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An alternative approach to developing compaction specifications for tailings materials

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Abstract

The adoption of the Global Industry Standard on Tailings Management requires that the most appropriate technology be adopted for the design, construction, and operation of a tailings storage facility (TSF). Dewatered tailings have been identified as the best technology for some sites. A structural zone is often considered when adopting a dewatered strategy. A structural zone can be built by placing/depositing tailings in controlled layers and compacting/trafficking the tailings as required. It is noted that the compaction specifications adopted today for tailings materials have mainly been based on those from the civil engineering industry. Often, the specifications for these materials are extensively expressed in 'standard' terms related to a laboratory compaction test method. Challenges arise because the laboratory compaction test was developed for different compactors from those used today. Consequently, such specifications may inadvertently lead to unmet engineering objectives and place unduly restrictive placement moisture content ranges on the tailings. The first part of the paper discusses the challenges of current compaction specifications. It highlights the benefits of defining a compaction specification using air content control and full compaction concepts, all in accordance with Proctor's seminal work in the 1930s. The second part of this paper discusses some of the features of tailings compaction curves. The discussion includes the review of a database of compaction curves digitised during the literature review undertaken for the study. A general guideline to define a suitable specification for tailings compaction using the concepts defined in the study is proposed.

Keywords*:* *tailings dams, compaction, dewatered tailings, dry stack, structural zone*

1 Introduction

Earthen fill compaction is the process of removing air (thereby increasing the soil density) and the rearrangement of soil particles by mechanical working with a compactor. Civil engineering compactors are designed specifically to achieve this goal and are available in different configurations to suit different soil types (for example, vibrating smooth drum rollers for cohesionless and pad or sheep foot rollers to apply a 'kneading' action for cohesive soils). The civil engineering industry generally follows the work of Ralph Proctor for the compaction of earthen fills. During work to construct the clay core of the Bouquet Canyon Dam, Los Angeles, in the 1930s, Proctor (1933) developed a laboratory test to simulate the sheep foot roller that was being used at the time (Figure 1). Proctor's laboratory compaction test is now known as the Standard Proctor Test (ASTM D698a). This test was designed to simulate:

- An 8 in (200 mm) loose lift thickness
- Full compaction (i.e. the point at which further passes of the compactor do not achieve further densification.

The sheep foot roller is illustrated in Figure 1, with a compaction effort of 12,400 ft lbs per cu ft (or ~600 kNm per m^3).

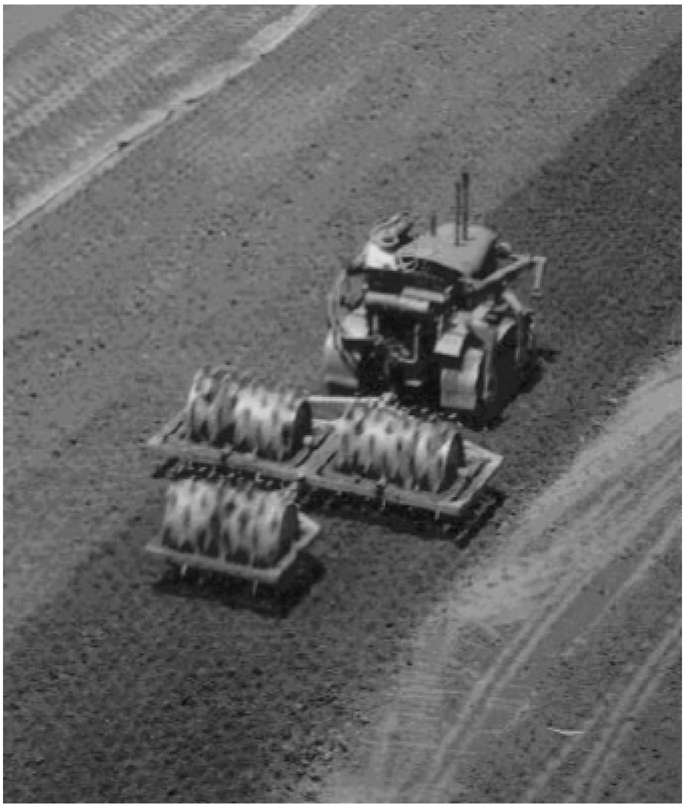

Figure 1 Standard Proctor roller

In the early 1940s, as the USAF bombers' aircraft size and weight increased, there was a crisis at the airfields, with severe damage to runway pavements. This was diagnosed as insufficient support being provided by the subgrade, and the US Army Corps of Engineers developed a laboratory compaction test based on Proctor's original principles to simulate the much heavier roller (Figure 2) being used to improve the compaction of the subgrades. The Modified Proctor Test (ASTM International 2021b), as it was called, represented a compaction effort of 56,000 ft lbs per cu ft (~2,700 kNm per m^3), or more than four times that of the Standard Proctor Test.

