Geotechnical Properties of Mine Tailings and Implications for Tailings Storage Facility Design

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ABSTRACT
Appropriate selection of geotechnical properties of mine tailings can have a significant impact on the design of tailings storage facilities. A database of typical mine tailings properties is maintained by Coffey to facilitate effective designs for a range of mineral commodities and tailings facility types. The data includes properties measured in the laboratory and in the field and includes gold, iron ore, nickel and tantalum tailings. The database provides a reference for typical tailings behaviour.

RÉSUMÉ
Une sélection adéquate des propriétés géotechniques des résidus minier peut avoir un impact significatif sur la conception des parcs à résidu. Afin de faciliter et ainsi obtenir une conception efficace de différent type de parc à résidus minier provenant de source minérale variée, Coffey maintient une base de données contenant les renseignements sur les propriétés géotechniques typiques de résidu minier. Les données proviennent de propriétés mesurées en laboratoire et sur le terrain et inclus des résidus d'exploitation aurifère, de fer, de nickel et de tantalum. Cette base de données fournie des références pour estimer le comportement type d'un résidu.

1 INTRODUCTION

Mine tailings are the waste residue of the milling process that is used to extract metals from mined ores. The design of tailings storage facilities (TSF) will vary depending upon the characteristics of the tailings to be stored. The geotechnical characteristics of tailings follow certain trends depending upon several factors including the mineralogy of the commodity mined, the mineral processing methods, and the type and operation of the TSF.

Mineral processing often involves crushing and grinding, leaching or separation, followed by dewatering or thickening before discharge to the TSF. Tailings are typically pumped by pipeline as a (slightly) thickened slurry. A typical tailings slurry will be deposited at between 25% to 45% solids by mass. To achieve high % solids, the tailings require thickening, and this approach is becoming more common across the industry. In the TSF, the relatively coarser grained fraction tends to be deposited nearer the deposition point, and the finer grained fraction settles out near the water recovery penstock or decant tower.

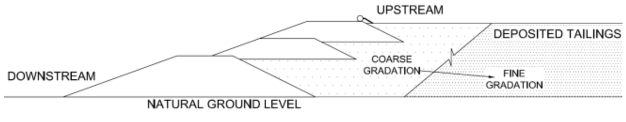

Figure 1. Typical section of upstream embankment construction for above ground 'paddock' type TSF.

Typical types of TSF include above ground paddock type (Figure 1) and valley storages. Where circumstances allow, in-pit facilities can provide an economic and effective method of tailings storage. The storage of tailings in an above ground facility that integrates mine waste dumps into the perimeter embankment design can also provide an effective alternative for secure storage of mine wastes.

Coffey Mining maintains a database of the measured geotechnical tailings properties obtained by laboratory and field tests. These tests were carried out as part of design and assessment of existing and proposed tailings storage facilities for a range of commodities, storage facility types, and locations. Selected test results from conventional tailings storage facilities in the database are presented in this paper. Tests on paste tailings, filtered tailings, and oil sands tailings are not included.

Laboratory and field characterisation of tailings properties and behaviour has been reported in the literature by several others. Qiu and Sego (2001) assessed tailings from Canadian copper, gold, coal, and oil sand operations. The copper and oil sand tails were sandy soils and classified as silty sand (SM) by the Unified Soil Classification System, while the gold tailings were sandy silt (ML) and the coal wash tailings were clayey silts (CL).

Bussière (2007) provides a summary of the 'hydrogeotechnical' properties of tailings. This work indicated that samples from nine different Canadian hard rock tailings were fairly similar *before deposition*, and were classified as sandy silts of low plasticity (ML). Further, data was presented showing the wide variation in *deposited tailings* across one storage with results varying from non-plastic silt (ML) to silty sand (SM).

