

Unsaturated mine tailings disposal

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Case Study

Keywords

Tailings dewatering
Filtered tailings
Flocculant
Tailings air-drying
Tailings compressibility
Dry stacking

Abstract

Filtered tailings is the disposal technology that is most likely to yield an unsaturated state of the tailings. Such state has important benefits. A dam to contain the mine wastes is no longer needed, the risk of polluting seepage is minimized, and liquefaction of tailings is prevented. Filtering also allows most of the water mixed with the tailings to be recovered and reused in the process. The resulting material can be handled with traditional soil moving equipment to form a stack, for instance. While the idea is simple, the multiple phenomena involved in the tailings unsaturated disposal make up a complex process. The present work is based on a case study, the Casposo Mine filtered tailings disposal facility, located in the central Andes of Argentina. Throughout ten years of operation, a series of field and laboratory studies have been carried out to characterize the phenomena that intervene in the disposal of filtered tailings. Two stages were studied in detail: air drying upon tailings discharge and tailings compression under the weight of the subsequent lifts of the stack. Flocculant agents were found to have an outstanding influence in the tailings behaviour. Because of the multiple influencing factors, the process outcome (namely, the tailings water content and their void ratio) is highly variable. To deal with such variability, projects must include enough redundancy. In this regard, the case study's incorporation of waste rock layers interspersed between tailings layers was a successful experience.

1. Introduction

Filtered tailings is a currently well-established technology for mine tailings disposal. Among the disposal methods, it is the one which allows achieving an unsaturated state of the disposed tailings in the most consistent manner. This is indeed a very desirable goal in a tailings deposit because of the multiple benefits of the unsaturated state. First and foremost, the need of a dam is eliminated. Moreover, a large fraction of the process water can be recovered, which otherwise is permanently trapped within the tailings voids, lost by evaporation or underground seepage. Recovered water can be reused in the extraction process allowing to save a high fraction of the process water. In the case of metal lixiviation, it also yields higher recovery ratios and spare of chemical additives. Moreover, unsaturated tailings are less prone to static or dynamic liquefaction failures. According to Franks et al. (2021), filtered tailings facilities show less than the half to one fifth the incidence of stability issues of the other tailings disposal methods (in % of the total number of facilities of each type). Contaminating leakages are also

less likely since there is no permanent hydraulic head acting over water-proof linings or barriers installed at the bottom of the disposal facility. Lastly, tailings dewatering reduces the volume and footprint of the disposal facility. The usual arrangement of a filtered tailings disposal facility is simply a stack (Figure 1a). Construction methods involve typical earthmoving equipment, front-loaders, trucks, dozers, graders and eventually compaction rollers. Conveyor belts are also used as an alternative means of placing the tailings in the stack (Lara et al., 2013).

In view of the above considerations, the use of filtered-tailings technology appears quite straightforward. However, the ultimate goal of storing the tailings in a permanent unsaturated condition has many implications, not only for the design of the facility but also for its operation, mainly due to the variable nature of the tailings water content. In the first place, the selection of the tailings water content at filter output is a trade-off between a desirable amount of dewatering and the technical constraints of the filtering method. Standard practice involves thickening of the slurry before filtration. Moreover, the filter output moisture of tailings is intrinsically variable,

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Figure 1. (a) Stack of filtered tailings under construction. Casposo Mine, San Juan, Argentina (Photo: courtesy of Casposo Argentina, published with permission); (b) Tailings transport and distribution with conventional earthmoving equipment requires achieving trafficability.

because of the variability of the ore grain size distribution and changes in its mineralogical composition affecting the filter performance (Crystal et al., 2018).

In any case, the achieved moistures are relatively high from a geotechnical standpoint. The commonly specified moistures of tailings at filter output (termed “filter cake”) typically range between 15 and 25% in weight (Wang et al., 2014; Hogg, 2010; Ulrich, 2019). Nonetheless, some mining operations specify higher moistures up to 30 or even 40% (Crystal et al., 2018, Copeland et al. 2006). It is worth noting that in the metallurgist usage water content is defined as water weight divided by the mixture weight (solids plus water), which differs from the geotechnical definition of the gravimetric water content (GWC), i.e., water weight divided by solids weight. Hence the above-referred moisture range translates into a GWC range of 18 to 67%. From a geotechnical perspective, it would be desirable for the moisture achieved by filtration to be close to the Proctor optimum. Nonetheless, such a condition is hardly achievable for many tailings (Ulrich, 2019). In fact, filtered tailings are delivered from the plant in a rather high saturation state.

Later, during the transport, discharge and spreading operations, water content can further change by segregation and water bleeding, drainage, evaporation, rainfall, or snowmelt. Additional factors affect the evolution of water content. For instance, the tailings production rates affect the timing of lifts placing and, hence, the period during which the recently discharged tailings remain exposed to atmosphere. Also, the placing procedure used, the spreading method, the lift height and the discharge area have influence on the evolution of water content. Finally, the site climate and meteorology factors are obviously relevant. Hence, the final water content of tailings in the deposit is far from being constant and rather difficult to control.

A key parameter in the disposal process is the moisture of tailings at the time of covering them with the following lift, also termed the target water content. In the first place,

moisture determines trafficability (Ulrich, 2019), which is vital when tailings transport and distribution rely on trucks and earthmoving machinery (Figure 1b). If compaction is specified in the standard placing procedure, a water content close to the Proctor optimum value should be approached. In any case, upon covering a tailings layer with the following lift of the stack, air-drying is mostly interrupted. In addition, from that moment on, overburden stresses will grow steadily due to the deposit rise. As a result, the saturation degree tends to increase due to volume reduction. Thus, if the intended goal is to keep tailings unsaturated, the target water content should be low enough to counteract the expected volume reduction during consolidation. So, it turns out that the whole disposal process is not as simple as it appears at first sight since the result depends on many mechanisms and factors.

