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Predicting material properties of commingled waste rock and tailings

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Abstract

Traditional mine waste management practices present numerous issues that may tarnish the view of the mining industry. In the worst of cases, failures of tailings dams or waste rock piles can lead to the loss of life, environmental damage, and large monetary costs that may fall on local governments. Even without failures, typical mine waste facilities occupy large areas of surface land, and contain toxic water and soil that may migrate into the local environment through the groundwater or as wind-blown dust. To maintain and improve the social license to operate, the mining industry needs to continue to improve mine waste management practices.

The co-disposal of waste rock and tailings have been utilised in many configurations, with some success. Commingling is an emerging idea, and a specific type of co-disposal that utilises dewatered tailings and waste rock together in a thoroughly mixed blend. These materials can be deposited at low moisture contents, with low hydraulic conductivity, and with proper compaction they can also maintain high saturation, limiting the influx of oxygen. The result is a physically stable material with low potential for acid generation, and a much smaller surface area required for deposition. Unfortunately, there are few full-scale trials or waste management facilities using this method. One possible issue is that the design of these materials is still in its infancy. This paper explores methods to predict material properties of commingled materials using conventional laboratory techniques. Tailings and waste rock samples have been collected from a dozen metal mines globally to study a variety of materials. It is demonstrated that important material properties can be predicted, allowing for the preliminary design of commingled waste facilities. With such design tools available, more field and full-scale trials can be conducted to further understand and improve this method of mine waste management.

Keywords: *commingling, mine waste management, closure*

1 Introduction

Serious issues related to safety and environmental contamination from mine waste deposits are well documented throughout the history of mining. Extractive mining processes typically generate 2 waste material streams that must be managed. The first is a coarse fraction of non-mineralised rock, generally referred to as waste rock (or mine rock, or country rock). The second is a fine fraction consisting of the remainder material after the ore has been crushed, milled, and/or chemically treated to recover the valuable minerals. The coarse rock is normally deposited in large stockpiles using heavy equipment to push or dump material over the leading edge of the pile. The segregation caused by these depositional techniques leaves large continuous voids for oxygen ingress, along with dense layers of fine material that transport moisture through the pile. This abundance of oxygen and moisture in the presence of sulphide minerals can lead to the generation of acid rock drainage (ARD), which leaches other contaminants out of the rock and degrades water quality (Bussière 2007). The GARD Guide (www.gardguide.com) was developed to address the growing need to manage ARD within the mining industry. The fine tailings material may also have an ARD risk, which

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is often mitigated by maintaining high saturation levels, or using a complete or partial water cap. This in turn creates a significant physical stability risk where tailings are stored above-ground behind man-made embankments known as tailings dams. Historically, tailings have been deposited as a loose, wet slurry that is slow to consolidate (Vick 1990). In the worst-case scenario, the tailings can liquify, breach containment and cause loss of life and/or environmental damage even long distances away from the mine. Large-scale failures over the past decades have led to the development of the *Global Industry Standard on Tailings Management* (GISTM) (Global Tailings Review 2020) in an attempt to reduce or eliminate tailings dam failures.

Initiatives such as the GARD Guide and the GISTM have led to improvements for these historical methods of mine waste management. However, it is important to also explore alternative practices that may be better suited to sustainability and mine closure that also address the chemical and physical stability challenges typical of mine waste materials. Tailings dewatering, and co-disposal methods have been slowly evolving and continue to show promise as potential solutions by using new technology and new depositional methods. Commingling is an emerging methodology that combines the advantages of dewatered tailings with co-disposal approaches. It is a specific type of co-disposal, utilising dewatered tailings and material blending to create homogeneous mixtures of non-segregating material.

Commingled materials could be beneficial for creating deposits that are both geotechnically stable, as well as geochemically stable. This geotechnically stable material may provide more options for building closure landforms than those available with rock or tailings separately, including covers or full-depth deposits. The geochemical stability is most valuable for projects where ARD is a concern but should not be detrimental at sites that are more geochemically stable. Despite continuing research into this topic, there remain few large or full-scale test sites that have adopted this approach. Our understanding of commingled deposits can only be completed with real-world observations. Recent and past research have provided many of the tools required to plan and develop full-scale trials. This paper aims to explore the measurements and predictions that are currently available, ranging from simple to advanced laboratory techniques.

2 Commingling theory

By collecting and analysing sample materials from numerous operating mines around the world (5–7 included in this review), the University of Alberta (UAlberta) Geotechnical Centre has been able to begin testing the broad applicability of existing commingling theory. Early developments in the field led to the definition of an optimum mixture, also known as the 'just-filled' condition (Williams & Gowan 1994). This was a useful approach for designing mixtures of coarse and fine materials, where the optimum mixture consisted of a skeleton of coarse material with all of the voids filled by saturated fines to achieve the maximum possible packing density (referred to as 'just-filled'). In general, the mix ratio is the ratio of rock solids to tailings solids, by mass. It is unlikely that this optimum condition will be reasonable for all materials at any given mine site. Efforts have been made to understand these mixtures that do not sit at the optimum point (such as fines-dominated or rock-dominated mixtures).

