Evaluation of South African gold tailings as a mine backfilling material

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Abstract

This paper presents the results of laboratory investigations conducted on gold mine tailings (GMT) to assess their chemical, mineralogical, leaching and geotechnical characteristics as well their acid generating potential in view of assessing its suitability as an alternative backfilling solution in mine reclamation. Chemical characterisation revealed that GMT is dominated by Si, Al and Fe with notable amounts of Cr, Zr, Zn, Pb, Ce, As, Ba, Ni, V, Sr, Nd, Cu, U and Co. Mineralogical characterisation revealed a composition of silicate minerals with secondary minerals such as jarosite, goethite and hematite. Acid base accounting (ABA) results showed that GMT are acid generating. During column leach experiments, leaching of elements and SO_4^{2-} was significant at initial stages and became negligible thereafter. GMT composites exhibited moderate strength parameters. The effect of curing age and addition of cement contributed to the shear strength of the material. Furthermore, GMT showed favourable characteristics for use in mine backfilling; however, solid/liquid ratios should be maintained to ensure maximum strength. The use of GMT for backfilling is therefore possible; however, blending with higher percentages of cement and alkaline materials such as coal fly ash should be considered to chemically stabilise the material.

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Introduction

Mineral waste is an inevitable consequence of mining and South Africa generates approximately 70% mineral waste annually from its mining activities [10]. Waste generated from gold mining alone accounts for 47% of the total mineral waste generated in South Africa [11]. There are approximately 400 gold tailings dams in South Africa, 270 of which are located within the Witwatersrand Basin covering an estimated area of 400 km^2 [28, 3]. Currently, a few of these tailings dams in South Africa have been reclaimed for re-mining, entailing significant potential to exacerbate the negative environmental footprint of mining. Small percentages of this waste are beneficially utilised for backfilling and construction purposes [21].

A few factors contribute to limited beneficiation of mineral waste in South Africa, such as the absence of a regulatory framework that actively promotes the use of mineral waste and the absence of standards and specifications for mine waste products. Conflicting approaches to mineral waste classification constitute another possible reason why mineral waste in storage facilities result in substantial environmental problems. Godfrey *et al.* [13] alluded to conflicts around the regulation of mineral waste in South Africa, arguing that the fact that “mineral waste” is not defined legally results in conflicts around legislation.

The consequences of mineral waste disposal are fully recognised [32, 24, 31, 27, 8]. As such, work has gone into ensuring atmospheric pollution prevention and mine waste stabilisation through rehabilitation. Moreover, alternatives to mineral waste management have been reviewed. For example, Malatse and Ndlovu [20] and Ogola *et al.* [29] studied the potential beneficiation of gold mine tailings (GMT) for brick manufacturing. Furthermore, Sibanda and Broadhurst [37] explored opportunities, drivers and barriers to re-purposing gold waste in South Africa. However, more research is needed to understand broader potential uses of GMT in mine reclamation such as backfilling. Underground mine backfilling has become an integral part of mine reclamation in most parts of the world. Backfilling provides ground support and regional stability, thus reducing subsidence and improving ore recovery [30, 12]. A wide range of backfilling methods have been assessed, including rock, hydraulic, cemented and silica alumina-based backfilling [36, 38]. The methods considered for backfilling often make use of mineral waste (waste rock and tailings) in conjunction with small proportions of binders such as cement to improve the properties of the backfill material [18]. The use of mineral waste in mine backfilling provides an effective means of disposal owing to cuts in storage costs and a reduced environmental footprint.

Previous studies on the viability of using GMT in mine backfilling (Amaratunga and Yaschyshyn [2], Benzaazoua *et al.* [6], Yilmaz [44]) were encouraging with very few studies of this nature having been carried out in South Africa. Realising the consequences of mineral waste disposal and the opportunity to use such waste in mine reclamation, this study aims to assess the properties of GMT produced by one of the mines in the West Rand Basin in South Africa for mine backfilling purposes.

Materials and experimental methods

Materials

GMT used in the study was a composite sample collected from one the tailings dams of a gold mine in west rand basin, South Africa. The sample was obtained using an auger from a depth of 0.5 m to 5 m to ensure that the non-oxidised layer was represented to the best of our ability. Lafarge CEM II 52.5N (at 3%) was used as an additive for GMT during geotechnical testing to improve the properties of the material. The cement is classified as a high-strength cement, capable of achieving strengths of >52.5 MPa at just 28 days under standard test conditions and fast early strength development of >20 MPa at 2 days.

Experimental methods

Geochemical and mineralogical composition

The chemical composition and mineralogy of GMT was analysed using X-ray fluorescence (XRF) and X-ray diffraction (XRD) respectively. To carry out the analysis, the tailings were air dried and milled to <75 µm. The XRF analysis was carried out using a PANalytical wavelength dispersive AXIOS X-ray fluorescence spectrometer equipped with a 4 KW Rh tube. Quality assurance was attained using an amphibole reference sample. Loss on ignition (LOI) was determined using the ASTM D7384-08 procedure.

XRD was conducted using pressed samples in plastic holders prepared for analyses as whole rock in a BRUKER D8 ADVANCE over a diffraction angle range of 2–70° at a speed of 0.02 2θ with step sizes of 3 sec. Crystallographic phase identification was based on the BRUKER DIFFRAC plus-EVA evaluation program.

Elemental analysis for leachates was carried out using inductively coupled plasma mass spectroscopy (ICP-MS) and anion analysis was carried out using ion chromatography (IC). The accuracy of the analysis was monitored using National Institute of Standards and Technology (NIST) water standards and the sulfate analysis was conducted turbid metrically.

ABA

The acid generating potential of GMT was evaluated using acid base accounting (ABA). The neutralisation potential (NP) and acid producing potential (AP) of samples were investigated using the modified Sobek method. Subsequently, the net neutralisation potential (NNP) and the neutralisation potential ratio (NPR), also known as the ABA, was determined using the same method [39].

Column leach test

Column leach experiments were conducted using a 1 m high column with an internal diameter of 26 mm. The column was filled with approximately 55 g dry GMT sample and the tests were run in a downward vertical flow mode using deionised water. Water flow was controlled using a peristaltic pump at a rate of three revolutions per second (rps) to give a controlled flow rate of 0.1 mL/minute. At the end of each leaching cycle (a week), the sample was filtered and preserved prior to ICP-MS and IC analysis.

