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Durability, Strength and Stiffness of Compacted Gold Tailings-Cement Mixes

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ABSTRACT: Compaction and Portland cement addition are amongst promising ground improvement procedures to enhance the mechanical properties of gold tailings. The present investigation intends to compute the impact of Portland cement content and dry density on the properties (durability, stiffness and strength) of compacted gold tailings-cement mixes. Its main significant addition to knowledge is quantifying the accumulated loss of mass (ALM) after wet/dry cycles, shear modulus at small strains and unconfined compressive strength (q_u) as a function of the porosity/cement index. In addition, the existence of an exclusive relation connecting accumulated loss of mass divided by the number of wetting/drying cycles and porosity/cement index is revealed empirically. This broadens the applicability of such index by demonstrating it controls not only mechanical but also endurance performance of compacted gold tailings-Portland cement mixes.

Keywords: Gold tailings, durability, Portland cement, shear modulus, strength, porosity/cement index.

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INTRODUCTION

A major environmental disaster occurred in southeast of Brazil in November 2015 with the failure of an iron ore tailings dam, containing 62 million cubic meters of iron ore fine-grained tailings (Agurto-Detzel *et al*. 2016). This disaster claimed the lives of dozens of people and contaminated the whole Doce river basin (destroying its regional ecosystem for about 500 km of length, until reaching the Atlantic Ocean) (Escobar 2015). In order to reduce the possibility of similar tragedies in the future, several measures have been studied to deal with the source of such problem. For one side, looking at reducing the liquefaction potential of the tailings already impounded behind tailings dams, taking measures to increase the safety, such as the use of ground improvement techniques to reduce tailings void ratio (Kumar 2001). On the other side, studies are focusing on its use as a composition material for the construction of compacted embankments, sub-base of pavements and mining backfill (e.g., Fahey *et al*. 2009; Consoli *et al.* 2008, 2009; Helinski *et al.* 2011). This study falls in the latter group. It aims to examine the mechanical behaviour of tailings to assess its potential for use as a sub-base material for low volume road when combined with Portland cement and compacted properly.

Understanding tailings management techniques is of fundamental interest for engineers and researchers who aim to utilise tailings as a construction material. Several researchers have discussed the features of different management techniques. According to the Ministerial Council on Mineral and Petroleum Resources and the Mineral Councils of Australia, there are nine key principles for effective mine tailings management, including the adoption of a risk-based approach, minimizing tailings production and maximizing tailings reuse, and considering relevant economic, environmental and social aspects (MCPR and MCA 2003). That publication includes detailed discussion on implementation and operation of mine tailings, including procedures, monitoring and audit programs. In addition, DTIR (2007) examines other aspects of the life of mine such as planning and design, construction, operation and closure planning. Despite the relevance of the existing studies on tailings management, further development tools such as environmental and social impact assessment are necessary since these aspects are not currently covered by most of the publications (Chryss et al. 2012; Nguyen et al. 2014; McLellan et al. 2009). Currently, most mines apply a conventional method that consists of disposing tailings by transporting slurry through pipes into a tailings storage facility (TSF) or a tailings dam (Adiansyah et al. 2015). Although this method requires a high amount of water and is not eco-friendly, it is widely employed because of its cost effectiveness (Adiansyah et al. 2015). Boger et al. (2012), Fourie (2012) and Moolman and Vietti (2012) claim that the implementation of new techniques such as thickened tailings (TT) and tailings paste (TP) technologies is capable of reducing future cost of mining rehabilitation and maintenance. Additionally, Boger (2011) affirms that these technologies increase the mine liability and hence the susceptibility to environmental damages.

In order to assess the use of tailings as construction material, strength tests are usually employed as a way to examine the influence of diverse variables on artificially cemented soil behaviour. A logical dose procedure for soil-Portland cement was created by Consoli *et al.* (2007) taking into consideration the porosity/cement index as a proper parameter to assess strength (q_u) of soil-Portland cement mixes. Yet, so far no research has examined the applicability of the porosity/cement index (η/C_{iv}) for compacted tailings-cement mixes in terms of loss of mass after dry/wet cycles to check durability, strength (q_u) and shear modulus at small strains. This study targets to determine straight relations between η/C_{iv} and accumulated loss of mass after wetting/drying cycles (durability), shear modulus and q_u for compacted gold tailings-cement mixes.

Accordingly, key issues for earthwork projects employing compacted gold tailings-cement blends that continue without a response are: Are the usual quantities of Portland cement and compaction energy ordinarily employed adequate to produce the requisite durability, stiffness and strength improvements? Are there single relations for the compacted gold tailings-cement mixes relating shear modulus and q_u with η/C_{iv}? Are there relations for the compacted gold tailings-cement mixes connecting accumulated loss of mass with η/C_{iv} after distinct wetting-drying cycles (during durability tests)? What about the existence of an exclusive correlation coupling accumulated loss of mass divided by number of cycles and adjusted porosity/cement index after wetting-drying cycles during durability tests? This research intends at addressing these issues.

BACKGROUND

Durability can be stated as the capability of a material to maintain stability and integrity over large periods of exposure to the detrimental weathering (Dempsey and Thompson 1968). This property, as well as strength, is one of the important engineering properties of cemented mixes. Thus studies have been carried out to evaluate the durability of soil-cement mixtures, most of them (e.g., Starcher *et al*. 2016; Jamshidi *et al*. 2016) centered on two ASTM standards: wetting and drying (ASTM 2015) and freezing and thawing (ASTM 2013a).

Shihata and Baghdadi (2001) immersed sets of silty sand-cement specimens in saline water for different durations prior to running 12 wetting-drying cycles followed by brushing strokes. The authors found that soils with larger amounts of fines presented higher weight loss values in such tests. They also observed a close relationship between percent mass loss and reduction of unconfined compressive strength after the cycles.

Zhang and Tao (2008) performed durability tests in low plastic silty clay stabilized with cement. The authors observed that the mass loss decreased with the increase in cement contents, but increased with the increase of water-cement ratio.

Gutschik (1978), Kelley (1988) and Cuisinier *et al.* (2012) showed qualitatively that the efficiency of lime treatment could be damaged by the alternation of wet/dry cycles in the long term. Such behaviour was also observed by Cuisinier *et al.* (2014). The latter authors also observed significant irreversible shrinkage strains at the end of the first cycle for lime treated clays. A dramatic decrease in yield stress brought by a loss of the lime cementation bonding was also evidenced after the first cycle.

Theivakularatnam and Gnanendran (2015) observed that the accelerated reaction of binders due to increasing temperature masked the detrimental effect of the wet-dry cycles.

Avirneni *et al.* (2016) assessed the durability of reclaimed asphalt pavements (RAP) mixed with fly ash and sodium hydroxide (NaOH). It was observed that for high RAP and low NaOH contents (for the same fly ash amounts) the weight loss is high.

Jamshidi *et al*. (2016) investigated the performance and structural changes in cement-treated soils under influence of freeze/thaw exposure.

Additionally, the use of tailings as construction material has been assessed by several researchers, especially as partial substitute of cement. Onuaguluchi and Eren (2012) employed copper tailings as a cement replacement material in cement pastes, mortars and concretes. These studies showed that the incorporation of tailings at 0% to 15% cement substitution levels (by mass) maintained both compressive and tensile strengths at similar levels respect to those of the control specimens. Concerning the durability of these materials, the loss of mass was shown to slightly reduce with the incorporation of copper tailings. Thomas et al. (2013) also analysed strength and durability of copper tailing concrete. However, these researchers employed this solid waste material as a substitute to natural sand. An increase in the compressive strength (90 day strength) with respect to the regular concrete was observed till 40% substitution when the water-cement ratio was 0.4. The durability risk rating of copper tailing concrete, assessed through water and air permeability, was shown to be medium, comparable to normal concrete. Taha et al. (2016) produced eco-friendly fired bricks using coal mine wastes. The addition of coal mine waste increased flexural strength and decreased water absorption and open porosity of fire bricks. Moreover, it was shown that the manufacturing process of coal mine bricks reduced the amount of greenhouse gas (GHG) emissions by more than 70% in comparison to normal fired bricks. Similar research conducted by Ahmari and Zhang (2012) showed that copper tailing bricks produced with a geopolymerization technique satisfy the physical and mechanical properties for their use in constructions. Concerning the use of tailings in actual field conditions, Argane et al. (2014) presented a case study in Moroccan constructions, where low sulfide tailings (LST) were mixed to rendering mortars. The authors showed that the leaching of metals was significantly lowered after incorporation of LST in renders. On the other hand, the addition of LST to renders lowered their resistance to wetting-drying cycles.