Several surveys have been carried out at Casposo Mine (Argentina) filtered tailings deposits along the decade elapsed since the mining operations started. The facility was specifically designed based on unsaturated soils mechanics concepts. The overall performance of the deposit was quite satisfactory, with no significant issues and having passed some moderate intensity earthquakes without visible effects. The goal of the survey program was to gather basic information for characterising the processes and factors previously mentioned. The present paper summarizes the lessons learned during this process as well as some general conclusions and recommendations.

2. Case description

Casposo is a moderate size gold and silver mine located in the east foothills of the Andes, in San Juan Province, Argentina. Metal extraction is done by milling followed by tank lixiviation with cyanide solution. To date, the exploitation has already been run for a decade, being the reserves close to exhaustion.

A distinct feature of this case is that filters are used for dewatering the mine tailings ahead of their disposition. It is

the first and, so far, the only experience in Argentina with filtered tailings. While processed, the ore pulp has a solids content of 53% in weight (computed as the weight of solids divided by the mixture weight). The whole dewatering process, involving the addition of a flocculating agent, thickening, and vacuum belt filters (Figure 2) allows recovering about 60% of the process water. Fresh water is sprinkled over the tailings travelling on the belt filter to rinse the pregnant solution. All the recovered water is reused in the process after going through a treatment for the separation of the dissolved metals. The tailings delivered by the filter have a mean solids content of 70% in weight. The plant was projected for an ore processing rate of 1000 tons/day.

The host rock of the mineral deposit includes rhyolite and andesite, while the mineralized veins are composed mostly by quartz. The solids specific gravity of tailings particles is 2.72 (ASTM, 2014). Grain size distribution of tailings is shown in Figure 3. D_{50} is 0.05 mm and $C_u = 6$. The content of

clay-sized particles is about 1% in weight and, consistently, Atterberg limits are $LL = 20.2$, $PL = 17.6$, $PI = 2.6$. Hence, the material would be considered a non-plastic silt in the Unified Soil Classification System. Two additional grain size distributions are displayed in Figure 3. One corresponds to mine ore milled in the lab to nearly the same grain size distribution as tailings and no further treatment. This was used as reference material for studying the influence of the metallurgical process on tailings properties. The third curve corresponds to waste rock which is also a component of the tailings disposal facility, as later explained.

Retention curve data were obtained with filter paper method (ASTM, 2016a; Kim et al., 2017), vapour equilibrium with saline solutions (Delage et al., 1998), and chilled mirror device (ASTM, 2016b). Figure 4a depicts the results of the two series of tests conducted on specimens of milled ore and actual tailings, respectively. All specimens were prepared from a known weight of oven-dried tailings, adding



Figure 2. Vacuum belt filter at Casposo Mine. (a) Tailings being fed to the filter band; (b) Tailings at filter output.

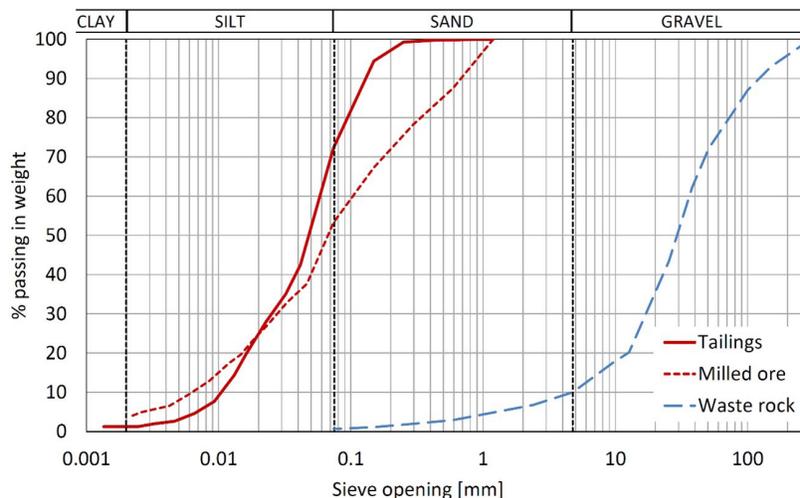


Figure 3. Grain size distribution of tailings milled ore and waste rock.

