

Research Article

Evaluation of copper tailings from the abandoned Messina Mine for possible reuse in recreational projects, South Africa

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Abstract

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Historic mining of copper around Musina Town left behind a sizeable unrehabilitated tailing dump. This article reports on the study conducted to investigate the suitability of using copper tailings as sand replacement in recreational projects. The methodology used involved analyzing the particle size distribution and plasticity index (PI) of the tailings and determining their particle density, bulk density, particle shape, total porosity, and permeability coefficient. The pH of the tailings, major element oxides, and heavy metals composition were all analyzed. The tailings were classified as poorly graded sand with silt (SP-SM). Low fines (9.6%) and PI (1.4) values revealed that the copper tailings were texturally suitable for application in rootzones of sports fields, courts for beach volleyball, and bunkers of the golf courses. Their particle density (2.90 g/cm³), bulk density (1.53-1.89 g/cm³), porosity (34.62-47.04%), and permeability (1.42 x 10⁻³ cm/sec) were all within the recommended range for application in rootzones. The angular particles of the tailings supported their uses in the bunkers. However, their pH (7.9) and high quartz content (69% SiO₂) confirmed their suitability for rootzones. However, the high concentration of Cu (1872.0 mg/kg) and Cr (159.5 mg/kg) was identified as a potential risk of using the copper tailings in rootzones. This and the relatively high Al₂O₃ (11%) and Fe₂O₃ (8%) suggested that the copper tailings should be first washed or processed before being used in any recreational projects. Developing a suitable technique for processing the studied copper tailings to enhance their properties for different recreational projects was recommended.

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Introduction

In many parts of South Africa, historic mining left behind large volumes of mine waste such as tailings, spoils, and waste rock dumps. These waste (especially tailings) are known for their environmental and health impact associated with their textural properties and composition. They are potentially subject to erosion,

acid generation, and release of both heavy metals and radioactive elements to the environment (Kon et al., 2007). Given this, it is essential that tailings found in historic and abandoned mine sites are rehabilitated, reused in other projects/products, and recycled to recover valuable minerals from the tailings. The reuse and recycling of mine waste turn to reduce their

volumes. However, they can also worsen or course new environmental problems (Bian et al., 2012). There has been an increase in studies investigating the suitability of the mine tailings for different uses. For example, the synthesis of a geopolymer from mine tailings is one of the most investigated reuses of mine tailings (Kuranchie et al., 2016; Gitari et al., 2018; Wang et al., 2019). Mine tailings have also been investigated for their utilization in the making of cement bricks (Malatse and Ndlovu, 2015; Lam et al., 2020), concrete material (Srinivasan and Sivakumar, 2013; Pyo et al., 2018; Huang et al., 2020), and glass (Okereafor et al., 2020).

This paper reports on the study conducted to investigate the suitability of copper tailings from the abandoned Messina Mine for application in recreational projects as replacement silica sand. The recreational sector is among the major consumers of silica sand. Such sand is used mainly in golf courses, stadiums and school fields, bowling greens, beach volleyball courts, and racecourses (Agnello, 2004). According to Mansour (2015), golf courses alone consume about 3% of the total world's silica sand. Although most of this sand can be sourced from the sea, inland sand is most preferred because of its resistance to erosion due to its high silica content.

Comparatively, sand from the sea is generally rich in carbonate (mostly calcium carbonate) material susceptible to dissolution (Shaour, 2007; Moretti et al., 2016; Wang et al., 2020).

The study area

The tailing dump of the Messina Copper Mine is found at the coordinates of 22°19'44.6"S and 30°03'01.5"E in the vicinity of Musina Town in the far northern part of South Africa. The copper deposits that were mined and processed created a colossal tailing dump in the area along 16 km long Musina Fault towards the north-east (Beale, 1985). These mines are Artonvilla, Spence, Messina, Harper, and Campbell (see Figure 1a). According to Wilson (1998), these mines operated in the area between 1906 and 1991. The copper tailing dump at Messina Mine shown in Figure 1b covers an estimated area of 87.8 hectares (Mhlongo et al., 2019). It was left unrehabilitated, and for many years they have been extensively affected by erosion. Figure 1c shows the devastating effect of erosion on the slopes of the dump. To a lesser extent, some of the copper tailings have been excavated (see Figure 1d) and used by the people from the nearby communities for different purposes.