Despite all the previous work on the durability of several materials, additional research concerning such aspect of tailings-cement blends is yet to be developed. A few authors have analyzed other characteristics of compacted gold tailings-Portland cement mixes. Mitchell and Wong (1982) carried out unconfined compressive strength tests of various cemented tailings and observed that unconfined strengths increase with increased cement content, decreased porosity and decreased curing humidity. The authors also proposed a relation between UCS and the failure envelope defined by cohesion intercept (c) and friction angle (ϕ). Additionally, Fall *et al.* (2008) performed an extensive set of tests on cemented paste backfill (CPB) in order to assess the main aspects controlling its behaviour. It was found that tailings grain size and density, as well as water-cement ratio were the main factors controlling CPB properties.

EXPERIMENTAL PROGRAM

The materials and methods used in the present research are discussed below.

Materials

The gold tailings physical properties are displayed in Table 1. The gold tailings utilized in the testing were taken from a tailings disposal site situated in northern Brazil, being classified (ASTM 2006) as silt with sand (ML). Gold tailings mineralogical characterization, using a X-ray diffractometer, detected the presence of seven compounds (Fig. 1): silicon oxide [SiO_2], arsenic iron [AsFe], arsenic oxide [As_2O_3], manganese hydroxide [$Mn(OH)_2$], iron arsenate [$FeAsO_4$], sulfur (S), and thiourea iron thiocyanate [$Fe(SC(NH_2)_2)_2(NCS)_2$]. Regarding the chemical composition of the studied gold tailings, the following elements were found: silicon (Si), iron (Fe), manganese (Mn), sulfur (S) and arsenic (As), amongst others.

High early strength (Type III) Portland cement (ASTM 2016) was used throughout this investigation. Its rapid strength gain permitted selecting seven days as the curing period. Cement grains' specific gravity is 3.15.

Distilled water was employed both for characterization tests and moulding specimens for the mechanical tests.

Methods

Moulding and Curing of Specimens

For strength (unconfined compression) tests, cylindrical specimens 50 mm diameter and 100 mm in length were employed. For durability (wetting and drying) and stiffness (ultrasonic pulse velocity) tests, cylindrical specimens 100 mm diameter and 127.3 mm from top to bottom were utilized. A target dry density for a particular specimen was then instituted as a result of the dry compacted gold tailings-Portland cement mix divided by the total volume of the specimen (ASTM 2009). As exhibited in Eq. (1) (Consoli *et al*. 2011), porosity (η) is a function of dry density (γ_d) of the mix and Portland cement content (C). Each substance (gold tailings and Portland cement) has a unit weight of solids (γs_{GT} and γs_C), which also must be measured for computing porosity.

$$\eta = 100 - 100\left\{\left[\frac{\gamma_d}{1+\frac{C}{100}}\right]\left[\frac{1}{\gamma s_{GT}} + \frac{\frac{C}{100}}{\gamma s_C}\right]\right\} \quad (1)$$

Once the gold tailings and Portland cement were weighed, they were blended until the mix attained visual uniformity. Moisture content of 17% (optimum moisture content for standard Proctor compaction effort – see Table 1) for the gold tailings-Portland cement blends was then supplemented, and mixing was resumed until a paste, homogeneous in appearance, was produced. The quantity of Portland cement for each blend was determined based on the mass of dry gold tailings. Hence the mixture proportions (cement: tailings) are: 1:33.3 (specimens with 3% C); 1:20.0 (specimens with 5% C) and 1:14.3 (specimens with 7% C). Specimens were statically compacted in 3 stratums in the interior of a cylindrical mould. Subsequently to moulding, specimens were removed from the moulds and their weights, diameters and heights measured with precisions of nearly 0.01 g and 0.1 mm, correspondingly. The specimens were cured in a humid room at 23º±2ºC and relative moisture of about 95% (ASTM 2013b).

Unconfined Compression Tests

Compression tests followed standard ASTM C 39 (ASTM 2010). Before testing, specimens were put underwater for 24 h to reduce suction (Consoli *et al*. 2011). Specimens were moulded with 17% of moisture content, dry densities of 17 kN/m^3, 16 kN/m^3 and 15 kN/m^3 (maximum dry unit weight for standard Proctor compaction effort – see Table 1, and other two values below), Portland cement contents of 3%, 5% and 7% [determined following international (Mitchell 1981) and Brazilian (Consoli *et al*. 2007, 2009, 2016) experience with soil–cement] and cured for 7 days.

Pulse Velocity Tests and Ultrasonic Elastic Parameters

Elastic parameters of artificially cemented fine-grained gold tailings at tiny deformations may be acquired carrying out ultrasonic pulse velocity tests following standard ASTM D2845 (ASTM 2008). Transducers are attached to the two extremes of the specimens using a coupler gel. Specimens were moulded with three different dry densities (15 kN/m^3, 16 kN/m^3 and 17 kN/m^3), three distinct early strength Portland cement contents (3%, 5% and 7%), moisture content of about 17%, and cured for 7 days.

Durability Tests

Durability (wetting-drying cycles) tests of compacted gold tailings-Portland cement mixtures were completed according to standard ASTM D 559 (ASTM 2015). Test procedures determine mass losses produced by recurrent (12) wet-dry series. Every cycle begins by oven drying through 42 h at 71°±2°C. Following, specimens are brushed a number of times using a force of approximately 15 N. Lastly, specimens are put underwater for 5 h at 23°±2°C. Tests were performed on the same specimens moulded for pulse velocity tests.

RESULTS

Influence of the Porosity/Cement Index on q_u

Figure 2 portrays q_u as a function of $\eta/(C_{iv})^{0.28}$ [stated as porosity (η) divided by the volumetric cement content (C_{iv}), the latter expressed as a percentage of cement volume to the total volume of the gold tailings-Portland cement mixes (Consoli *et al.* 2007, 2016) for the curing period studied (7 days). Fig. 2 indicates that the adjusted porosity/cement index is helpful in normalizing strength results for gold tailings-Portland cement mixtures. A very good correlation (R^2=0.98) exists between $\eta/(C_{iv})^{0.28}$ and q_u of the gold tailings-Portland cement mixtures studied.

$$q_u(kPa) = 2.52x10^9\left[\frac{\eta}{C_{iv}^{\ 0.28}}\right]^{-4.19} \quad (2)$$

The capability of the adjusted porosity/cement index to normalize strength of cement treated soils has been shown by Consoli *et al.* (2007, 2016). They have shown that rates of change of strength with porosity (η) and the inverse of the volumetric cement content ($1/C_{iv}$) are as a rule not the same. Thus, the application of a power (as a rule 0.28 – Consoli *et al.* 2016) to C_{iv} is required for the rates of η and $1/C_{iv}$ to be compatible.