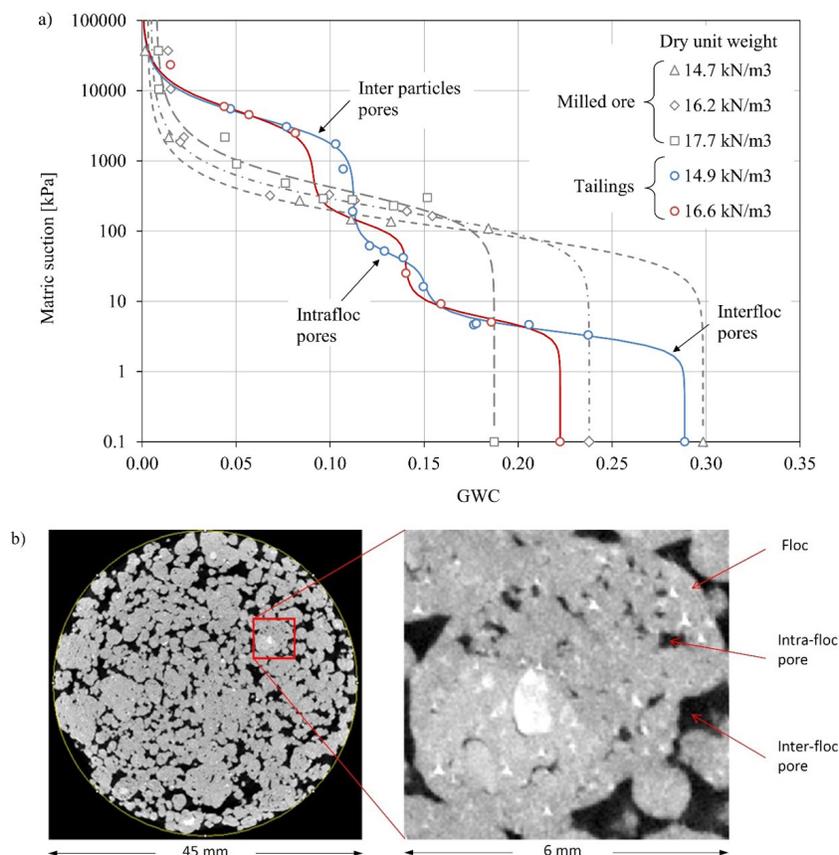


Figure 4. (a) Retention curves of Casposo Mine milled ore and tailings at different unit weights; (b) X-ray Tomography results on Casposo Mine tailings sample prepared at 10.5 kN/m³ dry unit weight.

the amount of distilled water needed to achieve the desired water content, and measuring the suction with the appropriate method. The points obtained with the latter methods are those with suctions above 1000 kPa. Strictly speaking, they are total suction values. However, measurements made with the chilled mirror device on samples of tailings leachate yielded zero reading for the osmotic suction component. Hence, total suction measurements can be considered equivalent to matric suction with reasonable approximation. In the filter paper technique, the paper was put in contact with the specimen and, therefore, measurements correspond to matric suctions.

From the beginning of mine operation, chemical additives incorporated while in the metallurgical process were suspected of having strong effects on the tailings behaviour. Certainly, some striking differences can be observed in the two sets of data displayed in Figure 4a. Milled ore retention curves have the shape of a typical silty soil. These data were fitted with a van Genuchten (1980) (VG) expression.

On the other hand, the retention curve points obtained for the tailings suggest, at least, bimodal or even trimodal distribution of pore sizes. An example of natural soil showing similar features is peat (Rezanezhad et al., 2012). Such drastic difference between milled ore and tailings is attributable to the effects of the flocculant agent (a long-chain polymer)

added in the extraction process. Figure 4b shows the result of an x-ray tomography performed on a tailings sample, where flocs, inter-floc and intra-floc pores are clearly visible. A third inter-particle pore system can be inferred, though not visible in the tomography due to image resolution limitations. Tailings retention curve data points were fitted with a weighted sum of three VG expressions as proposed by Ross & Smettem (1993):

$$S(\psi) = S_r + (1 - S_r) \sum_{i=1}^3 \frac{e_i}{e} \cdot \left[1 + (\psi / P_{0i})^{1-(\lambda_i)} \right]^{-\lambda_i}, \text{ with } \sum_{i=1}^3 e_i = e \quad (1)$$

where S is the degree of saturation, ψ is suction, S_r is the residual degree of saturation, e_i are the partial void ratios of each pore system, e is the material void ratio, P_{0i} and λ_i the VG expression parameters. Curve fitting parameters are indicated in Table 1. S -values were then converted to GWC according to the specimen's dry unit weight.

While preparing the retention curve specimens, it also became evident that the unit weight range achievable with each material was quite different. For tailings, dry unit weights higher than 17 kN/m³ are only achievable with heavy compaction or confining stress levels beyond the range of interest for this work. Moreover, tailings can attain very loose states, with unit weights as low as 11 kN/m³.

Table 1. Retention curve parameters.

Material	Dry unit w. [kN/m ³]	S_r	Inter-particle pores			Intra-floc pores			Inter-floc pores		
			e_1/e	P_{01} [kPa]	λ_1	e_2/e	P_{02} [kPa]	λ_2	e_3/e	P_{03} [kPa]	λ_3
Milled ore	14.7	0.01	1.00	75.8	0.52	---	---	---	---	---	---
	16.2	0.02	1.00	139.5	0.51	---	---	---	---	---	---
	17.7	0.05	1.00	259.5	0.50	---	---	---	---	---	---
Tailings	14.9	0.00	0.39	3300.0	0.60	0.13	43.3	0.75	0.48	3.4	0.75
	16.6	0.00	0.41	4200.5	0.60	0.22	123.7	0.75	0.37	5.4	0.75

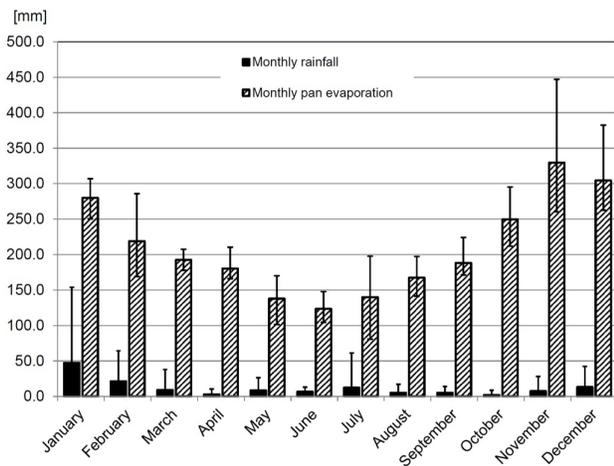


Figure 5. Casposo site precipitation and evaporation. (reprinted from Oldecop et al. (2017) by permission from Springer Nature ©2017).