One such method is the use of ternary diagrams, as first demonstrated by Burden (2021). These ternary diagrams demonstrate the general material behaviour to be expected by any given mixture based on the material solids contents and mixture ratio. An example ternary diagram is shown in Figure 1; it should be noted that the authors have modified this and other figures from their originals, introducing the convention to always have mix ratio as the x-axis with coarse content increasing from left to right, on a log scale. These ternary diagrams are generalised with only the red line (representing the just-filled boundary between rock-dominated and fines-dominated behaviour) subject to change based on specific material properties (solids contents, moisture contents, and porosity). The material properties are determined from laboratory testing, and the just-filled boundary line is calculated as described in Burden (2021). Designers can use this tool to begin their mix design with simply measured material properties, incorporating their available tailings dewatering technology, and material volumes. For example, a given site may utilise thickened tailings, and have 3 times as much rock as tailings (by mass) giving a mix ratio of 3:1. From Figure 1, it would appear that an optimum mixture is possible. However, if the site only had twice as much rock as tailings (hence a 2:1 ratio to utilise all material), it can be seen that the mixture would be fines dominated.

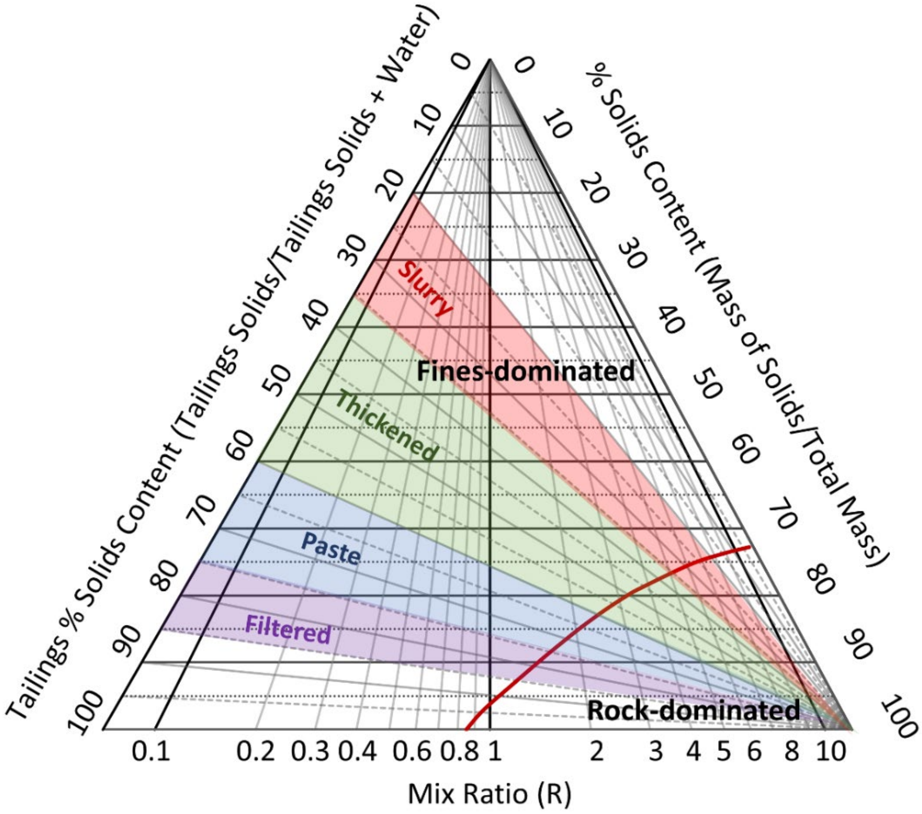

Figure 1 Ternary diagram (after Burden 2021)

In order to be more site specific, a property boundary chart (Figure 2) can be used to further categorise the predicted material behaviour. The curves in this type of chart are all specific to the materials at a given site. The waste rock skeleton deformation line is determined using the maximum porosity and the specific gravity of the waste rock, along with the mix ratio. The tailings consolidation line is calculated using the specific gravities and moisture contents of both the rock and tailings, and the mixture ratio. This line can shift quite drastically based on the moisture contents of the materials involved. Finally, the just-filled line denotes the optimum mixture ratio, and occurs at the intersection of the first 2 curves. A full explanation of this chart and the equations are included in Burden (2021).

Beyond just estimating the optimum mixtures, the property boundary chart can be used to plot actual measured data, such as from compaction tests. As such, it can be valuable for illustrating both theoretical and measured results. Whether using predicted or measured data, results can fall into any of the 5 zones that describe the material at deposition. The 5 zones are further expanded upon in a mix design chart as shown in Figure 3. This diagram illustrates a number of different blends with increasing mix ratios, as well as how these materials evolve as they are compressed. Depending on the mix ratio and material properties, the mixture may undergo further compaction, consolidation, or some combination of both.

The process described so far provides a high-level exploration of the potential material behaviour of commingled materials at any given site. By utilising basic material properties and overall material volumes, one can explore mix ratios, tailings dewatering requirements, potential material density ranges, and predicted material behaviour. This can provide further insight into the overall feasibility of using commingled materials at the site or for any further testing that may be required.

