CHARACTERIZATION AND EVALUATION OF MAGNESITE TAILINGS FOR THEIR POTENTIAL UTILIZATION: A CASE STUDY OF NYALA MAGNESITE MINE, LIMPOPO PROVINCE OF SOUTH AFRICA

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ABSTRACT

Magnesite has many uses and these include the preparation of cement, decolouring agents, fertilizer, animal feed, and its use in refractory and refractory products. Extraction of magnesite generates huge amount of waste such as tailings and spoil materials. These magnesite tailings are generally inert and therefore their possible uses can be identified and evaluated. The main objective of this study was to characterize and evaluate the tailings of the derelict Nyala Magnesite Mine for their potential uses. This involved physical and chemical characterization of the materials and determining general geometry, volume, and area coverage of the waste dumps. These tailings dumps were found to be highly eroded and the total volume and area coverage were 953862 m^3 and 102713 m^2, respectively. Based on laboratory analyses the tailings were classified as well-graded sand with $C_u \geq 6$ and $1 \geq C_c \leq 3$. The physic al properties of the tailings were compared with those of the soils used as fill material in foundation and/or road construction and river-sand used for different engineering purposes. The filling material possessed the same properties as tailings and was also classified as well-graded sand whilst the river sand was classified as poorly-graded with $C_u \leq 6$ and/or < 3. In addition, the tailings material has the plastic index of 19 and composed of high silica level (±43.32% SiO_2). Based on the determined engineering properties of tailings and the fact that they are characterized by high SiO_2 content, it was concluded that they are suitable for use in different engineering works requiring well-graded soils with medium plasticity, medium dry strength and medium swelling potential. It was recommended that the local community use this material for different engineering applications as it will contribute in cleaning up the environmental impacts of the historic Nyala Mine. This will also have socio-economic benefits as it will improve the aesthetic appearance of the landscape, convert mine tailings into useful resources and provide an alternative for river-sand used in various construction works. Moreover, it will eliminate or reduce the environmental and socio-economic impacts of excavating construction soils from borrowed pits.

Keywords: magnesite tailings, tailings characterization, 3D terrain modeling, abandoned mines, nyala mine.

INTRODUCTION

The northern region of Limpopo province of South Africa is in abundance of magnesite deposits. This raw material is mined for various utilities in different parts of the region. Some of the known magnesite mines in this area include Sytfafontain (still operational), Vanmag and Nyala Mine (both abandoned). The abandoned Nyala Magnesite Mine is situated 5 km west of Klain Tsipise in the village of Zwigodini.

According to Strydom (1998), the main magnesite body at Nyala Mine occupies an area of 1060 by 200 m and it occurs up to the depth of about 200 m. The deposit is amorphous in nature and is hosted by metamorphosed ultrabasic and calcareous rocks of the Mobile Belt (Herzberg, 1976). It constitutes about 12% magnesite (The Mineral Potential and Mining Development in the Black Homelands of South Africa, 1977 and Strydom, 1998). Mining of magnesite in the area was carried out by surface mining method in which the ore body was quarried by means of heavy equipment and hand sorted into a product that contains up to 98% $MgCO_3$ (Strydom, 1998).

Magnesite mining at Nyala Mine left two large volume unrehabilitated tailing dumps; spoil materials and hazardous excavations (Mhlongo, 2012). The recent growth and expansion of the village towards the mined out areas justify the need for rehabilitation of the derelict Nyala mine site. In the process of making decisions on the appropriate options of cleaning up the abandoned minesite, there is a need for evaluation of the abandoned mine features for their possible alternative uses. The main purpose of this study was to characterize and evaluate the potential utility of magnesite tailings material of the abandoned Nyala mine site.

LITERATURE REVIEW

The derelict Nyala Mine site is generally characterized by extremely rugged terrain due to the presence of extensive excavations (denoted as Pit-I to V), two large volume tailings (Tailing-A and B) as well as spoil materials scattered all over the mine site (see Figure-1). These features are the major sources of both physical and environmental impact in the area (Mhlongo, 2012; Mhlongo *et al*., 2013).

