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Assessing the effects of polymer treatment – segregation considerations

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ABSTRACT

Observations and field investigations of tailings behaviour following implementation of polymer treatment (PT) at the point of discharge have frequently indicated increased rates of initial dewatering, reduced segregation, and increased rates of consolidation.

Despite the increasing evidence and published test programs on the effects of PT, limitations to assessing the potential benefits of this technology remain. In particular, consolidation test programs typically utilise a non-segregated untreated sample, to enable "direct" comparison to other tests on PT specimens. For a slurry that, in an untreated state, would segregate along the tailings beach, comparison of a PT specimen to an untreated, non-segregated sample does not provide a realistic simulation of field behaviour.

To attempt to address the effects of segregation within a laboratory test program, a series of tests were undertaken on untreated slurry intentionally segregated, to produce a two gradations that would likely be relevant across a real tailings beach. These results were then used as inputs to a series of one dimensional consolidation models representing. Comparison of this analysis to those undertaken for PT, and untreated "non-segregated" slurry indicates that inclusion of the effects of segregation may improve the assessment of the potential benefits of PT for increase in situ density of a tailings deposit.

1. INTRODUCTION

1.1 General

The trialing and implementation of polymer treatment (PT) of tailings at or near the point of discharge, to attempt to improve initial dewatering rates, reduce segregation, improve return water clarity, increase rates of consolidation, and/or increase beach slope is an increasingly popular technology in tailings management (Kaiser et al. 2006, Adkins et al. 2007, Brumby et al. 2008, Viettie et al. 2008, Daubermann & Földvári 2008, da Silva 2011, Wells et a. 2011, COSIA 2012, Mizani et al. 2013, COSIA 2014, Guang et al. 2014, Riley and Utting 2014, Beveridge et al. 2015, Reid and Boshoff 2015, Riley et al. 2015). Prior to implementation of PT, it is typical to undertake laboratory testing, often with parallel numerical modelling, and, in some cases, small-scale trial deposition to assess the potential benefits of the technology for a given tailings storage facility (TSF). Comparisons between the behavior of PT and untreated (UT) material can be made in this manner. The laboratory testing undertaken is usually based on available and commonly used geotechnical techniques to characterize slurries and soils. For example, hydraulic consolidation devices such as the Rowe Cell or Slurry Consolidometer are frequently used to assess the effects of PT on consolidation behavior, and hence expected in situ densities within a TSF.

Whereas the geotechnical characterization and modeling of tailings behavior is a mature practice, it suffers from inherent limitations and uncertainties. For example, tailings are often deposited at segregating slurry densities. Thus, although the gradation of the material prior to deposition is known, an infinite number of potential gradations are possible as segregation occurs along the tailings beach – each with different mechanical properties, including those related to consolidation. This presents difficulties in both the laboratory testing and analysis of a given TSF. In the laboratory, the potential for segregation forces the following choice: (i) preparing a uniform sample from a non-segregating slurry (or other sample preparation technique), (ii) working with the material at a the expected depositional slurry density and accepting that samples prepared in test devices are non-uniform, or, (iii) undertaking additional work in an attempt to simulate the segregation process, and test sub-samples resulting from this. Although the process of segregation is well established for UT materials, PT has been shown to reduce or prevent segregation (for example, da Silva 2011, COSIA 2012). Therefore, to fully capture the potential benefits of PT for some tailings, inclusion of segregation effects with UT material may be required.

1.2 Previous Related Work

Reid and Fourie (2015b, 2015c) previously undertook laboratory studies to investigate the effects of PT on a low plasticity slurry. The slurry material was developed from a set of standard laboratory soils, to enable a large number of tests to be undertaken on a reproducible material. Included in this assessment was consolidation testing on untreated UT and PT materials. The results indicated that PT resulted in higher hydraulic conductivities and rate of consolidation compared to UT, across a wide range of vertical effective stresses. Further, the PT material was seen to result in lower final densities at a given vertical effective stress. However, the UT material used for comparison in the work was prepared as a thick, non-segregating slurry. Therefore, comparisons between the two materials may suffer limitations, for idealized deposition scenarios where segregation may occur with conventional (UT) tailings.

1.3 Purpose of This Work

As noted, the previous studies undertaken on PT and UT material did not provide an indication as to how segregating UT material would behave compared to PT. Segregation may result in a fine-grained product reporting to the decant area of a given TSF, which generally has lower densities and permeability compared to the coarser material deposited near the perimeter. PT material, where segregation is eliminated or significantly reduced, may be compared more favorably (and realistically) to UT materials, if cognizance of this segregation is included in comparisons. The purpose of this study is to quantify the behavior of fine and coarse-grained UT material, intentionally segregated in a controlled manner in the laboratory. This will then enable comparison of the segregated materials to PT material, and assessment of the implications of segregation on the comparison to be made.