However, lab specimens with such low unit weights are impossible to handle for performing measurements with the filter paper method. This aspect is addressed again in the paper when analysing the oedometer tests. Otherwise, specimens of milled ore for filter paper method hold only for relatively low moisture states (for instance, under 18% for the 14.7 kN/m³ specimen as it follows from the lack of higher GWC points in Figure 4a). Datasets with zones of lacking points were fitted with curves that follow a similar pattern as the complete series.

Finally, it is worth mentioning that the site climate is arid, with a year-round water deficit (Figure 5). Mean annual precipitation is 150 mm and mean annual evapotranspiration is 1250 mm. Most rainfall occurs in summer when evaporation is higher, causing their effects to cancel out to some extent.

3. The tailings disposal process

At the filter outlet, tailings were loaded in trucks, transported to the disposal facility, dumped, and spread with a bulldozer, forming layers roughly 1m in thickness. The stack is placed over a water-proof barrier covering all the valley floor. Such a barrier is underlain by a subdrain layer which allows bypassing uncontacted surface and subsurface waters (very scarce at the site) and covered by a

top drainage layer for collecting contacted waters eventually draining from tailings.

Newly deposited tailings need to undergo some air-drying to become trafficable. The arid site climate grants significant drying in a relatively short time. No compaction was applied. Instead, once drying has progressed far enough, a layer of waste rock (also roughly 1 m thick) was spread over the air-dried tailings to create a new work-platform, where trucks could travel and dump the following tailings layer. Besides the improved trafficability, the design alternating tailings and waste rock layers provides some additional strengths to the deposit:

- Free drainage of tailings with eventual excess water;
- Capillary barrier effect at the bottom of each tailings layer;
- Structural reinforcement.

Eventual excesses of water may occur for a variety of reasons: variability of filter performance, rainfall events, temporary rise of the ore processing rate or temporary shortage of the deposition area due to constructive issues, etc. In any event, the draining capability provided by the waste rock layers adds flexibility and redundancy to the operation, since eventual excess waters can drain with no harmful consequences. Some trench drains, also filled with waste rock, were built-in to collect the drained water, leading it to the bottom draining layer. Thereafter, water is collected in a reservoir at the downstream toe of the stack. All contacted waters are recycled in the mineral extraction process. Furthermore, the capillary barrier effect prevents deep percolation. Thereby, rainfall water is always kept in the topmost layer from where it is readily eliminated by capillary rise and evaporation. Finally, as for most fine-grained materials, the shear strength of tailings depends on the water content (or matric suction). Hence, introducing reinforcement layers of the coarse-grained waste rock adds redundancy to the stability of the deposit, reducing its sensibility to eventual water excess.

Figure 6 illustrates the stages of the tailings disposal process explained in the previous section, and the corresponding phase diagrams for each stage. Key parameters regarding water management are w_f = gravimetric water content at filter output; w_0 = target gravimetric water content by the time of covering a layer with the following lift and w_c = final gravimetric water

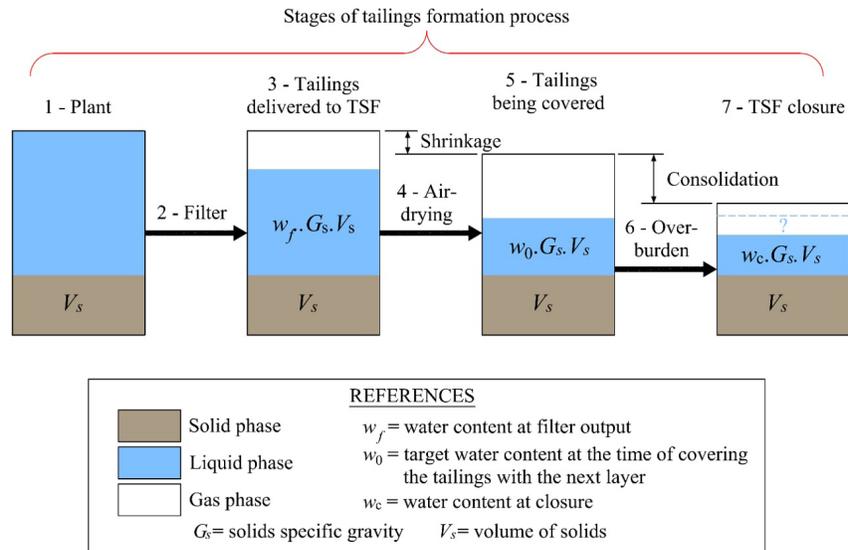


Figure 6. Phase diagrams of tailings along the stages of their disposal process.

content of tailings, i.e., by the closure of the facility. Moreover, the final void ratio e_c is also a relevant parameter since, together with w_c , determine the degree of saturation at closure.

A primary design hypothesis assumed in the design phase was that little to no moisture change would occur after tailings cover by the following layer. Hence, w_c should result nearly equal to w_0 , allowing to estimate the final saturation water content by estimating the final void ratio e_c , assuming that the tailings compressibility properties are known. As shown in the following sections, tailings layers do not seem to behave that way, essentially, because drainage of tailings starts ahead of saturation. Otherwise, recharge could occur in already covered layers with waters draining from upper layers. So, in the end, the closure water content, w_c , could be lower or higher than w_0 . In any case, volume reduction under the increasing overburden loads will increase the degree of saturation during Stage 6. Therefore, the final degree of saturation is certainly difficult to evaluate.

Regarding the conceptual model presented above (Figure 6) two basic phenomena are worth to study:

- Tailings air-drying which determines the required duration of the air-drying period (Stage 4) needed to achieve w_0 .
- Tailings volume reduction due to consolidation (Stage 7) which shall determine the selection of the target water content, w_0 .

