The viability of using the Witwatersrand gold mine tailings for brickmaking

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Synopsis

The Witwatersrand Basin is the heart of South Africa'a gold mining industry. The cluster of gold mines located in the Witwatersrand Basin generates a significant amount of mine tailings, which have adverse effects on the environment and ecological systems. In addition, disposal costs are very high. The exponential population growth in the Witwatersrand area has resulted in pressure on the reserves of traditional building materials. Quarrying for natural construction material is very expensive and damages the landscape. This work therefore examines the use of gold mine tailings in the production of bricks.

Different mixing ratios of gold tailings, cement, and water were used. The resulting bricks were then cured in three different environments – sun dried, oven dried at 360°C, and cured in water for 24 hours. The bricks were then tested for unconfined compressive strength, water absorption, and weight loss. The results showed that the mixture with more cement than tailings had a compressive strength of approximately 530 kN/m^2. It was also found that the best brick curing system was in a water environment. Bricks made from tailings cost more than conventional bricks because of the higher quantity of cement used, but the manufacturing process consumes less water. Overall, the results indicated that gold mine tailings have a high potential to substitute for the natural materials currently used in brickmaking.

Keywords
gold mine tailings, construction materials, brickmaking.

Introduction

South Africa is a mineral-rich country with metals such as gold, copper, and platinum group metals being exploited to a significant extent in the country's mining history. Mining generates large volumes of tailings, with consequent disposal and environmental problems. By far the most gold that has been mined in South Africa (98%) has come from the Witwatersrand goldfields (Messner, 1991). The gold mines in this area are situated around an ancient sea (over 2700 million years old) where rivers deposited sediments in the form of sand and gravel that became the conglomerate containing the gold (Messner, 1991). The extensive exploitation of the gold resources has led to numerous mine tailings heaps scattered around the Witwatersrand Basin. As long as mining contributes significantly to the economic development of South Africa, generation of these tailings is inevitable.

The major environmental impacts from waste disposal at mine sites can be divided into two categories – the loss of productive land following its conversion to a waste storage area and the introduction of sediment, acidity, and other contaminants into surrounding surface and groundwater (Mining Facts, 2014). The gold mining and processing wastes contain large amounts of sulphide minerals such as pyrite, which generate acid mine drainage (AMD) (Rosner and van Schalkwyk, 2000). South Africa is currently faced with the challenges resulting from AMD and the government and mining companies are under pressure to find viable solutions to this problem. This, coupled with the increasing landfill costs, and stricter implementation and enforcement of environmental legislation, has caused the scientific community to focus on finding innovative methods of utilizing mine tailings. Even though some applications of the generated tailings have been exploited, such as in the building of slimes dams and backfill in underground mines, these uses do not take up more than a fraction of the total amount of tailings in the Witwatersrand region. There is therefore a significant need to developing other long-term, commercially viable uses for mine tailings in order to minimize the disposal costs and the impact on the environment.

According to Statistics South Africa (2013), South Africa has a human population of about 52.98 million. This population is growing, and this consequently results in an increasing demand for housing, which places severe stress on the natural resources used for construction materials. Conventional bricks are produced from clay fired in high-temperature kilns or from ordinary Portland cement (OPC) concrete. Clay, the common material used for

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brickmaking, is usually mined in quarries. Quarrying operations are energy-intensive, adversely affect the landscape, and generate a high level of waste (Zhang, 2013; Bennet *et al.*, 2013). Furthermore, in many areas of the world, there is already a shortage of natural resource material for the production of the conventional bricks (Zhang, 2013). To conserve the clay resources and the environment, some countries such as China have started to limit the use of bricks made from clay (Zhang, 2013). Thus the depletion of these natural resources has created a need need for an alternative source of construction materials in order to sustain development.

Extensive research has been conducted on the production of bricks using waste material (Zhang 2013; Saeed and Zhang, 2012). These waste materials include mining waste, construction and demolition waste, wood sawdust, cotton waste, limestone powder, paper production residues, petroleum effluent treatment plant sludge, kraft pulp production residue, cigarette butts, waste tea, rice husk ash, crumb rubber, cement kiln dust, and coal fly ash (Zhang 2013; Bennet *et al.*, 2013; Saeed and Zhang, 2012). The mining and mineral processing waste includes mining overburden, waste rock, mine tailings, slags, granulated blast furnace slag (GGBS), mine water, water treatment sludge, and gaseous waste (Zhang, 2013; Saeed and Zhang, 2012; Koumal, 1994; Dean *et al.*, 1968; Bennet *et al.*, 2013).