The primary measure by which potential benefits of PT are measured herein is the average in situ density of a tailings deposit. An increase in density is desirable as it can result in reduced earthworks construction costs - or, more generally, storage volume construction costs.

2. LABORATORY TESTING

2.1 Materials and Sample Preparation

This study made use of the same material developed by Reid and Fourie (2015b) to assess the effects of PT on a variety of geotechnical behavior, and on the effects of shear on PT samples (Reid and Fourie 2015c). This material was developed from a mixture of laboratory-standard Silica Fine sand, Silca 200G silt, and kaolin clay, produced by Sibelco Australia Ltd. Salt equivalent to 2 g per litre of slurry was added, to give a dissolved solids concentration approaching that of a typical tailings slurry. The slurry was developed to produce a material of sufficiently low plasticity to be susceptible to liquefaction-related strength loss (for example, Seed et al, 2003; Bray and Sancio, 2006), while being amenable to improved dewatering rates and reduced segregation potential following PT. The resulting material was 67% fines (<75μm) by mass, had a liquid limit of 24% (measured with a fall cone), and a plasticity index of 9%.

PT was undertaken following screening and dosage assessment by BASF Australia Pty Ltd. This indicated that the high molecular weight polymer Rheomax® ETD DPW 1687 was well suited to the treatment of the slurry developed from this study, at a dosage of 500 g of polymer per tonne of dry solids. PT resulted in an increased liquid limit and plasticity index, to 49% and 24%, respectively. The increase in liquid and plastic limits observed is consistent with previous studies on the effects of PT (Jeeravipoolvarn et al. 2009; Beier et al. 2013). PT of material was not required for this study, as consolidation test data was available from previous studies of the material.

UT material for this test program was initially prepared using similar techniques to those of Reid and Fourie (2015b). The constituent soils and salt were mixed in a dry condition and the material was then mixed to a slurry at 122% gravimetric water content (GWC). In previous studies on this material, the UT was then allowed to hydrate and settle for two days, at which time the clear water was decanted, resulting in a thick, non-segregating slurry at 45% GWC. This material is referred to as UT – Total Sample subsequently. Without this decanting process, the material at 122% GWC would have segregated if poured into test devices, preventing direct comparisons being made to PT materials. .

In sample preparation for this study, the clear water was also decanted following initial mixing, hydrating, and settling from 122% GWC. However, at that point, the finer-grained top half of material was "spooned" off the sample and then stored in a separate container. The fine and coarse components of the material were then tested separately. They are referred to as UT – Fine and UT – Coarse in this paper.

The gradations of the two sample types developed by this artificial segregation process as described are presented in Figure 1, against the original non-segregated material. The particle size distributions shown were obtained using wet sieving on 38, 53, and 75 µm sieves. The UT- Total sample consists of 67% fines, while the UT - Coarse and UT - Fine samples consist of 52% and 93% fines, respectively. This variance in fines content produced is consistent with the magnitude of segregation often observed on TSFs, and hence was deemed suitable for the purposes of the current study.