Influence of the Porosity/Cement Index on Initial Shear Modulus (G_0)

An analysis, analogous to the one done for compressive strength, was also performed for G_0 (Fig. 3). Results show that $\eta/(C_{iv})^{0.28}$ correlates well with G_0 for compacted gold tailings-Portland cement mixes (Fig. 3). A sound correlation (R^2=0.95) is detected concerning $\eta/(C_{iv})^{0.28}$ and G_0 of the compacted gold tailings-Portland cement mixtures considered, reflecting 7 days of curing [Eq. (3)].

$$G_0(MPa) = 2.51x10^8 \left[\frac{\eta}{C_{iv}^{\ 0.28}} \right]^{-3.63} \quad (3)$$

Influence of the Cement Content, Porosity and Porosity/Cement Index on Durability (wetting and drying cycles) of Compacted Gold Tailings-Cement Blends

Figure 4 shows loss of mass as a function of the number of wetting-drying cycles. Gold tailings-Portland cement blends with distinct dry unit weights (15, 16 and 17 kN/m^3) and cement contents (3, 5 and 7%), after a 7-day curing period, are included in Figure 4. X-Ray diffraction analysis of the studied gold tailings detected the presence of sulfur (S), which could cause deleterious effects on the Portland cement-tailings blends. On the other hand, it is possible to observe in Fig. 4 the constancy of the loss of mass of each specific specimen, after brushing following wet-dry cycles, for all 12 cycles. It can also be seen that the representative loss of mass of each specimen is reduced with increasing cement contents and dry unit weights. A conceivable inference is that in present case study, possible expansive minerals formed by sulfur in an alkaline environment were suppressed by the formation of strong cementitious bonds.

Furthermore, Fig. 5 presents relations of accumulated loss of mass versus number of wetting/drying cycles for compacted gold tailings-Portland cement mixes (for a curing period of 7 days) in view of distinctive dry unit weights (15, 16 and 17 kN/m^3) and cement contents (3, 5 and 7%). It is quite clear that increasing both the amount of cement and the dry unit weight enhances the durability of the compacted gold tailings-Portland cement blends.

Figure 6 exhibits compacted gold tailings-Portland cement blends accumulated loss of mass (ALM) versus adjusted porosity/cement index [$\eta/(C_{iv})^{0.28}$] after 3 [Eq. (4) – R^2=0.99], 6 [Eq. (5) – R^2=0.98], 9 [Eq. (6) – R^2=0.98] and 12 [Eq. (7) – R^2=0.97] wet-dry cycles (during durability tests). This relationship has not been shown in the literature for any artificially cemented materials.

$$ALM(\%) = 1.95x10^{-10} \left[\frac{\eta}{C_{iv}^{0.28}} \right]^{6.65} \quad (4)$$

$$ALM(\%) = 9.00x10^{-9} \left[\frac{\eta}{C_{iv}^{0.28}} \right]^{5.81} \quad (5)$$

$$ALM(\%) = 8.24x10^{-9}\left[\frac{\eta}{C_{iv}^{0.28}}\right]^{5.94} \qquad (6)$$

$$ALM(\%) = 1.81x10^{-8}\left[\frac{\eta}{C_{iv}^{0.28}}\right]^{5.80} \qquad (7)$$

It is clear that the accumulated loss of mass is correlated to by $\eta/(C_{iv})^{0.28}$ for all cycles. It is worth noting that the curves diverge for higher values of the adjusted porosity/cement index. This trend seems reasonable as the loss of mass in each cycle is more pronounced for specimens with higher porosities and lower cement contents, as shown in Figs. 4 and 5.

In order to further normalize the durability results, compacted gold tailings-Portland cement blends accumulated loss of mass for 3, 6, 9 and 12 cycles are divided by number of cycles and plotted versus adjusted porosity/cement index (see Fig. 7). A unique relationship (R^2=0.98) linking accumulated loss of mass divided by number of cycles (ALM/NC) and adjusted porosity/cement index [$\eta/(C_{iv})^{0.28}$] after distinct wet-dry cycles is found [see Eq. (8)]. So, it can be demonstrated, for the first time ever, that the porosity/cement index is also a predictor of the durability of compacted gold tailings-Portland cement blends.

$$\frac{ALM}{NC}(\%) = 6.48x10^{-10}\left[\frac{\eta}{C_{iv}^{0.28}}\right]^{6.03} \qquad (8)$$

In the end of wet-dry durability cycles 3, 6, 9 and 12 cycles the shear modulus of artificially cemented fine-grained gold tailings at tiny deformations was also measured through ultrasonic pulse velocity tests. Fig. 8 presents shear modulus (G_{max}) variation according to wet-dry cycle during durability tests for gold tailings-Portland cement blends considering distinct dry unit weight (15, 16 and 17 kN/m^3) and cement content (3, 5 and 7%). Similarly to loss of mass after each studied cycle, it is possible to observe in Fig. 8 that the shear modulus of each specific specimen increases with an increase in the of cement content and with an increase in dry unit weight. Another fact that points out similar trends between loss of mass and shear modulus is that specimens with γ_d=15 kN/m^3 and C=5% show a similar behaviour respect to those specimens with γ_d=17 kN/m^3 and C=3% regarding loss of mass versus number of cycles (Fig. 4) and G_{max} versus number of cycles (Fig. 8) . Such similar behavior can be explained by the fact that these specimens have similar porosity/cement indexes [$\eta/(C_{iv})^{0.28} \approx 38$ for the first and $\eta/(C_{iv})^{0.28} \approx 36$ for the latter]. Similar trends in the performance of G_{max} and loss of mass for specific cycles denote that there might be a link between G_{max} and the average loss of mass (LM) of specific wet-dry cycles. To check possible links among them, G_{max} and loss of mass are plotted against each other, G_{max} versus LM for third and twelfth cycles (see Fig. 9). Fair linear relations are obtained for third cycle (R^2=0.97) [see Eq. (9)] and twelfth cycle (R^2=0.96) [see Eq. (10)]. Further studies considering distinct tailings and cements are necessary in order to define possible trends that might be used to determine durability through G_{max} measurements instead of loss of mass (the latter considerably time consuming and whose results might vary to the skills of the operator).

$$G_{max}\ (\text{MPa}) = -16{,}339\ x\ LM(\%) + 1{,}381 \qquad (9)$$

$$G_{max}\ (\text{MPa}) = -11{,}020\ x\ LM(\%) + 788 \qquad (10)$$

Finally, a plot of accumulated loss of mass (ALM) (wetting and drying durability at 3, 6, 9 and 12 cycles) versus unconfined compressive strength (q_u) for gold tailings-Portland cement blends is presented in Fig. 10. The relations ALM vs. q_u found for each distinct wetting and drying durability cycle (3 [Eq. (11)], 6 [Eq. (12)], 9 [Eq. (13)] and 12 [Eq. (14)] cycles) have the same power function shape and high correlations (R^2=0.98), differing just in a scalar that increases with increasing durability cycle.

$$ALM(\%) = 1.53 \times 10^5\ q_u^{-1.58} \qquad (11)$$

$$ALM(\%) = 3.10 \times 10^5\ q_u^{-1.58} \qquad (12)$$

$$ALM(\%) = 4.67 \times 10^5\ q_u^{-1.58} \qquad (13)$$

$$ALM(\%) = 6.05 \times 10^5\ q_u^{-1.58} \qquad (14)$$

These relations may enable researchers to reduce time in assessing durability of such blends, as wetting-drying durability tests (ASTM 2015) require at least 24 days to be concluded after curing.

CONCLUDING REMARKS

From the studies described in this document the succeeding conclusions can be drawn:

- Unconfined compressive strength of compacted gold tailings – Portland cement mixes was shown to have good relation with the adjusted porosity/cement index $[\eta/(C_{iv})^{0.28}]$. This relationship and the exponent 0.28 are compatible with previous studies on fine-grained soils mixed with cement (e.g. Consoli *et al.*

2016), but for the first time this it is shown to be useful for mine tailings compressive strength;

- The accumulated loss of mass (ALM) (durability quantification) of individual wetting/drying cycles of compacted gold tailings – Portland cement mixes were originally perceived in present research to be directly associated with the adjusted porosity/cement index. This relationship between ALM and $[\eta/(C_{iv})^{0.28}]$ was shown for the first time for cemented materials;

- An unique relationship linking the ratio of accumulated loss of mass to the number of cycles (ALM/NC) and adjusted porosity/cement index $[\eta/(C_{iv})^{0.28}]$ after distinct wet-dry cycles is presented for the first time;

- Linear relationships between stiffness (G_{max}) and loss of mass (LM) were presented. Specimens with similar porosity/cement ratios showed similar trends in both G_{max} and LM. A power relationship was shown between accumulated loss of mass (ALM) and unconfined compressive strength (q_u). This enables researchers and engineers to assess durability using distinct methods and tests;

- The porosity/cement index is correlated to strength, stiffness and endurance of the compacted gold tailings-Portland cement blends. So, according to the strength, stiffness and durability requirements, the earthwork designer can establish the adjusted porosity/cement index that fulfills the design needs. Lastly, distinct dry unit weights and Portland cement amounts can fulfill the project requirements.