Considerable effort was devoted to study these two aspects. The methods and results are described in the following sections.

4. Tailings air-drying

Tailings air-drying is an essential component of the disposal scheme used in the case study. The process, namely the tailings-atmosphere interaction, was studied both ahead and

during the mine exploitation phases. The available timespan for air-drying (Stage 4) is controlled by the lift placing cycle, which, in turn, is determined by the available working area and the tailings production rate. Hence, for a given set of external constraints (climate, tailings properties, filter performance and production rate), an appropriate stack geometry is required to ensure that the length of the air-drying period always spans the time for achieving the target water content, w_0 .

The evolution of the water content of tailings during the air-drying stage was monitored by means of random sampling of the tailings as layers were placed, simultaneously recording the time-since-placing at each sampling point. Samples were taken from the mid-height of the layers and GWC was determined by oven-drying (ASTM, 2019). The data set gathered along a four-year sampling period, is shown in Figure 7. A first attempt was made analysing the data grouped by season, in the supposition that meteorological factors would considerably differ from one season to another and this would influence the tailings desiccation rate. No definitive trends were observed and hence, it was decided to carry on with the analysis of the data set as a whole. The following expression was fitted by minimum squares (Rodari & Oldecop, 2021):

$$w_0 = (a - b)e^{-ct} + b + \epsilon_w(0, s) \quad (2)$$

where w_0 is a random variable, t is air-drying time elapsed since placing of tailings, a , b , and c are fitting parameters and ϵ_w is the residue assumed as normally distributed with zero-mean and standard deviation s .

Some conclusions can be drawn from Figure 7:

- The water content from samples gathered in the deposit bears a significant variability, attributable not only to

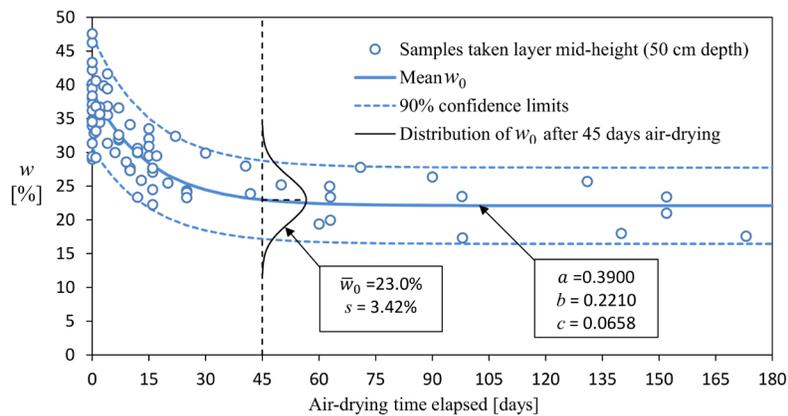


Figure 7. Evolution of GWC in the upper tailings layer while exposed to the atmosphere, determined by random sampling at the layer mid-height (modified from Rodari & Oldecop (2021) in print, reproduced with permission).



Figure 8. Exploration trenches dug in the upper tailings layer while exposed to the atmosphere.

the initial variability caused by filter performance, but also to the action of meteorological factors.

- The desiccation process gradually slows down during the initial period (lasting 45 to 60 days in the case studied) and becomes almost nil thereafter. This can be attributed to the formation of a very dry superficial zone in the tailings layer (see Figure 8), in which capillary rise is impeded by loss of liquid phase continuity.
- At the time of covering a certain tailings layer with the following waste lift, the water content, w_0 , within the tailings being buried, can be described as a normally distributed random variable, with a mean value given by ec. (1) and a standard deviation obtained by variance analysis of the residuals. In Figure 7 such distribution is depicted for an air-drying period of 45 days, for instance.

A second method was used to study the tailings drying process. Water content profiles were obtained in trenches dug in the top layer during the air-drying stage (Figure 8), for various times elapsed since tailings placing. In-situ unit weight was also determined in the same sites at two or three different heights within the layer (ASTM, 2007). A summary of the results of those surveys is presented in Figure 9. Desiccation proceeds from an initial (estimated) uniform profile (w_f with a mean value of 41%). The profiles from days 7 and 10 suggest loss of water from both the layer top boundary (surface evaporation) and bottom boundary (drainage). In the following weeks, drying continues mainly by capillary rise and evaporation from the layer upper surface. Between days 45 and 50 the profile seems to approach a limit, suggesting that, beyond that period, drying reaches a standstill. The average GWC in the 50-days profile is 23.6% (indicated