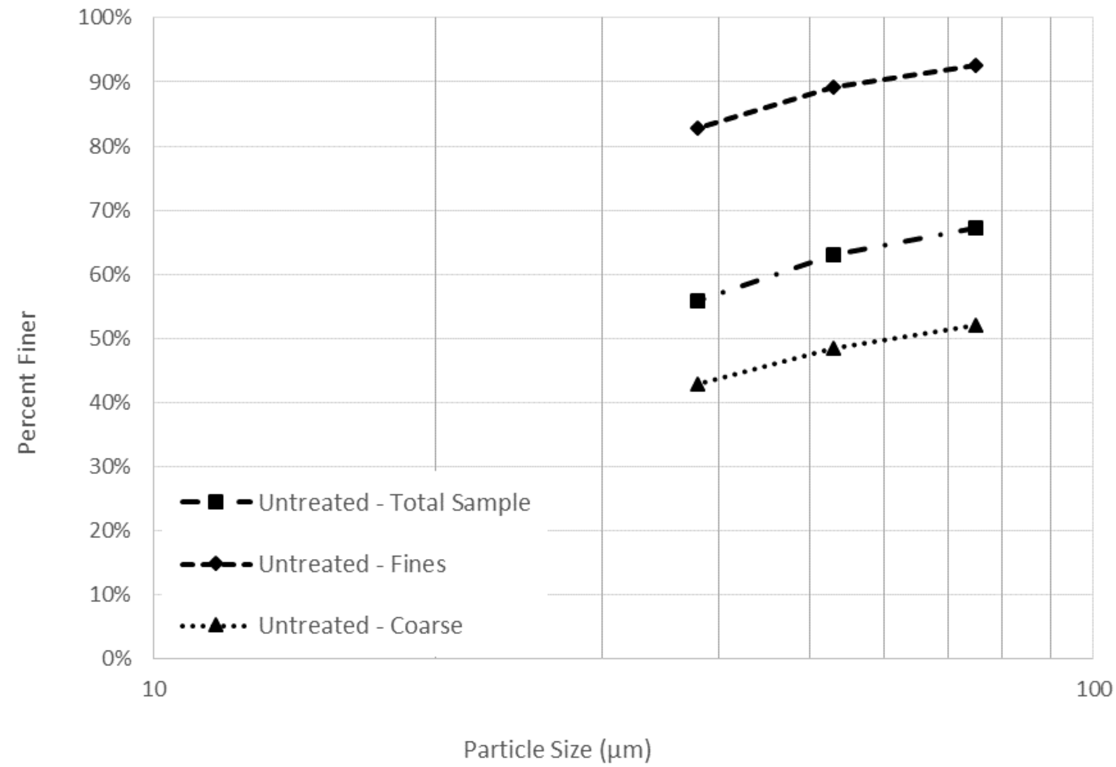

Figure 1. Particle size distribution of samples

After separation as described above, the different constituent materials were then prepared from thick, non-settling slurries, for pouring into the slurry consolidometer tests. The initial/settled void ratio (e_0) of the samples are provided in Table 1.

Table 1. Initial void ratio for materials considered in this study

UT - Coarse	UT-Fine	UT-Total	PT
0.81	1.60	1.18	1.76

2.2 *Consolidation Testing*

Consolidation and hydraulic conductivity testing of both UT – Fine and UT – Coarse samples was undertaken within a 71 mm internal diameter slurry consolidometer, using identical techniques to those of previous studies on the material. Initial sample depth after pouring into the cell was approximately 70 mm. Incremental vertical effective stresses from 10 kPa to 800 kPa were applied to the specimen. Constant head tests were undertaken after each vertical load from 10 kPa. The sample was then unloaded, and removed from the cell for determination of density based on mass of dry solids and sample volume

2.3 *Results*

The results of the consolidation tests undertaken in this study on UT-Coarse and UT-Fine materials, along with previous testing on UT-Total and PT-Total samples (Reid and Fourie 2015b), are presented in Figures 2 and 3. The UT-Coarse sample shows the highest final density at a given vertical effective stress, followed by UT-Total, PT-Total, and UT-Fines. The difference in density between the UT-Coarse and UT-Fine sample is what is typically observed in active TSFs, where the material near the decant is usually softer and at a lower density than the perimeter. That the UT-Coarse sample is denser than UT-Total likely is a result of the initial particle size distribution (PSD) of this material. For example, non-plastic sand-silt mixtures typically achieve optimum packing efficiency at fines contents of 20 to 40% (for example, Lade et al. 1998). For the materials presented here, the UT-Coarse sample was closest to this range, consistent with it having the highest final densities. Had the original, unsegregated UT-Total material been of a lower fines content, it is conceivable that it would have exhibited higher densities than either of its constituent segregated products.

With respect to hydraulic conductivity, UT-Coarse and UT-Fine exhibit significantly divergent ranges, "straddling" the UT-Total sample, consistent with the fines contents for the three materials. The PT-Total sample exhibits higher hydraulic conductivities than all the samples except for the UT-Coarse. Indeed, the PT and UT-Coarse samples appear to, coincidentally, follow a similar void ratio – hydraulic conductivity trend. Although in practice, at a given vertical effective stress, PT would exhibit a higher hydraulic conductivity owing to the higher void ratios relevant to this material at a given vertical effective stress.