The extensive research on the utilization of waste materials to produce bricks can be divided into three general categories based on the production methods – firing, cementing, and geopolymerization,

Production of bricks from waste materials through firing uses waste material(s) to substitute partially or entirely for clay and follows the traditional method of kiln-firing. Chen *et al.* (2011) studied the feasibility of utilizing haematite tailings and class F fly ash together with clay to produce bricks. Tests were performed to determine the compressive strength, water absorption, and bulk density of brick samples prepared under different conditions.

Bennet *et al.* (2013) conducted research on the development of geopolymer binder-based bricks using fly ash and bottom ash. During the synthesizing process, silicon-aluminium bonds are formed that are chemically and structurally comparable to those binding the natural rocks (Bennet *et al.*, 2013), giving geopolymer binder-based bricks advantages such as rapid strength gain and good durability, especially in acidic environments. Research into geopolymer bricks has also incorporated copper mine tailings and cement kiln dust (Bennet *et al.*, 2013). In this process, an autoclaved aerated cement (AAC) material is produced (Koumal, 1994). Ahmari and Zhang (2012) investigated the utilization of copper mine tailings to produce geopolymer bricks by using sodium hydroxide (NaOH) solution as the alkali activator. They produced cylindrical brick specimens by using different initial water contents, NaOH concentrations, forming pressures, and curing temperatures. Copper mine tailings bricks have been found to have good physical and mechanical properties such as a water absorption of 17.7%, compressive strength of 260 kg/cm^2, and density of 1.8 g/cm^3 (Be Sharp, 2012).

The method of producing bricks from waste materials through cementing is based on hydration reactions similar to those in OPC to form mainly C–S–H and C–A–S–H phases contributing to strength (Zhang, 2013). The cementing material can be the waste material itself or other added cementing material(s) such as OPC and lime. Again, many researchers have studied the utilization of waste materials to produce bricks based on cementing. The brickmaking process has involved the use of waste and tailings such as those from copper, nickel, gold, aluminium, molybdenum, and zinc processing as additives replacing some of the cement (Jain *et al.*, 1983). Morchhale *et al.* (2006) studied the production of bricks by mixing copper mine tailings with different amount of OPC and then compressing the mixture in a mould. The results showed that the bricks had a higher compressive strength and lower water absorption when the OPC content increased. Roy *et al.* (2007) used gold mill tailings mixed with OPC, black cotton soils, and red soils in different proportions to make bricks. The cement-tailings bricks were cured by immersing them in water for different periods of time and their compressive strengths were determined. Bricks with 20% cement and 14 days of curing were found to be suitable. Gold mine tailings have also been used to produce autoclaved calcium silicate bricks (Jain *et al.*, 1983). The bricks are cured under saturated steam and in the process, lime reacts with silica grains to form a cementing material consisting of calcium silicate hydrate. Some mining companies such as Bharat Gold Mines in India have explored the idea of brickmaking using gold ore tailings (Be Sharp, 2012).

Table I shows the chemical composition of some of the waste materials used in bricks as well as the composition of quarry clay material that comprise the conventional feed material (Bennet *et al.*, 2013). The gold mine tailings are from a Chinese mine (Yang *et al.*, 2011).

Table I

Composition of material used in brickmaking (Bennet *et al.*, 2013; Yang *et al.*, 2011)

Oxide component	Fly ash Mass %	GGBS Mass %	Bottom ash Mass %	Clay material Mass %	Gold mine tailings Mass %
SiO_2	53.3	35.47	56.76	61.8	38.60
Al_2O_3	29.5	19.36	21.34	25	7.06
Fe_2O_3	10.7	-	5.98	8	12.76
CaO	7.6	33.25	2.88	-	29.24
SO_3	1.8	-	0.72	-	3.21
FeO	-	0.8	-	-	=-
MgO	-	8.69	-	1.2	7.85
Na_2O	-	-	-	0.1	-
K_2O	-	-	-	2.76	-

From the chemical compositions shown in Table I, it can be seen that the waste materials have similar major oxides in their compositions. The compositions are also relatively similar to the typical clay material used in brickmaking. The waste materials all have a predominantly high content of silica, alumina, and haematite (with the exception of the granulated blast furnace slag, GGBS, which contains no haematite), which are important in brickmaking materials. Considering the source of the gold deposits in the Witwatersrand Basin (river sediments in the form of sand and gravel), it is therefore likely that the tailings from this area will also contain a high level of silica.