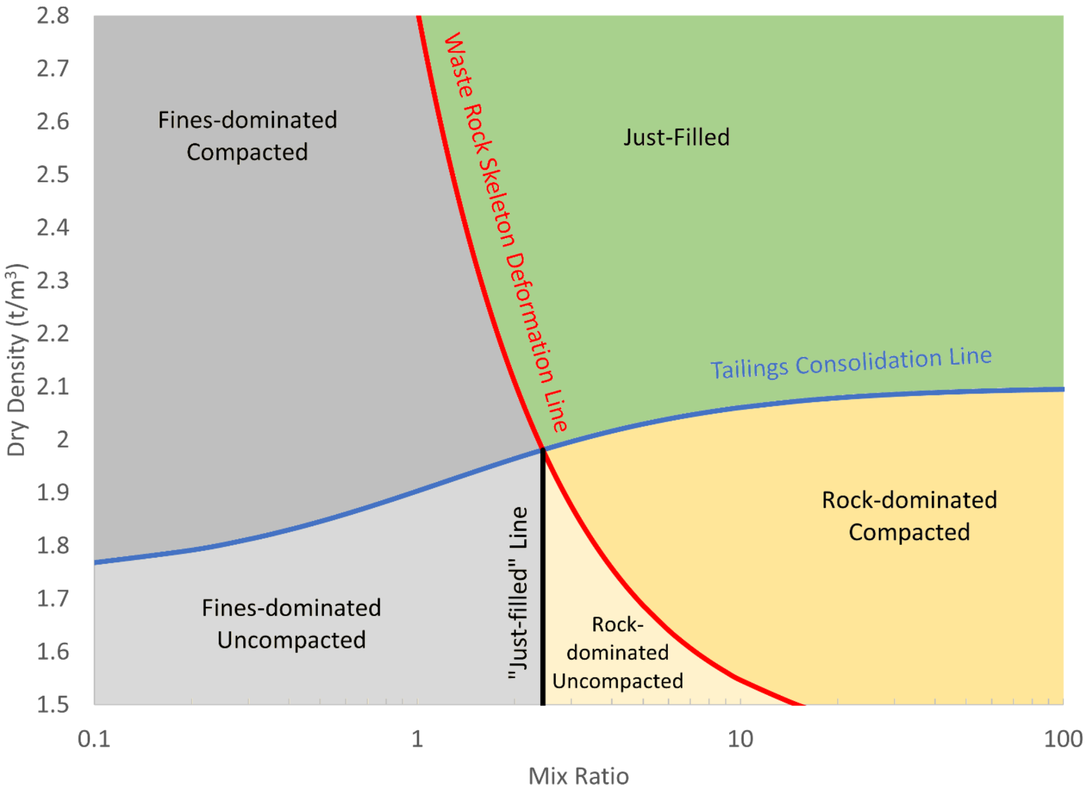

Figure 2 Property boundary chart

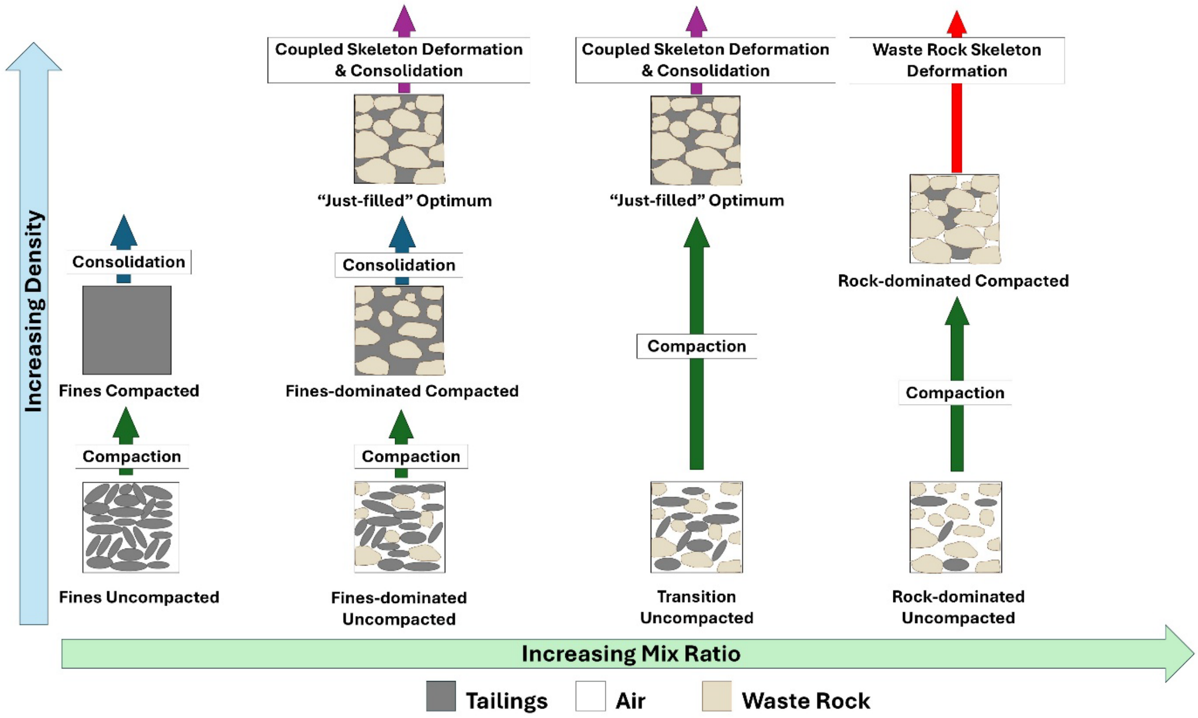

Figure 3 Mix design chart

3 Data

Along with theoretical approaches, there are numerous laboratory techniques, ranging from rudimentary to advanced, that can be used for direct measurement and/or prediction of material properties. Many of these measurements can be conducted in most soil labs with standard equipment. Measured data can be used for the prediction of additional properties that are not easily measured. However, advanced laboratory techniques do exist for measuring additional properties, but these often require specialised equipment and may be costly to perform.