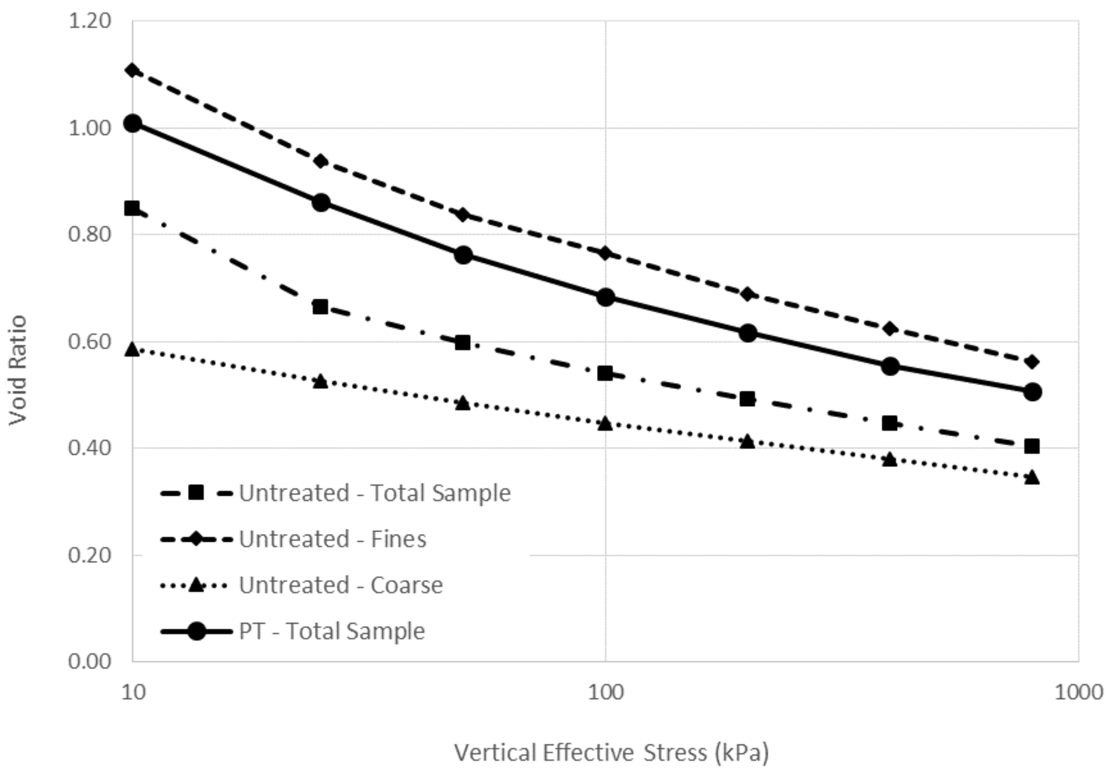

Figure 2. Vertical effective stress – void ratio results

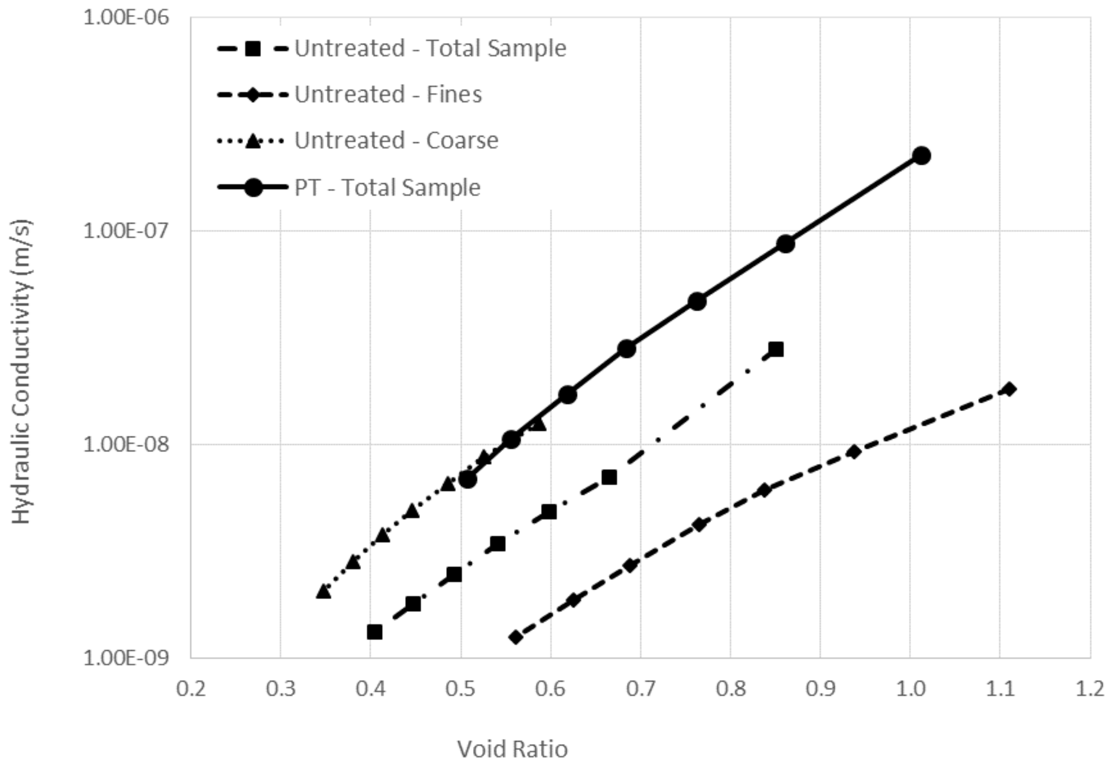

Figure 3. Vertical effective stress – void ratio results

2.4 Implications

The results are mixed at first inspection, when assessing the potential benefits of PT on increasing in situ density of a deposit of tailings. Comparing the total-PSD samplings, UT-Total and PT-Total, the PT material achieves lower final densities at a given vertical effective stress. In isolation, this is a negative outcome, as it means a lower in situ density, in a fully consolidated deposit. However, the fabric created by PT, while having lower final densities, also has considerably higher hydraulic conductivities. The higher hydraulic conductivities of PT material means that the rate of consolidation will be increased. Hence, although a PT material may have a lower final density at a given vertical effective stress, the average in situ density within a TSF may, in some cases, be higher than UT material. For example, in a deposit with a high rate of rise (ROR), a material that consolidates faster may achieve a higher average in situ density, despite having lower final densities at a given vertical effective stress. This was suggested by modelling undertaken by Riley et al. (2015). It is further investigated subsequently in this paper, extended to include the effects of segregation of UT material.

3. NUMERICAL MODELLING

3.1 General

To enable assessment of the potential implications of PT for average in situ density within an idealized TSF, finite strain numerical modelling was undertaken using the software code CONDES0 (Yao and Znidarcic, 1997). Finite strain consolidation modelling enables a more realistic simulation of the tailings deposition process, and the variation in materials properties with increasing vertical effective stress, to be captured, compared to infinitesimal strain consolidation procedures. CONDES0 assesses one-dimensional consolidation, i.e. for a column of tailings of unit dimension. It is noted that undertaking such comparisons by means of a one-dimensional consolidation model involves a number of implicit assumptions. Such an approach assumes that within the idealized deposit, tailings are deposited evenly across the entire area, and increase in all areas with a consistent ROR. Such uniform behavior is never observed in actual TSFs. However, such an idealized approach is required to enable a practical comparison to be made with current tailings analysis technology and techniques.