The purpose of this work is therefore is to ascertain the technical and economic viability of using the Witwatersrand gold tailings for brickmaking using the cementing method. The tailings-based bricks will be compared with the commercial bricks available on the market. The evaluation will be based on parameters such as compressive strength, water absorption, and weight loss tests. This work has the potential to unlock large resources of material needed in the construction industry that would help conserve the natural resources commonly used. In addition it would eliminate the land requirements for waste disposal, thus realizing savings on disposal and landfill costs and also lessening environmental damage. But above all, this work has the potential to provide an additional revenue stream for the gold mining sector.

Materials and methods

The materials used in this test work were gold mine tailings, water, and cement as a binding material. Gold mine tailings were provided by a local gold mining company, AngloGold Ashanti. The Larfarge 42.5 kN cement was provided by the Planning, Infrastructure and Maintenance Department at the University of the Witwatersrand, Johannesburg. The cement was used on the day of delivery and tap water was used in the mixing process.

Characterization of gold mine tailings

Representative samples used in all experiments were prepared using a riffle splitter (model 15A, Eriez Magnetics, South Africa). The gold tailings were characterized by investigating the phase mineralogy, particle size, and quantitative chemical analysis. The particle size analysis was done by physically screening the samples using test sieves (Fritsch, Germany) of various screen sizes up to 212 μm. The phase mineralogy analysis was carried out using an X-ray diffractometer (X'Pert, PANalytical, Netherlands) operated with Co-K radiation generated at 40 kV and 50 mA. The chemical analysis was carried out using wavelength dispersive X-ray fluorescence (XRF) spectrometry (Axios, PANalytical, Netherlands) operated with a rhodium tube excitation source.

The brickmaking process

Different mixing ratios of tailings, cement, and water were used in the brickmaking process (Table II). From each mixture, a number of bricks were cast and dried.

The three feed material (tailings, cement, and water) were mixed in the appropriate ratios in a commercial mixing machine. Dry mixing was done first and then a controlled amount of water was added while continuing to mix thoroughly. The total mixing time was 15 minutes. The mixture was then cast into the brick moulds. The brick moulds were then placed on a vibrating machine for 5 minutes in order to fill the voids in mixture comprehensively and thus prevent the formation of air pockets. The bricks were then labelled and allowed to cure for 24 hours. Three curing methods were used. These included atmospheric drying under the sun, curing in water, and drying in an oven at 360°C. After curing, the bricks were de-moulded using an air compressor, weighed, and tested for compressive strength.

Unconfined compressive strength testing

The cast and cured bricks were tested for compressive strength using a Tinus Olsen compressive strength testing machine. In the compressive strength testing process, a force was applied on the brick until the brick failed and the force measured at failure was documented. The compressive strengths obtained were then averaged. The mixture ratio that gave the highest compressive strength was subsequently employed to manufacture bricks for water absorption, weight loss, and leaching rate tests. Unconfined compressive tests were also done on commercial bricks to provide a basis for comparison.

Water absorption rate and weight loss tests

Two solutions with different pH values, one acidic and one neutral, were used for these tests. The tailings bricks were first prepared from mixture 7 (Table II) and cured in water for 24 hours. Tests were conducted on four samples in each solution. The bricks were immersed in water baths, one containing water at pH 7 and the other an acidic solution at pH 4. The solid–to-liquid ratio was maintained at 15. The saturated weight of the bricks (W_s) was measured every 24 hours over a 5-day period. After 5 days, the bricks were dried at 110°C for 24 hours and the oven-dried weight (W_d) recorded. The bricks were again tested for compressive strength. The percentage water absorption rate was then calculated as

$$\text{Water absorption (\%)} = [(W_s - W_d]/W_d \times 100$$

The weight loss tests were done in the neutral environment only (pH 7). The average weight loss was measured after the bricks had been soaked in neutral water for seven days then dried overnight at 110°C.