Sherriff et al. (2009) recently presented characteristics of gold tailings in Manitoba. That work showed differences in geotechnical characteristics between oxidized and non-oxidized tailings, and also that the tailings particle size decreased further from the original point of deposition. In addition, they reported the in situ dry density varied between 1.3 g/cm^3 and 1.7 g/cm^3. Aubertin et al. (1996) presented geotechnical characteristics of tailings and noted that the hydraulic conductivity, *k*, of tailings is one of the most important properties required to establish a design basis for tailings impoundments. The authors presented an equation for *k* of the deposited tailings based in part on the particle size curve.

Gold tailings at eleven TSF's in Western Australia were assessed by the Australian Centre for Geomechanics (Newson and Fahey, 1998). A wide range of field and laboratory tests were carried out at these sites and a range of material properties including particle size, salinity, and density were measured. More recently deposited and thus less consolidated tailings were sampled and tested from a small hovercraft and where surface access was possible a standard truck-mounted rotary drill rig equipped with augers was used.

Fell et al. (2005) contains a good overview of the characteristics of mine tailings and current tailings disposal practice.

Generally, the relatively wide range of characteristics for tailings deposits makes parameter selection for design a challenge, even when laboratory results for design mixtures are available. Accordingly, it is useful to have a database of material properties for a range of commodities and conditions that can be a useful design guide.

2 DATABASE OF TAILINGS CHARACTERISTICS

Coffey Mining maintains a database of field and laboratory test results for a wide range of mine operations in different climates, different commodities, and different TSF design and operational settings. The database is updated periodically when time allows between assignments. It is endeavoured to include as much relevant data with the test results as possible, including the commodity type, the facility type, and the test location. Most of the data was generated from disturbed and undisturbed tailings samples obtained during field investigations. Some data was obtained from laboratory tests on samples retained from metallurgical testing. Also included in the database are records of the reconciled dry density in various TSFs, based on surveyed volumes of the storage and the mine's reported tonnes of tailings waste deposited.

The tailings data from approximately 40 gold operations mainly includes facilities in arid Western Australia's Goldfields and Pilbara regions, but also includes data from South Australia, east and west Africa, and Indonesia. The iron ore tailings data was obtained from seven mines located in Western and South Australia. The nine sets of nickel tailings data were obtained from Western Australian nickel sulphide mines with both 'oxide ore and fresh hard rock ore. In addition, selected data from tantalite mine tailings and aluminum tailings in Western Australia are presented.

The database provides reference values for critical design elements that allows comparison of new test results against expected, or provides a typical set of values for use in the absence of test results when developing conceptual designs.

There are some data gaps and a measure of uncertainty in some test result details; however, the general trends in the test results provide an indication of the material properties of tailings.

3 TRENDS IN TAILINGS CHARACTERISTICS

Selected data were grouped by commodity type and facility type to assess the characteristics of each group.

The % fines (<75 micron) for gold, nickel, iron, and tantalum tailings are shown on Table 1. The nickel tailings tended to be finer grained (average 75% fines) than both iron (67% fines) and gold (58% fines). Tailings from a tantalum mining operation were comparatively sandy, with only 38% fines.

Table 1. % Fines test results by commodity.

	Gold % fines	Nickel % fines	Iron % fines	Tantalum % fines
Average	58	75	67	38
Minimum	7	61	43	35
Maximum	96	95	100	42
Standard deviation	19.8	11.5	26.0	4.9
No. samples	129	16	7	2

The plasticity index and liquid limit of selected samples is plotted on Figure 2. The majority of tailings were non-plastic or of low plasticity.

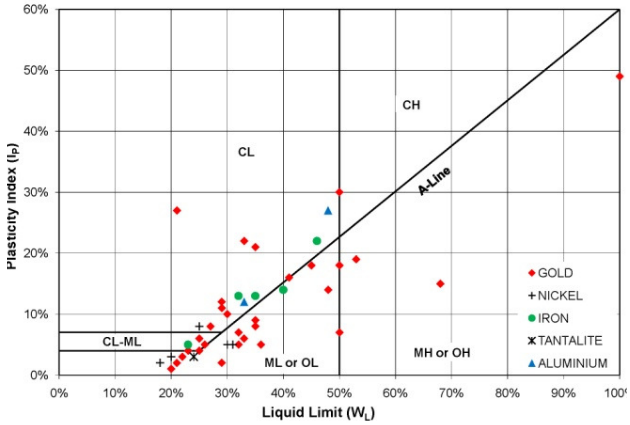

Figure 2. Plasticity chart for mine tailings with results grouped by commodity.