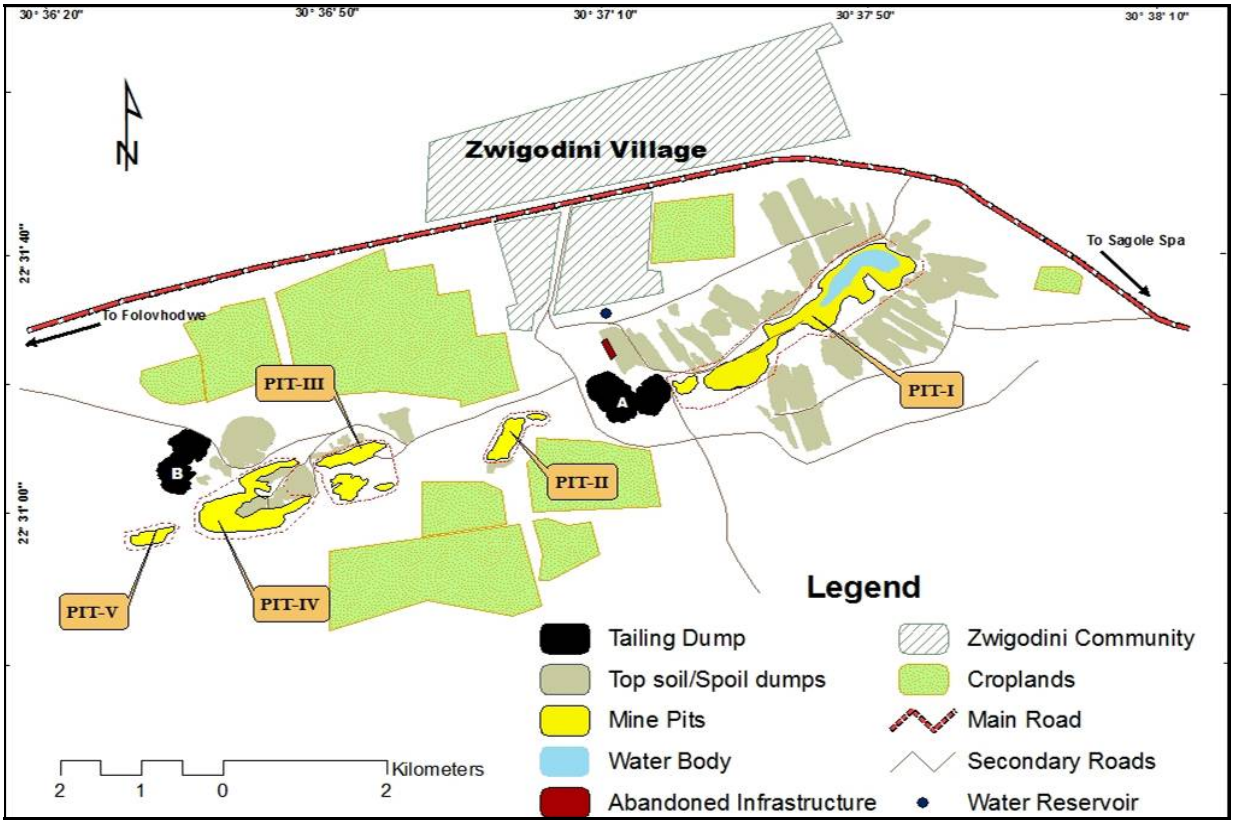

Figure-1. Layout of existing features of abandoned Nyala Mine (from Mhlongo, 2012).

Magnesite mining

The magnesite deposits of South Africa are generally mined by open pit mining method at a relatively high stripping ratio (Cardavelli, 2008). According to Wicken (1990), open pit mining method is highly adopted where the ratio of waste and overburden to ore is moderate. The country has only two operating magnesite mines, namely; Strathmore Mine and Syferfontein Mine in the vicinity of Malelane and Folovhodwe village, respectively. In both mines, magnesite extraction is by surface mining methods (Ratlabala, 2003).

Magnesite deposits around Folovhodwe area are suitable for artisanal mining due to the fact that they occur as soft clay-like matrix above the water Table (Paul *et al.*, 1997). The geological setup of these deposits and their host rock make their extraction possible without blasting; consequently excavators were used at Nyala Mine to remove the top soil and to expose the magnesite seams to the collectors who gathered the materials in piles. The collected ore is normally processed in small-scale processing plants constructed near the mine site to yield magnesia products. Some degree of sorting is applied to the ore prior to heat treatment (Kogel *et al*., 2009).