3.1 Measured data

Perhaps the most basic test available is that for particle size distribution (PSD). The UAlberta Geotechnical Centre utilises both a large-size and a standard-size sieve shaker allowing for size determination between 75 and 0.075 mm. However, mixtures are most often limited to a maximum particle size of 25 mm to function well with other testing equipment and ASTM standard test methods. Figure 4 illustrates an example PSD examination for a given site. Individual curves for rock and tailings are shown in black and green, respectively. A mixture at a ratio of 3.3:1 (rock to tailings) is shown in blue, with the red line showing a prediction for that mixture. The prediction is based purely on proportionality of the 2 base components. While it is not a perfect match, it fits quite well based on the variability that is typically seen in waste rock materials (Barsi 2017; Cash 2014). If we accept the prediction as representative, then the optimum (or any) mix can also be predicted based on proportionality (as shown in yellow).

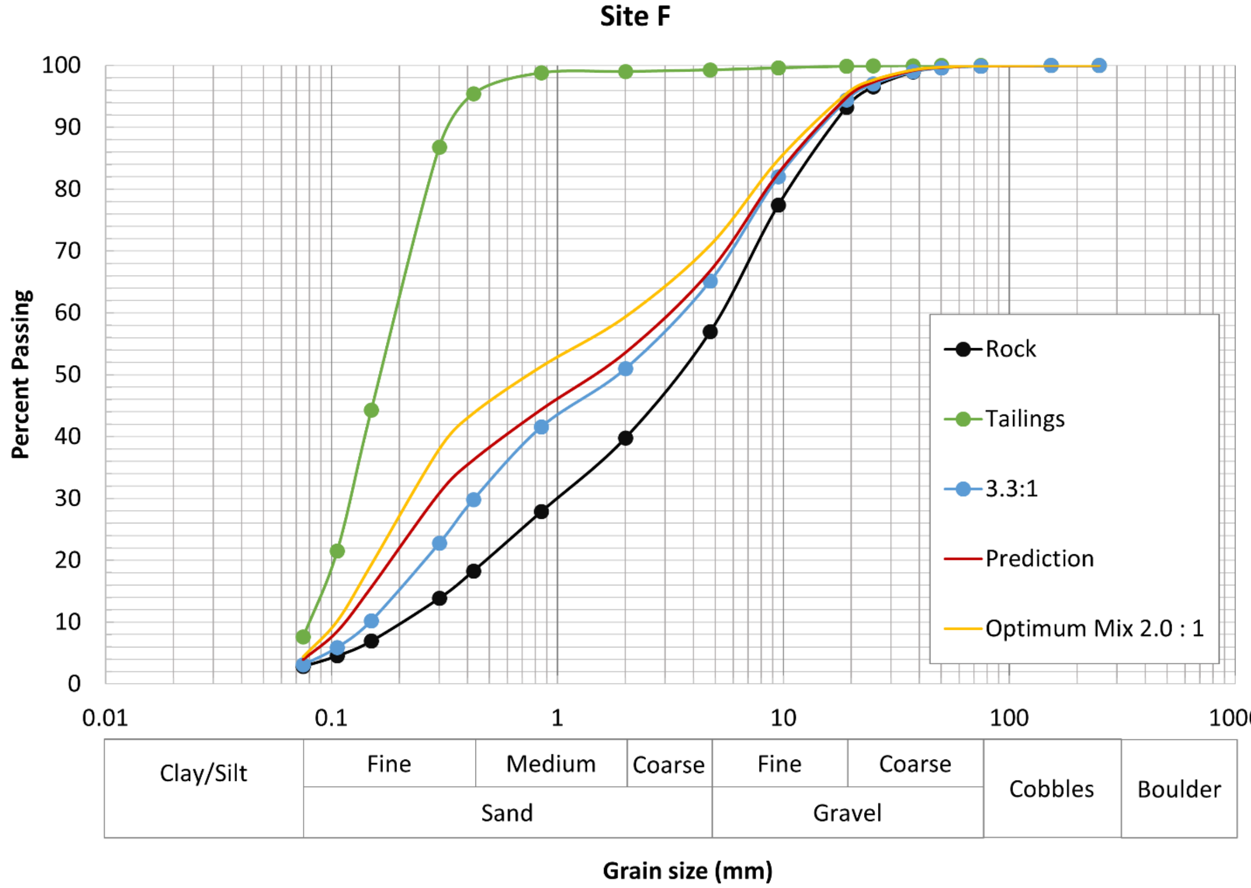

Figure 4 Particle size distribution chart

Another common testing method is Proctor compaction testing. Compaction curves can readily be measured for tailings materials, and mixtures. Waste rock can often be measured as well, but sometimes the fabric may be too coarse for reliable results. An example compaction dataset is shown in Figure 5 and includes rock, tailings, and 2 mixtures. Proctor testing of materials from 7 sites has revealed the general trends of the waste rock having the highest and steepest curve, the tailings having the lowest and shallowest curve, and the mixtures lying between, shifting their position and inflection based on the mix ratio.