- The potential encapsulation produced by the cement contents and/or the dry densities on the examined blends should be assessed in further studies, particularly considering arsenic and thiocyanate (potential pollutants) detected in the X-Ray diffraction test. Eventually, higher cement contents and additional compaction energy might be required to encapsulate such pollutants and should be verified in leaching tests.

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REFERENCES

Adiansyah, J.S., Rosano, M., Vink, S. and Keir, G. 2015. "A framework for a sustainable approach to mine tailings management: disposal strategies." *Journal of Cleaner Production*, 108, 1050-1062.

Agurto-Detzel, H.; Bianchi, M.; Assumpção, M.; Schimmel, M.; Collaço, B.; Ciardelli, C.; Barbosa, J. R., and Calhau, J. 2016. "The tailings dam failure of 5 November 2015 in SE Brazil and its preceding seismic sequence." *Geophysical Research Letters*, 43(10), 4929-4936.

Ahmari, S., and Zhang, L. 2012. "Production of eco-friendly bricks from copper mine tailings through geopolymerization." *Construction and Building Materials*, 29, 323–331.

Argane, R., Benzaazoua, M., Bouamrane, A., and Hakkou, R. 2015. "Cement hydration and durability of low sulfide tailings-based renders: A case study in Moroccan constructions." *Minerals Engineering*, 76, 97-108.

ASTM 2006. "Standard classification of soils for engineering purposes." *ASTM D 2487*, West Conshohocken, Philadelphia.

ASTM 2008. "Standard test method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock." *ASTM D 2845*, West Conshohocken, Philadelphia.

ASTM 2009. "Standard test methods for laboratory determination of density (unit weight) of soil specimens." *ASTM D 7263*, West Conshohocken, Philadelphia.

ASTM 2010. "Standard test method for compressive strength of cylindrical concrete specimens." *ASTM C 39*, West Conshohocken, Philadelphia.

ASTM 2013a. "Standard test methods for freezing and thawing compacted soil-cement mixtures." *ASTM D560*, West Conshohocken, Philadelphia.

ASTM 2013b. "Standard specification for mixing rooms, moist cabinets, moist rooms, and water storage tanks used in the testing of hydraulic cements and concretes." *ASTM D560*, West Conshohocken, Philadelphia.

ASTM 2015. “Standard test methods for wetting and drying compacted soil-cement mixtures.” *ASTM D 559*, West Conshohocken, Philadelphia.

ASTM 2016. “Standard specification for Portland cement.” *ASTM C 150*, West Conshohocken, Philadelphia.

Avirneni, D.; Peddinti, P. R. T., and Saride, S. 2016. "Durability and long term performance of geopolymer stabilized reclaimed asphalt pavement base courses." *Construction and Building Materials*, 121, 198-209.

Boger, D.V. 2011. “A personal perspective on paste and thickened tailings e a decade on.” In: Jewell, R.J., Fourie, A. (Eds.), 14th International Seminar on Paste and Thickened Tailings (Paste 2011), 5-7 April 2011, Perth, Australia. Australian Center for Geomechanics, Australia, pp. 3-11.

Boger, D.V., Scales, P., and Sofra, F. 2012. “Rheological concepts.” In: Jewell, R.J., Fourie, A. (Eds.), Paste and Thickened Tailings Guide, 2. ed. Australian Center for Geomechanics, Australia.

Chryss, A., Fourie, A., Monch, A., Nairn, D., and Seddon, K.D. 2012. “Towards an integrated approach to tailings management.” In: Jewell, R.J., Fourie, A., Paterson, A. (Eds.), Paste 2012. Australian Centre for Geomechanics, Sun City, South Africa.

Consoli, N.C.; Foppa, D.; Festugato, L., and Heineck, K.S. 2007. “Key parameters for strength control of artificially cemented soils.” *J. Geotech. Geoenviron. Engng.*, 133(2), 197–205.

Consoli, N.C.; Dalla Rosa, A., and Saldanha, R.B. 2011. “Variables governing strength of compacted soil–fly ash–lime mixtures.” *J. of Materials in Civil Engng.*, 23(4), 432–440.

Consoli, N.C.; Thomé, A.; Donato, M., and Graham. J. 2008. “Loading tests on compacted soil, bottom-ash and lime layers.” Proceedings of the Institution of Civil Engineers - Geotechnical Engineering 161(GE1), 29–38

Consoli, N.C.; Dalla Rosa, F., and Fonini, A. 2009. “Plate load tests on cemented soil layers overlaying weaker soil.” *J. Geotech. Geoenviron. Engng.*, 135(12), 1846–1856.

Consoli, N.C.; Quiñónez Samaniego, R.A.; Marques, S.F.V., Venson, G.I., Pasche, E., and González Velázquez, L.E. 2016. “A single model establishing strength of dispersive clay treated with distinct binders." *Canadian Geotechnical Journal* (DOI: 10.1139/cgj-2015-0606).

Cuisinier, O.; Gandille, D.; Robinet, A.; Stoltz, G.; Mehenni, A., and Robin, V. 2012. "Long term behaviour of treated soils – case study of a lime and cement stabilized backfill." *3rd Int. Seminar on Earthworks*, 189-200. Berlin, Germany: Technische Universität München.

Cuisinier, O.; Stoltz, G., and Masrouri, F. 2014. "Long term behavior of lime-treated clayey soil exposed to successive drying and wetting." *Geo-Congress 2014 Technical Papers*, 4146-4155. Atlanta, Georgia, USA: American Society of Civil Engineers.

Dempsey, B.J., and Thompson, M.R. 1968. Durability properties of lime-soil mixtures. *Highway Research Record 235*, Highway Research Board, Washington, D.C., 61–75.

DITR. 2007. "LPSD: Tailings Management." Department of Industry, Tourism, and Resources, Canberra, Australia.

Escobar, H. 2015. "Mud tsunami wreaks ecological havoc in Brazil." *Science/AAAS*, 350(1126), 1138-1139.

Fahey, M., Helinski, M., and Fourie, A. 2009. "Some aspects of the mechanics of arching in backfilled stopes." *Canadian Geotechnical Journal*, 46(11), 1322-1336.

Fall, M.; Benzaazoua, M., and Saa, E. G. 2008. "Mix proportioning of underground cemented tailings backfill." *Tunelling and Underground Space Technology*, 23, 80-90.

Fourie, A.B. 2012. "Perceived and realised benefits of paste and thickened tailings for surface deposition." In: Jewell, R.J., Fourie, A.B., Paterson, A. (Eds.), Paste 2012: 15th International Seminar on Paste and Thickened Tailings, 16-19 April 2012. Australian Centre for Geomechanics, Perth, Sun City, South Africa, pp. 53-63.

Helinski, M., Fahey, M., and Fourie, A. 2011. "Behavior of cemented paste backfilling two mine stopes: measurement and modeling." *Journal of Geotechnical and Geoenvironmental Engineering*, 137(2), 171-182.

Jamshidi, R. J.; Lake, C. B.; Gunning, P., and Hills, C. D. 2016. "Effect of freeze/thaw cycles on the performance and microstructure of cement-treated soils." *J. of Materials in Civil Engng.*, 10.1061/(ASCE)MT.1943-5533.0001677 , 04016162.

Kelley, M. 1988. "A long range durability study of lime stabilized bases at military posts in the southwest." *Bulletin 328*, National Lime Association, WSA, 1-20.

Kumar, S. 2001. "Reducing liquefaction potential using dynamic compaction and construction of stone columns." *Geotechnical and Geological Engineering*, 19, 169-182.