Processing of magnesite ore

The simplified unit operations in magnesite processing can be divided into crushing, sizing and washing (Shand, 2006 and Cardavelli, 2008). The mined magnesite is normally hand-cobbed by the work force of about 25 to 30% of the total labor. The hand-sorting includes trimming of the ore from siliceous impurities and of remnant of serpentine that adhere to the magnesite. However, the ore is furthermore broken up into lumps of the required sizes (Paul *et al*., 1997). This is done due to the fact that some magnesite uses require that magnesite products be of a specific size. For example gas works require magnesite grains that range between 50.8 to 101.6 mm in diameter (Cardavelli, 2008).

The final stage in magnesite processing is calcination which is the process of converting magnesite into magnesite oxide by means of burning it in batch kilns erected near the mine site. According to Paul *et al.* (1997), two methods of magnesite calcinations were used at Venmag Magnesite Mine found in the vicinity of Tshipise magnesite field. The first method included firing of kilns filled with washed and upgraded material with coal, while the second method included the labour intensive primitive method mostly used in bricks firing. In the second method, magnesite and coal were piled in layers into a box-shaped heap and sealed with clay prior to the ignition at the bottom of the heap.

METHODS AND MATERIALS

The characterization of magnesite tailings of the abandoned Nyala Mine started with quantifying the dumps in terms of the volume of the material that make up the dumps and the general dumps geometry. The physical properties of the tailings materials were established at the laboratory using different techniques. These involved grain size analysis, carrying out atterberg limits tests and pH determination. The analysis of major element concentration in the tailings materials was also conducted.

Tailing dumps quantification

In order to quantify the dumps with precision, terrain model representing the two magnesite tailings dumps of the Nyala Mines were constructed. The development of the tailing dumps models required that several (x, y, z) coordinates are collected across the tailing dumps and that was accomplished through the use of RTK-GPS system. The system provides the point accuracy of up to ±2 cm horizontal and ±4 cm vertical. For accurate readings, the base and rover of the GPS were set at 15° and 10° elevation muck respectively. The base was localized to Lwandze trig station (-22.55431S; 30.6949E and the height of 633.6) found approximately 3 km away from the mine site. The survey points were then collected at every 1 to 2 m vertical intervals along the traverse lines designed to be at 15 m apart from each other.

The model of the dumps were created by feeding the height data into Suffer11® software and the data was manipulated using the triangulation with linear interpolation technique. The volume of material making up the dumps was estimated as an average of the volume calculated using extended Trapezoidal rule, extended Simpson's rule and Simpson's 3/8. The accuracy of the estimate was determined by the difference between the volumes computed using the three volume determination methods.

Grain size distribution analysis

The main purpose of carrying out particle size analysis was to classify the tailings material into standard particle size classes and determine their texture. Particle size analysis was carried out by passing soil through a stack of sieves placed on a mechanical shaker. The sieves were shaken for 1 hour. It also worth mentioning that the sieves were nested in an order in which the coarsest (4 mm) is at the top and the pan at the bottom. Prior to sieving, the soil samples were dried for 12 hours at 110˚C using the VACUTEC drying oven.

Material retained in each sieve was weighed and expressed as a percentage of the whole sample. The results of sieve analysis expressed as percentage passing were plotted using Dplot® Software on the logarithmic graph. From the plotted gradational curves, the coefficient of uniformity (C_u) and curvature (C_c) were calculated using equation 1 and 2.

$$C_u = \frac{D_{60}}{D_{10}} \tag{1}$$

$$C_c = \frac{D_{30}^2}{D_{10} \times D_{60}} \tag{2}$$

where: D_{10} is grain size corresponding to 10% passing, D_{30} is grain size corresponding to 30% passing, and D_{60} is grain size corresponding to 60% passing.

The materials used for different engineering purposes, namely; river sand (used mostly for making of bricks and construction purposes in the area) and the material used for road and foundation filling purposes were also analyzed for comparison purposes.

Atterberg limits tests

The purpose of carrying out the Atterberg limits tests was to determine the basic nature of fine-grained fractions of the tailings material. The Atterberg limits determined the boundaries between different states of fine grained soils. The different states in clay are liquid, plastic, semisolid and solid.