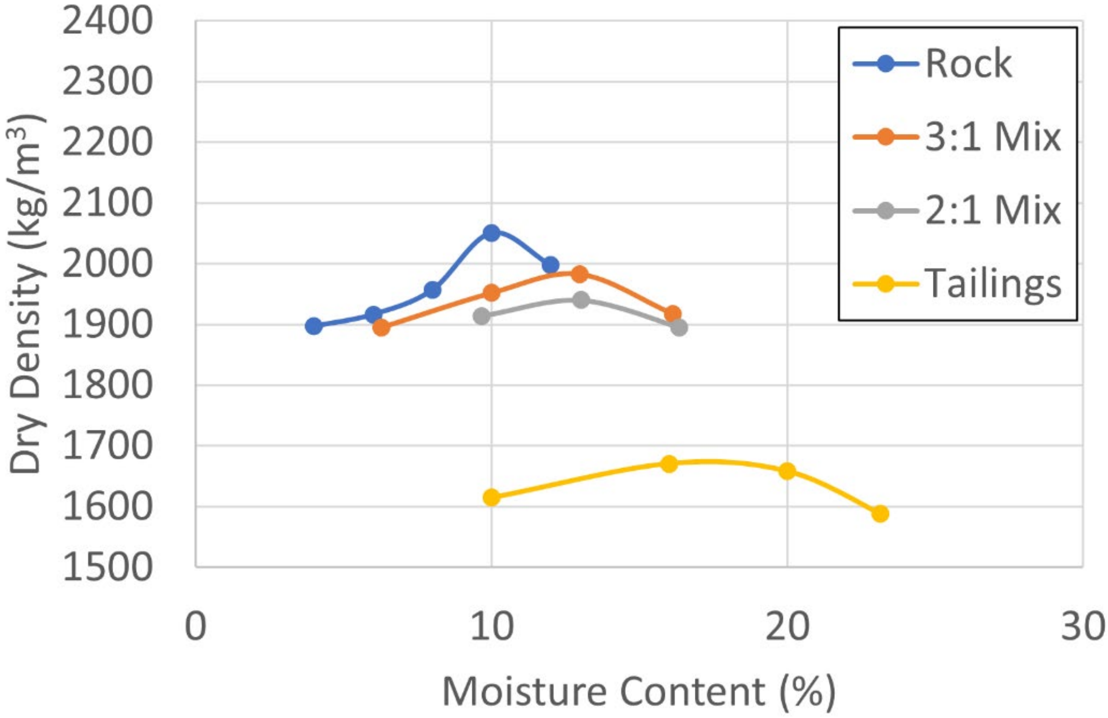

Figure 5 Optimum density chart

Depending on the equipment used, saturated hydraulic conductivity (ksat) can often be measured directly in the compaction cell; however, dedicated cells may be used as well. If using a compaction permeameter, there is opportunity to measure a curve for the ksat, relating it to the level of compaction, as shown with the mixtures in Figure 6 (full curves were not measured for the rock and the tailings; each have a single point that was measured wet of optimum density). Again, general trends appear across multiple sites, with increased compaction yielding a lower ksat. It has also been observed that ksat values for compacted mixtures on both sides of the optimum mixture (fines-dominated and rock-dominated) are often comparable to that of the tailings alone. This reinforces the idea that mixtures can gain the hydraulic properties of the tailings.

Measuring the soil water characteristic curve (SWCC) can range from relatively simple to quite complex, depending on the materials and the desired level of detail. For example, measuring the SWCC for large, coarse materials is much more challenging than that of a clean sand or silt. It is generally understood that the fine portion of a material (<4.75 mm) tends to control the hydraulic behaviour in waste rock materials, as demonstrated by Herasymuik (1996). As such, valuable data can be gathered by measuring the SWCC of the tailings material. Figure 7 shows the SWCCs for several tailings materials that have been used for commingling laboratory tests. These plots can provide information on the air entry value (AEV) – the point at which a material begins to desaturate – as well as the saturated water content and ksat values.