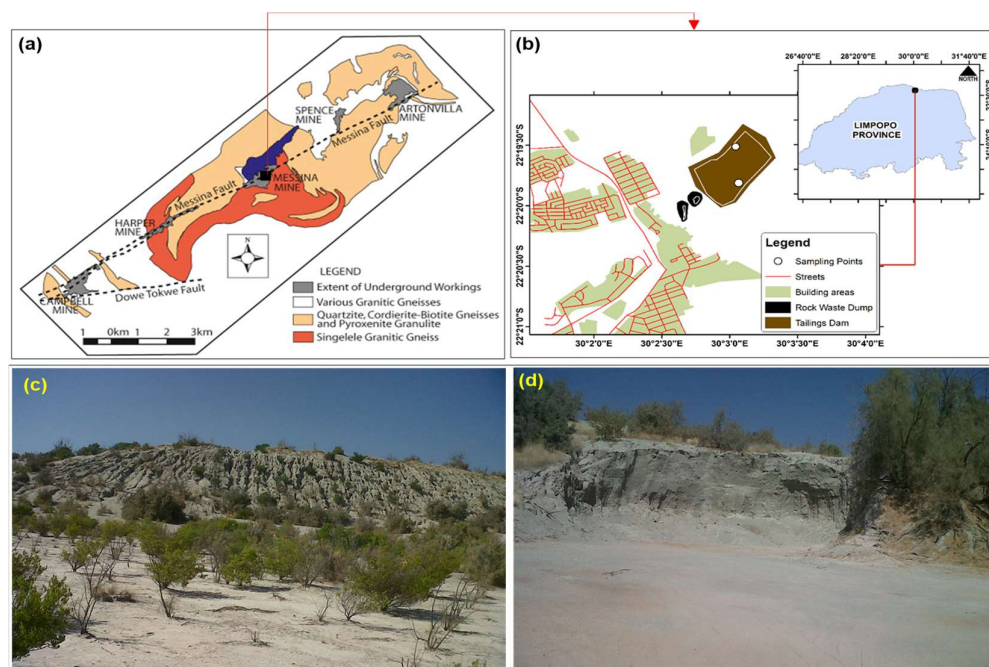


Figure 1. The location and physical appearance of the abandoned Messina Mine tailing dam ((a) adopted from Chaumba et al., 2016).

The mines that generated this dump were all mining along the Central Zone of the Limpopo Belt. The deposits mined were hosted by gneisses and quartzites of the basal Mount Dowe Formation of the Beit Bridge Complex (Beale, 1985; Cairncross, 1991). This indicates that the tailings produced from copper

mining in the area will have relatively high silica that is an essential specification of sand for different industrial applications (Plantias et al., 2014). This is because rocks such as gneisses and quartzites (called quartzo-feldspathic gneisses) comprise more dominantly silica (SiO_2) (Howard, 2005).

Materials and Methods

The samples of the tailings were taken to the laboratory to analyze their physical and chemical properties. The particle size distribution of the tailing material was conducted using the sieve analysis technique (ASTM-D6913-04, 2014). The sieve analysis results were used to plot a gradational curve from which the coefficient of uniformity (C_u) and curvature (C_c) were determined. Based on the interpretation of the curve and the C_u and C_c values, the textural classification of the tailings was performed using the Unified Soil Classification System (USCS). Moreover, the plasticity index (PI) of the material was calculated from the liquid and plastic limits obtained in the laboratory. This index assisted in the interpretation of the cohesiveness of the tailings. The shape of the particles of the tailings was analyzed under the microscope (Zeiss Stemi 2000-C model) and interpreted using the Krumbein's chart for visual determination of roundness (R) and sphericity (S) (Hryciw et al., 2016; Cruz-Matias et al., 2019).

