Stabilization of gold mine tailings: The effect of hydrated lime on the unconfined compressive strength

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Abstract. Stabilization of gold mine tailings for application in the building and construction industry, provides a significant solution to the shortage of building and construction materials for the country's growing population. The use of gold mine tailings in the production of building blocks / bricks, is examined in this study. The tailings used in the study were characterized by having an optimum moisture content (OMC) of 14.92% and a maximum dry density (MDD) of 1 757 kg/m^3. The specimens were cured at a temperature of 80°C and hydrated lime was added as a stabilizing additive to enhance the chemical and geotechnical properties of the material. The use of lime as a stabilizing additive was successful in increasing the unconfined compressive strength (UCS) of the material. UCS was improved from 0.04MPa to a maximum strength of 3.02MPa. As far as the UCS is concerned, the optimum tailing: lime was obtained at a ratio of 70:30 and the produced material is suitable as masonry.

1 Introduction

In large volumes, materials considered as wastes or by-products are generated by numerous industrial activities and most are disposed into a sensitive environment [1]. South Africa is a mineral rich country, by far the most gold that has been mined in South Africa (98%) has come from the Witwatersrand goldfields [2]. The gold mines in this area are situated around an ancient sea, where the age of uraninite grains provide valuable evidence in the old placer-hydrothermal controversy regarding the origin of gold and uranium mineralization [3].

The extensive exploitation of the gold resources led to numerous mine tailings scattered around the Witwatersrand Basin [2]. The tailings dams, particularly in Johannesburg and its neighbouring cities, are the main source of airborne particulate matter pollution, dust blown into the surrounding communities can potentially have adverse effects on human health [4]. Mine waste dump sites become a permanent toxicological problem in the ecosystem and are deleterious to human health [5]. The long history of gold mining of led to an increase in the generation of gold tailings. Historically, South Africa's economy was built chiefly on the mining sector. This resulted into the need for building dams for tailing disposal, which in turn occupy large areas that can better be used for human settlement. Another major problem associated with gold tailings, is the adverse effects on the natural balance of the environment and ecological system. The mine leachates from gold mine wastes impoundments mostly contain high concentrations of sulphates and metals which negatively affect the quality of ground water [6]. In 1998, Rösner and Van Schalkwyk identified 270 tailings dams related to gold mining and discovered that these tailings occupy a total area of about 180km^2 in South Africa [7].

Over the years, studies were conducted by many researchers with the aim of finding applications for mine tailings in the construction and building sector. Any study focusing on utilizing the gold mine tailings for building and construction purposes is a potential solution to combat the building of dams for tailing disposal as well as mitigating environmental pollution. The production of building and construction materials from gold mine tailings offers solutions to utilise the resources that are readily available to help solve the environmental challenges, add valued to the waste, supplement the supply of building material and build low-cost housing from wastes. According to statistics South Africa, South Africa's population increased from 40.6 million in 1996 to 51.7 in 2011 and 55.6 million in 2016 [8]. The growth in population has resulted in an increasing demand for housing, which places severe pressure on natural resources used for construction materials, due to depletion of raw materials. There is therefore an urgent need to find innovative alternatives to supplement these natural resources.

Gold mine tailings can be used in brick making and cement production to benefit the country regarding low cost housing. The utilization of gold mine tailings can be used to produce conventional bricks which are manufactured using fired clay in high temperature kilns and ordinary Portland cement (OPC) [9]. The most commonly used material for the production of bricks,

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clay, is in most cases made by artisanal, small- scale manufacturers utilising sand and gravel. These quarrying operations are energy intensive and have a negative impact on the landscape, as they generate large volumes of waste [9].