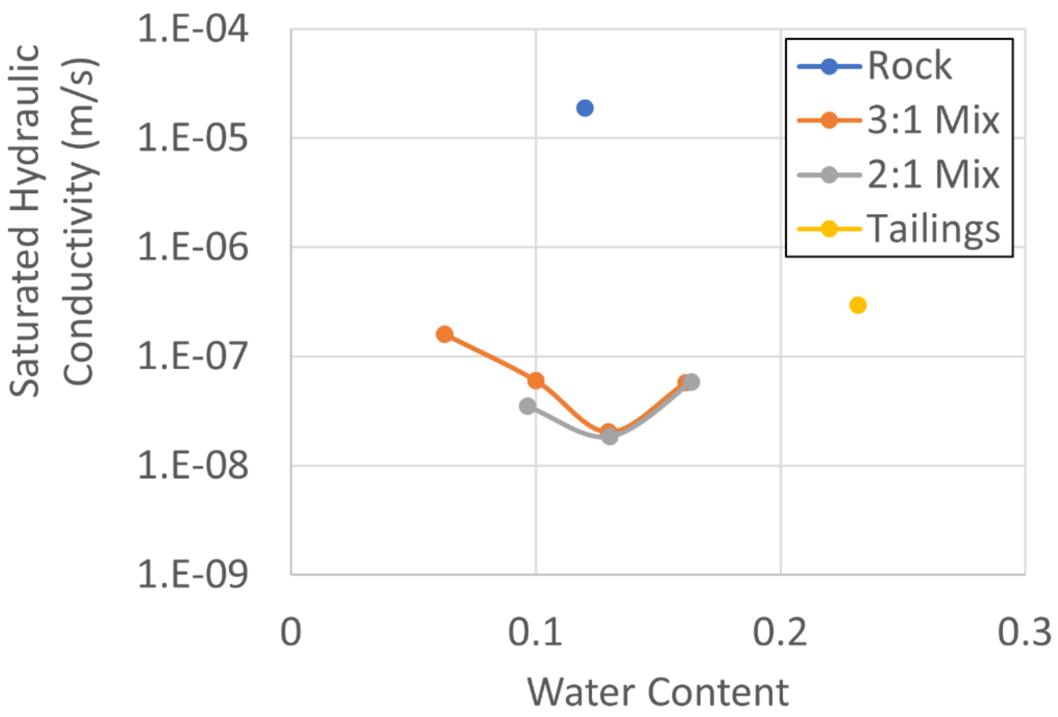

Figure 6 Saturated hydraulic conductivity chart

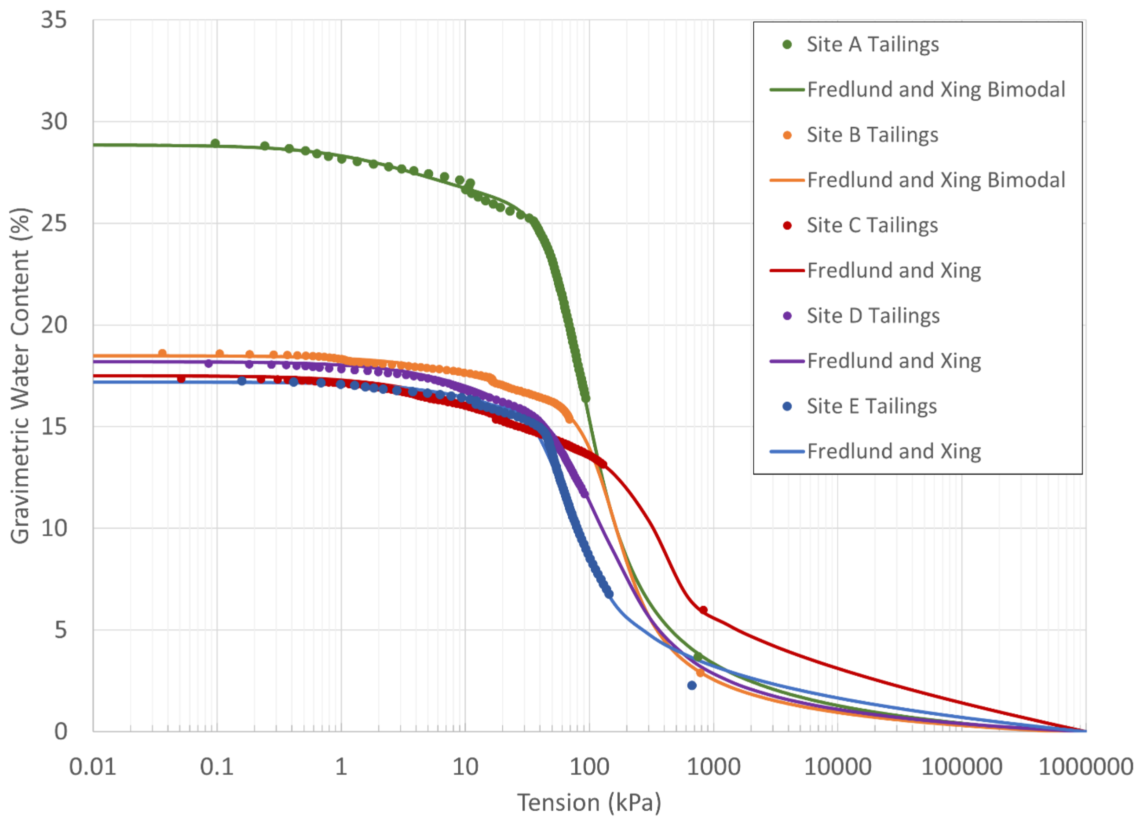

Figure 7 Soil water characteristic curves

3.2 Advanced data

There are numerous advanced laboratory measuring techniques available, though these may be limited to specialty labs. Material shear behaviour can be measured in large-scale shear boxes that can accommodate large granular materials. Pore pressure response and material loading behaviour can be measured in a slurry consolidometer cell. Large diameter SWCC cells can be utilised to measure the SWCC of complete mixtures, while computerised axial tomography (CAT) scanning can be used to image the internal structure of the mixtures. Perhaps the most difficult laboratory test is that of the large-scale triaxial cell for determination of critical state properties.

Large-scale shear boxes are a valuable tool for measuring the friction angle of commingled mixtures. Such devices typically operate with a shear box of 300 × 300 mm, allowing for particles of up to 37 mm. In one previous study, Burden et al. (2018) measured several mixtures and found that mixtures of "waste rock and filtered tailings are always stronger than tailings alone." It was also found that, at high shear stresses, commingled materials could have higher shear strength than rock alone, as the tailings could help to prevent breakage of larger particles.

A slurry consolidometer device uses a 150 mm diameter cell and a computer-controlled loading frame to apply loads to commingled samples, while recording stress and pore pressure responses in the samples. Loading rates can be controlled to mimic a range of deposition patterns that may be utilised in the field, such as rapid deposition of thick lifts, or slow deposition of numerous thin lifts. The study by Burden (2021) demonstrated that commingled mixtures effectively reduced pore pressures in the material as they were loaded, compared against tailings alone. These tests also supported the notion of how commingled materials will evolve with loading, as compression behaviour turns into consolidation behaviour.