Liquid limit tests

The liquid limit property of the fine-grained fraction of the samples was tested using of liquid limit device (Casagrande), grooving tool, water bottle, mixing dishes, spatula, and the drying oven. The procedure of testing the liquid limit of the spacimens began with calibration and cleaning up of the Casagrande equipment. The calibration involved setting of the drop of the cup to a consistency drop height of 10 mm. Water was added on the dry sample spacimen in the dish to increase its moisture level. The moist sample was placed on the Casagrande's cup and smoothened to the maximum depth of 8 mm. The groove was cut at the centre line of the sample in the cup and the device was cranked at 2 revolutions per second until the two halves of the soil pat come into clear contact of about 13 mm long at the bottom of the groove. The number of blows (N) that caused the closure was recorded. The sample in the pat was collected weighed together with the can, labeled and dried in the oven at 110°C for more than 6 hours. The weight of the dried sample was also determined. The trial was repeated 3 times in different moisture content, producing successively lower numbers of blows to close the groove, which were blows between 25 to 30, 20 to 30 and 15 to 25. The number of blows in each trail was plotted against the water content and the best-fit straight line through the plotted points was constructed for which the liquid limit (LL) was determined as the water content at 25 blows.

Plastic limit tests

The plastic limit (PL) of soil is generally the water content at which the soil begins to crumble when rolled into a thread of 3 mm in diameter. This was tested by taking 3 ellipsoidal-shaped masses of the sample and rolling them using a plastic limit device with a calibrated opening of 3.18 mm until the soils crumbles. The crumbled soil was collected and weighed, dried and weighted again for water content determination. Prior to weighing the moist soil and the can, the mass of the can was determined separately. Three trails of the test were performed as well. In both liquid limits and plastic limit the water contents were determined using equation (3).

$$\text{Water content (w\%)} = \left(\frac{W_2 - W_3}{W_3 - W_1}\right) \times 100 \tag{3}$$

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where: W_1 is the mass of the can, W_2 is the mass of the can plus wet soil, and W_3 is the mass of the can plus dry soil.

The plastic index of magnesite tailings was then calculated using equation (4).

$$\text{Plasticity Index} = LL - PL \quad (4)$$

Major oxide analysis

The concentration of oxides in tailings was detected in the laboratory using X-ray fluorescence spectrometer (XRF). The tailings samples were prepared to allow direct XRF analysis on solid powdered spacimen. This made the sample preparation process simpler and more accurate without the risk of contamination. The procedure for samples preparation involved milling of the tailings material to the fraction less than 75 µ. The Retsch RS 200 vibratory disk milling machine set at 1500 min^{-1} motor speed for 5 minutes was used.

The milled spacimen was then roasted at 1000 °C for at least 3 hours to oxidize ion (Fe^{2+}) and Sulfur (S). This was also done to determine the Loss on Ignition (L.O.I) of the samples. For the analysis of major oxides by XRF required the preparation of glass disks. This was prepared by fusing 1 g roasted sample and 8 g (12-22) flux consisting of 35% alkali borate ($LiBO_2$) and 64.71% lithium tetraborate ($Li_2B_4O_7$) at 1050 °C. The glass disks were then analyzed by a PAN analytical Axios X-ray fluorescence spectrometer equipped with a 4 kW Rhodium (Rh) tube.

Tailings pH and EC determination

The determination of tailings pH required that the slurry is prepared using the homogenized tailings sample and deionizered water. The stainless riffle splitter was used to split and reduce the homogenized samples to a fraction less than 50 g. The content of one bin of the splitter was placed aside while the other content was passed through the chutes of the splitter until the required size of the sample was obtained.

The sample slurry was prepared by adding 20 ml of deionizered water to the 20 g scoop of the sample in the beaker. Each sample was vigorously stirred for 15 minutes with a glass stirring rod and let to stand for 30 minutes. The pH meter was calibrated over the appropriate alkaline range of 7.00 to 9.00 using the buffer standard solution. The pH and electrical conductivity (EC) rods were them immersed into the beaker with slurred samples. The pH of the tailings and its corresponding EC were then recorded from the pH meter and the electrical conductivity meter respectively.