McLellan, B.C., Corder, G.D., Giurco, D., and Green, S. 2009. “Incorporating sustainable development in the design of Mineral processing operations - review and analysis of current approaches.” *Journal of Cleaner Production*. 17, 1414-1425.

MCMPR and MCA. 2003. “Strategic Framework for Tailings Management.” The Ministerial Council on Mineral and Petroleum Resources, and Minerals Council of Australia, Canberra.

Mitchell, J. K. 1981. “Soil improvement—state-of-the-art report.” *Proceedings 10th Int. Conf. on Soil Mechanics and Foundation Engineering*. International Society of Soil Mechanics and Foundation Engineering, Stockholm, pp. 509–565.

Mitchell, R.J., and Wong, B.C. 1982. "Behaviour of cemented tailings sands." *Canadian Geotechnical Journal*, 19(3), 289-295.

Moolman, P.L., and Vietti, A. 2012. “Tailings disposal: an approach to optimize water and energy efficiency.” In: Platinum 2012: 5th International Platinum Conference: a Catalyst for Change. The Southern African Institute of Mining and Metallurgy, Sun City, South Africa.

Nguyen, M.T., Vink, S., Ziemski, M., and Barret, D.J. 2014. “Water and energy synergy and trade-off potentials in mine water management.” *Journal of Cleaner Production*, 84, 629-638.

Onuaguluchi, O., and Eren, Ö. 2012. “Recycling of copper tailings as an additive in cement mortars.” *Construction and Building Materials*, 37, 723–727.

Portland Cement Association (PCA). 1992. “*Soil-cement laboratory handbook*.” Skokie, Illinois.

Shihata, S.A., and Baghdadi, Z.A. 2001. "Long-term strength and durability of soil cement." *J. of Materials in Civil Engng.*, 13(3), 161–165.

Starcher, R. D.; Gassman, S. L., and Pierce, C. E. 2016. "The durability of chemically treated soils subjected to cycles of wetting and drying." *Geo-Chicago 2016*, 728–737.

Taha, Y., Benzaazoua, M., Hakkou, R., and Mansori, M. 2016. "Coal mine wastes recycling for coal recovery and eco-friendly bricks production". *Minerals Engineering*, (DOI: 0.1016/j.mineng.2016.09.001).

Theivakularatnam, M., and Gnanendran, C.T. 2015. "Durability of Lightly Stabilized Granular Material Subjected to Freeze-Thaw and Wet-Dry Cycles." *IFCEE 2015*, 1410-1419. San Antonio, Texas, USA: American Society of Civil Engineers.

Thomas, B.S., Damare, A., and Gupta, R.C. 2013. "Strength and durability characteristics of copper tailing concrete." *Construction and Building Materials*, 48, 894-900.

Zhang, Z. and Tao, M. 2008. "Durability of cement stabilized low plasticity soils." *J. Geotech. Geoenviron. Engng.*, 134(2), 203–213.

NOTATION

ALM	*accumulated loss of mass*
C	*cement content (expressed in relation to mass of dry gold tailings)*
C_{iv}	*volumetric cement content (expressed in relation to the total specimen volume)*
D_{50}	*mean particle diameter*
G_o	*initial shear modulus*
G_{max}	*shear modulus after 3, 6, 9 and 12 cycles*
GT	*gold tailings*
LM	*loss of mass*
NC	*number of wetting/drying cycles*
q_u	*unconfined compressive strength*
R^2	*coefficient of determination*
η	*porosity*
η/C_{iv}	*porosity/cement index*
γ_d	*dry unit weight*
γ_s	unit weight of solids
w	*moisture content*

FIGURE CAPTIONS

FIGURE 1. X-ray diffractometry of studied gold tailings.

FIGURE 2. Variation of unconfined compressive strength (q_u) with adjusted porosity/cement index for gold tailings-Portland cement blends for 7 days of curing.

FIGURE 3: Initial shear modulus (G_0) versus adjusted porosity/cement index for 7 days of curing.

FIGURE 4: Loss of mass versus number of cycle for gold tailings-Portland cement blends considering distinct dry unit weight (15, 16 and 17 kN/m^3) and cement content (3, 5 and 7%) specimens and 7 days as curing period.

FIGURE 5: Accumulated loss of mass versus number of wet/dry cycles for gold tailings-Portland cement blends considering distinct dry unit weight (15, 16 and 17 kN/m^3) and cement content (3, 5 and 7%) specimens and 7 days as curing period.

FIGURE 6: Gold tailings-Portland cement blends accumulated loss of mass versus adjusted porosity/cement index after 3, 6, 9 and 12 wet-dry cycles (during durability tests).

FIGURE 7: Gold tailings-Portland cement blends accumulated loss of mass versus adjusted porosity/cement index after wet-dry cycles during durability tests.

FIGURE 8: Shear modulus (G_{max}) versus number of the cycle after wet-dry cycles during durability tests for gold tailings-Portland cement blends considering distinct dry unit weight (15, 16 and 17 kN/m^3) and cement content (3, 5 and 7%) specimens.

FIGURE 9: Linear relations between shear modulus (G_{max}) at specific number of the cycle after wet-dry cycles versus loss of mass in that same specific cycle during durability tests for gold tailings-Portland cement blends considering distinct dry unit weight (15, 16 and 17 kN/m^3) and cement content (3, 5 and 7%) specimens.

FIGURE 10: Relations ALM versus q_u for gold tailings-Portland cement blends.

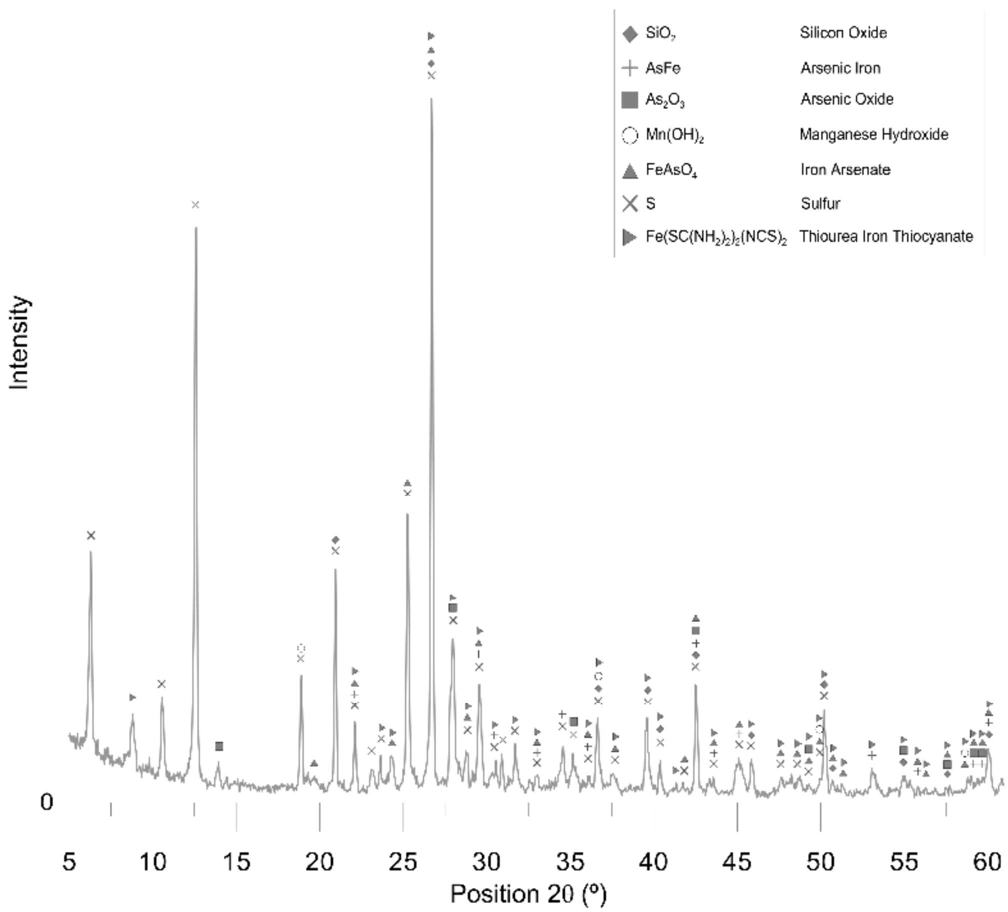


FIGURE 1. X-ray diffractometry of studied gold tailings.