Table 2. Laboratory air drying test results by commodity.

	Gold dry density (t/m^3)	Nickel dry density (t/m^3)	Iron dry density (t/m^3)
Average	1.38	1.16	1.51
Minimum	0.98	0.51	0.87
Maximum	1.79	1.61	2.05
Standard deviation	0.18	0.36	0.32
No. Samples	29	10	11

The maximum dry density obtained in laboratory air drying tests are summarised in Table 2. The highest dry densities were measured in iron ore tailings, lower in gold tailings, and lower still in nickel tailings. In these tests, beakers of tailings are dried at temperatures in the range of 40 to 50 degrees Celsius for approximately four to seven days until the density change is insignificant.

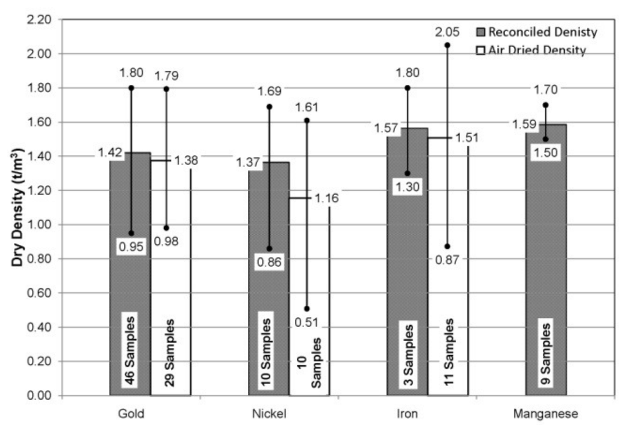

Figure 3. Tailings dry density by commodity. Average results with bars showing minimum and maximum result.

Table 3. Reconciled dry density results by commodity.

	Gold dry density (t/m^3)	Nickel dry density (t/m^3)	Iron dry density (t/m^3)	Manganese dry density (t/m^3)
Average	1.42	1.37	1.57	1.59
Minimum	0.95	0.86	1.30	1.50
Maximum	1.80	1.69	1.80	1.70
Standard deviation	0.18	0.27	0.25	0.08
No. Samples	46	10	3	9

The reconciled tailings dry density data measured by commodity (gold, nickel, manganese, and iron) is summarised in Table 3. For gold and iron, the reconciled tailings dry density data exhibit fairly good agreement with the air drying test results (Figure 3) and show that relatively higher dry density occurs in iron and manganese tailings compared to gold and nickel tailings. The relatively lower average laboratory dry density for nickel due to two of the ten samples being from a lateritic nickel tailings that have particularly low density due to the intense nickel extraction process. The average laboratory air drying density of the other eight nickel samples is 1.31 t/m^3 which agrees fairly well with the reconciled dry density for nickel.

The reconciled tailings dry density data measured by storage type (Paddock, In-pit, and Valley storage) is summarised in Table 4 and Figure 4.

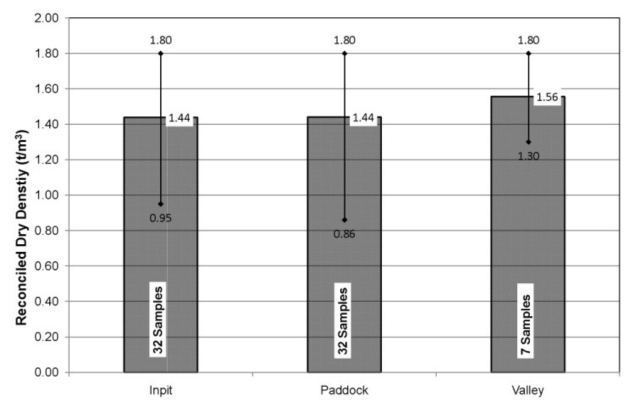

Figure 4. Reconciled dry density by TSF type. Average results with bars showing minimum and maximum result.