Geotechnical tests

A geotechnical testing programme was conducted for the GMT samples, remoulded to 95% maximum dry density (MDD) with the addition of 3% CEM II 52.5N cement. The samples were cured in moisture over 7, 28 and 56 days curing periods at a room temperature of about 23 °C. The laboratory tests included a particle size distribution test, Atterberg limit test, a Proctor test, a permeability test, compression tests using unconfined compression strength (UCS) and standard oedometer and shear strength tests by means of box shear testing.

The grain size distribution of the material was carried out as per ASTM D422-63 using a sieve method. The particle size was characterised using the basic particle size classification for soils. Atterberg limit tests were conducted as per ASTM D4318 to measure the critical water content of the material. The test was evaluated on a 100 g sample passing through a 245 µm sieve. Liquid limit tests were carried out using Casagrande’s equipment.

The compaction characteristics of the material were studied using a modified Proctor test as per ASTM D1557 to determine the MDD and optimum moisture content (OMC) of the material. To obtain the variables, samples were mixed with water as per the requirements of the standard and compaction procedures in five equal layers in a mould by delivering 25 blows with a hammer on each layer. After the samples had been fully compacted, the moisture content and the dry density of the samples were determined.

Permeability tests were performed as per BS1377 part 6 to assess the hydraulic conductivity of the material. A flexible wall permeameter induced by a cell pressure of 10 kPa was used for the test. The relationship between the void ratio and the degree of saturation in relation to the coefficient of permeability was established.

The compression strengths of the samples were evaluated using the UC) (as per ASTM D2166) and standard oedometer (BS1377 part 5) tests to accurately measure the unconfined compressive strength of the materials.

Consolidation was achieved using static loads of pressures 10, 25, 50, 100, 200, 400, 800 and 1 600 kPa up to 12 hours per loading while unloading was achieved using 400, 100 and 10 kPa. Changes in thickness and void ratios in response to the effective stress were subsequently recorded.

The shear strength of the samples was assessed using box shear testing (ASTM D2166) to determine the consolidated drained shear strength of the samples under confining vertical stress applied at 50, 100 and 200 kPa. The total shear strength characteristic of the material cohesion (c) and the angle of shearing resistance (φ) in terms of Mohr Coulomb were established.

Results and discussions

Geochemistry and mineralogy of GMT and cement

The chemical composition (major and trace elements) of GMT and cement are summarised in Table 1. The major constituents of the tailings are Si, Al and Fe. The tailings contained varying concentrations of metals and metalloids, as follows, from moderate to high: Cr, Zr, Zn, Pb, Ce, As, Ba, Ni, V, Cu, U and Co exceeding the threshold concentrations for soils [9].

The presence of these elements in the GMT qualifies gold tailings as a possible source of soil and water pollution within the storage boundary as reported by Kneen *et al.* [16]. Aucamp and Schalkwyk [4] noted that elements such as Cr, Zn, Pb, Ni, Cu and Co are highly mobile in tailings materials and their mobility is pH dependent. The authors noted that the mobility of these elements is prominent at pH values below 3.5 becoming more stable at a neutral pH. The presence of pyrite in the tailings (Figure 1) reduces the pH during oxidation, triggers the mobility of elements and results in the formation of acid.

The cement used in this study, similar to most cements on the market, contains reasonable amounts of alkali oxides (Table 1), which play an important role in cement hydration. LOI for GMT and cement was low, indicating the low percentage of moisture, carbonates and organic matter [15].

Mineralogical analysis by XRD revealed that the major minerals present in GMT are quartz (SiO_2), mica ($KAl_3Si_3O_{10}(OH)_2$) and kaolinite ($Al_2Si_2O_5(OH)_4$) (Figure 1). Elevated quantities of SiO_2 (23.3%) may be attributed to its abundance in nature together with its high resistance to weathering and dissolution, related to hardness (7 on a Mohs scale) [19]. The presence of pyrite (FeS_2) is common in Witwatersrand GMT as it is commonly found in nature. When pyrite is found in tailings, the oxidation of this mineral increases the acidity and consequently the mobility of potentially toxic elements. The concentration of secondary minerals such as jarosite ($KFe^{3+}{}_3(OH)_6(SO_4)_2$), goethite (FeO(OH) and haematite (Fe_2O_3) is an indication of the oxidation of sulphide minerals, in this case pyrite, as well as an indication that the tailings are acid producing [24]. Moreover, the absence of calcite in the tailings is synonymous with studies conducted by Rosner *et al*. [34], Rosner and Van Schalkwyk [33] and Van Rensburg [42]. These authors noted the presence of calcite in trace concentrations, which suggests that the tailings have low neutralising potential.

Acid base accounting test (ABA)

The ABA results of GMT are presented in Figure 2. The paste pH of GMT was acidic registering a pH value of 3.21. The acidity of the tailings could be attributed to low concentrations of Ca wt.% (0.68%) which control the alkalinity of the material and the dissolution of sulfur (recorded at 0.750%), Al (7.25%) and Fe (4.27%) which plays a role in the release of acid and the mobilisation of metals and metalloids. The net neutralisation potential (NNP) of the GMT was recorded at -42% and the neutralisation potential ratio (NPR) was recorded at -0.8, which theoretically suggests that the tailings have the potential to generate acid [17].

Column leach tests

Mine waste, GMT in particular, has been reported to contain metals and metalloids in concentrations that are potentially hazardous to the environment. Studies conducted by Grover *et al.* [14], Munyai [23], Netsiongolwe [25] have alluded to the leaching characteristics of GMT and their impact upon disposal. The authors have noted that the dissolution and mobilisation of elements depend on various factors such as pH, leaching medium, leaching time and the solid-liquid ratio. The prediction of the leaching behaviour of mine waste is therefore critical to assessing the environmental impact of storage and to choosing appropriate waste management methods to minimise the impact of such waste.

This study used column leaching to establish the leaching characteristics of GMT by analysing the concentrations of certain environmentally sensitive elements in leachates. In addition to the environmental conditions to which GMT will be exposed, as represented by the leaching medium, column leach tests also give an indication of the long-term leaching behaviour of GMT. Column leach tests with deionised water simulate GMT coming in contact with groundwater over the long term.

Column leachate pH

The variation in pH of leachates as a function of time (eight weeks) for column experiments is presented in Figure 3. The results show that the pH of the GMT leachate was low, coinciding with the chemistry of the tailings.