The potential for re-use of gold mine tailings as secondary construction materials and in phytoremediation was investigated by Mapinduzi et al., (2016), the major tailings oxides are: silicon dioxide (SiO_2), which forms more than 50% w/w, aluminium oxide (Al_2O_3) (9.61 to 14.60); iron oxide (Fe_2O_3) (10.4 to 17.47); and sulphur trioxide (SO_3) (11.40 to 12.10). The pH varies from 7.2 to 7.5, typical for soils with large amounts of calcium and magnesium [10]. Preethi et al., 2017, conducted a study on gold ore tailings as a partial replacement for fine aggregates in concrete [11]. Compressive and flexural strength increased marginally from 5% to 15% replacement. There was a slight decrease in the corresponding compressive and flexural strengths at 20% replacement. Good correlation was observed between compressive strength and flexural strength. It was observed that the addition of gold ore tailings that would replace the fine material at a particular proportion, demonstrated an enhancing effect on mechanical properties of concrete. An investigation of cemented backfill technology with ultra-fine tailings in a gold mine was comprehensively conducted. The analysis results of chemical components of tailings showed that the content of SiO_2 is relatively low, i.e., 33.08%, but the total content of calcium oxide (CaO), magnesium oxide (MgO) and Al_2O_3 is relatively high i.e., 36.5%. After settlement of 4–6 hours, the tailing slurry with the initial concentration of 40% achieved the maximum settling concentration of 54.692%, and the corresponding maximum settling unit weight was $1.497 g/cm^3$.

The two major gold mines in the Paleoarchean Barberton Greenstone Belt (BGB) of Southern Africa are Fairview and Sheba mines [12]. Gold at these mines is associated with quartz–carbonate ± rutile veins and occurs both as invisible gold finely dispersed in sulphides (primarily pyrite and arsenopyrite), and as visible electrum grains hosted in pyrite [12]. The gold distribution in the BGB is structurally controlled [13], and recent work has shown that the main phase of gold mineralisation in the BGB was controlled by pre-existing faults and fractures, and postdates the main structural and metamorphic episodes [14-16]. Altigati et al., (2016) identified sulphides (mainly pyrite), either as inclusions (10-30μm) or as sub-microscopic gold and large gold grains (≥ 100μm) within the silicates (mostly quartz) as the two main types of mineralization in BGB [17]. This study was carried out to investigate whether the gold mine tailing from the Barberton mine can be applied and effectively used for building and construction applications.

2 Experimental details

The gold mine tailings were collected from Pan African Resources Gold Mine situated in Mpumalanga. The material was dried and then the initial work was conducted to characterize the gold mine tailings by conducting the baseline studies and chemical characterization. Sieve analysis was undertaken to study the particle size distribution of the material. The X-ray fluorescence, X-ray diffraction and scanning electron microscope were used to study the elemental composition, mineralogy and morphology of the material, respectively.

A standard compaction test, following ASTM D698 [18], was carried out on the material to obtain the optimum moisture content (OMC) and maximum dry density (MDD) of the tailings. The brick specimens were cast in a 100mm x 100mm x 100mm mold and cured at different temperatures at room temperature for 7 days and an elevated temperature of 80oC for 4 days. The unconfined compressive strength (UCS) was determined before and after stabilisation by using the UCS machine to measure the strength with a loading rate of 15kN/min. Lime was then used as a stabilising additive and added at ratios of 90:10, 80:20 and 70:30 to gold tailings. The UCS of the stabilised gold tailings was measured thereafter. To ensure consistent results, three composites were cast for each test and results presented are an average of the three casts.

3 Results and discussion

3.1. Relative density and pH of gold tailings

The relative density of the gold tailings was found to be $2.8064 g/cm^3$. The pH of the material was found to be 8.94, showing that the gold tailings are not acidic, but moderately alkaline. The gold tailings proved to have a relative high density. The relative densities of the soils fall between 2.5 for clays, 2.65 for silica beach sand and above 2.65 for red/brown sand. When compacted, these materials could be up to $1\,600\ kg/m^3$ and the material of such densities could mobilise UCS greater than 6 MPa in most cases with lime and fly ash.