The other physical properties of copper tailings studied are their permeability (coefficient of permeability), bulk density, and particle density. The permeability of copper tailings was determined using the constant head method (ASTM-D 2434-19, 2019). This method is recommended for measuring the permeability of fine-grained soils. This made this method suitable for use to determine the permeability of copper tailings in this study. The particle and bulk densities of the tailings were determined using the standard methods for determining soil density (ASTM-D7263, 2018). Based on the results of bulk density (ρ_b) and particle density (ρ_s), the percent porosity (f) of the copper tailing material was computed using Equation 1.

$$f = 1 - \left(\frac{\rho_b}{\rho_s} \right) \times 100 \quad (1)$$

The chemical composition (major element oxides and heavy metals) of copper tailing material was analyzed using X-ray Fluorescence spectrometry (S2 Ranger), while the pH value of the material was determined using an ACCSEN PC8 (pH/mV/Cond/Temp) meter.

Results

Physical properties of the copper tailings

The gradational curve of the copper tailings shown in Figure 2 demonstrates that the tailings consist of 90.4% sand and 9.6% fines (silt plus clay). The absence of gravel, low fines (5-12%), as well as the C_u and C_c values of 3.87 (<6) and 1.49 (<3) respectively resulted in the classification of the tailings as poorly graded sand with silt (SP-SM). Their plasticity index of 1.4 indicated that they fall under the category of slightly plastic soils (Shamsai et al., 2007). They had a particle density of 2.90 g/cm³. In general, this particle density is greater than that of natural soils (2.50 to 2.80 g/cm³) and that of silica minerals (2.65 g/cm³) that is dominant in most soils and tailings (Huang et al., 2011; Martín-Crespo et al., 2019). The bulk density of unconsolidated tailing was 1.53 g/cm³ while that of consolidated material was 1.89 g/cm³ (see Table 1). The calculated porosity of the tailings was 47.04% for uncompacted material. It reduced to 34.62% in compacted tailings. The determined average permeability (1.42×10^{-3} cm/sec) of the tailings revealed that their permeability was generally low. It is typically the permeability of silty sand (Ishbashi and Hazarika, 2011).