Table 4. Reconciled dry density by TSF type.

	Above Ground dry density (t/m^3)	In-Pit dry density (t/m^3)	Valley dry density (t/m^3)
Average	1.44	1.44	1.56
Minimum	0.86	0.95	1.30
Maximum	1.80	1.80	1.80
No. Samples	32	32	7

The results indicate that the settled dry density for in-pit storages is similar to that achieved in above ground ‘paddock’ storages.

4 DISCUSSION OF TRENDS IN TAILINGS CHARACTERISTICS

Many of the data trends may be understood based on the origin of the tailings material and the nature of the mine treatment process. In addition, the tailings facility type and operation, and the sample location in the facility can have a significant impact on the measured characteristic.

The particle size and nature of the minerals hosting the ore typically have a significant impact on the tailings particle size. More resistant minerals in the host rock will typically persist through the process. The grind size of the processing plant is typically established based on mineral extraction requirements. Where conventional tailings deposition is well managed and good tailings beaches result, the tailings particle size will decrease with distance from the discharge point. It is typically much easier to access tailings samples from the perimeter of the storage and a natural bias to relatively coarser results in the database may thus be introduced. Similarly, sampling for typical site investigations to assess the potential for upstream raising construction will focus on the perimeter areas where construction will occur. This would also introduce a sample location bias to the test results. The wider variation in the % Fines content of the gold and iron tailings likely reflects the wider range of mineral processing and tailings deposition conditions that were included in the database samples for these groups. In addition, the variation in sample location will impact the results.

The tailings plasticity test results are similar to those reported in the literature (Fell et al., 2005) and the wide variation in results occurs for the same reasons as discussed for the particle size test results. Sample position in the TSF was not identified in the database, and as such, the tailings fines fraction (slimes) which may contain more plastic material were not typically distinguished from tailings near perimeter embankments which may tend to be less plastic.

The relatively higher laboratory measured dry density results for the iron ore tailings from the air drying tests are likely a result of the relatively heavy iron minerals (e.g. hematite) and the limited active clay minerals present in these iron ore tailings. Iron ore tailings are typically a mixture of relatively low specific gravity (SG) alumina and silica particles (slimes) and high SG iron minerals. The heavy fraction can promote relatively steep beaching, and the residual fines portion can be relatively slow to settle in the decant pond as it may contain clay minerals rather than amorphous clay-sized particles. The nickel and gold tailings are typically comprised of fine waste from materials mined in greenstone belts. Where ‘fresh rock’ is mined from underground deposits or deep pits, the material will typically have a relatively higher SG than the waste from an ‘oxide ore’ stream.

It may have been expected that the in-pit storages would not drain as effectively as the above ground storages and this would result in a lower reconciled settled density for this group. However, many of these in-pit storages were above the water table during operation and designed with underdrainage or perimeter water recovery systems that likely had a beneficial impact on the tailings settlement and consolidation. In addition, there are several Integrated Waste Landform (IWL) TSFs included in the ‘Above Ground’ category. Because the IWLs typically have a robust embankment structure that incorporates a wide mine waste dump, a higher rate of tailings rise may be acceptable. The higher rate of rise typically results in relatively lower density tailings.

The 32 above ground TSF included gold, manganese, nickel, and zinc tailings. The 32 in-pit TSF included gold, manganese, and nickel tailings. The similarity in tailings dry density for above ground and in-pit TSF can therefore not be attributed to an unbalanced quantity of commodity type in the group.

Above ground paddock-type storages typically require a higher degree of management than in-pit storages or integrated waste landform (IWL) type storages where a higher rate of tailings rise may be acceptable. The higher rate of rise typically results in more water entrained within the tailings, a lower settled density, and a reduction in storage capacity.