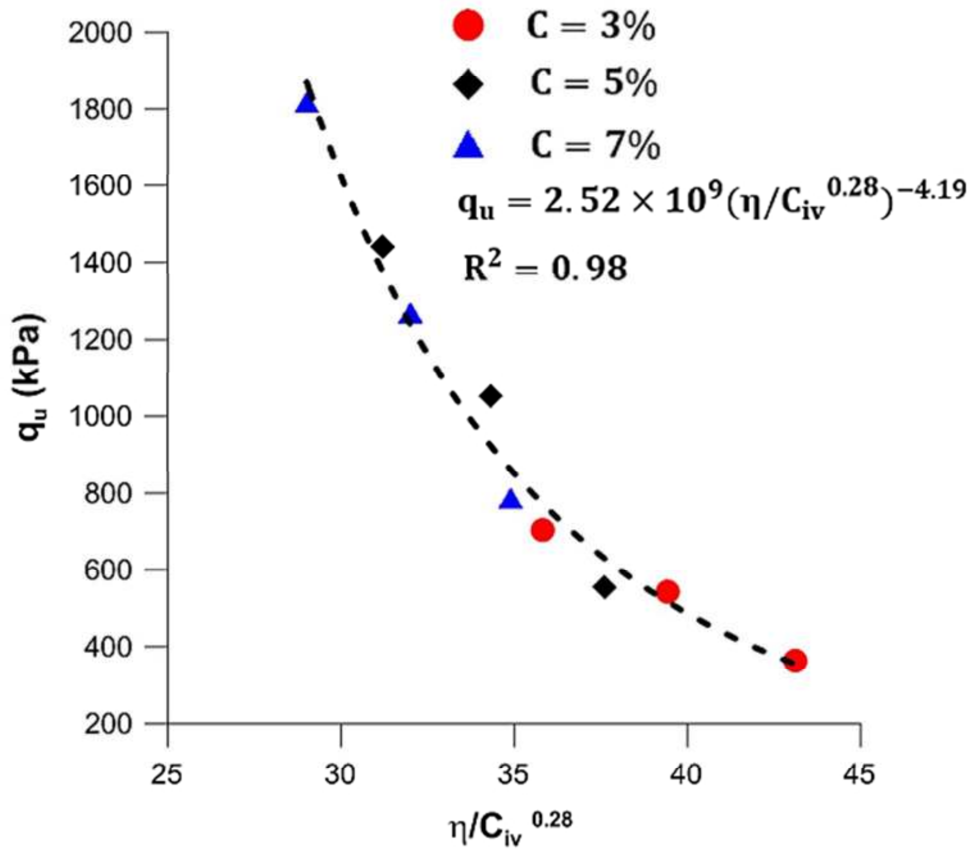


FIGURE 2. Variation of unconfined compressive strength (qu) with adjusted porosity/cement index for gold tailings-Portland cement blends for 7 days of curing.

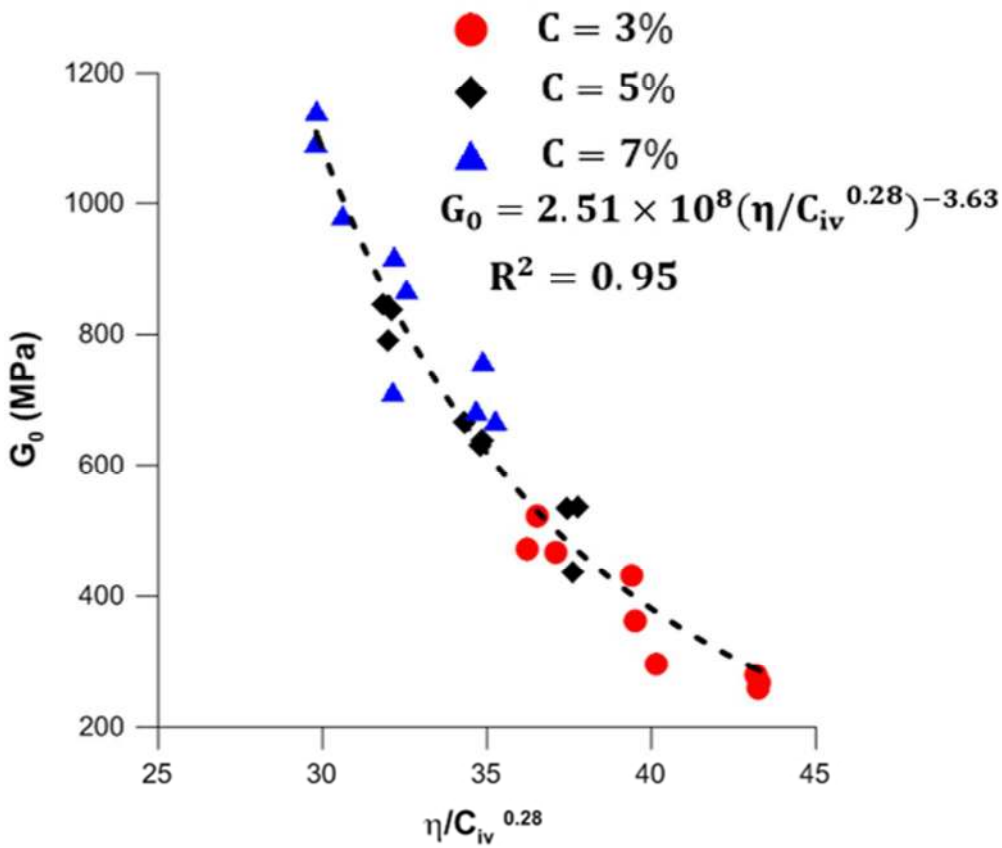
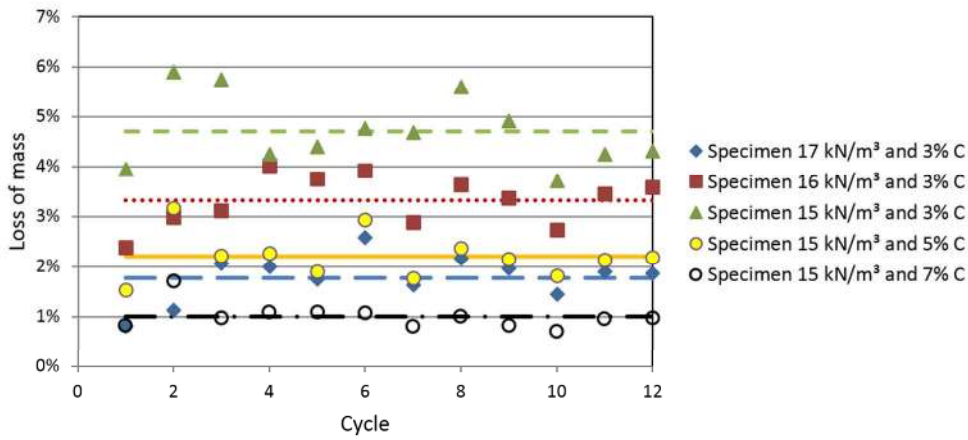


FIGURE 3: Initial shear modulus (G0) versus adjusted porosity/cement index for 7 days of curing.