The pH values of leachate from GMT ranged from 5.3 to 3.1 over the eight week leaching period. The drop in pH during the eight weeks leaching is an indication of the oxidation of pyrite in the presence of water, which can increase the acidity and consequently mobilise metals.

Leaching characteristics

Column leach

The concentrations of some of the environmentally sensitive chemical species in GMT column leachates are presented in Table 2.

In general, all the elements under investigation and SO_4^{2-} from the GMT were partially mobilised and leached out into the solution during week 1 of leaching (except for U and Fe). Thereafter, the concentrations were either gradually reduced or remained constant in the leachates collected from week 2 to week 8. This indicates that the soluble fraction of these chemical species was reduced with increasing time and exposure to water, showing resistance to leaching after the initial cycles of flushing. The concentrations of Pb, Al, Cu and Cr after week 1 of leaching were below the detection limit, in spite of their moderate to high concentrations in the GMT as indicated by XRF analysis. Based on these results, it can also be noted that leaching of elements was not controlled by the pH of the leachates, but rather, that it represents a function of contact time with water. Moreover, the leaching medium, which is deionised water in this instance, was not strong enough to mobilise these sensitive elements into solution in spite of a drop in pH and an increase in acidity. However, the concentrations of some of these elements and the SO_4^{2-} are higher than the permissible limits for domestic water (SANS 241:2015) [35], although this standard is perhaps conservative in terms of comparative purposes, as we are evaluating the leaching behaviour of a waste material.

Furthermore, the leaching experiments were carried out without blending GMT with cement to assess what leaches out from the unblended sample and to represent a worst-case scenario, in case the material were to disintegrate when placed underground by adding cement. Blending GMT with cement would have solidified the sample in the column and the flow of water would not have been possible to assess the leaching characteristics.

Geotechnical tests

Utilisation of mineral waste as a geo-material requires a thorough understanding of its geotechnical characteristics, especially in terms of its strength, resistance to water flow and shear resistance. This section provides a detailed discussion of the geotechnical characteristics of GMT in view of understanding their rheological characteristics and feasibility in applications such as mine reclamation. The results presented in this section were obtained from the test work conducted on untreated tailings (zero curing and zero cement addition) and treated tailings (3% cement addition and curing).

It is important to note that all indicator tests (particle size distribution, Atterberg limits and Proctor tests) were conducted on untreated tailings, while all the other tests were conducted on treated tailings cured for 7, 28 and 56 days.

Grain size distribution

The particle size distribution of GMT is shown in Figure 4. Details regarding particle size distribution characteristics are presented in Table 3.

It can be observed that the particle size distribution obtained for GMT is composed of 52% sand, 40% silt and 8% clay fractions with ranges of 0.01mm to 1 mm. The coefficient of uniformity (Cu) for the tailings was 12, which is comparable to well-graded sand. The coefficient of curvature for the tailings was 0.5, therefore outside the range for well-graded sands. Upon the addition of the 3% cement, the particle size composition was changed to 21% sand, 67% silt and 12% clay fractions, resulting in more silt fractions. The coefficient of curvature (Cc) value was also adjusted to 2.6, providing for a categorisation under well-graded sand (Table 3).

Atterberg limits

Atterberg tests revealed that the tailings are non-plastic. Therefore, the liquid limit and plastic index could not be determined. According to Bartle [5], non-plastic soils have an inherent shear resistance to sliding with the addition of water and can only lose 50% shear strength because of water floating on top, contrary to clays that lose 99.5% of their total shear resistance to sliding due to drainage. Based on the particle size distribution and plastic limit, it can be resolved that the tailings are likely to have shear resistance.

Compaction characteristics

The compaction characteristics of GMT are given in Table 4. Furthermore, the compaction curve is presented in Figure 5.

The tailings without cement exhibited a high MDD of 1 588 kg/m^3 and a moderate OMC of 14.9%. Upon the addition of cement, the MDD and OMC of the tailings decreased to 1 555 kg/m^3 and 10.4% respectively, similar to trends noted by Al-Khafaji [1]. The author noted that additives such as cement decreases the MDD of soils owing to chemical reactions between the molecules of cement, clay and water.

Tatt and Ali [40], however noted, that decreases in MDD and OMC values are dependent on the type of soils; for example, soils predominantly comprising sand particles will result in an increase in MDD and a reduction in OMC, whereas soils with mostly clay particles will show a slight reduction in MDD and an increase in OMC with the increasing addition of cement. The decrease in OMC noted upon the addition of cement could be attributable to the cementation of the tailings induced by the 3% addition of cement, which resulted in the decreased moisture of the tailings.

The tailings also possessed high densities compared to the tailings containing 3% cement. However, the impact of compaction had a minimal effect on the tailings compared to the tailings composite. For example, a decrease in densities with varying moisture was noted for the tailings, while an increase in densities was noted for the composite sample (Table 5). Based on the results presented, it may be concluded that the addition of cement to the tailings greatly increased the compaction properties of the tailings. Furthermore, these compaction results indicate that the material can be used in civil works, based on the Indian Road Congress (IRC) compaction specifications.

Permeability characteristics

The permeability coefficient (k) of soils is an important parameter in mine backfilling in order to limit seepage into groundwater. Table 5 presents the values of the coefficient of permeability (k) for compacted GMT cured in moisture for 7, 28 and 56 days and induced by a consolidation pressure of 100 kPa. The table also provides the void ratio of the material in response to pressure.

An increase in the coefficient of permeability was noted for tailings after increased curing periods and the addition of the cement. The average coefficient of permeability ranged from 3.8E-07, 2.9E-07, 9.0E-07 to 9.0E-07 m/s. Based on the results it appears that the addition of cement to GMT increases the fine fractions, resulting in larger interparticle voids, which are responsible for hydraulic conductivity. The coefficient of permeability of the tailings was observed to be in the range of silt sand (between 10^{-3} and 10^{-5}). This permeability range is attributed to the well grading of particles in the tailings.

Compression characteristics

Unconfined compressive strength (UCS)

The measure of resistance to external loading was evaluated using UCS and a standard oedometer. The specimens were prepared at MDD and OMC by standard compaction at a room temperature of about 23 °C. Tailings containing cement were cured for 7, 28 and 56 days and the tailings without cement did not undergo curing. The UCSs of GMT at varying ages of curing are presented in Table 6.