CAT scanning allows the internal structure to be imaged, providing information about the distribution of materials and properties, including hydraulic conductivity, porosity, and tortuosity (Dadashi & Wilson 2024). These scans can be compared to the theoretical predictions and provide insight into how a given mixture may perform in a real-world deposit. Examples are shown in Figure 8.

Large-diameter SWCC cells can be used to measure the SWCC of an entire mixture, not just the fines portion. While much of the hydraulic behaviour is expected to be controlled by the fines, measuring large-scale mixtures as well can help to understand the scale-up effects as larger and larger particles are incorporated into mixtures.

Critical state parameters of rock and tailings blends have been explored in the past and require substantial effort (Jehring 2014; Khalili 2009). Past studies have mostly utilised 75–150 mm diameter samples, limiting the maximum particle size to 12.5 or 25.4 mm, respectively. There are several research institutions currently developing triaxial systems for testing samples larger than 150 mm in order to increase the maximum particle size allowable. Measuring critical state parameters at various scales will be helpful in understanding scale-up effects between the laboratory and a full size deposit.

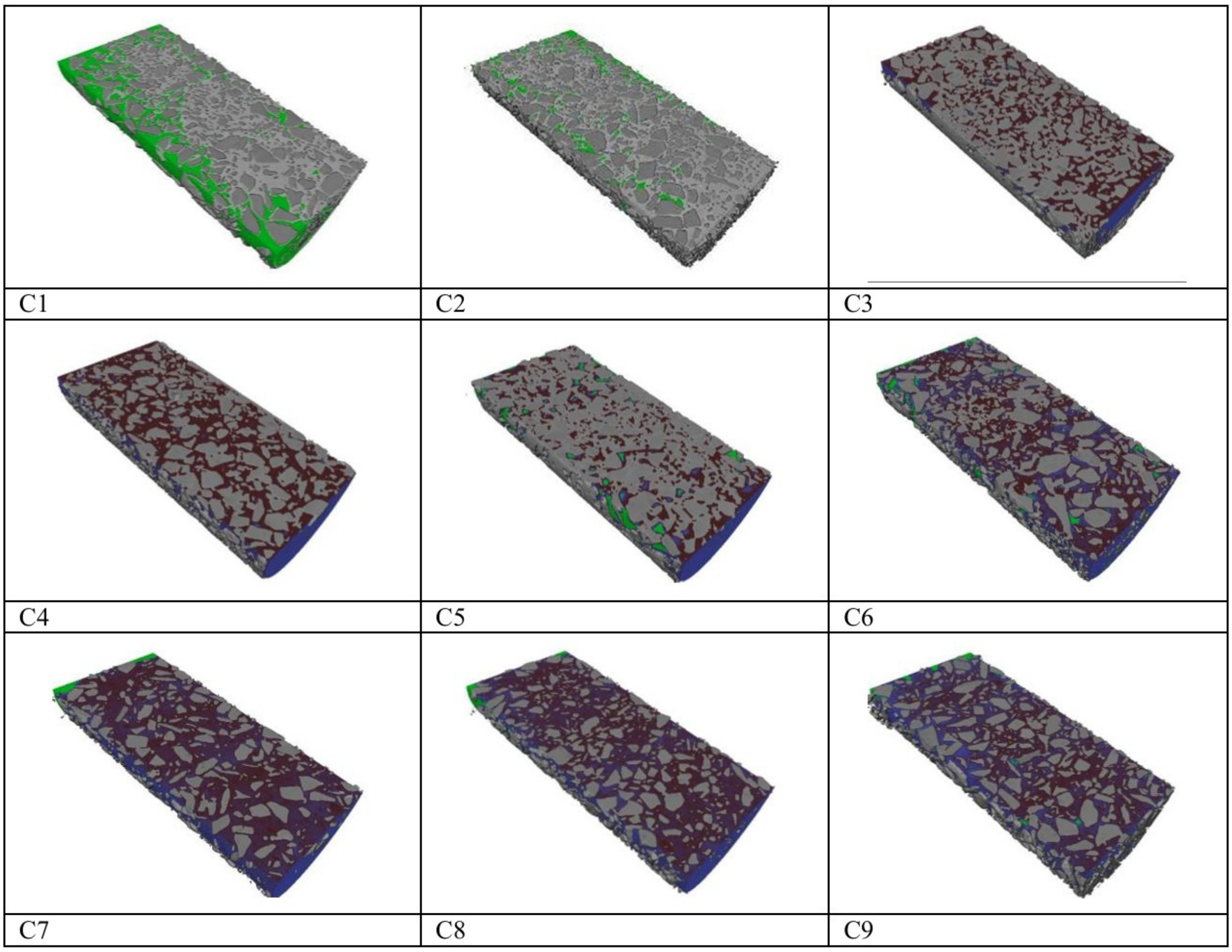

Figure 8 CAT scans of commingled mixtures. Solid phases (grey and brown), air (green), and water (blue). Figure used with permission from A Dadashi

3.3 Calculated data

Much of the data that is measured in the laboratory can also be used to predict additional material behaviours. As discussed in Section 2, simple lab data can be used to predict optimum mixtures and their PSD curves. Data relating to the solids concentrations can be used for predictions of material flow behaviour. PSD data can be used for analysis of seepage behaviour by predicting the hydraulic conductivity.

Figure 9 shows an example of a property boundary chart that was generated with only a few laboratory-measured values, including maximum porosity of the rock mass (n_{max}), specific gravity of the rock (Gs_r), specific gravity of the tailings (Gs_t), water content of the rock (w_r), and water content of the tailings (w_t). With these parameters, the optimum mix ratio can be calculated, providing a target for further testing. The waste rock skeleton deformation line and the tailings consolidation line can also be calculated and plotted, defining zones of different material structure and behaviour. Compaction data of various mixtures can also be plotted (square data points in Figure 9), showing actual measured examples of material behaviour.