Material parameters for four different slurry types were developed:

- UT – Total Sample
- UT – Fines
- UT – Coarse
- PT – Total Sample

The material parameters were developed through curve-fitting of the available consolidation results and initial void ratio values (e_0) for each material. The input parameters developed are outlined in Table 2.

Table 2. CONDES0 input parameters for this study.

CONDES0 Parameter	Unit	UT - Coarse	UT-Fine	UT-Total	PT
A	-	0.78	1.62	1.18	1.46
Z	-	0.71	1.08	1.01	0.32
B	-	-0.12	-0.16	-0.16	-0.16
C	m/s	8.0×10^{-8}	1.2×10^{-8}	4.5×10^{-8}	2.1×10^{-7}
D	-	3.4	3.9	4.0	5.1

3.2 Rate of Rise Input

The rate of rise (ROR) of a tailings deposit is an important input, and output, of a finite strain consolidation model. However, ROR can be defined in a number of ways when working with finite strain input and outputs. Therefore, the various ways of describing ROR are outlined below for clarity:

- *Slurry ROR*: This represents the conceptual ROR that would occur, were the material deposited into an idealised TSF at a given rate, and if no settling or consolidation of the material occurred. Hence, this is a function of only the deposition rate, slurry density, and the storage area. This ROR will not be realised in most TSFs. However, it represents the starting point for developing the ROR input for the models undertaken, in that Slurry ROR is consistent between the different materials when making comparisons. As the dewatering behaviour of the materials considered here differ, the Slurry ROR is the last point of convergence for the simulations undertaken.
- *Depositional ROR*: This refers to the ROR that would occur, were the material deposited into an idealised TSF at a given rate, and settling, but no consolidation, were to occur. Therefore, this is a function of the deposition rate, settled density (assumed ~e_0, herein), and deposit area. Similar to Slurry ROR, this form of ROR is unlikely to be realised in most TSFs. However, Depositional ROR is important as it forms the input to CONDES0. CONDES0 then operates in the range of soil behaviour where effective stresses are present, i.e. beyond e_0.
- *Realised ROR:* This refers to the actual ROR observed following model runs across a given time interval. It is an output of CONDES0, based on the depositional ROR, and the consolidation characteristics of the material. It simulates, as far as practical, the actual ROR that would be observed in the idealised TSF under consideration, under the conditions modelled.