3.2 Elemental analysis of un-stabilised gold tailings

The elemental composition (major oxides) results of the gold mine tailings determined by X-Ray fluorescence (XRF, Rigaku ZSX Primus II) are presented in Table 1. From the results in Table 1, it is evident that the results of the gold mine tailings exhibit results similar to other researchers, and are composed mainly of SiO_2. Using the classification system employed by Vassilev and Vasseleva, 2007, the major elements (>1%) are: silica (SiO_2); iron oxide (Fe_2O_3); alumina (Al_2O_3); calcium oxide (CaO); magnesium oxide (MgO); potassium (K_2O), and arsenic trioxide (As_2O_3). The relative concentration of calcium is a result of liming, which is added to the acid slime before disposal onto the tailings dam [7]. In Table 1, the results indicate that the elemental composition of the cyanide treated gold tailings bear close similarities with the composition of the conventional materials used for commercial specimen making where the major oxides are silica, aluminium and calcium oxide - as the tested

gold mine tailings confirm [19]. The material does not contain uranium, this is advantageous as it is undesirable in specimen- making materials. Some previous studies showed the presence of uranium oxide, but as a trace element. Although it can be found in traces, its presence is worth noting as uranium is a highly radioactive element and therefore can present health and safety implications [2].

Table 1. XRF analysis of gold tailings before stabilisation, mass %.

Oxide Content	SiO_2	Al_2O_3	Fe_2O_3	CaO	As_2O_3	MgO	K_2O
Mass (%)	49.63	12.22	13.48	8.31	1.03	5.01	3.62

Table 2. XRD analysis of gold tailings before stabilization.

Minerals	Quartz, SiO_2	Anorthite, $CaAl_2Si_2O_8$	Magnetite, Fe_3O_4
Raw gold tailings	35.93	63.39	0.68

Table 3. XRF analysis of gold tailings cured at elevated temperature

Oxide content	Mass (%)	Oxide content	Mass (%)	Oxide content	Mass (%)
F	0.109	Cl	0.020	Fe_2O_3	14.80
Na_2O	0.399	K_2O	4.004	CO_2O_3	0.010
MgO	4.647	CaO	9.756	NiO	0.097
Al_2O_3	11.84	TiO_2	0.802	CuO	0.021
SiO_2	45.75	V_2O_5	0.042	ZnO	0.024
P_2O_5	0.010	Cr_2O_3	0.409	As_2O_3	1.209
SO_3	5.414	MnO	0.329	Rb_2O	0.021
SrO	0.023	ZrO_2	0.033	Nb_2O_5	0.005
BaO	0.125	PbO	0.009		

Table 4. XRF analysis of gold tailings cured at lower temperature

Oxide content	Mass(%)	Oxide content	Mass (%)	Oxide content	Mass(%)
F	0.129	Cl	0.019	Fe_2O_3	14.04
Na_2O	0.394	K_2O	3.920	CO_2O_3	0.013
MgO	4.929	CaO	9.540	NiO	0.097
Al_2O_3	13.05	TiO_2	0.767	CuO	0.020
SiO_2	44.78	V_2O_5	0.037	ZnO	0.023
P_2O_5	0.087	Cr_2O_3	0.337	As_2O_3	1.390
SO_3	5.974	MnO	0.309	Rb_2O	0.018
SrO	0.018	Y_2O_3	0.022	ZrO_2	0.028
BaO	0.043	PbO	0.008		

Table 5. Proportions of gold mine tailings and lime

Tailings		Lime	
%	Mass (g)	%	Mass (g)
90	1 581.3	10	175.7
80	1 405.6	20	351.4
70	1 229.9	30	527.1

3.3 X-Ray diffraction (XRD) analysis of gold tailings

The mineralogical analysis by means of XRD shows that the gold tailings are composed of three phases; mainly quartz, anorthite and magnetite. The material is comprised of quartz (SiO_2) and quartz bearing constituent, as the primary major mineral (See Table 2). This is due to quartz being highly resistant to chemical weathering. The chemical composition of the gold mine tailings depends on the mineralogy of the ore deposits, the characteristics of processing fluids used from the processing plant [20-21]. The XRD analysis did not show