RESULTS AND DISCUSSIONS

The historic Nyala Mine site has two large-volume tailing dumps (denoted as Tailing-A and Tailing-B) and several spoil dumps. The estimated volumes of Tailing-A and Tailing-B were 385699 m^3 and 568163 m^3 respectively. The total area covered by magnesite tailings dumps at Nyala Mine was found to be 102713 m^2. The slope angles of the tailing dumps was measured and found to be ranging between from 30° to 35°. The average estimated height of Tailing-A and B were found to be 27 m (above 495 m level surface) of and 28 m (above MSL the level surface of 490 m), respectively. The results of volume computations for both tailing dumps are presented in Table-1 and the general geometry of the dumps are shown by the terrain models in Figure-2.

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Table-1. The result of tailing dumps volume computations.

Tailing-A	**Calculated tailing volume** (m^3)			**Total volume** (m^3)
Selected level surface (z)	**Trapezoidal**	**Simpson's**	**Simpson's 3/8**	
495	279989	279185	279170	279448
	Cut volume	Fill volume	Net volume [Cut-Fill]	
	385699	105710	279989	
Planar areas (m^2)				
	Area - cut	Area- fill	Blanked planar area	Total planar area
	39163	30542	26161	95865
Surface areas(m^2)				
	Cut surface area	Fill surface area		
	42310	31414		
Tailing-B	**Calculated tailing volume** (m^3)			Total volume (m^3)
Selected level surface (z)	Trapezoidal	Simpson's	Simpson's 3/8	
490	534376	534283	533686	534115
	Cut volume	Fill volume	Net volume [Cut-Fill]	
	568163	33787	534376	
Planar areas(m^2)				
	Area - cut	Area- fill	Blanked planar area	Total planar area
	63550	10987	39072	113609
Surface areas(m^2)				
	Cut surface area	Fill surface area		
	68666	13184		

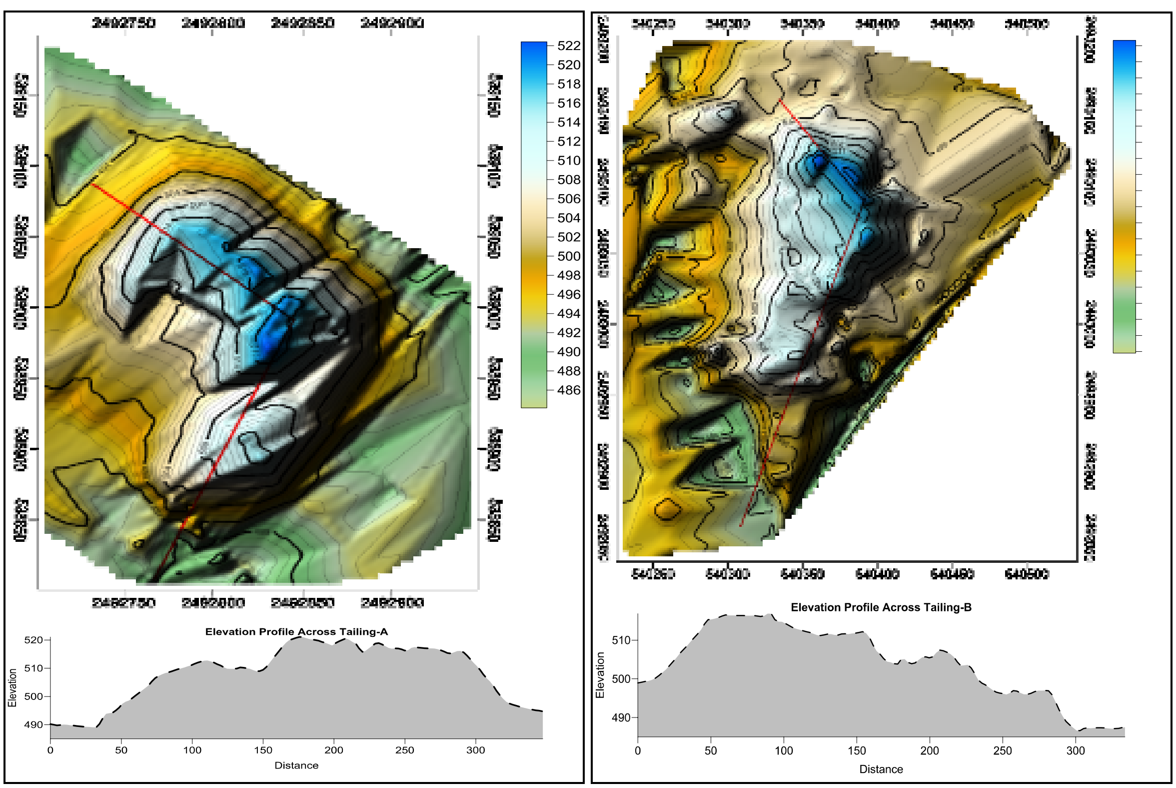

Figure-2. 3D representation of both Tailing-A and B.