Proctor's laboratory compaction test relates the compacted density to moisture content at the time of compaction for a fixed level of compaction effort. The compaction characteristic for many soils (particularly those with a plasticity index greater than 8) shows a maximum dry density (MDD) at a particular moisture content, known as the optimum moisture content (OMC). The OMC and associated MDD are not a constant for a particular soil but vary with the amount of compaction effort. Similarly, the OMC and associated MDD are not a constant for a particular level of compaction effort but vary with soil type. This is self-evident from a comparison of 'Standard' Tests on different soils and 'Standard' and 'Modified' tests on the same soil.

The industry no longer uses the compactors which the laboratory tests were designed to simulate, and engineers today have a much wider range of compactors to choose from (see Figure 3). Often, tailings are compacted due to construction plant traffic, such as bulldozers or excavators. Unfortunately, the two Proctor laboratory compaction tests do not simulate the behaviour of contemporary compactors well. By developing compaction controls and specifications based on Proctor tests, the industry finds itself in the strange situation of forcing field operations to match laboratory conditions. This approach can result in the unintended and inadvertent consequence of failing to meet engineering objectives in earthwork construction, particularly for cohesive fill where the prime objective is to compact such soils 'wet of optimum'.

Figure 2 Modified Proctor roller

CAT 825 (Static)
Tamping Foot
Operating Weight – 32,750 kgs (72,200 lbs)

CAT 563 (Vibratory-Dynamic)
Pad Foot
Operating Weight – 11,570 kgs (25,500 lbs)

CAT 433 (Vibratory-Dynamic)
Pad Foot
Operating Weight – 7,170 kgs (15,800 lbs)

CAT 815 (Static)
Tamping Foot
Operating Weight – 20,770 (45,800 lbs)

CAT 56 (Vibratory-Dynamic)
Pad Foot
Operating Weight – 11,390 kgs (25,100 lbs)

CAT 323 (Vibratory-Dynamic)
Pad Foot
Operating Weight – 4,630 kgs (10,200 lbs)

Figure 3 Selection of contemporary compaction plants available

2 The laboratory compaction test and its reliability

The laboratory compaction test is quite complex, requiring skill and attention from the technician performing the test. In the US, AASHTO, under their testing program (formerly) AMRL, conducts the qualification of a large number (>1,000) of soil testing laboratories on an annual basis. The testing program database contains 27 reference soil samples and over 26,000 Standard Proctor Test results. Under the proficiency sampling program, laboratories receive a pair of soil samples carefully selected by AASHTO to have similar properties. They conduct various laboratory tests that use disturbed samples on them. Two such tests are the Proctor compaction tests (Standard and Modified). The results are compiled and presented as Youden plots where the property for one sample is plotted against the same property for the other sample. This analysis returns the grand average for each tested parameter and the standard deviation of the distribution. An example Youden plot for OMC for the Standard Proctor Compaction Test is shown in Figure 4. This example is typical of the Standard and Modified Proctor Tests database. The ellipse shown on the plot represents the 95% confidence level, and it is notable that at this level of confidence for soil sample 147 the OMC could be determined as anywhere between 8 and 18% when the grand average is 14%. This realisation causes us to question the setting of moisture content target ranges of the form OMC ±2%.

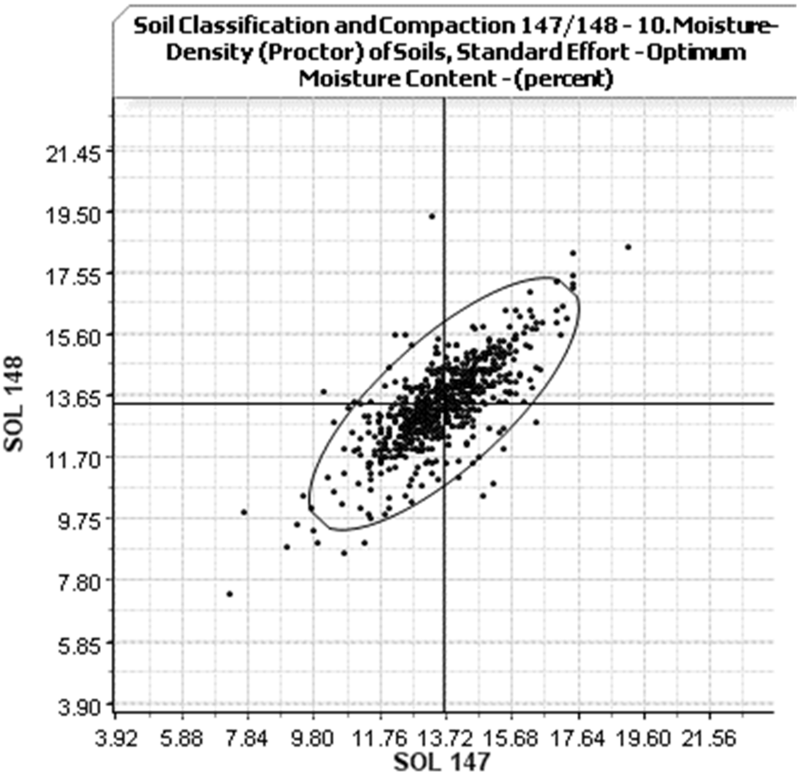

Figure 4 Youden plot for optimum moisture content for the Standard Proctor Compaction Test