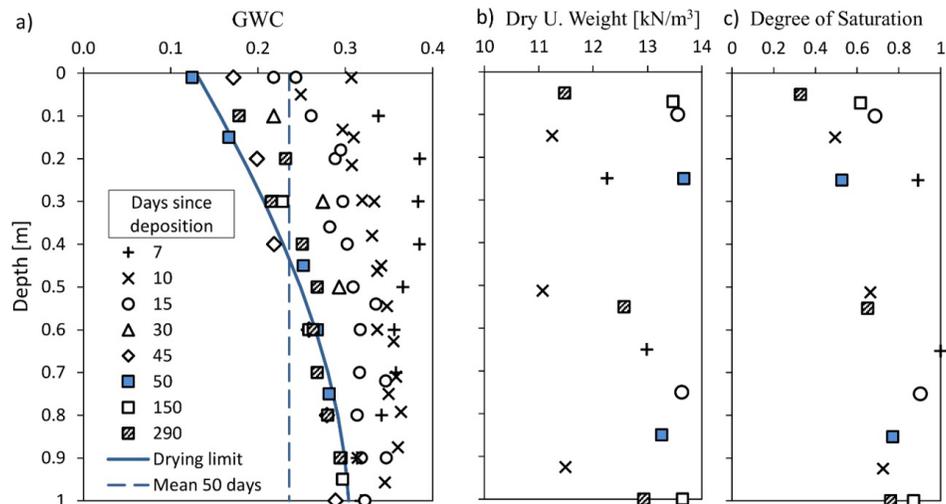


Figure 9. GWC and unit weight profiles surveyed in the upper tailings layer while exposed to the atmosphere (adapted from Rodari & Oldecop (2021) in print, reproduced with permission). (a) GWC profiles for different periods elapsed since deposition; (b) In-situ dry unit weight determinations; (c) Computed degree of saturation profiles.

Table 2. Testing conditions of tailings and milled ore specimens.

MATERIAL	ID	MOUNTING		TEST INITIATION		TEST END	
		GWC w_f	GWC w_0	Void ratio e_0	Max. applied stress [kPa]	GWC w_c	Void ratio e_c
Tailings	T1	0.409	0.409	1.497	1540	0.205	0.561
	T2	0.406	0.336	1.504	1582	0.201	0.554
	T3	0.394	0.206	1.400	1542	0.196	0.573
	T4	0.386	0.212	1.425	1582	0.200	0.569
Milled ore	O1	0.250	0.250	0.840	1570	0.148	0.402
	O2	0.150	0.150	0.901	1570	0.150	0.472
	O3	0.100	0.100	1.510	1570	0.100	0.618

ID: Specimen identification, GWC: gravimetric water content.

with dash line in Figure 9). This is roughly consistent with the GWC data gathered with random sampling (Figure 7).

The dry unit weight data (Figure 9b) do not reveal a clear relationship with the time elapsed since placing of the tailings layer nor with the depth. The measured values are noticeably low. Simultaneous determinations of dry unit weight and GWC allowed to compute the in-situ degree of saturation which is depicted in Figure 9c. These values are consistent with the interpretation made in the previous paragraph.

5. Tailings compressibility

Compressibility of tailings was primarily studied by means of oedometer tests. Specimens were prepared and tested attempting to mimic the tailings disposal process depicted in Figure 6 (for a more straightforward interpretation, moisture and void ratios characterising the test specimens were named with the same notation defined in Figure 6). The testing procedure comprised the following stages: 1) Oven-dry

tailings were mixed with water to reach the mounting water content w_f ; 2) Tailings were poured in the oedometer ring with no compaction. The resulting void ratio was computed from the poured tailings mass and the ring volume 3) The specimen was allowed to air-dry until reaching a specific target water content w_0 ; 3) During a 24hs-period the specimen was kept isolated from the environment, to allow moisture uniformization within the specimen; 4) Load was applied in steps, recording the vertical strain and mass of water expelled by the specimen. In some specimens the air-drying stage was omitted and, hence, w_0 is equal to w_f in those tests. The testing device is a piston-cylinder assembly, allowing drainage from both upper and lower specimen ends. The water expelled was measured at each stage of the test by collecting and weighting the drained water. Table 2 summarizes the conditions of all specimens tested. Figure 10 displays the oedometer results in the compression plane (void ratio vs. vertical stress).

Some interesting observations can be made regarding the results depicted in Figure 10. The first feature that

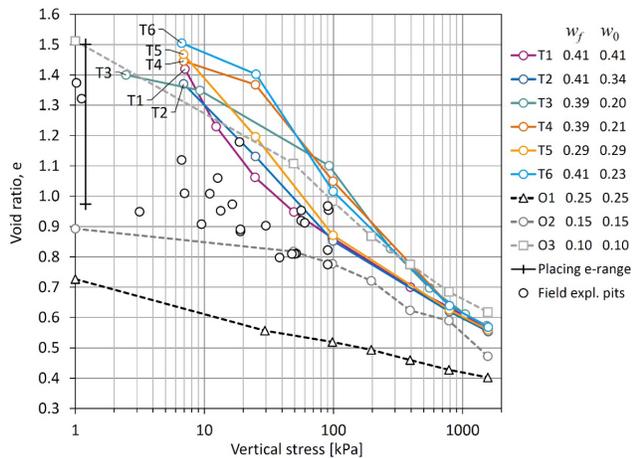


Figure 10. Oedometer tests performed on specimens of tailings and milled ore specimens, prepared at different initial water contents. Results shown in the compression plane. Additionally, points of void ratio vs. vertical stress obtained from in situ measurements in field exploration pits are included.

stands out is the relationship between the void ratios and the mounting water content of each specimen. In the milled ore, higher pore indexes are attained for lower preparation water contents. The loosest state is achieved with $w_f = 10\%$, while the densest state corresponds to $w_f = 25\%$, for which the material is almost saturated. This appears to be attributable to the bulking effect caused by the action of the capillary water menisci. The effect diminishes for higher water contents and completely vanishes at saturation. In contrast, tailings attain void ratios similar to the loosest state of the milled ore, but for much higher water contents (30–40%). The difference could be ascribed to the action of the flocculant agent.

To get a field reference to check how representative are the laboratory compressibility data of the real behaviour of tailings, information gathered in exploration pits dug at different stages of the deposit construction are used, i.e., in-situ dry unit weight (ASTM, 2007) and water content of tailings (ASTM, 2019). The vertical stress at each measurement point was calculated from the known depth and the estimated unit weight of the overburden layers. The in-situ void ratios were calculated from the unit weight determinations. Thereby, void ratio vs. stress points representing the encountered field states were included in Figure 10. Although the field datapoints cover only a limited range of stresses (since the limited depth of the exploration pits), the data cloud is fairly consistent with the compression lines obtained from oedometer tests. A second notable feature of this field dataset is the notably wide variability range of void ratios, though with a trend to narrow as the vertical stress increases.