3.4 SEM and EDS of gold tailings

Figure 1 and Figure 2 show the gold mine tailings SEM micrograph and EDS. The SEM micrograph indicates the broad distribution of particles of finer particles. The gold mine tailings consist of irregular shaped flakes. Which represent how the material looks and it presents as flat, intermediate and granular particles [22]. SEM confirms that particles of the material have a porous and cracking structure associated with numerous gold mine tailings properties. The EDS shows that the material contains

constituents such as silica, calcium, iron, potassium, aluminium and magnesium, whose oxides and mineralogy were also detected in the elemental composition by XRF and XRD, respectively.
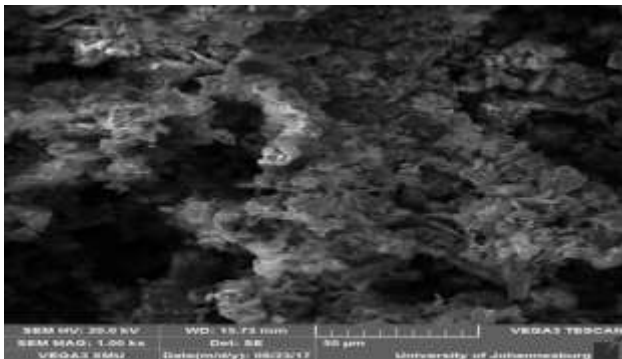

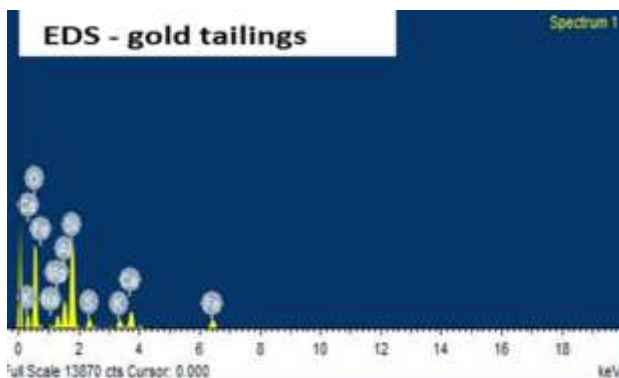**Figure 1.** Gold mine tailings SEM image

Figure 2. Gold mine tailings EDS

3.5 Particle size distribution and standard proctor compaction test of gold tailings

Figure 1 and Figure 2 show the gold mine tailings SEM Mass loss during sieve analysis was calculated and the percent of mass loss was found to be 0.4 %. This was also reflected by the total cumulative percentage of 99.6%. The results are presented in percentage cumulative form, in which the total amount of sizes retained or passed by a single notional sieve is given for the range of sizes. The

results indicate that most of the particles fell into 53μm to 300μm range. Cumulative percentage shows that 91% of the material passed the 212 μm screen aperture while about 20% passed the 75 μm screen. The particle size range used in standard commercial specimen making includes coarser sand particles as well as fine particles. The material used for the test was, in comparison, relatively finer.
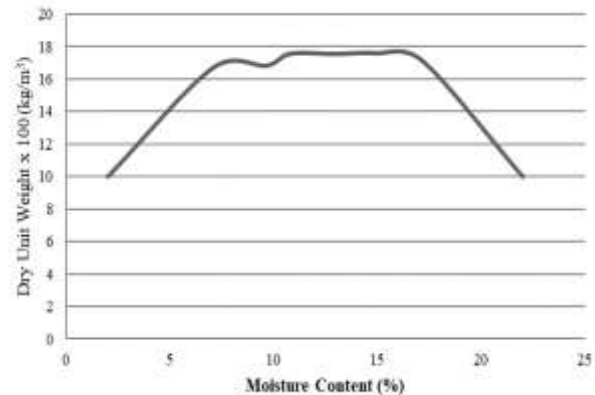

Figure 3. MDD and OMC of gold tailings.