From these results, it is apparent that the GMT had a good strength of 129 kPa. The early high strengths recorded for the tailings could be attributed to the well grading of the particles that resulted in the interlocking of particles and subsequent artificial cementation.

Moreover, it is apparent that UCS increased with the age of curing. By the 56th day of curing, the tailings had achieved a high strength of 412 kPa, indicating the effectiveness of the addition of cement and increased age of curing on the strength gain. This is agreement with what was reported by Tatt and Ali [40], namely that the UCS of soils increases with cement addition and age of curing.

Changes in moisture were also observed for GMT; the moisture of the tailings decreased with the age of curing. The initial moisture recorded for the GMT was 15.1 and decreased by 1.32% after seven days of curing and the addition of cement. A gradual loss until the 56th day of curing was noted consistent with the compaction effort.

Based on the UCS results presented, cement addition and the age of curing greatly enhanced strength developments of the tailings. Moreover, the strain variables achieved at these compressive strengths are an indication of the stiffness of the sample. It would be interesting to evaluate the effect of varying cement percentages on the strength properties of the tailings, to prove reports by Bergado *et al*. [7] that high additions of cement result in rapid improvements in the strengths of soils compared to scenarios where the soils percentages of cement are added.

Standard oedometer

Figure 6 shows variations in the void ratios for the tailings with increasing stresses at MDD of 1 315 kg/m^3 and OMC of 36.0. The one-dimensional consolidation for the tailings was induced by a vertical normal stress range of 10–1 600 kPa; unloading was achieved by stresses of 400, 100 and 10 kPa applied over 12 hours for each load.

A decrease in void ratio with an increase in stress was observed, followed by an increase upon unloading. At low stress levels, the changes in void ratios was minimal and increased as the load increased. It can be noted that the void-stress curve for GMT with zero cement and zero curing bent rapidly as loading was applied compared to the tailings to which cement had been added and which had been subjected to varying curing ages.

A rapid compressibility of the tailings was noted with increasing stress. This is demonstrated by a rapid drop in the void ratio which is indicated by the height of the specimen (Table 7). The rapid compressibility of the tailings may be attributed to the differences in particle sizes of the tailings resulting in gradual crushing with applied load. The steady drop in void ratios noted for tailings cured for 7, 28 and 56 days, together with cement could be attributed to the stiffness of the tailings resulting from the hydrolysis of the cement.

The decrease in voids corresponds to decreases in the height and moisture content of the specimens (Table 7).

During compression, GMT with zero curing and cement experienced increased strain at vertical stresses of 50–1 600 kPa (Figure 7). The cured samples experienced strain at varying vertical stresses. The 28th day cured sample experienced maximum strain compared to the 7 and 56th day cured sample. However, the 56th day sample experienced lower strains than all the cured samples.

Based on the results obtained, the importance of curing and the addition of cement for enhancing the strength of the tailings was demonstrated. No failure points in stress-strain behaviour were noted with the imposition of increasing vertical stresses. However, the materials showed enhanced strengths at high stresses corresponding to the age of curing.

Shear strength characterisation — box shear

The shear strengths for the tailings compacted to their MDD and OMC and induced by normal effective stress of 50, 100 and 200 kPa are presented in this section. Figure 8 shows the relationship between normal stress and shear stress for the GMT. Variations of shear strengths in response to varying curing ages are shown in Table 8 and Figures 9 and 10.

At the initial stage (no cement and zero days of curing) of the shear test, the results revealed minimum values of the angle of internal friction (φ), recorded at 29° for the tailings. No increase in the angle of internal friction was noted for the tailings after the seventh day of curing. By the 28th day of curing, an increase of 31.03% was noted and by the 56th day of curing, a slight decrease in φ was noted. Based on the results, it is concluded that the effect of curing on the φ

of the tailings was observed only by the 28th day of curing and that, beyond the 28th day, curing had no impact on the φ.

Values of cohesion were minimal at zero cement addition, and improved with increasing curing periods and cement addition, as noted by Uchaipichat and Limsiri [41]. An increase in cohesion was noted during the seven days of curing, followed by a slight decrease during 28 days of curing and, again, a significant increase at 56 days of curing. Studies conducted by Moayed *et al.* [22] corroborate the significance of cement on cohesion and the angle of internal friction. The authors noted the significant increase in these shear properties of soils with cement addition.

The increase in cohesion during the seven days of curing could be attributed to the initial cementation reaction between the tailings and the cement at the right moisture content. This is apparent from the cohesion values of the tailings where there had been zero curing and zero cement addition. The drop in cohesion noted at 28 days of curing could be attributed to the saturation of the samples with moisture, resulting in a loosening of the particles. By the 56th day of curing, the tailings saw an increase that resulted in cohesion values of 42 kPa, which is an indication of a highly cohesive material (Figure 10) and the long-term impact of curing.

Based on the φ and c parameters recorded for the tailings, it may be concluded that the material has a moderate capability to withstand shear stress and may indeed be suitable for backfilling. However, the possibility of increasing the percentage of cement used should be explored to ensure maximum shear strength.

Conclusion

Storage and management of GMT in South Africa present challenge and alternate applications are continually being sought. Studies related to mine backfilling using GMT in the South

African context are scarce. Therefore, this study was carried out to evaluate the geochemical and geotechnical characteristics of tailings generated by the gold mines in South Africa to investigate their potential use as a mine backfilling material.

Geochemical investigations indicated that leaching of chemical species is a reality when this material is placed underground. In general, it was observed that the leaching of elements/ions decreased or stabilised as the number of leaching cycles increased, indicating that the material will stabilise after initial contact(s) with underground water. However, in the absence of a representative "monolithic leaching protocol", the conditions under which this material was investigated represents a worst-case scenario. The material that was subjected to leaching was loose (like a soil) with no additive (cement) added for the leaching experiments. In reality, for backfilling purposes, the tailings will be mixed with an additive and placed underground. Therefore, it is safe to assume that the material will consolidate while underground and its leaching behaviour will be more conservative. Moreover, ABA studies indicated that GMT is acid generating and that the leaching of these elements will be more pronounced in acidic conditions. Considering the geochemical nature of tailings, it is recommended that GMT be blended with a pozzolanic alkaline material such as fly ash and studied before placing underground. Studies (e.g. Yeheyis *et al.* [43]) indicate that geopolymers made of GMT blended with fly ash can be used as lining material for mine dumps. The GMT-fly ash geopolymers gained enough strength and chemical stability over the curing period and the results were quite promising [26].