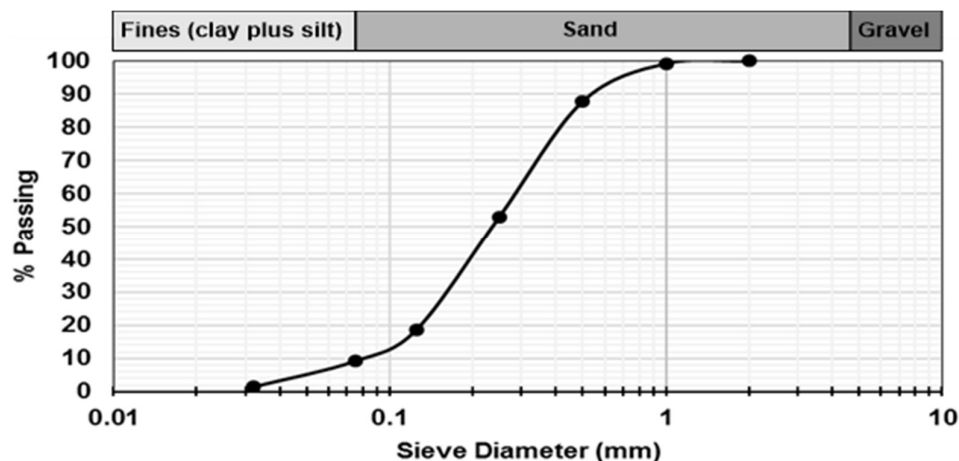


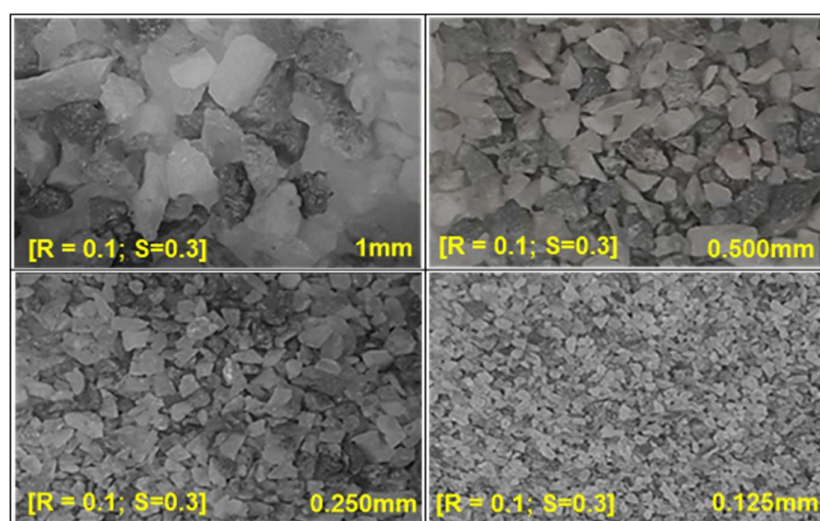
Figure 2. Gradational curve of the copper tailings.

The average roundness and sphericity of sand fractions of the copper tailing material were estimated to be 0.1 and 0.3, respectively. The microscopic view of the tailing particles is depicted in Figure 3. The particle roundness and sphericity are essential factors for sand

for recreational projects/products. For example, according to Moore (1998), some sand that has particles that match those required for golf course bunkers are unsuitable because of their particle shape, which makes them too firm or soft for play.

Table 1. The physical properties of copper tailings from Messina Mine.

No.	Physical Properties	Symbol	Units	Values
1	10% of the particles are finer	D_{10}	-	0.08
2	30 % of the particles are finer	D_{30}	-	0.17
3	60 % of the particles are finer	D_{60}	-	0.29
4	Coefficient of uniformity	C_u	-	3.87
5	Coefficient of curvature	C_c	-	1.49
6	Sand	-	%	90.4
7	Fines	-	%	9.6
9	Particle density	ρ_s	g/cm^3	2.90
10	Bulk density - Uncompacted	ρ_b	g/cm^3	1.53
11	Bulk density - Compacted	ρ_b	g/cm^3	1.89
12	Porosity - Uncompacted	f	%	47.04
13	Porosity - Compacted	f	%	34.62
14	Permeability	k	cm/sec	1.42×10^{-3}

Figure 3. Microscopic view of the shape of the sand fraction of copper tailings. Note: **R** is the roundness of the particles and **S** is the sphericity of the particles.

Chemical composition of the copper tailings

Generally, the chemical composition of sand used in recreational projects is not specified. However, to understand the potential risks of using copper tailings in recreational projects/products, their chemical composition needed to be determined. The results of the major element oxides showed that the tailings comprised dominantly of SiO_2 , Al_2O_3 , Fe_2O_3 , and MgO in the decreasing order. As shown in Figure 4, the K_2O and Na_2O contributed 1% each in the composition of this copper tailing. These results are consistent with those reported in the study of the same tailings material by Gitari et al. (2018).

The use of tailings in some recreational projects requires that the material be free of toxic materials such as heavy metals. The Texas-USGA Root Zone Mix Specification (1994) recommends that any material used in the latter should be free of heavy metals. The heavy metals concentration measured in the tailings was compared with the permissible limits

in soils (Figure 5). The concentration of Cu (1782.0 mg/kg) and Cr (159.5 mg/kg) surpass the permissible limits by a large magnitude while the Ni (57.8 ppm) slightly exceeds the WHO limit. The pH of the tailings was 7.9.

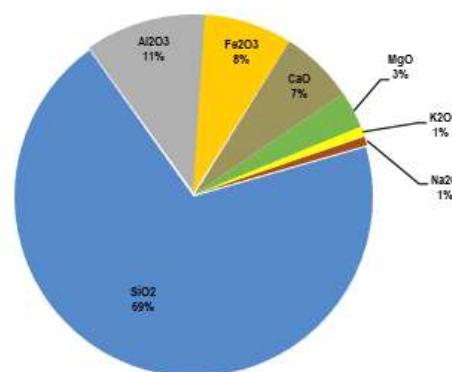


Figure 4. Chemical composition of the copper tailings from abandoned Messina Mine.