Concerning the reliability of the Proctor compaction test, we conclude that they are not representative of a wide range of compaction equipment in use today, and the test itself shows poor repeatability. To be able to properly control compaction in the field, engineers need to know the 'field' compaction curve appropriate to the soil being compacted, the compactor being used, and the loose lift thickness being adopted. Perhaps this requires a suite of compaction tests to be developed by the industry to simulate the actual levels of compaction effort of modern compactors, and the repeatability of the laboratory tests is improved by performing more tests per sample and averaging the results. Alternatively, an analytical compaction model can be used to develop the field compaction curve for any combination of soil, compactor and lift thickness.

3 Long-term behaviour of compacted fills

Early soil mechanics researchers realised that the long-term behaviour of compacted cohesive fills (as their moisture content changed) depended on whether they were initially compacted at moisture contents wet or dry of OMC. It is known that cohesive materials compacted in a 'dry of optimum' state will exhibit increased swell and loss of stiffness and strength on wetting during service life (Figure 5). The figure shows density and the California bearing ratio (CBR) versus moisture for a typical low plasticity clay (CL). Accordingly, most compaction specifications seek to ensure that cohesive fills are compacted in a 'wet of optimum' compacted state.

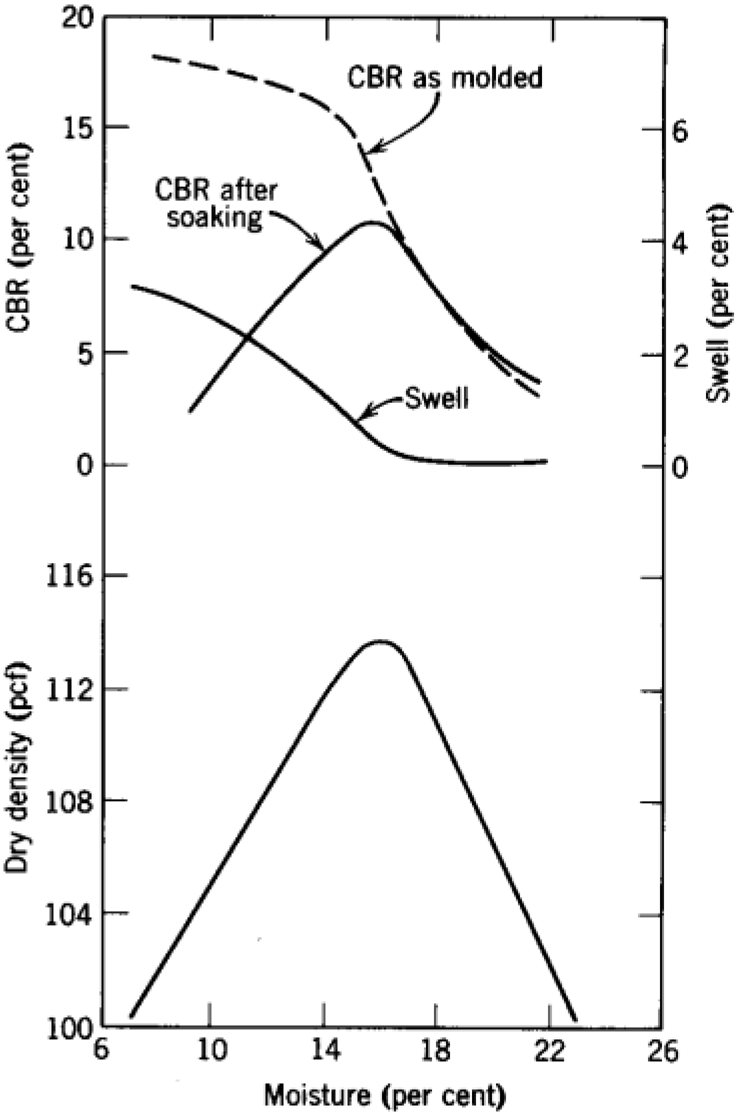

Figure 5 Density and California bearing ratio (CBR) versus moisture for a typical silty clay (CL) (Yoder 1967)

4 The importance of air content

Compaction is the removal of air by mechanical working. Full compaction represents the reaching of the density asymptote and, hence, the asymptote of minimum air (Figure 6). Full compaction can occur at any moisture content and indeed occurs all the way along the Proctor compaction curve. MDD represents full compaction at the OMC, the point where minimum voids ratio is achieved. Full compaction is typically achieved in eight to 10 one-way passes of the compactor. A typical compaction curve is illustrated in Figure 7.