Models were run for each material at Slurry RORs of 5, 10, 20, 30, and 40 m/year. These values provide a wide spectrum of potential tailings behavior. The highest RORs used are beyond those typically relevant to deposition with TSFs, perhaps with the exception of cellular TSFs that are filled in series as part of mining works (for example, Beveridge et al. 2015, Riley et al. 2015). However, they have been included to provide a wide range of potential material behavior for comparison.

Models were run to simulate deposition over a five year period, with comparisons made based on the predicted condition of the deposit at the end of this period. Post-deposition consolidation was not included in the comparisons made. The bottom of the models were assumed to be impermeable – i.e. excess consolidation pore pressure could only dissipate to the top surface of the model.

3.3 Comparisons of Total-PSD Samples

The modelling process was first used to compare the behavior of the total-gradation samples, UT-Total and PT-Total. The UT-Total in this case represents the potential behavior of UT material if it were mechanically dewatered sufficiently to produce a non-segregating material – in this case to 45% GWC. The comparison is provided in Figure 4. The comparison is made on the basis of the average in situ dry density realized within the one dimensional model, after a simulated five years of deposition. The results are compared based on the Slurry ROR used for each model – two models with the same Slurry ROR have the same deposition rate into the same deposit area.

The results indicate that a low ROR, where consolidation is largely completed during deposition for both materials, UT-Total material achieves higher in situ densities. This is consistent with the higher final densities observed at a given vertical effective stress. However, as ROR is increased, the consolidation process becomes inhibited for UT material, resulting in a reduction in average realized in situ density. Hence, at higher ROR this modelling predicts PT achieving higher overall densities.

It is interesting to note that increasing Slurry ROR does not have a consistent effect on realized dry density for either material. Rather, an increase in Slurry ROR may increase or decrease average in situ realized dry density, dependent on the progress of consolidation for a given material at a given ROR. For example, if the increase in Slurry ROR is such that self-weight consolidation will be largely complete despite the increase, this can serve to increase average realized dry density, as a larger quantity of solids are deposited – and with an increase in solids, an increase in potential vertical total and vertical effective stress. Higher vertical effective stresses thus enable higher densities to be achieved. Alternatively, when ROR increases such that self-weight consolidation becomes inhibited, this can reduce the average realized dry density, as indicated in Figure 4. The point at which increasing ROR results in a decrease in average realized dry density is different for the two materials, as they undergo consolidation at different rates.

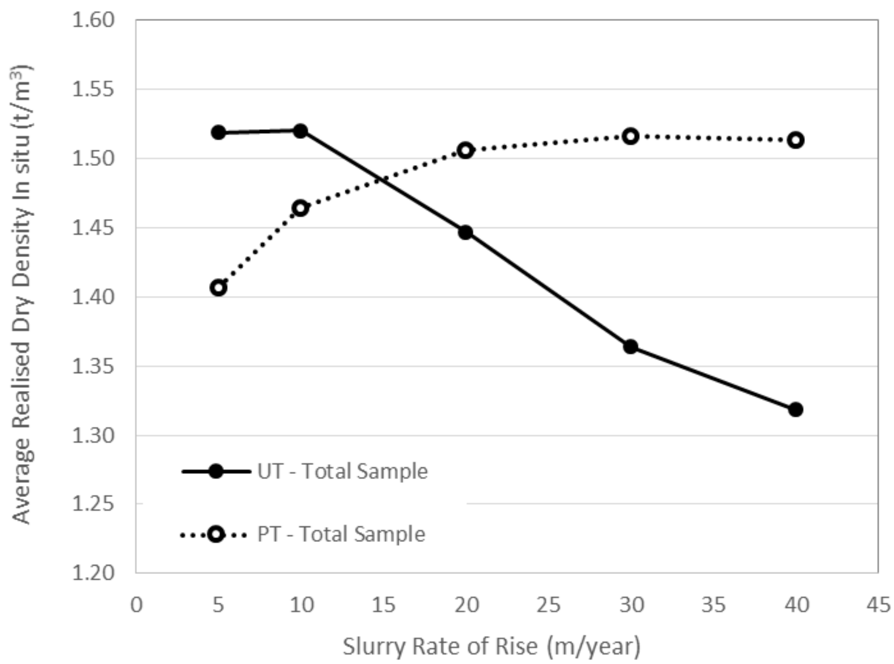

Figure 4. Average realized in situ dry density comparison – Total PSD samples

3.4 Comparison of Segregated UT Samples

The effects of segregation on the behavior of UT material were compared, as outlined in Figure 5. As would be expected based on the consolidation test results, the UT-Fine material achieves relatively low densities, while the UT-Coarse material densities are significantly higher. The results "straddle" the results of the UT-Total material.