The GMT cement composites evaluated in this study revealed appreciable strength properties, which are attributed to the 3% cement addition and the age of curing. The tailings showed enhanced strength properties at high stresses corresponding to the age of curing. Moreover, the tailings showed a likelihood for shear resistance, together with a stiffening with the addition of cement and increased curing age. In essence, the tailing composites yielded appreciable geotechnical properties suitable for application in mine backfilling; with the only drawback being the permeability properties of the material, which showed increased permeability with age of curing. It is therefore advised that the addition of a wider variety of percentages of cement be evaluated to improve the permeability properties of the tailings and to further ascertain the geotechnical properties of the GMT. Moreover blending with coal fly ash should be assessed in order to chemically stabilise the material.

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Declaration of interest statement

The authors wish to confirm that there are no known conflicts of interest associated with this publication, furthermore, there has been no financial support given to influence the outcome of this work.

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FIGURE CAPTIONS

Figure 1 *XRD results (in wt. %) for the GMT.*

Figure 2 *NP and AP for GMT.*

Figure 3 *Leachate pH of GMT over an eight weeks leaching period.*

Figure 4 *GMT particle size distribution.*

Figure 5 *Compaction curves for GMT.*

Figure 6 *Relationship between void ratio and vertical stress for GMT.*

Figure 7 *Relationship between strain and vertical stress for GMT.*

Figure 8 *Relationship between normal stress and shear stress for GMT.*

Figure 9 *Relationship between curing period and shear stress.*

Figure 10 *Relationship between curing period and cohesion.*

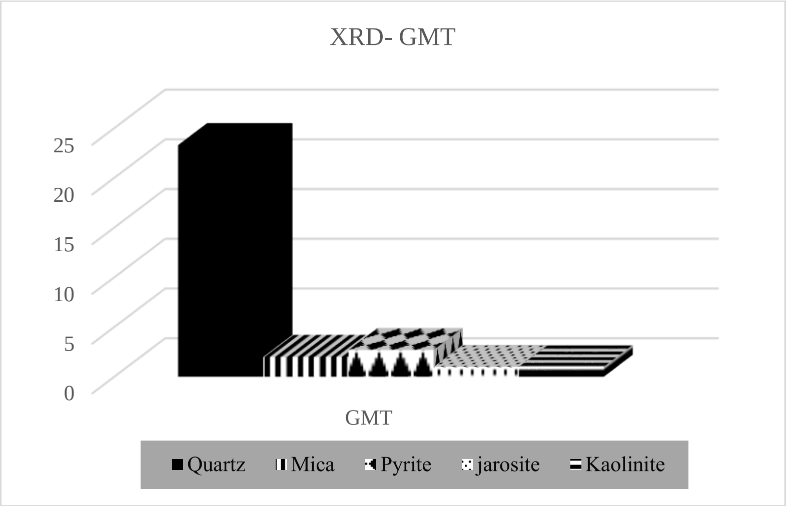

Fig. 1

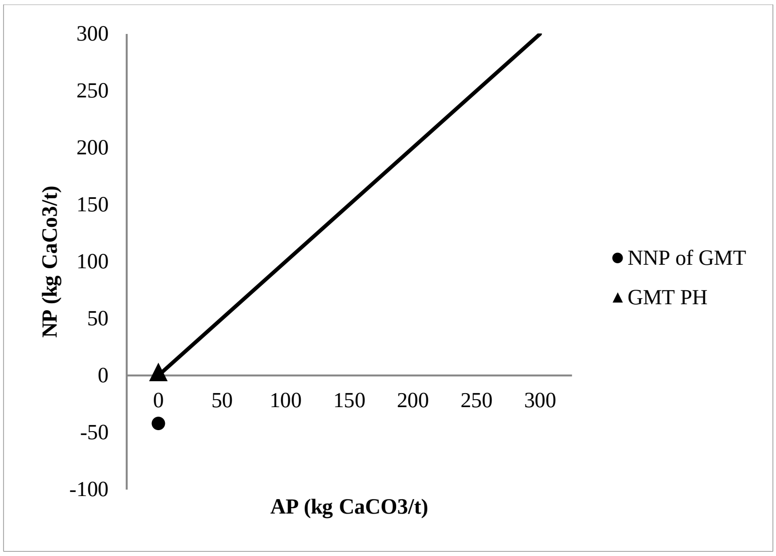
300
250
200
150
100
50
0
-50
-100
NP (kg CaCo3/t)
0
50
100
150
200
250
300
AP (kg CaCO3/t)
● NNP of GMT
▲ GMT PH

Fig.2

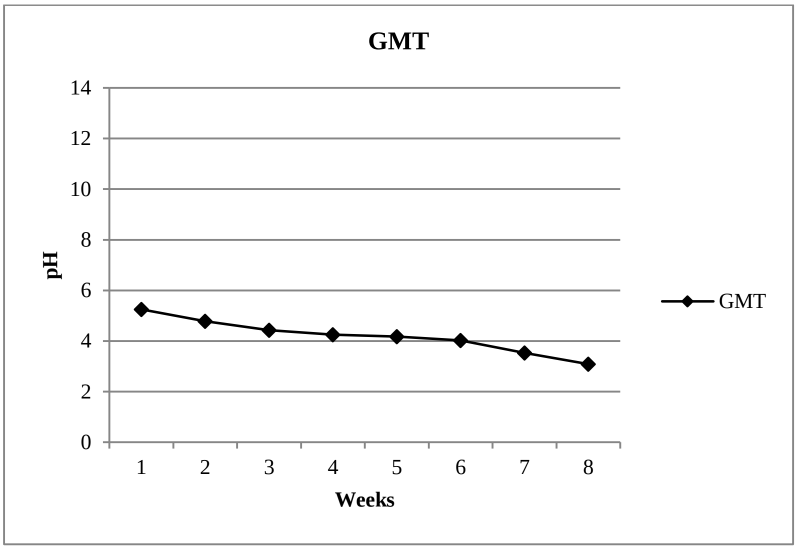
GMT
14
12
10
8
6
4
2
0
pH
1
2
3
4
5
6
7
8
Weeks
GMT