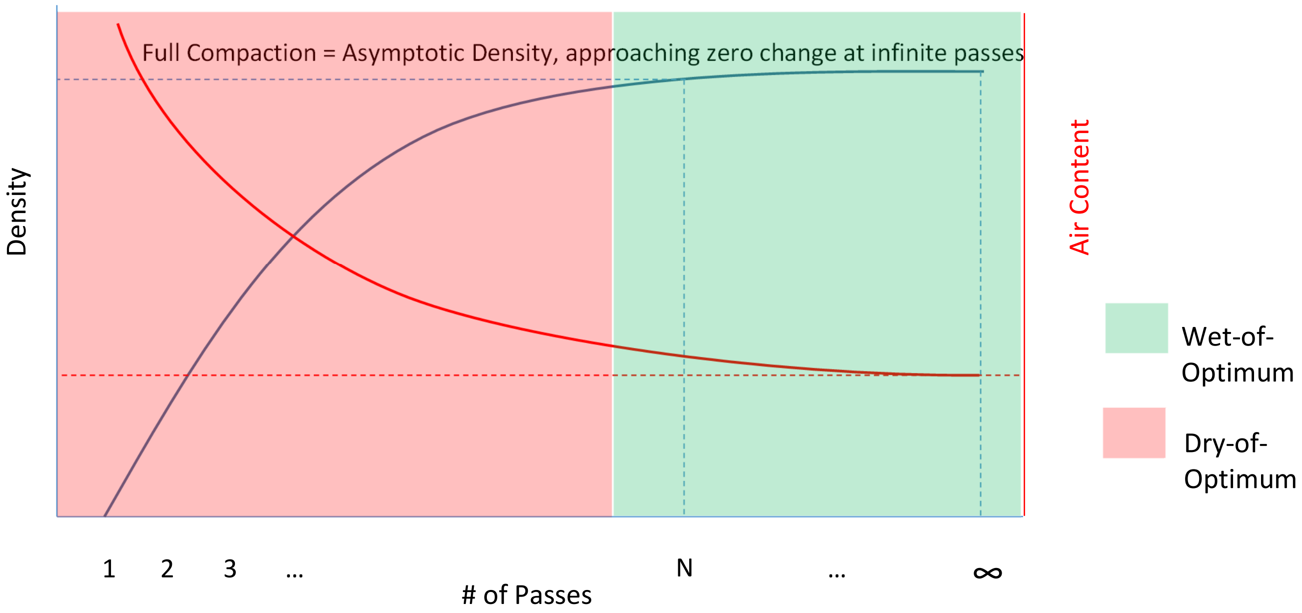

Figure 6 Relationship between air content, density and the number of passes during compaction

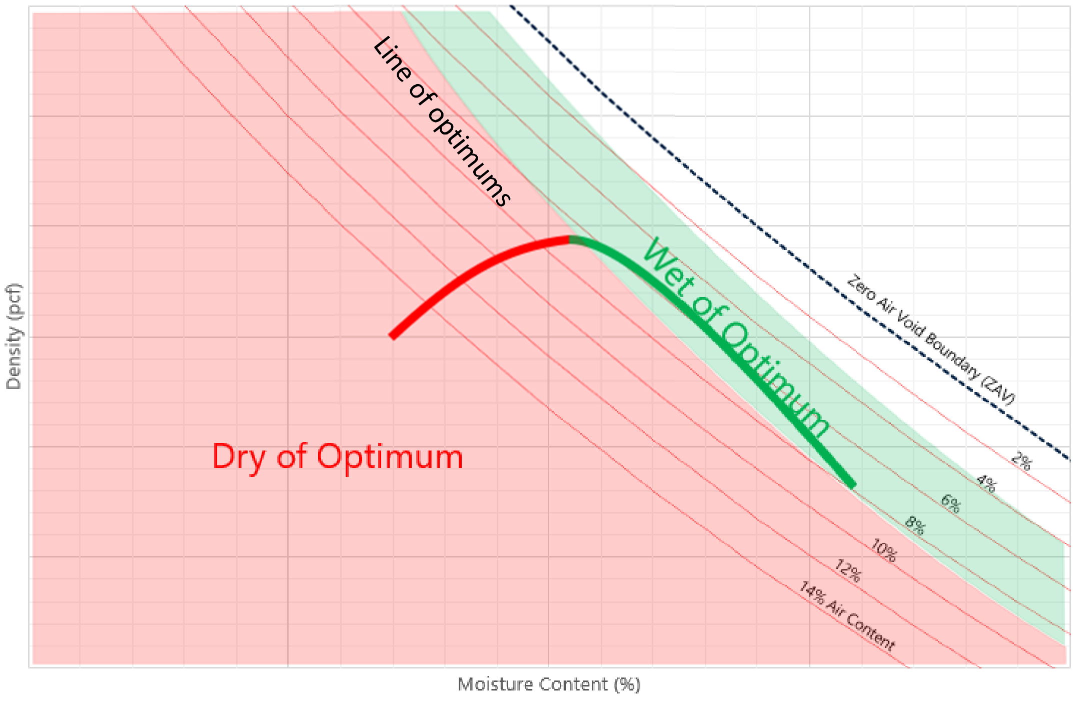

Figure 7 Compaction curve features

Figure 7 shows some notable features:

- Lines of constant air content are shown including the zero air void boundary. The air content of a fill is its capacity to absorb water during its life.
- For moisture contents ‘wet of optimum’, the compaction curve is essentially parallel to a line of constant air content and represents the minimum air content achievable for the particular soil. Minimum air content is achieved for wet of optimum compacted states because the OMC is the point at which the mechanical working of compaction causes the fill material particles to realign from a flocculated to a dispersed structure. The flocculated structure causes the high voids ratio

which at low moisture content are filled with air, hence high air content. One can visualise OMC as the critical amount of lubrication that allows the clay particles to reorientate into a dispersed structure. The more compactive effort, the less lubrication needed for reorientation and therefore the OMC is lower for more compactive effort on the same soil (Lambe & Whitman 1969).

- For moisture contents 'dry of optimum', the compaction curve is essentially orthogonal to the lines of constant air content, i.e. small reductions in moisture content below OMC at the time of compaction lead to large increases in air content.
- To have a 'wet of optimum' compacted state, the fill must have minimum air. This can only be achieved for full compaction.
- Cohesive fills compacted on the dry side of optimum have high air content, therefore high moisture potential, high permeability, high swell and high susceptibility to stiffness reduction on wetting. Fills compacted on the wet side of optimum conversely have low air voids, low moisture potential, low permeability, low swell and low susceptibility to stiffness reduction on wetting.
- The boundary between the dry of optimum and wet of optimum regions is defined as the line of optimums.

5 Typical civil engineering compaction specifications for earthen fills

Civil engineering fill compaction specifications are typically developed by reference to one of the laboratory compaction tests (noting that the chosen laboratory test most likely does not represent a reasonable simulation of field conditions) setting a percent relative compaction (e.g. 95% of Standard Proctor MDD) and an acceptable range of placement moisture contents (e.g. OMC ±2% points of moisture). Engineers believe that such a specification achieves two things:

1. Reasonably 'wet of optimum' compacted states.
2. Reasonable working room for the contractor to place fill within the moisture content specification range.

This specification is illustrated in Figure 8.

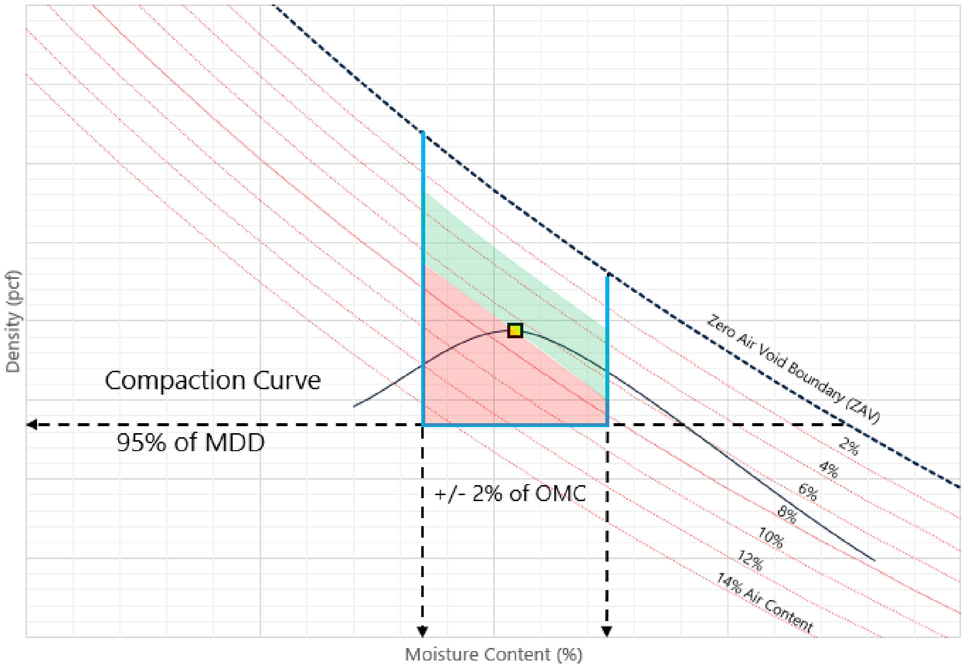

Figure 8 Illustration of a conventional civil engineering compaction specification

The blue line in Figure 8 represents the boundary of specification acceptance, with the bottom left corner allowing an air content of >14%, which is hardly a 'wet of optimum' compacted state. Traditional civil engineering specifications build in poor fill performance in terms of swell and stiffness loss on lifetime wetting. Improved compaction specifications refer to a maximum permissible air content and full compaction (Money & Hodgson 2016).

6 Field compaction curves for contemporary compactors

Tritico & Langstone (1995) performed carefully controlled field compaction trials using a CAT815 compactor and compared the compaction curves obtained with Standard and Modified Proctor compaction tests. Unsurprisingly, from an assessment of the compaction effort of the CAT815, its compaction curve was between two laboratory test curves (Figure 9). They also developed curves for different numbers of passes (i.e. cumulative compaction effort). We can conclude from a theoretical assessment of the compaction effort of two common compactors, the CAT 56 and the CAT 815, that their compaction curves will lie between the two laboratory curves, with the CAT815 curve representing a higher MDD and lower OMC than the curve for the CAT 56.