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It was observed during the field visit that the surfaces of the tailings dumps are characterized by deep and wide gully formation as a result of extensive erosion and rapid run-off reoccurrence during rainy seasons. The maximum width and depth of the gullies on the dumps were measured to be 8 and 6 m, respectively.

Physical classification of tailings

The physical characterization of magnesite tailings was carried out in order to establish their physical properties in terms of their grain size distribution. Comparison of the tailings with other materials used for engineering purposes (river sand and fill materials in road and foundation construction) was also performed. The plotted gradational curves of the three materials indicated that these materials are generally comprised of more or less similar particles. The similarity of grain particles comprising these materials is shown by their gradational curves steeply lying within the same range of particles sizes (that is between 0.03 µm to 4 mm) as depicted in Figure-3. Comparatively, river sand curve showed the material to be poorly- or uniformly-graded sand as the curve is relatively steeper within the sand fraction of the grain size distribution curve. Generally, gravels and sands are desirable soils for use as foundation under roads and buildings. This is due to the fact that they have good drainage characteristics, acceptable low to medium shrink-swell potential; they have good strength and resistance to frost actions (Threlkeld and Feenstra, 1974).

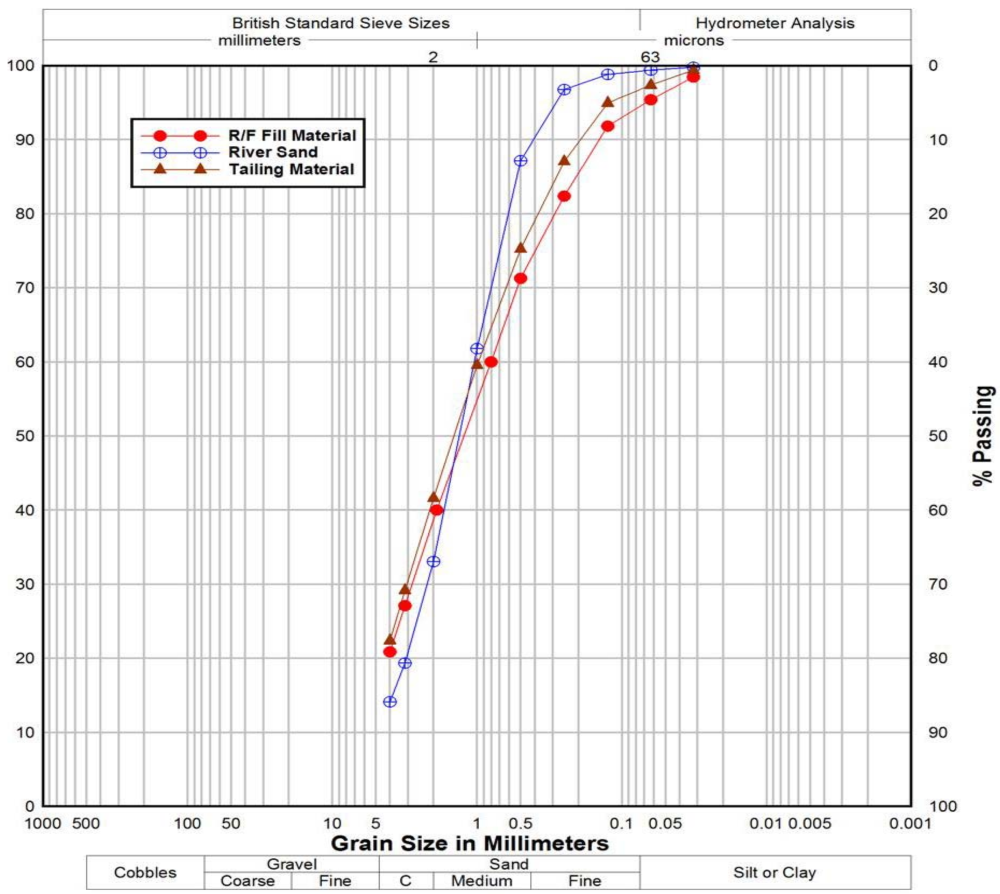

Figure-3. Grain size distribution curve of tailings, sand and fill material.