Table II

Different mixtures used in brickmaking

Mixture number	Tailings (kg)	Cement (kg)	Water (L)
1	2	1	0.6
2	14	2	2.65
3	9	6	3.0
4	7	8	2.5
5	10	5	2.5
6	12	3	2.5
7	5	10	3.3
8	10	5	3

Results and discussion

Particle size distribution

Figure 1 shows the particle size distribution of the material used in the brickmaking process. The results are presented in cumulative form, in which the total amount of all 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 90–200 μm range. 80% of the material passed the 200 μm screen aperture while about 12% passed the 90 μm screen. The particle size range used in standard commercial brickmaking includes coarser sand particles as well as fine particles. The material used in these tests was, in comparison, relatively fine. A cost analysis study done by Roy *et al.* (2007) showed that cement-tailings bricks are generally uneconomical compared to the soil-tailings based bricks, therefore future test work will have to consider the addition of coarse particles, possibly from mining overburden.

Mineralogical and chemical analysis

Table III shows the mineral phases and the respective quantities present in the sample as determined by XRD and XRF analysis. The table indicates that the mineralogical and chemical composition of the tailings bear close similarities with the composition of the conventional materials used for commercial brickmaking, as well as with the waste materials that have been tested in the past (see Table I). The results indicate that the major oxides in the mine tailings sample are silica, magnesium oxide, alumina, sulphur trioxide, potassium oxide, calcium oxide, and haematite. The other constituents such as uranium oxide are found in trace quantities. Although uranium oxide is present only at 0.0064% its presence is worth noting as uranium is a very radioactive element and therefore can present safety implications.

Unconfined compressive strength

The main mechanical property of bricks that is tested for is compressive strength. A good brick should be hard and strong. The compressive strength tests on commercial bricks were undertaken in order to provide a basis for comparison with the gold mine tailings bricks. Table IV shows the results of the compressive strength of the commercial bricks. It was noted during the tests that the more uneven and rough the surface of the brick, the quicker it failed.

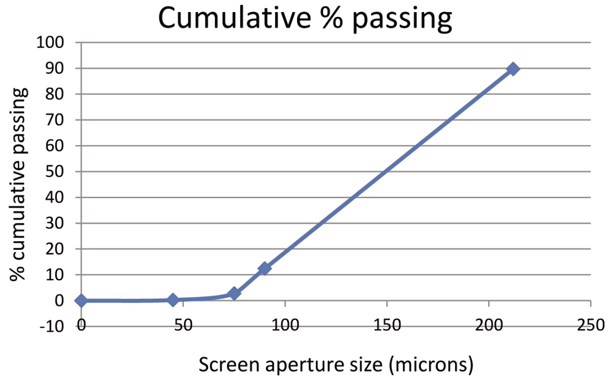

Figure 1—Particle size distribution of the gold mine tailings

Unconfined compressive strength of the gold tailings bricks

The quality and durability of the concrete mix depend not only on the quality and properties of the ingredients, but also on the method of preparation and the curing environment (Ahmad and Saiful Amin, 1998). Proper curing is indispensable in developing optimum properties. Table V shows the compressive strength for the gold tailings based bricks cured in different environments.

The average values shown in Table V are depicted graphically in Figure 2. For mixture 1, high-temperature drying in an oven yielded the highest compressive strength. For mixture 2, ambient drying conditions resulted in the highest compressive strength, followed by oven drying for mixture 3, curing in water for mixtures 4 and 5, oven drying for mixture 6, and curing in water for mixtures 7 and 8. The overall trend reveals that the majority of the mixtures yielded higher compressive strength when cured in water (50%), followed by oven drying (37.5%), and lastly drying under ambient conditions (12.5%). This can be attributed to the fact that curing the bricks in water contributes to the cementation process and hence increases the strength of the bricks. An