To provide an estimate of the average realized in situ density for an idealized deposit where segregation was occurring, the UT-Coarse and UT-Fine material trends have been averaged. This is a simplified, and probably speculative, assumption which implicitly assumes that the UT-Fine and UT-Coarse materials each occupy half the surface area of the TSF deposit. Rather, there will be a gradual variation in the deposited materials PSD along the beach as segregation occurs. Fully accommodating this process is likely beyond the practical capabilities of current tailings practice. For example, it would require testing a nearly infinite number of gradations, and developing a distribution of each to enable consolidation modelling and density estimation. For the purposes of the current paper, the authors believe the technique adopted is sufficient to enable comparisons and broad trends to be interpreted.

The results also indicate that the average value in the idealized segregated deposit is lower than that of a non-segregating situation. Separate to the consideration of PT, this is noteworthy for consideration of the potential benefits of thickened tailings deposition, as such deposition schemes will generally eliminate or greatly reduce segregation occurring within a TSF. This is independent of the potential increase in final vertical effective stresses often seen as a result of increased slurry density across a range of non-segregating slurry densities (for example, Reid and Fourie 2015a).

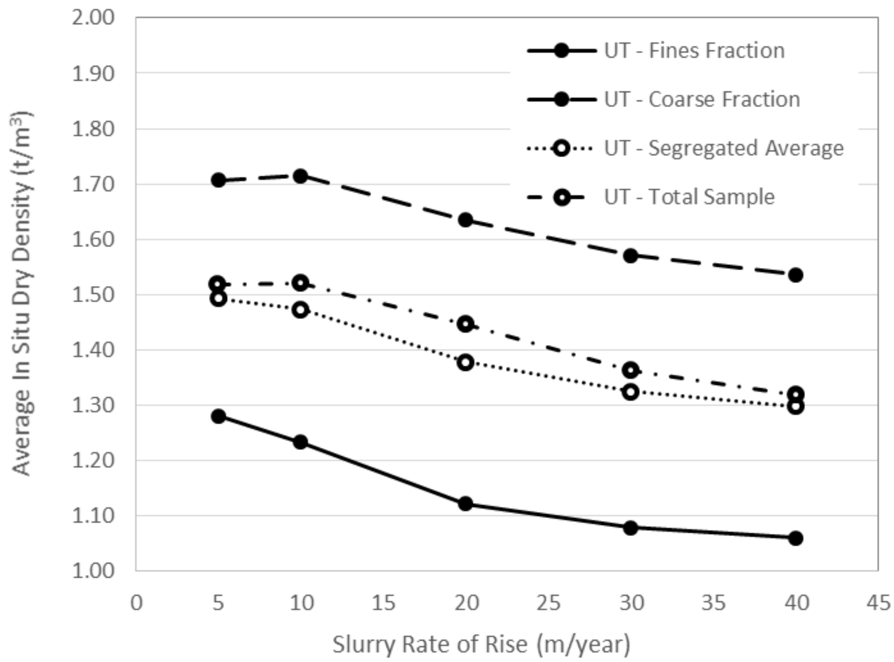

Figure 5. Average realized in situ dry density comparison – Effects of UT segregation

3.5 Comparison of Segregated UT Samples with Total-PSD PT

The results of the above models are combined for comparison in Figure 6. The inclusion of segregation considerations to the assessment of the potential benefits of PT is seen to be meaningful for the material studied in this work. When segregation effects are included, the ROR at which the PT material is predicted to give better average realized in situ dry densities decreases by 50%. Whether the inclusion of segregation in such an analysis would affect the decision to potentially implement PT for a particular deposit would depend on a number of factors related to the various costs involved in doing so (or not). However, the authors believe that the results obtained herein provide some guidance on the potential negative implications of segregation on in situ dry density, and present a relatively straightforward method to include segregation in such an analysis.