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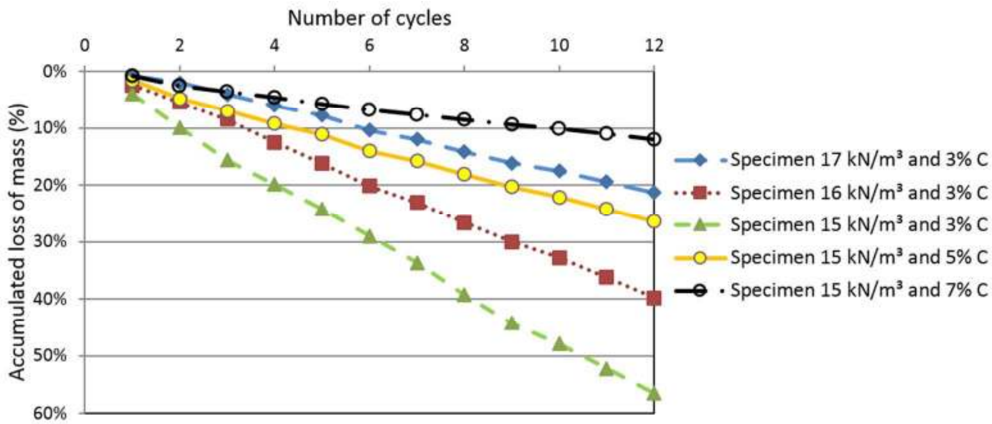

FIGURE 5: Accumulated loss of mass versus number of wet/dry cycles for gold tailings-Portland cement blends considering distinct dry unit weight (15, 16 and 17 kN/m3) and cement content (3, 5 and 7%) specimens and 7 days as curing period.

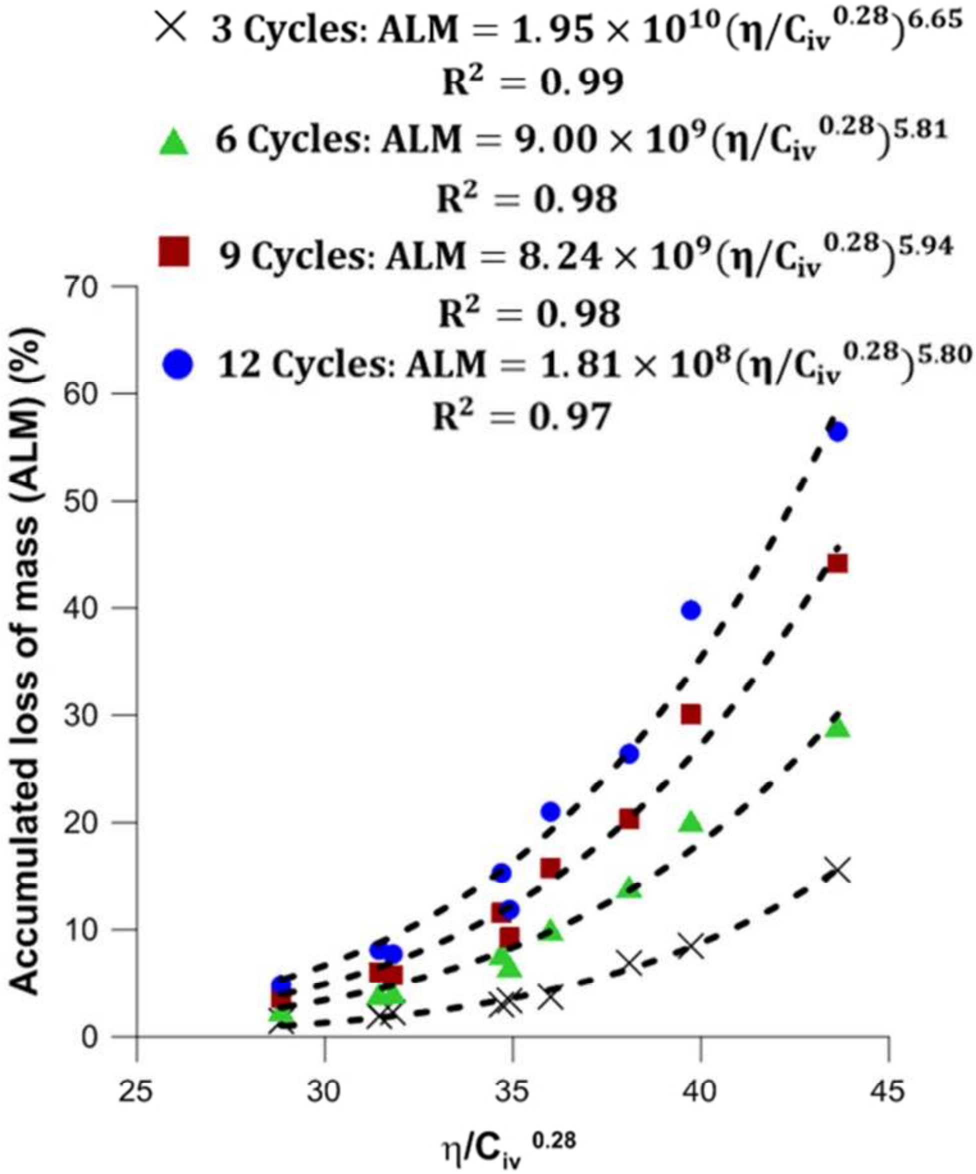

FIGURE 6: Gold tailings-Portland cement blends accumulated loss of mass versus adjusted porosity/cement index after 3, 6, 9 and 12 wet-dry cycles (during durability tests).

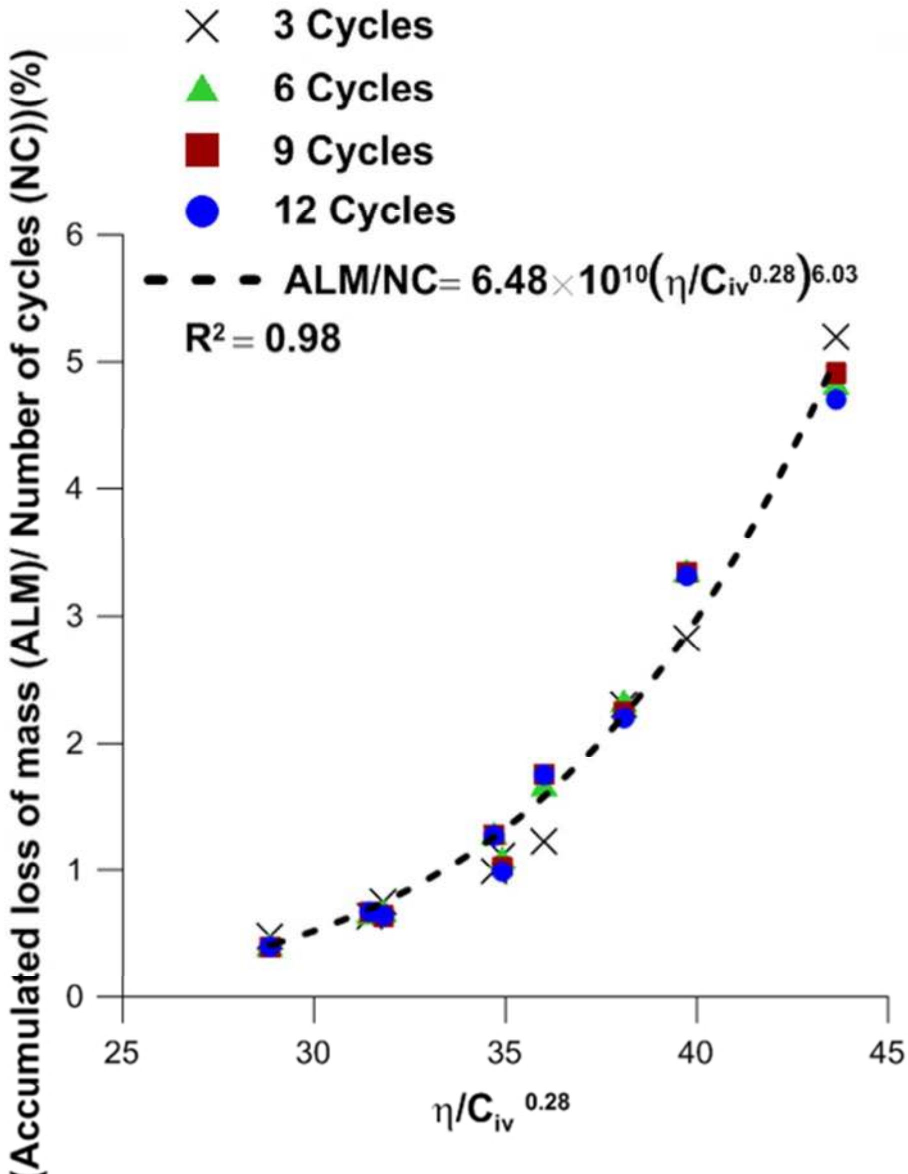

FIGURE 7: Gold tailings-Portland cement blends accumulated loss of mass versus adjusted porosity/cement index after wet-dry cycles during durability tests.