According to the Unified Soil Classification System (USCS), the tailings material as well as the road-and-foundation filling materials can be classified as well-graded sands; while the river sand used most commonly for block/bricks making was found to be falling into the class of poorly-graded sands (see Table-2). The determined C_u value for both tailings and foundation-and-road construction material was found to be greater than 6 and it corresponding C_c was less than 3. These results justified the classification of these materials as well-graded sands. On the other hand, the C_u and C_c values for river-sand were found to be less than 6 and equal to 1 respectively. River-sand was therefore classified as poorly-graded sand.

Comparing both tailings and road-and-foundation construction materials with river-sand, both materials were found to be composing of relatively less percentage of sand and slightly high gravel and silt plus clay particles.

Table-2. Physical properties of tailings and the material used for different engineering purposes.

Materials						Soil composition			USCS
	D_{10}	D_{30}	D_{60}	C_u	C_c	Gravel (%)	Sand (%)	Silt and clay (%)	♠Class
Road and foundation fill	0.1	0.5	2.1	18	1	39	53	8	SW
River sand	0.4	0.8	1.7	4	1	33	66	1	SP
Tailing dump	0.2	0.6	2.1	11	1	43	53	5	SW

♠SW is well-graded sand and SP is poorly-graded sand

Atterberg limit tests results

The determined average plastic limit (PL) and liquid limit (LL) of the tailings material was found to be 49 and 68, respectively. Based on these results, the plastic index of this material was found to be 19. According to the plastic index classification of soils by Sower (1979) as shown in Table-3, it can be deduced that the tailings material is classified as being of medium plasticity, medium dry strength and difficult to crush with finger. It can be also deduced from the determined PI that the tailings have medium swelling potential (Murthy, 2003).

Table-3. Characteristics of soils with different plasticity indices (Sowers, 1979).

PI	Classification	Dry strength	Visual Identification of dry sample
0 - 3	Non-plastic	Very low	Falls apart easily
3-15	Slightly plastic	Slight	Easily crushed with fingers
15-30	Medium plastic	Medium	Difficult to crush with fingers
> 30	Highly plastic	High	Impossible to crush with fingers

Chemical composition of tailings

The major element analysis indicated that tailing materials are characterized by high percentage of SiO_2. The average concentrations of major oxides in tailings are presented in Table-4. Other oxides present in these material includes Cr_2O_3, MnO, and Na_2O, respectvely contributing less than a percent of the composition. In addition, about 13.70% of the composition was found to be corresponding the Loss on Ignition (L.O.I) properties of the material. The pH analysis of magnesite tailings revealed that the material is generally alkaline with the pH value of ±8.5. The measured EC of this material was found to be ±738 µS/cm.

Table-4. Chemical characteristics of tailing materials.

Composition	Concentration (%)
SiO_2	43.32
TiO_2	2.22
Al_2O_3	3.99
Fe_2O_3(t)	11.43
MnO	0.15
MgO	20.56
CaO	3.74
Na_2O	0.12
K_2O	0.42
P_2O_5	0.15
Cr_2O_3	0.20
L.O.I.	13.70
Total	100.00

CONCLUSIONS

This study revealed that Nyala Mine consists of about 953862 m^3 volume of tailings that occupies the total planer area of 102713 m^2 of the mine. Based on this finding it was deduced that there is sufficient amount of tailings that can be converted into useful resources if their alternative uses are identified and realized by the nearby communities.

The USCS showed that the tailings material is well-graded sand similar to the soils used in road and foundation filling and comparable to river sand classified as poorly-graded sands. Based on the results of sieve analysis; PL classification; and the fact that the tailings material contains 43.32% silica, it was concluded that magnesite tailings at Nyala Mine are suitable for use in different engineering works requiring well-graded soils with medium plasticity and dry strength, and medium shrink-swell potential.

The use of this material for various engineering work by the nearby communities is highly recommended as this will contribute in cleaning-up the negative legacy of magnesite mining in the area while improving the aesthetic beauty of the environment, and converting mine tailings into useful resources by provide an alternative for river-sand used in various construction works. This will also reduce the environmental and socio-economic impacts that can arise when construction soils are obtained from the borrowed pits.

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