Fig.3

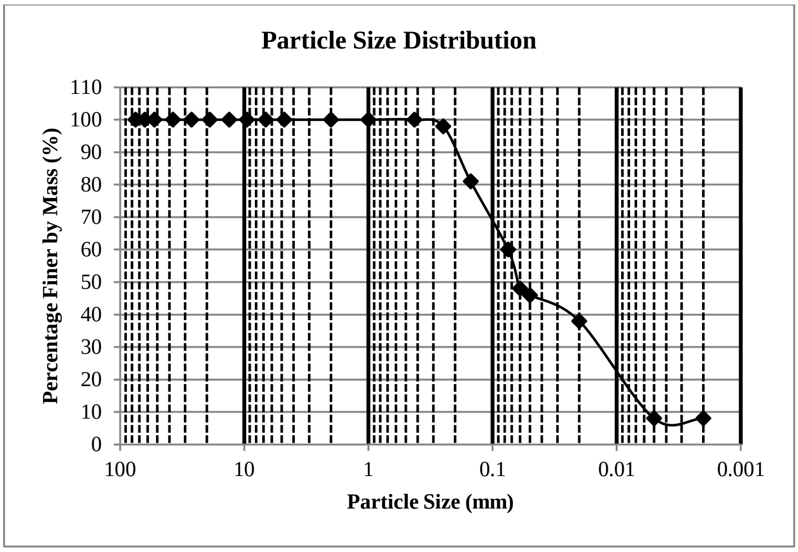
Particle Size Distribution
Percentage Finer by Mass (%)
110
100
90
80
70
60
50
40
30
20
10
0
100
10
1
0.1
0.01
0.001
Particle Size (mm)

Fig.4

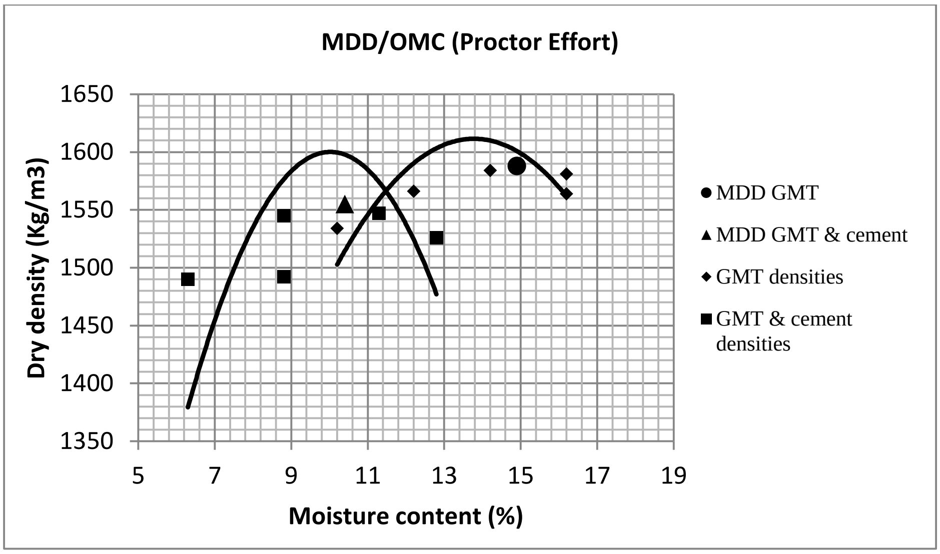
MDD/OMC (Proctor Effort)
Dry density (Kg/m3)
1650
1600
1550
1500
1450
1400
1350
5
7
9
11
13
15
17
19
Moisture content (%)
● MDD GMT
▲ MDD GMT & cement
◆ GMT densities
■ GMT & cement densities

Fig.5

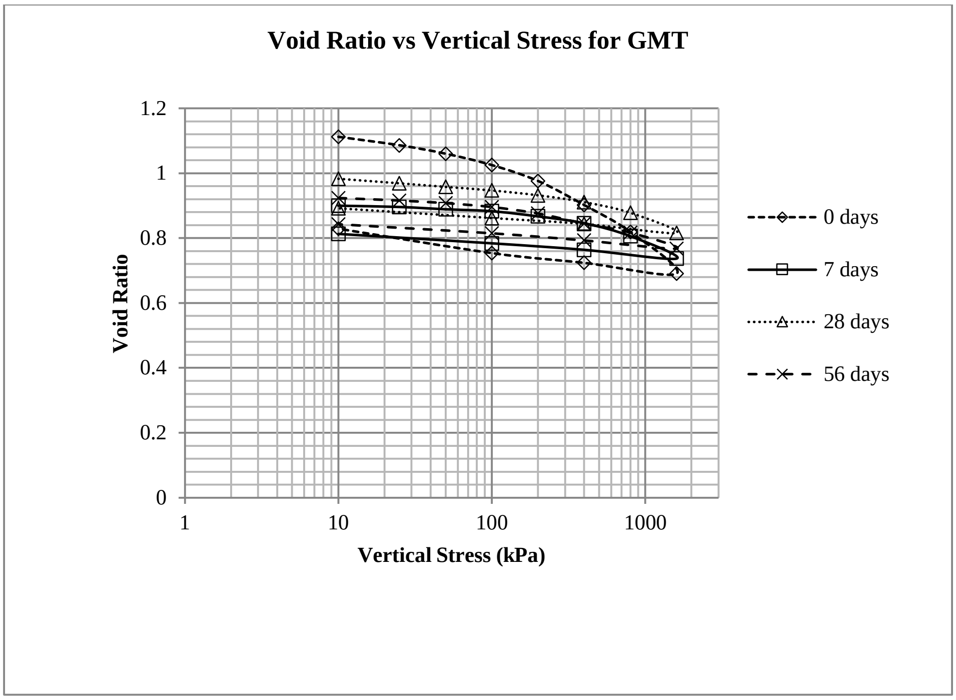
Void Ratio vs Vertical Stress for GMT
1.2
1
0.8
0.6
0.4
0.2
0
Void Ratio
1
10
100
1000
Vertical Stress (kPa)
0 days
7 days
28 days
56 days