The compaction test was conducted to determine the maximum dry unit weight/maximum dry density (MDD) of compaction of gold mine tailings as well as the optimum moisture content (OMC). The obtained results are presented in Figure 3. The maximum point obtained, illustrating the maximum dry density and optimum moisture content obtained is shown in Figure 3. The MDD of the material is 1 757kg/m^3 and the OMC is 16%. This shows a significant alterations of the specimen resulted from the lime-stabilization process.

3.6 Unconfined compressive strength (UCS) for raw gold tailings.

A total of 6 specimen were prepared and 3 specimens were cure for 7 days at room temperature and a further 3 were cured for 4 days in the oven at a curing temperature of 80°C. The tests were repeated thrice for consistency. When measuring the strength of a specimen, the specimen failed at once. The maximum load that was measured and recorded was 0.1kN. In order to calculate the strength, equation 2 was used and the strength from the maximum load was found to be 0.04MPa. The material is regarded as having a fine texture. Load =0.1kN; Area = 2 500 mm^2; 1N/mm^2 = 1MPa.

$$q_u = \frac{Load}{Corrected\ Area} \tag{1}$$

### 3.7 XRF of gold tailings after curing at low and elevated temperature

Table 3 shows the elemental composition of the material after compaction. The specimen was cured for four days

at elevated temperatures. Using classification used by Vassilev and Vasseleva (2007), the major elements found (>1%) were: silica (SiO_2),Iron oxide (FeO); alumina (Al_2O_3); calcium oxide (CaO); magnesium oxide (MgO); sulphur trioxide (SO_3); potash (K_2O) and arsenic trioxide (As_2O_3) [22]. The minor elements range is (0.1% – 1%) and the trace elements range (<0.1%). The relative proportion of silica, which was predominant in the tailings, decreased. The results after compaction still indicate that the chemical composition of the cyanide treated gold tailings bear close similarities with the composition of the conventional materials used for commercial specimen making, with major oxides similar to those of the raw material [19].

Table 4 shows the elemental composition of the material after compaction of the specimen that was cured for seven days at room temperature. The major elements are still similar to the raw sample with minor differences of decrease and increase in their mass percentage. The

3.8 PSD of gold tailings after curing at low and elevated temperature

Figure 4 shows the volume size distribution of raw gold mine tailing before compaction of the specimen that was cured for 7 days at room temperature and for 4 days in the oven at a temperature of 80°C. The data was obtained using a Malvern analyser. A significant modal size shift in the volume distribution is evident, when comparing the raw and cured specimen. The raw sample and the sample of specimen that was cured for 7 days at room temperature showed a unimodal volume distribution around 500 μm whereas the sample of the specimen that was cured in the oven showed a unimodal volume distribution around 200μm.
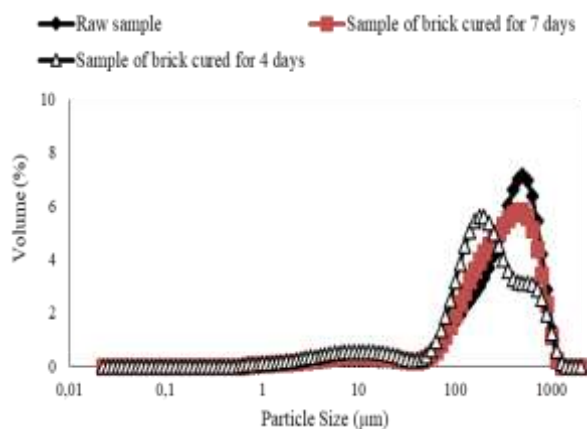
Figure 4. PSD of raw and un-stabilized gold tailings cured at low and elevated temperature.

3.11 XRF analysis of lime stabilised gold tailings at different lime ratios and PSD of raw and stabilised tailings

relative proportion of the major element SiO_2 decreased from 49.6 of raw to 44.8 of the sample specimens.