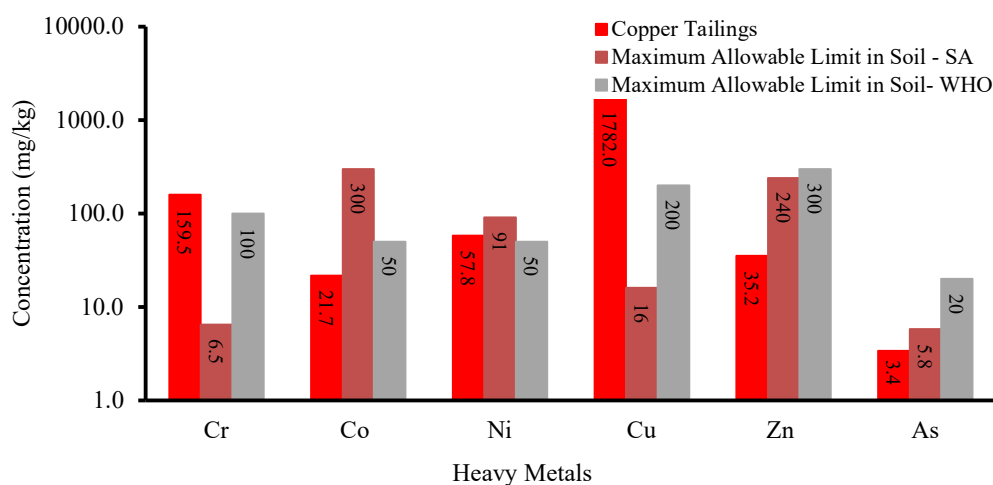


Figure 5. A comparison of heavy metals concentration in tailings with the permissible limits in soils.

Discussion

The textural analysis of the copper tailings showed that this material is poorly graded sand with silt. It had a low fines percentage (9.6%) that make them potential materials for use in the sports field rootzones, golf course bankers, and beach volleyball courts. In general, sand with low content of fines is recommended for most recreational projects/products. This is because such sands infiltrate and drain rapidly (Bigelow and Smith, 2008; Kowalewski et al., 2015). According to Kowalewski et al. (2015), the material that drains quickly is preferable in golf course bankers to reduce erosion (especially on bankers' build of slopes). The content of fines also affects the porosity of sand and its water holding capacity that is important for the growth of the grass and other plants on rootzones. The study by Brown et al. (2019) showed that a considerable increase in fines in the rootzone mixtures; leads to increased water holding capacity of the material.

The percent content of fines in the copper tailings can be considered adequate as their determined total porosity of 34.62% to 47.04% was within the recommended range of 35% to 50% in rootzone uses (Latham, 1989). The other factor that affects the porosity of the soil is its organic matter. This is because the organic matter in the soil absorb moisture and form porous spaces in which water is stored in soil (Ward and Trimble, 2004). The determined high particle density (2.9 g/cm^3) of the copper tailings indicates that this material has low organic matter. Therefore, this particle density can be due to the relatively high hematite (Fe_2O_3) content in tailings. The other factor that is influenced by the content of fines in the sand is the bulk density. In general, bulk density increases with an increase in fines. The bulk density of the tailings was from 1.53 to 1.89 g/cm^3 . These bulk

density values fall within the values of 1.2 to 1.6 g/cm^3 , recommended by the USGA for rootzone uses (Hummel, 1993).

The bulk density and porosity of the copper tailings supported their use in rootzones. However, the estimated sphericity of their sand-size particles does not support their uses in rootzones. According to Hryciw et al. (2016), the asphericity value less than 0.5 is found in materials produced by crushing rocks. The high angularity of the particles of tailings to some degree affects their potential use in recreational projects. The use of this material in rootzones of sports fields and golf courses can result in the shearing of the grass's roots, especially when the lawn areas are subjected to traffic (Kowalewski et al., 2015). However, using sand with angular particles in golf course bunkers is preferred. This is because this material forms a mechanically resistant surface that prevents landing golf balls from being buried in the sand (Moore, 1998). Angular sands turn to resist compaction and drain better to be used in volleyball courts (Drakich, n.d). Although the copper tailings are expected to have high permeability because of their highly angular particles, their estimated permeability coefficient was $1.42 \times 10^{-3} \text{ cm/sec}$. This indicates that the copper tailings have low permeability due to their high percentage of fine sand with silt particles. It is important to note that the role played by particle shape in the selection of sand for use in recreational projects/products is generally less (Hummel, 1993). There is also no set value for the permeability of sand required for recreational projects/products (Latham, 1989).