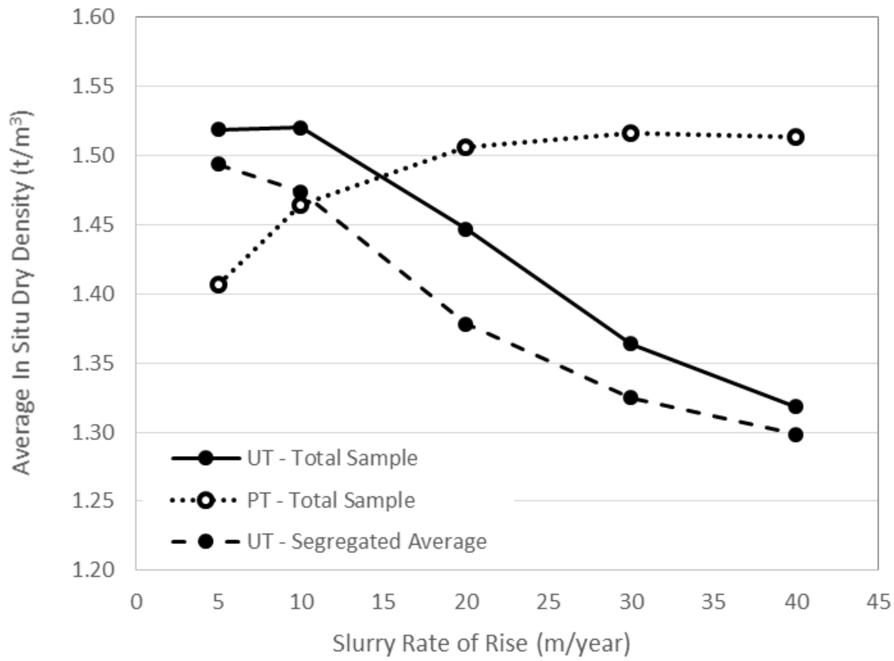

Figure 6. Average realized in situ dry density comparison – Segregated average UT and PT

3.6 Limitations

In order to undertake the comparisons presented herein, significant idealization of tailings deposition has been required. For example, it was assumed that deposition would be uniform over the plan area of the idealized TSF storage area, with the same ROR in all locations. Further, accounting for the different densities of the segregated material was simplified to a simple unweighted average between UT-Coarse and UT-Fine. It is unknown if this is a reasonable assumption as, to the author's knowledge, no such modelling to include segregation has been previously undertaken.

Whether the magnitude of average realized dry density increases that were observed at some ranges of ROR would warrant implementation of PT for this material is beyond the scope of this paper. This would require financial comparisons considering, at a minimum, the cost of TSF wall raise construction (or more generally, storage capacity construction) and the cost of implementing PT.

It is noted that an increase in dry density is only one of a number of different reasons for potentially implementing PT. Others include improving return water clarity, increasing beach slope and/or increasing strength gain on the surface of a deposit to enable rehabilitation works. These were not considered in this work.

The potential for significant post-depositional shearing of the PT material was not included in this study. Testing of sheared PT materials has indicated that this may reduce some of the potential benefits of PT, depending on the magnitude of shear (Jeeravipoolvarn et al. 2014, Reid and Fourie 2015c).

4. CONCLUSIONS

A series of consolidation tests were undertaken on intentionally-segregated UT material, to assess the effects of such segregation on the consolidation behavior of the material. Segregation was seen to result in a relatively coarse-grained material (UT-Coarse) with high hydraulic conductivity and final density, and a finer-grained material (UT-Fine) with low hydraulic conductivity and final density.

The consolidation results obtained in this study were then compared to previous testing on the material from a thick non-segregating slurry (UT-Total) and PT material, and used to develop input parameters for finite-strain consolidation models for each of the four materials. The consolidation models were undertaken to assess the effects of the different consolidation characteristics of each material on the average in situ dry densities realized in a series of idealized deposition scenarios with different ROR.

The consolidation modelling indicated that both ROR, and potential segregation had a significant effect on the comparisons between UT and PT materials. At high ROR, the higher rate of consolidation for PT material resulted in an increased average in situ realized dry density within an idealized deposit. This would imply that less storage volume would be required, all else being equal. The segregation of UT magnified the potential of PT to increase average in situ dry density, owing to the slow rate of consolidation for the UT-Fine material.

The limitations of the work include significant idealization of deposition to enable comparisons to be made, the lack of consideration of financial considerations as to whether the increase in dry density achieved is sufficient to warranted PT implementation, and potential effects of shear-degradation on the behavior of PT samples.

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