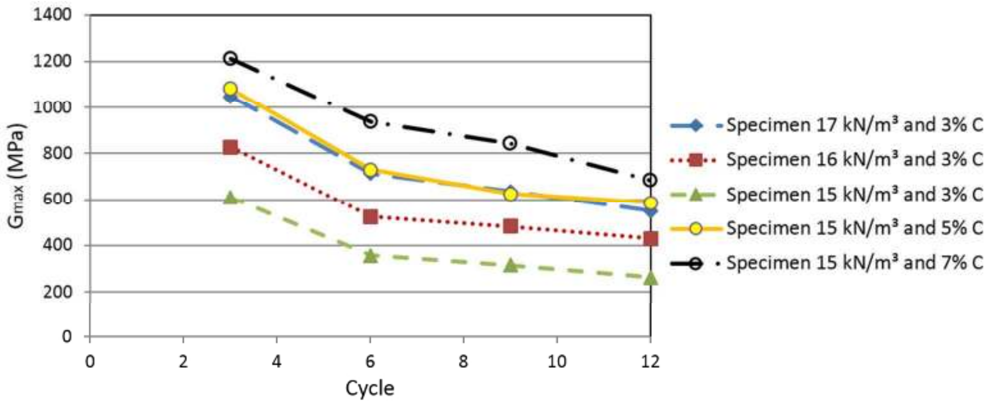

FIGURE 8: Shear modulus (Gmax) versus number of the cycle after wet-dry cycles during durability tests for gold tailings-Portland cement blends considering distinct dry unit weight (15, 16 and 17 kN/m3) and cement content (3, 5 and 7%) specimens.

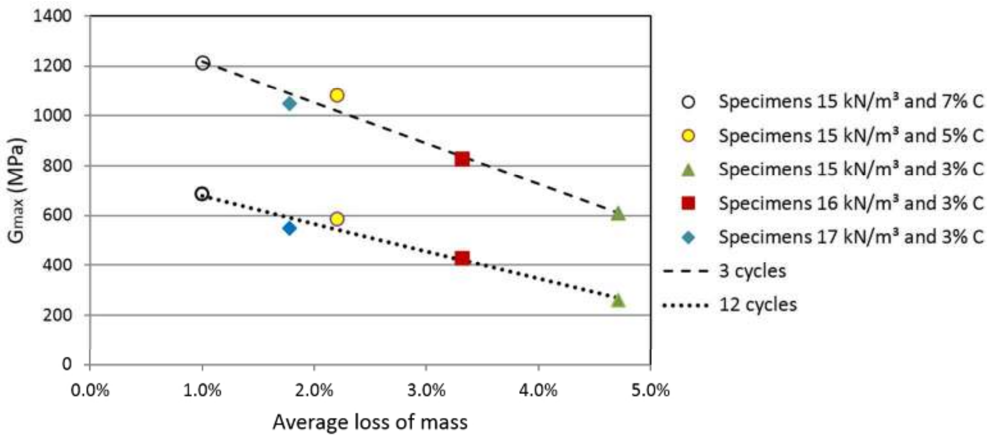

FIGURE 9: Linear relations between shear modulus (Gmax) at specific number of the cycle after wet-dry cycles versus loss of mass in that same specific cycle during durability tests for gold tailings-Portland cement blends considering distinct dry unit weight (15, 16 and 17 kN/m3) and cement content (3, 5 and 7%) specimens.

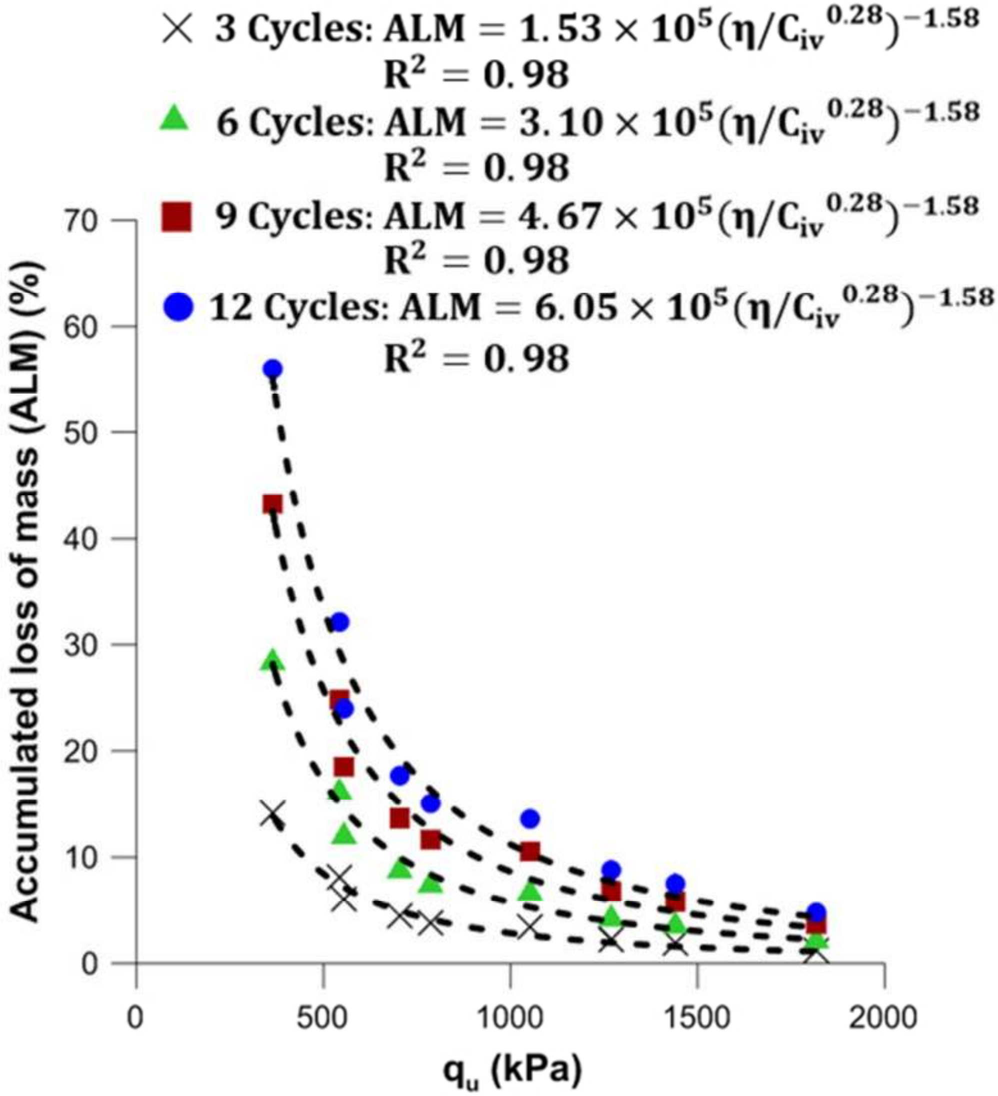

FIGURE 10: Relations ALM versus qu for gold tailings-Portland cement blends.

Table 1. Physical properties of the gold tailings sample.

Liquid limit (%)	-
Plastic limit (%)	-
Plastic index (%)	Non-plastic
Specific gravity	2.86
Fine sand (0.075mm < diameter < 0.425mm) (%)	28
Silt (0.002 mm < diameter < 0.075 mm) (%)	71
Clay (diameter < 0.002 mm) (%)	1
Mean particle diameter, D_{50} (mm)	0.06
Maximum dry unit weight for standard Proctor compaction effort (kN/m^3)	17.0
Optimum moisture content for standard Proctor compaction effort (%)	17
USCS class	ML (silt with sand)