The compression lines obtained for the tailings show a dependence on the testing water content, w_0 . The specimens with lower w_0 (near 20%) are initially less deformable than the specimens with higher w_0 (30–40%). In fact, a similar trend is observed to a lesser extent also between the

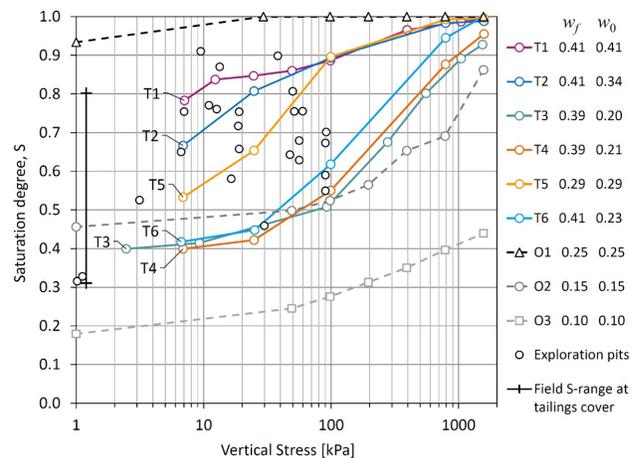


Figure 11. Oedometer tests performed on specimens of tailings and milled ore specimens, prepared at different initial water contents. Results shown in saturation vs. vertical stress plot. Additionally, points of degree of saturation vs. vertical stress obtained from in situ measurements in field exploration pits are included.

specimens with w_0 of 30 and 40%. This can be explained by the effect of suction on increasing the material stiffness. However, compression lines tend to converge into one for high stresses (above 1000 kPa). This is a second difference in the behaviour with the milled ore specimens, which compression lines do not merge in the range of stresses of interest for this study.

Since the expelled water was measured for each loading step, the evolution of the degree of saturation could also be computed. It is interesting to note that no tested specimen was observed to drain by its upper end, suggesting that drainage mostly occurs by gravity-driven water flow and, likely, with no pore pressure build-up. Figure 11 shows the plot of degree of saturation vs. vertical stress. Milled ore specimens show a typical behaviour for a non-plastic silt. The specimen with 25% GWC, being close to saturation at the beginning of the test, reaches saturation in the first load step. The other two milled ore specimens, prepared and tested at 15% and 10% GWC, did not expel any water during the test and did not reach saturation under the applied stresses.

By contrast, the behaviour of the tailings is notably different. All the tailings specimens expelled water at some loading step. The degree of saturation increased gradually but the 100% saturation condition is approached at considerably high-stress levels. A striking contrast is given by the milled ore specimen with $w_0 = 25\%$ which reaches saturation under 30 kPa vertical stress while all tailings specimens reach saturation above 900 kPa, even with extreme values of $w_0 = 40\%$. Figure 11 also includes field data points computed from in situ dry unit weight and water content measurements and the vertical stress estimated as explained before for Figure 10. Field data are fairly consistent with the experiments and, again, display a notable variability.

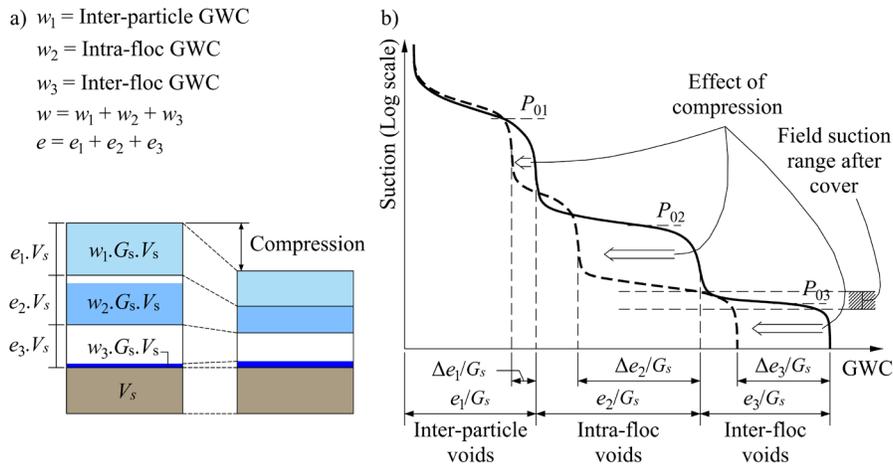


Figure 12. Conceptual model proposed for explaining the tailings behaviour observed in the field and in laboratory tests during the compression stage (referred as stage 6 in Figure 6). (a) Phase diagrams; (b) Retention curves.

6. Discussion

The observed behaviour of the tailings evidently departs from that of a typical silty soil. A possible explanation is proposed based on the observed multimodal pore structure, by means of the conceptual model depicted in Figure 12. According to such model, the inter-floc pore system is large enough to form a free-draining network. This is supported by the pore size that can be observed in the X-ray tomography (Figure 4b) and the notably low air entry value that results from the fitting of the retention curve for that pore system ($P_{03} = 3.4 - 5.4 \text{ kPa}$). Under increasing confining stresses, it can be assumed that flocs are squeezed, causing the intra-floc pores to collapse. The water expelled from the flocs drains through the inter-floc pore system. Hence, the intra-floc pores are the ones that act as the main capillary water storage. The air entry value of the intra-floc pores is $P_{02} = 43 - 124 \text{ kPa}$, which means that this pore system can support without desaturating the capillary height equivalent to the thickness of a 1-meter-thick layer of tailings. Finally, the high air entry value of the inter-particle pore system leads to think that the water stored there would drain neither by gravity nor by squeezing. The only way to extract this water would be evaporation.