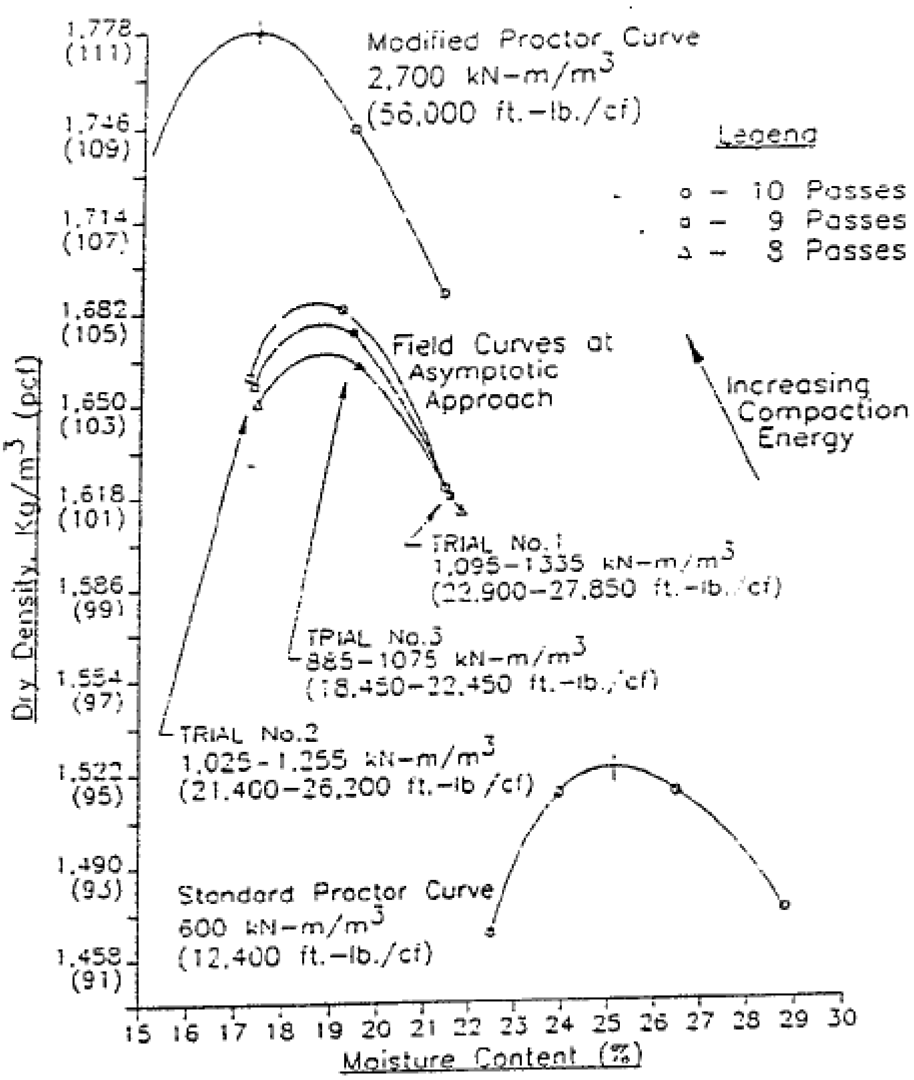

Figure 9 Comparison between field and laboratory compaction curves (Tritico & Langstone 1995)

7 Compaction curves of tailings materials

A literature review of compaction curves was undertaken for this study. The literature review results were complemented with compaction curves tested by the authors. The selection of compaction curves includes iron ore, red mud, bauxite wash, polymetallic (Lara & León 2011), silver (Butikfer et al. 2017), and gold (Goldup et al. 2019). All compaction curves were generated with the standard energy (Figure 10).