Table III

Major constituents of the gold mine tailings

Number	Component	Result (%)
1	$Na_2 0$	0.613
2	MgO	1.79
3	Al_2O_3	10.2
4	SiO_2	77.7
5	P_2O_3	0.085
6	SO_3	0.905
7	K_2O	1.19
8	CaO	1.93
9	TiO_2	0.469
10	Cr_2O_3	0.45
11	MnO	0.0549
12	Fe_2O_3	4.51
13	Co_2O_3	0.0063
14	NiO	0.0177
15	CuO	0.007
16	ZnO	0.008
17	As_2O_3	0.01
18	Pb_2O	0.0041
19	SrO	0.0151
20	ZrO_2	0.0312
21	U_3O_8	0.0064

Table IV

Compressive strength of commercial bricks

Brick	Force (kN/m²) Flat face
1	890
2	920
3	665
4	695
5	690
6	641

Table V

Average compressive strength of bricks cured under different

Mixture	Average compressive strength (kN/m²)		
	Water	Oven	Ambient
1	141	165	157
2	20	25	29
3	325	359	318
4	440	439	323
5	262	261	234
6	215	235	230
7	530	479	454
8	149	98	127

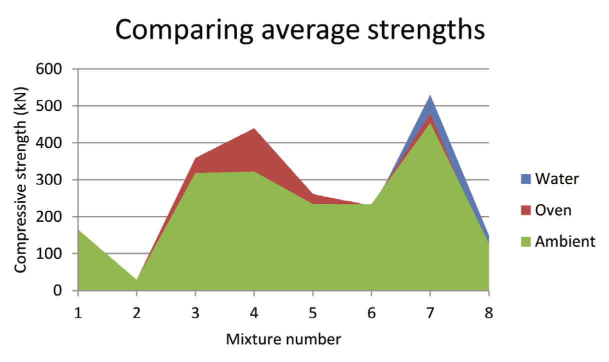

Figure 2—Compressive strength of the cement tailings bricks cured in different environments

adequate supply of moisture is necessary to ensure sufficient hydration for reducing the porosity to such a level that the desired strength and durability are attained

The results also show that in general, bricks from mixture 7 had a higher compressive strength in all three curing system used. However, the highest overall compressive strength was obtained from mixture 7 that was cured in water. This mixture had a higher amount of cement compared to the tailings (2:1 cement to tailings mass ratio), which resulted in a larger surface area of the tailings being in contact with the cement and hence resulting in a stronger mixture. These results also follow for mixtures 3 and 4. The higher strength is probably due to the superior plasticity and binding properties provided by the higher amount of cement. It is also known that cement cures well in water (America's Cement Manufacturers, 2014); hence the mixture with the largest quantity of cement cured in water resulted in the highest compressive strength.

Water absorption and weight loss tests

Compressive strength and water absorption are two common parameters considered by most building materials researchers as required by various standards. Water absorption will influence the durability and strength of the bricks. Figure 3 shows the water absorption rate.

For both solutions, the absorption was highest on the first day of the test followed by a more constant rate in subsequent days. It can also be seen from Figure 3 that the absorption rate was slightly higher in the neutral solution than in the acidic solution. The unconfined compressive strengths after water absorption are shown in Table VI.

The results show that the bricks soaked in the neutral environment had a higher compressive strength than those soaked in an acidic environment. This can be attributed to the fact that during the water absorption test, the neutral solution acts as a natural curing agent and further strengthens the bricks.

The weight loss over the seven day period was quite negligible at 0.06%. This means that although the bricks show significant water absorption rate, they regain their original weight after drying.

Cost analysis

It is important to check if the outcome of the research project is economically viable for it to be beneficial to society. In order to market the bricks, cost comparison with traditional bricks is essential. The following factors were considered.

Gold tailings are available in abundance and are expected to be free of cost

Portland cement=R65 per 50 kg bag (OLX, 2014).

Using a base figure, for commercial brickmaking, the masonry cement recipe can be estimated as follows:

8 bags of cement=1000 bricks (Kreh, 2003), or 1 bag of cement=125 bricks.

For commercial brickmaking, the water addition should be 20 litres per 50 kg of cement (Hydraform, 2014). The price of water for industrial companies according to the City of Johannesburg's Mayoral Committee is R20.96 per kilolitre. (COJ: Mayoral Committee, 2013).

