.issmge.org/uploads/publications/1/42/1953_01_0014.pdf.

[43] F. G. Bell, *Engineering Geology*, Linacre House, Jordan Hill, Oxford OX2 8DP, UK, 2007, pp. 1–207. https://shop.elsevier.com/books/engineering-geology/bell/978-0-7506-8077-6.

[44] C. S. Naresh & P. E. Nowatzki, "Soils and foundations", Ref. Man. Fed. Highway **2** (2006) 8. https://rosap.ntl.bts.gov/view/dot/53656.

[45] Federal Ministry of Works and Housing (FMWH) "General specifications for roads and bridges", Federal Government of Nigeria, Lagos, Nigeria, 1997, pp. 1–71. https://worksandhousing.gov.ng/themes/front_end_themes_01/images/uploads_images/1569352815.pdf.

[46] O. O. Olofinyo, O. F. Olabode, & I. O. Fatoyinbo. "Engineering properties of residual soils in part of Southwestern Nigeria: implication for road foundation", SN Appl. Sci. **1** (2019) 507. https://doi.org/10.1007/s42452-019-0515-3.

[47] B. T. Kamtchueng, V. L. Onana, W. Y. Fantong, A. Ueda, F. D. R, Ntouala, H. D. M. Wongo, B. G. Ndongo, N. A. Ze, K. B. V. Kamgang, & J. M. Ondoa, "Geotechnical, Chemical and Mineralogical evaluation of lateritic soils in the humid tropical area (Mfou, Central Cameroun): implications for road construction", International Journal of Geo-Engineering **6** (2015) 1. https://doi.org/10.1186/s40703-014-0001-0.

[48] A. O., Oladele, J. O, Olusola & T. A. Emmanuel, "Engineering properties of lateritic soils around Dall Quarry in the Sango area, Ilorin, Nigeria", Earth Sci Res **1** (2012) 71. http://dx.doi.org/10.5539/esr.v1n2p71.

[49] D. A. Alao & S. T. Opaleye, "Geotechnical analysis of slope failure of a kaolin quarry at Kura, Jos North-Central". Int J Sci Res **1** (2011) 87. http://www.jmess.org/wp-content/uploads/2019/04/JMESSP13420449.pdf.

[50] O. Igwe, W. Mode, O. Nnebedum, I. Okonkwo & I. Oha, "The analysis of rainfall induced slope failure at the Iva Valley area of Enugu

State", Environ. Earth Sci. **71** (2013) 2465. https://doi.org/10.1007/s12665-013-2647-x.

[51] S. Zhao, J. Zhang & S. Feng, "The era of low-permeability sites remediation and corresponding technologies: a review", Chemosphere **313** (2023) 137264. https://doi.org/10.1016/j.chemosphere.2022.137264.