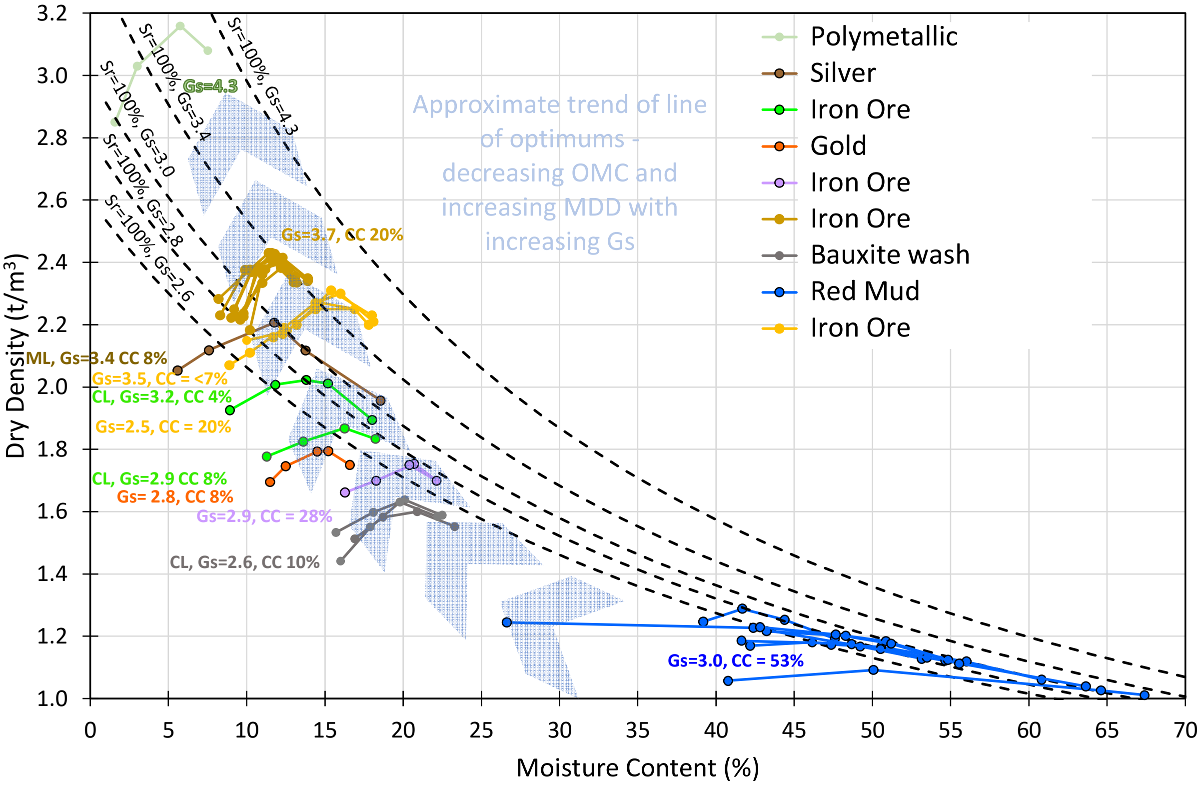

Figure 10 **Summary of compaction curves measured on tailings produced from different commodities**

Several of the compaction curves show the same general form as compaction curves for clay soils in that there is an identifiable peak corresponding to the traditional MDD/OMC point and the ‘wet’ leg of the curve is more or less parallel to the zero air voids line (Sr =100%). The compaction curves for red mud are flat with the OMC difficult to identify. It is noted that a loose line of optimums is present and sketched by the light blue arrows.

Notwithstanding that earlier sections of this paper have explained that compacted air void content is the main driver of the adverse behaviour of cohesive fills (i.e. swell and stiffness loss on wetting), it is recognised that clay mineralogy affects this behaviour. Swell potential, for example, is often related to the plasticity index in design charts and tables (Jones & Jefferson 2012). Figure 10 reveals that increasing clay content reduces the MDD and increases the OMC. Tailings with higher OMC contain clay which impacts compaction and swelling potential, for example red mud tailings have the lowest MDD and a clay content of 53%. The clay content of some tailings is reported next to the corresponding compaction curve in Figure 10 when available. Increasing Gs increases the MDD and decreases the OMC, as expected. Gs values are also reported next to its corresponding compaction curve when available (Figure 10).

Some mine tailings are either non-plastic (no plastic limit can be determined) or have low plasticity indexes. Traditional soil mechanics understandings would suggest, therefore, that adverse effects on the engineering properties of tailings materials will be small. Tailings materials have shown themselves on occasion not to behave as conventional soils, and the industry would be unwise to contemplate major earthen structures without properly characterising their behaviour on a mine-by-mine basis.

8 Implications for the compaction of dewatered tailings in the mining industry

The mining industry conducts earthworks operations on a large scale, and this activity will increase as more mines move over to dewatered tailings as an alternative to impounded slurry tailings.

Dewatered tailings stacks will be among the largest earthen structures built by man. There is already justifiable concern in the industry for the risk of static liquefaction of materials at depth in high stacks of these materials, which were unsaturated at the time of placement and compaction, approach saturation during their lifetime. If they were also to lose stiffness on wetting and suffer hydro collapse, this could be a triggering mechanism for liquefaction.

Without knowing whether compacted tailings suffer adverse engineering property behaviour on wetting, it is not possible to establish whether, as an industry, engineers should be concerned that tailings materials need to be compacted on the wet side of OMC. Tailings practitioners should not be applying civil engineering compaction specifications (which the authors have demonstrated in this paper often do not deliver the intended engineering objectives) to dewatered tailings.