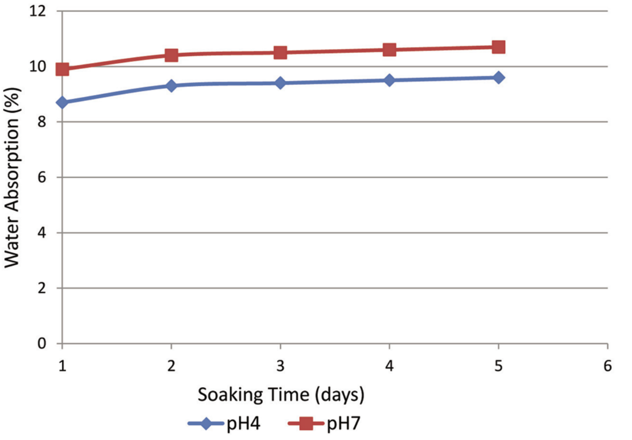

Figure 3—Water absorption rate

Table VI

Average compressive strength after absorption tests

Solution	Compressive strength (kN/m²)
pH 4	445
pH 7	476

In this research project, it was found that the highest strength was obtained in mixture 7, with 5 kg of tailings and 10 kg of cement mixed with 3.3 litres of water, followed by mixture 4 with 7 kg of tailings and 8 kg of cement mixed with 2.5 litres of water. Using the option with the highest strength, it was found that one bag of cement is equivalent to 55 bricks (compared with 125 commercial bricks per bag of cement). However, the water consumption was calculated to be 16.5 litres per bag of cement, which is less than the 20 litres used in commercial brickmaking. Water is an expensive commodity in South Africa and using tailings to make the bricks saves water. Thus, the more economical option would be the second mixing ratio, since it uses less water and cement but still results in relatively high brick compressive strengths. Even though the second option is economically acceptable, the high cement content is a disadvantage. However, regarding the overall brickmaking process some other factors should be considered. The brickmaking plant can be close to the tailings dumps in order to cut down on costs. In addition, it is important to note that most of the tailings material already occurs in fine form, therefore not much size reduction (which is an energy-intensive process) is required.

Since the use of tailings for brickmaking conserves natural resources, one could say that the benefit to the environment outweighs mere economic considerations. The use of tailings would mean that the companies have to spend less on waste management, while at the same time reducing human exposure to tailings, consequently reducing the effect that mine waste has on the health of inhabitants in the mining area. The use of gold mine tailings for brickmaking also constitutes an additional source of revenue for the gold mining companies and in the process creates jobs.

Conclusions and recommendations

This laboratory-scale study was aimed at utilizing Witwatersrand gold mine tailings in making bricks. The results from XRD and XRF showed that the chemical composition of the Witwatersrand gold mine tailings is similar to that of the clay material used for commercial brickmaking. It was then concluded that it would be technically viable to use the tailings for brickmaking. Following the South African masonry standards for brickmaking and testing, it was found that the commercial bricks have an average compressive strength of 750 kN and that the strongest bricks made from the tailings gave an average compressive strength of 530 kN.

Results from water absorption tests showed that water absorption is higher in neutral solutions compared to acidic solutions. The rate of absorption is high in the first day, but then stabilizes. The weight loss over a seven-day period was negligible at 0.06%.

It is recommended that more tests be conducted with a wider range of tailings to cement ratios as this might lead to identifying a ratio that yields a stronger brick than what has been observed in this project. In addition, the sizes of the tailings used as aggregate should be varied to a wider range. This can be achieved by adding overburden to the fine tailings material.

As regards the economic considerations, the tailings bricks were found to utilize more cement than the commercial bricks, possibly due to lack of plasticity in the tailing materials used. This is a disadvantage since cement is expensive. It is thus recommended that cheaper alternative additives that have a high plasticity or binding properties be explored in the place of cement. Looking at the bigger picture, the use of tailings as brickmaking material would have great advantages in terms of environmental conservation and reduction of waste management costs.

Since the XRD analysis showed that uranium is present in Witwatersrand gold tailings, extensive research with regard to the chemical properties and the chemical stability of the bricks produced from gold mill tailings is required.

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