The high content of silica (69%) in the tailings supports their uses in the rootzones of greens. According to Kowalewski et al. (2015), sand that is predominantly silica is preferred in rootzone mixes. This is because silica is chemically inert and resistant

to weathering. Therefore, when the copper tailings are used in rootzones, they will be less affected by continuous fertilization and irrigation of the greens or lawn. The tailings also had a relatively high alumina (11%) and ferric oxide or hematite mineral (8%) content. GWP Consultants (2010), in its report on Silica Sand Quality and End-Uses in Surry and Kent, indicated that Al_2O_3 is mainly found in clay and/or feldspar grains in the sand. The clay can be removed or reduced by washing the material before its application in any recreational projects. The similar density of quartz grains and feldspar makes the separation of the two through processing very difficult. However, using sodium polytungstate in the floatation separation process has been cited as an effective method of separating the two minerals. High iron (Fe_2O_3) content in the sand is generally responsible for its brownish colors and its relatively high particle density. Suppose such sand or material is to be used in recreational projects. In that case, it is recommended that the material be first washed in the processing plant to reduce its Fe_2O_3 content and other gangue minerals (Hummel, n.d). These minerals include clay, feldspar, heavy minerals such as hematite and epidote, and carbonates found in these tailings (Gitari et al., 2018).

Sand that is characterized by a $\text{pH} < 8$ is preferred for rootzone mixes. This is to prevent excessive physical and chemical weathering (Moore, 1998). The main reason for this is that a pH greater than 8 indicates that sand has a high content of carbonate minerals that are easily affected by weathering. Because of this, the pH of rootzone sand is generally less than 8.5 (McClella et al., 2009). Given this background, the measured pH (7.8) of the copper tailings made them suitable for rootzones. The copper tailings also had concentrations of Cu and Cr that surpassed the recommended limits in soils. This will affect their utilization in rootzones mixes. If the copper tailings are used in rootzones, their elevated concentration Cu and Cr will affect the growth, length, and morphology of the roots (Sheldon and Menzies, 2005; Shanker et al., 2005). According to Gitari et al. (2018), Cr exists in less extractable fractions in copper tailings compared to readily extractable Cu. This indicates that Cu in the tailings is potentially bioavailable to organisms. This presents an environmental and health risk. The high content of these metals in tailings washing reduces the level of heavy metals leaching from sand by significant margins (Wuana et al., 2010; Imteaz and Arulrajah et al., 2019). This also justifies why the copper tailings should be washed and/or processed before their utilization in different recreational projects/products.

Conclusion

The physical and chemical properties of copper tailings from the abandoned Messina Mine (South Africa) showed their potential uses in different recreational projects/products. Their physical

properties (i.e., particle density and bulk density, textural characteristics, porosity, and permeability) of the copper tailings, together with their high content of silica, supported their use in rootzones. The use of copper tailings in sports field rootzones was further supported by their average pH value that indicated that the material was less calcareous and resistant to erosion. However, the angular particle shape showed that the tailings were preferable suitable for use in golf course bunkers.

The high Cu and Cr content in tailings was identified as a significant risk of using the copper tailings in rootzone mixes. This is because these metals might be toxic to the roots of the lawn in sports fields. They also constitute a potential risk to the environment and health of people and animals. This, together with the relatively high percentage of alumina and ferric oxide, indicated that the tailings should be first washed and/or processed before their application in any recreational project/products. Based on these findings stated above, it is recommended that a technique for processing the tailings to enhance their suitability for utilization in different recreational projects or products is developed. Such a method should mainly reduce the concentration of Cu, Cr, alumina (Al_2O_3), and hematite (Fe_2O_3) from the tailings.

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