5 TAILINGS GEOTECHNICAL CHARACTERISTICS IMPACT ON TSF DESIGN

Embankment earthworks are typically the most costly element of construction of conventional above ground tailings storage facilities. Where possible, embankments are constructed in stages to defer capital costs, take advantage of construction materials generated during mining, and provide flexibility to match operational requirements. Accordingly, an optimised starter embankment size can be a significant factor in effective TSF design and a relatively accurate estimate of the expected settled tailings dry density can be significant. If the starter embankments design provides insufficient storage, there is limited operational flexibility and a requirement to undertake TSF embankment raising construction when mining operations are still wrestling with optimising plant performance and mining issues. If the starter embankments in the TSF are constructed with significant excess capacity, there may be wasted capital expenditure.

Another important design factor for TSF embankment design is the maximum acceptable tailings 'rate of rise'. The tailings rate of rise is the vertical deposition rate that is typically described in metres/year. The relatively low cost upstream raising technique requires adequate beaching and sufficient time for tailings drying and consolidation to allow safe raising construction. Typical design values for upstream raised paddock storages in arid Western Australia are in the range of 1.5 – 3 m/yr. Where tailings are fine grained and tend to release water more slowly, the design rate of rise will be lower and a larger facility footprint is required for a given production rate. For relatively coarse tails which may release water more readily, a higher 'rate of rise' may be allowed for in the tailings design. The relatively coarse tailings in a tantalum mine tailings facility drained more rapidly and are likely more stable under a higher rate of rise than typically allowed for in tailings designs for other commodities.

The benefits of extensive underdrainage systems may be limited where fine tailings don't readily release entrained water and the risks of clogging the drain are higher. In these cases, the designer must look to alternate approaches, such as reducing the embankment slope angle, removal of water from the process at the mill by thickening/filtration, or improvement of tailings deposition management to optimise water return and reduce seepage. Even for fine tailings, an underdrainage system may be useful to mitigate lateral seepage from a TSF.

The suitability of tailings for embankment raising construction will depend on several geotechnical properties, including particle size distribution, plasticity, and dispersivity. Dispersive tailings typically require encapsulation and are not suitable for embankment construction.

Where poor tailings management has occurred and beaches have not been well developed, the quality of the borrow may make construction more difficult. Uneven beaches will increase the amount of earthworks required, and the extra fines at the facility perimeter may result in poorly drained conditions near the embankments. These conditions are inherently less stable for the existing embankment and also for the proposed raised embankment footprint. In addition, wetter and softer material near the perimeter may increase the difficulty in accessing borrow.

The slurry density (% solids) has a significant impact on the tailings beaching characteristics. Lower slurry density tends to result in flatter tailings beaches. It has been observed that mine operators sometimes tend towards this approach as it allows them to 'get rid' of excess site water and it has lower operational requirements; however, the outcome increases risks (water on storage, less beach freeboard results in increase overtopping risk), lowers tailings density (and TSF capacity). In addition, poor tailings deposition management can increase construction costs where upstream embankment raising techniques are used.

Similarly, multi-point spigotting tends to improve beaching characteristics when compared to single point discharge (end of pipe).

6 SUMMARY AND CONCLUSIONS

The geotechnical characteristics of selected mine tailings were presented from a database containing laboratory and field test results. Trends in tailings density and particle size were examined based on commodity type and TSF type. The trends may be understood based on the mineralogy, the ore treatment process, and the TSF operation. Laboratory measurements of tailings properties can provide reasonable approximations of field behaviour but must be carefully interpreted and applied. The data trends provide reference values useful in the design of TSF.

Follow-up work will include building the database and incorporating key additional data such as slurry density spigotting method (e.g. single-point vs. multi-point) and sample position relative to the deposition point so the observed trends can better assessed. As mineral extraction technologies advance (finer grind, different chemicals added, etc.), the tailings properties can be expected to evolve so the reference database should only be used a guide.

7 ACKNOWLEDGEMENTS

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