Fig.6

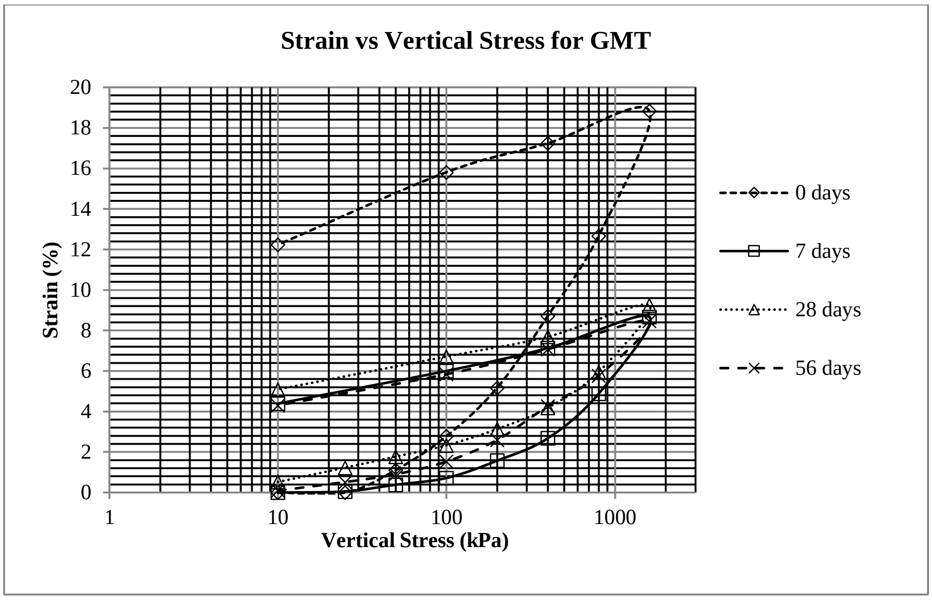
Strain vs Vertical Stress for GMT
20
18
16
14
12
10
8
6
4
2
0
Strain (%)
1
10
100
1000
Vertical Stress (kPa)
0 days
7 days
28 days
56 days

Fig.7

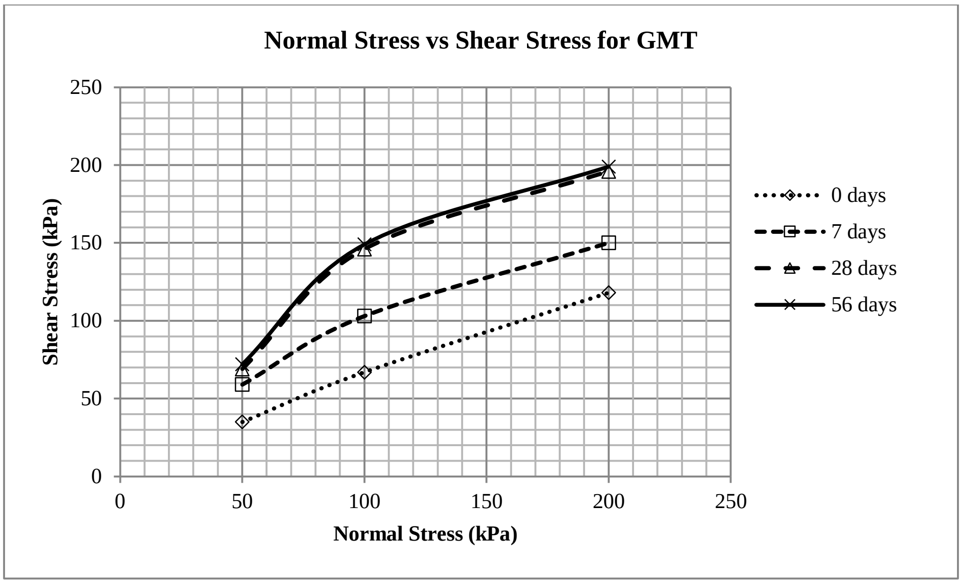
Normal Stress vs Shear Stress for GMT
Shear Stress (kPa)
250
200
150
100
50
0
0
50
100
150
200
250
Normal Stress (kPa)
0 days
7 days
28 days
56 days

Fig.8

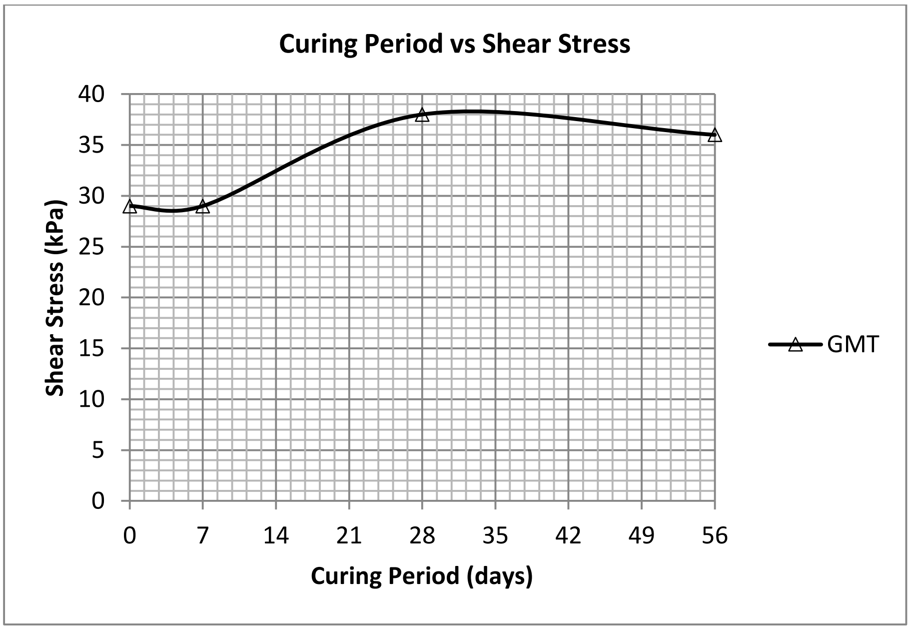
Curing Period vs Shear Stress
Shear Stress (kPa)
40
35
30
25
20
15
10
5
0
0
7
14
21
28
35
42
49
56
Curing Period (days)
GMT