The proposed model explains the mechanism by which the tailings can drain water well before reaching saturation. It also explains why saturation is only reached under unexpectedly high stress levels for relatively elevated water contents, when compared to the milled ore tests.

The behaviour of tailings described here means an obstacle to the estimation of the final state of tailings by the time of deposit closure. As referred in section 3, the hypothesis of constant GWC during the compression stage does not hold, at least for the tailings studied here. More laboratory research is needed to formulate a constitutive model enabling to make a precise estimation of the final

degree of saturation. In any case, given the behaviour depicted in Figure 12 and considering the variability of w_0 , it can be concluded that the saturation condition would have been reached only marginally in the deepest layer, at the point of greatest height in the central zone of the Casposo deposit (the worst-case location within the deposit).

7. Conclusions

The basic phenomena involved in filtered tailings disposal were studied for a particular study case, during follow-up surveys carried out throughout almost a decade of operation of Casposo Mine tailings disposal facility. The facility performed notably well, under the normal operation actions, meteorological events, and moderate seismic shaking.

Although metallurgical tailings can be assimilated to some types of soil, such as silt, based on similarities in grain size distribution and plasticity properties, the case study suggests that their hydromechanical behavior can differ dramatically from soils due to the treatment applied during the metal extraction process.

Disposal of filtered tailings turn out to be a complex process mainly because of the large number of factors determining the outcome of the process, namely the final water content of tailings and their void ratio. The interactions between the mine, the processing plant and the tailings disposal facility must be carefully considered during the design stage since many design constraints arise from those interactions. For example, the area of deposition platforms at different building heights, the cadence of lifts, the need for contingency areas for placing tailings with excess water, the need for rainfall water management, etc.

A conceptual model for the whole tailings disposal process was proposed. Then, this work focused on two particular stages of the process: 1) tailings air-drying after discharge into the deposit and before covering with the following lift

of the stack; and 2) tailings compression under the increasing overburden due to the growth of the stack in height.

In arid climates, it seems viable to rely on air-drying to achieve a significant additional water loss in the recently placed tailings. Two features of the drying process are worthy of note: 1) unless the tailings are reworked by ploughing or some similar technique, the drying process will reach a halt sometime after discharge (two months in the study case) and, 2) the outcome of the drying stage, namely the so-called target water content, bears a significant variability. Hence, specifying single-value target moisture seems completely unsuitable for the deposit design and operation. Using a probabilistic criterion would be much more appropriate and useful.

Multiple factors seem to influence tailings compression. The initial void ratio, resulting from the tailings being dumped from trucks plus some spreading work with bulldozers, appears to be strongly influenced by the water content of the tailings at discharge, which, in turn, depends on the filter performance. This, plus other possible unknown factors, result in a significant variability observed in the void ratio and degree of saturation obtained from field measurements in exploration pits. The laboratory work done so far indicates that compression of the studied tailings involves uncommon mechanisms, such as flocs mechanical behaviour and multimodal porosity water retention and flow. These aspects deserve additional research.

The capability to cope with the variability of the whole tailings disposal process is a key aspect to ensure its viability. Variability needs to be accommodated through redundancy and increased safety margins. An interesting feature of the studied deposit is the inclusion of waste rock layers interspersed between tailings layers. Besides ensuring trafficability with no compaction, the deposit benefited from an ample flexibility to accommodate the variability of the tailings water content, allowing drainage, and preventing stability issues.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the paper's contents and there is no financial interest to report.

Authors' contributions

Luciano A. Oldecop: Conceptualization, Data curation, Methodology, Supervision, Validation, Writing – original draft. **Germán J. Rodari:** Conceptualization, Data curation, Visualization, Writing – original draft.

List of symbols

D_{50}	Sieve opening allowing to pass 50% of the sample weight
C_u	Grain size distribution uniformity coefficient
LL	Liquid limit
PI	Plasticity index
S	Degree of saturation
ψ	Suction
γ_w	Water specific weight
G_s	Solids specific gravity
S_r	Residual degree of saturation
e	Void ratio
e_i	Partial void ratio of the i -pore system. $i = 1$ Inter-particle, 2 Intra-floc, 3 Inter-floc.
P_{0i}	Air entry value of the i -pore system. $i = 1$ Inter-particle, 2 Intra-floc, 3 Inter-floc.
λ_i	VG parameter i -pore system. $i = 1$ Inter-particle, 2 Intra-floc, 3 Inter-floc.
w_f	Water content at filter output. Mounting water content of oedometer specimens.
w_0	Target water content by the time of covering tailings with the following lift of the stack. Testing initial water content of oedometer specimens
w_c	Water content at facility closure. Test-end water content of oedometer specimens
V_s	Volume of solids
e_0	Void ratio by the time of covering tailings with the following lift of the stack. Initial void ratio of oedometer specimens
e_c	Void ratio at facility closure. Test-end void ratio of oedometer specimens.
t	Air-drying time elapsed (equal to the time elapsed since placing of tailings)
a, b, c	Fitting parameters of Equation 2
ϵ_w	Residue of Equation 2, normally distributed with zero-mean
s	Standard deviation of ϵ_w
w_i	Water content of the i -pore system. $i = 1$ Inter-particle, 2 Intra-floc, 3 Inter-floc.

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