3.9 Stabilisation of gold tailings with lime

In terms of lime stabilisation, it is worth mentioning that it is expected that lime will significantly contribute to strength development and forming pozzolanic reaction with aluminum and silica, when water is added. Lime has an optional content for the maximum possible strength gain, which mainly depends on the type of gold mine tailings and mineralogy [23].

3.10 Mixed design and lime ratios for tailing stabilisation

Different proportions of gold mine tailings and lime were mixed together in preparing the specimen and the investigated ratios are presented in Table 5.

From Figure 5, the elemental composition of the lime stabilised gold tailings is presented. The chemical composition of the sample showed a drastic decrease in the relative proportion of silica from 49.6 mass% of the raw sample to 35.6wt% of the stabilised sample, due to the significant increment in the relative proportion of calcium oxide, which increased from 8.31wt% to 24.8wt% at of the ratio 90:10. For the a 80:20 ratio, there was a decrease in the relative proportion of silica 49.6 mass% of the raw sample to 27.7 wt%, while calcium oxide increased from 8.31 mass% of raw sample to 37.3%. This clearly shows that the addition of lime as a blending material has an effect on the chemical composition of the material. In the 70:30% ratio, the relative proportion of silica was reduced from 49.6 mass% of the raw sample to 30.4% and calcium oxide increased from 8.31 mass% of raw sample to 32.8%.
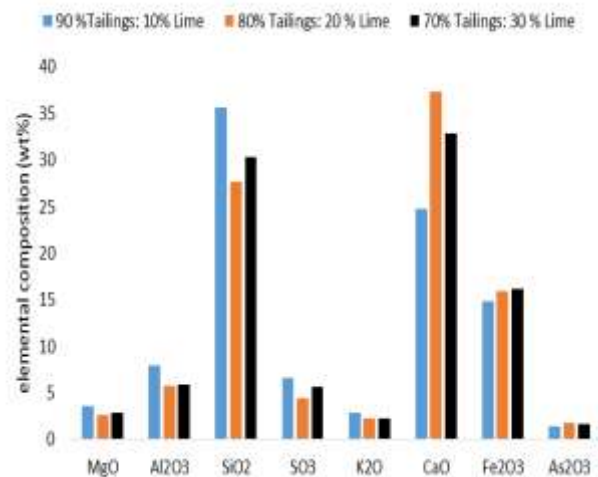
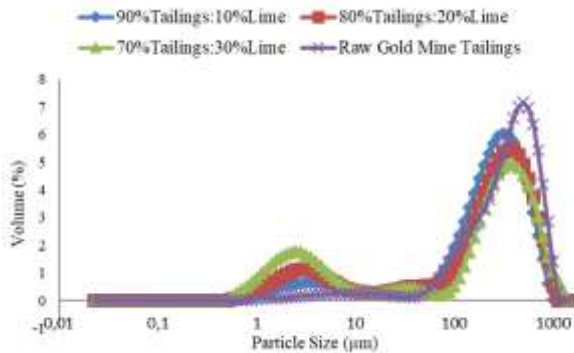**Figure 5.** XRF analysis of stabilised gold tailings

Figure 6. PSD of raw and stabilized gold tailings

Figure 6 shows the volume size distribution of raw gold mine tailing before compaction, a sample of 90%tailings:10%lime specimen, sample of 80% tailings: 20%lime specimen and a sample of 70% tailings: 30%lime specimen. The specimens were cured for 7 days in the oven at a temperature of 80ºC. The raw sample showed a unimodal volume distribution around 500µm whereas the samples of ratios of tailings:lime specimens showed a bimodal volume distribution around 300µm.