Fig.9

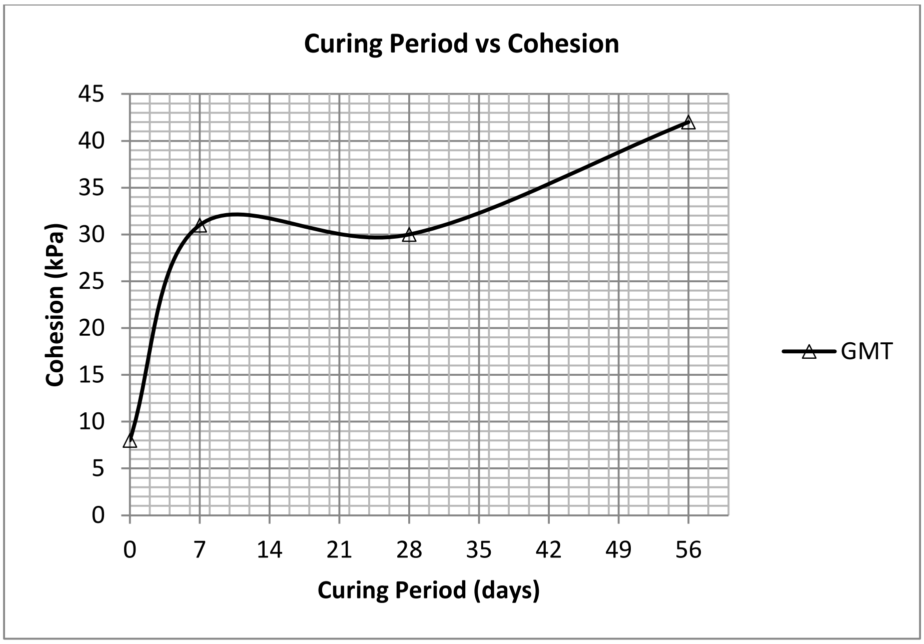
Curing Period vs Cohesion
Cohesion (kPa)
45
40
35
30
25
20
15
10
5
0
0
7
14
21
28
35
42
49
56
Curing Period (days)
GMT

Fig.10

Table 1 The XRF results of major and minor elements (in wt. %) for GMT and cement

		GMT (wt. %)	Cement (wt. %)			GMT (ppm)
Major Elements	**SiO_2**	36.6	20.0	**Trace Elements**	**As**	51
	TiO_2	0.27	0.2		**Ba**	51
	Al_2O_3	7.25	4.0		**Zn**	60
	Fe_2O_3	4.27	2.5		**Ce**	53
	MnO	0.03	-		**Co**	11
	MgO	2.20	2.9		**Cr**	182
	CaO	0.68	63.7		**Cu**	20
	Na_2O	0.13	0.1		**Ni**	34
	K_2O	0.30	0.7		**Pb**	58
	P_2O_5	0.05	0		**U**	14
	Cr_2O_3	0.04	-		**V**	34
	LOI	2.59	3.8		Zr	148

Table 2 Leaching characteristics of environmentally sensitive chemical species (in mg/l) from GMT over 8 week leaching period

Week	**SO_4^{2-}**	**As**	**Zn**	**U**	**Mn**	**Fe**	**Pb**	**Al**	**Cu**	**Cr**
1	2063	0.36	1.1	0.16	0.38	0.33	0.05	0.07	0.74	0.04
2	1677	0.01	0.04	0.56	0.32	0.48	0.001	<0.100	0.010	0.01
3	1812	0.02	0.02	0.47	0.34	0.50	<0.001	<0.100	0.007	0.01
4	1720	0.03	0.04	0.25	0.28	0.35	<0.001	<0.100	0.007	<0.001
5	1687	0.05	0.04	0.25	0.21	0.49	<0.001	<0.100	0.001	<0.001
6	1600	0.05	0.04	0.23	0.19	0.50	<0.001	<0.100	0.001	<0.001
7	1523	0.06	0.06	0.23	0.19	0.53	<0.001	<0.100	<0.001	<0.001
8	1473	0.06	0.06	0.22	0.18	0.59	<0.001	<0.100	<0.001	<0.001

Table 3 Particle size distribution characteristics of GMT

Properties	**GMT**
Sand sizes (0.06mm-2mm)	52
Silt sizes (0.002mm-0.06mm)	40
Clay size (<0.002mm)	8
D60 (mm)	0.075
D30 (mm)	0.015
D10 (mm)	0.006
Coefficient of uniformity Cu	12
Coefficient of curvature Cc	0.5 and 2.6

Table 4 Compaction characteristics of GMT

Properties	GMT	GMT with 3% cement
MDD (kg/m^3)	1588	1555
OMC (%)	14.9	10.4
Dry density (kg/m^3)	1584	1547
	1581	1526
	1566	1545
	1534	1490
	1564	1492
Moisture content (%)	14.2	11.3
	16.2	12.8
	12.2	8.8
	10.2	6.3
	16.2	8.8

Table 5 Values of permeability at a normal stress of 100 kPa

Samples	Initial void ratio (e)	Coefficient of permeability (m/s)	Dry density (kg/m^3)	Initial degree of saturation
GMT (0 days)	0.933	3.8E-07	1417	38.8
GMT + 3% cement (7 days)	0.932	2.9E-07	1382	31.8
GMT + 3% cement (28 days)	0.932	9.0E-07	1382	27.7
GMT + 3% cement (56 days)	0.861	9.0E-07	1434	21.6

Table 6 Unconfined compressive strength for GMT

Samples	Moisture content (%)	Dry density (kg/m^3)	Compressive strength (kPa)	Axial strain at max. (%)
GMT (0 curing)	15.1	1416	129	1.96
GMT + 3% cement (7 days)	14.9	1419	315	1.49
GMT + 3% cement (28 days)	13.7	1416	386	1.14
GMT + 3% cement (56 days)	12.2	1402	412	0.89

Table 7 Specimen height vs. moisture content

Samples	Specimen Height (mm)			Moisture Content (%)	
	Initial Height before loading	Height after final loading	Height after unloading	Before test	After test
GMT (0 curing)	25.4	20.61	22.29	15.7	36.0
GMT + 3% cement (7 days)	25.4	23.198	24.285	12.1	31.5
GMT + 3% cement (28 days)	25.4	23.053	24.109	10.2	33.3
GMT + 3% cement (56 days)	25.4	23.250	24.307	4.6	33.5

Table 8 Changes in the angle of internal friction in response to curing

Samples	**Angle of internal friction (φ)**	**Cohesion**	**MMD (kg/m^3)**	**OMC (%)**
GMT (0 curing)	29	8	1555	10.4
GMT + 3% cement (7 days)	29	31	1555	10.4
GMT + 3% cement (28 days)	38	30	1555	10.4
GMT + 3% cement (56 days)	36	42	1555	10.4