In the context of the volumes of material that will likely be placed and compacted at any mine site, a cost-effective approach to defining the compaction behaviour of the tailings and developing ‘fit for purpose’ compaction controls would be to:

- Perform a full-scale compaction trial at the stack site with early tailings from the mine production. The exercise would involve compacting a 100 m long by 50 m wide test strip at five different moisture contents with the compactor (or dozer) and loose lift thickness proposed for the production tailings storage. The loose fill would be fully compacted, i.e. with sufficient compactor passes to reach maximum density
- Make in situ moisture density measurements on the test strip
- Take Shelby tube samples from each compacted test strip
- Perform laboratory tests on ‘as compacted’ and ‘fully wetted’ samples to determine if relevant properties deteriorate on wetting for compaction on either side of OMC (see Pickens 1980)
- Develop compaction specifications/controls based on the compaction curve thus determined for the actual site conditions of the compactor, materials and loose lift thickness
- Develop QA/QC program for control of production compaction
- Repeat the test strip periodically or when the tailings’ composition or compactor changes.

Such a test strip program would define the correct compaction curve for site operations and allow the responsible tailings facility engineer to develop the broadest possible range of placement moisture contents, thereby benefiting tailings throughput and minimising cost.

9 Closing comments on tailings compaction

Traditional compaction on tailings usually takes advantage of construction plants such as dozers and haul trucks to improve the engineering properties of a structural zone (Figure 11). Other compaction considerations include scheduling the placement of consecutive layers to avoid excessive drying that might result in loose arrangements. Compaction also considers periods of wet weather, particularly in tropical regions such as in the north of Australia, where internal drainage can be used to prevent saturation during the life of the TSF.

The authors highlight that haul trucks and dozers are not designed for compaction. A misapplication of Proctor’s understanding of compaction resulted in conventional compaction specifications being met without full compaction. This has led to multiple issues when compacting cohesive clay fills in the civil engineering industry. This paper aims to trigger a critical outlook on conventional compaction specifications and foster the study and understanding of compaction in the context of filtered tailings. It does not mean that filtered tailings will exhibit the concerning behaviour of many cohesive fills reported in the civil engineering industry. For example, well-executed field trials will allow the tailings industry to develop specifications favourable to the contractors and operators in charge of building tailings stacks. Filtered tailings could be compacted either wet or dry of optimum, allowing construction plants other than compactors to achieve the designed void ratios (aiming for dilative properties) necessary for the long-term stability of tailings stacks.

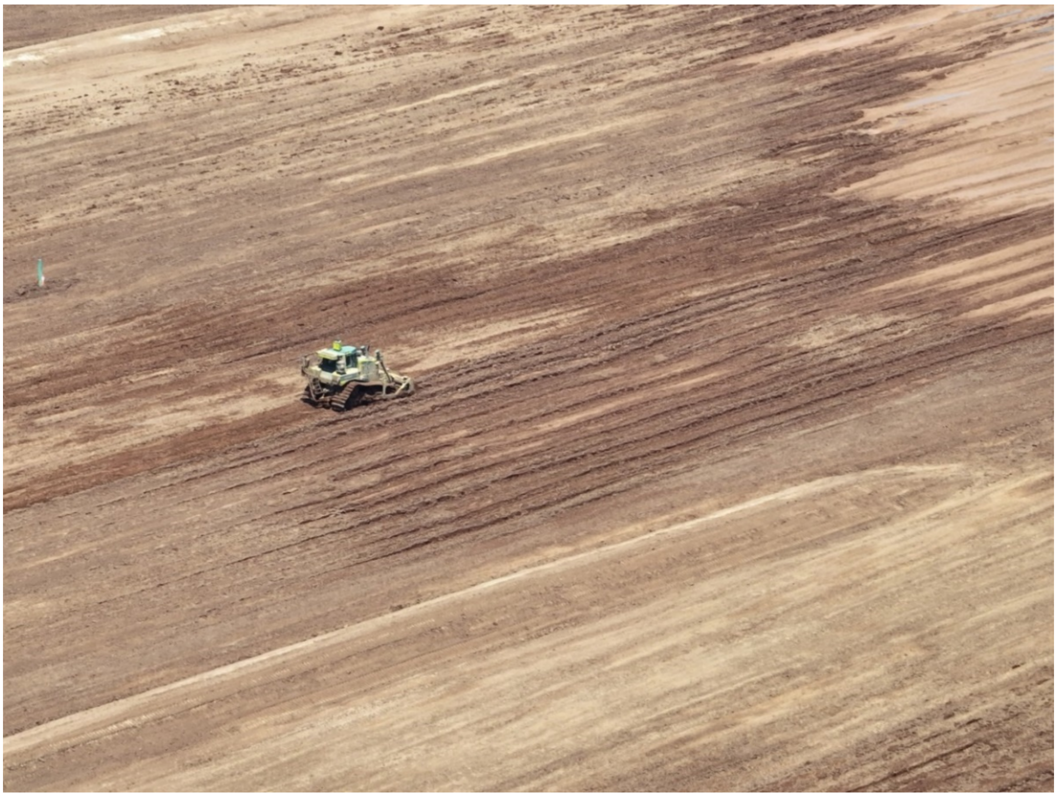

Figure 11 Compaction of tailings, also known as mud farming, being undertaken with a low-ground pressure undercarriage dozer at a tailings storage facility in Australia

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