3.12 Unconfined compressive strength of lime stabilised gold tailings

Figure 7 shows the strengths of the stabilized sample with different lime ratios. The strength of the raw material increased drastically after stabilisation with lime. The UCS obtained for the raw material was 0.04MPa. According to the South African standard, the minimum strength required for load bearing is 3.5MPa [24]. The ratio of 70% tailings to 30% lime had the highest strength of 3.02MPa which is closer to 3.5MPa. The difference between the two strengths was calculated to be (3.5 – 3.024 = 0.476MPa).

The strength of the raw material was found to be 0.04MPa which clearly showed that the material was weak without the addition of a stabiliser. Lime reacted with silica and alumina pozzolans and formed a strong cementitious matrix that characterizes a lime-stabilized layer. In respect to the UCS obtained, there is also potential for the material to be used in road construction as pavement material. The strength requirements for using lime stabilised layers as structural layers in pavement systems vary considerably from agency to agency [25]. Lime stabilization causes a significant improvement in the tailings UCS.

In a study conducted by Plowman and Caprera (1984), the addition of lime in a mix design activates the alumina and silica phases; these are the constutuents that play a role in improving the strength of the material [26]. The high lime content required to stabilise the gold tailings and yield the highest strenghts in Figure 7, shows that lime was consumed in the curing process when the content of gold tailings was reduced from 90% to 70%. There was therefore a higher demand for lime to further improve the unconfineed comprehensive strength when tailings content was reduced in the mix design [27]. This also indicate that in the high content gold tailings mix

design lime reacted with the constituents in the tailings and was significantly consumed, hence the greater demand.

The standardized documents reviewed by Delgado and Guerrero (2007) indicate that compressive strength standards range between 1.3MPa and 2.1MPa for use in non-load bearing walls [28]. Unconfined compessive strength within a range of 0.3MPa – 2MPa is indicated when used as backfill bearing material; therefore 10% lime modification can be utilised in that area. The results obtained yielded UCS of 1.7 MPa at 90% gold tailings and lower lime content of 10% investigated, showing that the material can be used in bulk for applications that require low strengths material such as backfilling. At 80% gold tailings to 20% lime, the UCS obtained is 2.9 MPa. Although 30% lime mobilised higher strength of 3.02 MPa, this option however result into utilisation of lower content of the gold tailings (70%) and it may not be cost effective. Therefore for bulk utilisation of gold tailings from Barbeton the lower content of lime is therefore highly recommended.
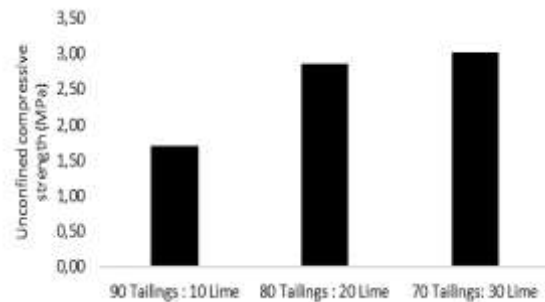

Figure 7. PSD of raw and stabilized gold tailings

Conclusion

Vast quantities gold tailings are discarded in the natural environment resulting into environmental pollution and covering a considerable area. This study was conducted to investigate the potential of stabilising Barberton gold mine tailings and produced a material that can be used for building and construction. The material structure and composition was studied by XRD, XRF and SEM. Utilising lime as a stabilising additive showed that with the incremental addition of lime concentrations, the proportion of calcium oxide also increased drastically, as expected. There was a significant enhancement of unconfined compressive strength when gold tailings were stabilised with lime. The strength of the material improved from 0.04MPa to 1.7MPa with 10% lime, 2.87MPa with 20% lime to the highest strength of 3.02MPa with 30% lime. The higher the lime content used, the higher the strength. In respect to the strengths obtained after stabilisation using 10%-30% lime, the stabilised tailings are indicated for use as masonry, as a backfill bearing material and for construction of pavements. Large volumes of gold tailings can therefore be stabilised by improving their strength by using a lime content as low as 10% in the process. This option does not only mobilise the strength of the gold tailings, but it utilised higher volume of tailings and is cost effective as it uses low lime content.

Acknowledgement

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