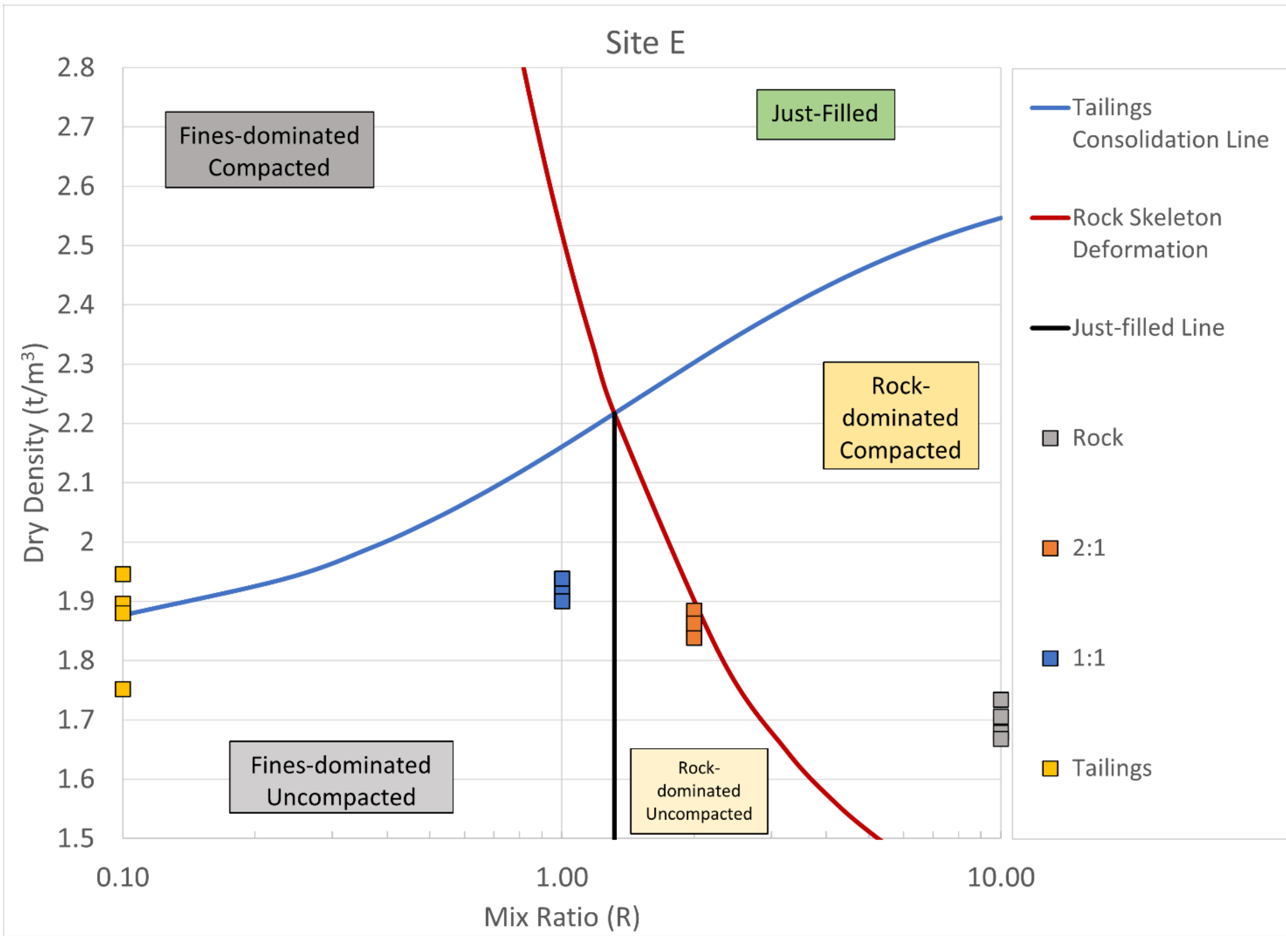

Figure 9 Property boundary chart example with compaction data points

Measurements of the material solids concentrations (both by weight and by volume) provide valuable information for the prediction of material flow behaviour. Using a method developed by O'Brien (1986), and later adopted by the Canadian Dam Association (Martin et al. 2019), this data can be plotted onto a material flow prediction chart, as shown in Figure 10. This method was developed through observation of numerous past failures and mudflows. Dewatered tailings themselves have the potential to improve these flow characteristics, shifting tailings from mud flood/mud flow behaviour into the realm of landslides. Laboratory-measured values of the solids concentrations for commingled samples generally plot favourably, with expected behaviour in the landslide or slumping zones.

General seepage behaviour can be explored by predicting the hydraulic conductivity of the mixtures. Results from a PSD curve can be used to determine values such as the D_{10}, or the particle diameter through which 10% of the soil mass passes through. This D_{10} value has been used in numerous methods that predict hydraulic conductivity. The simplest and most well known of these methods is likely the Hazen equation, though more recent versions, like that from Chapuis (2004), may be better suited for mixtures of finer and coarser materials. The exploration of predicting hydraulic conductivity values from the PSD of commingled material is ongoing, with a variety of predictive methods being tested against an ever-growing database of PSD records.

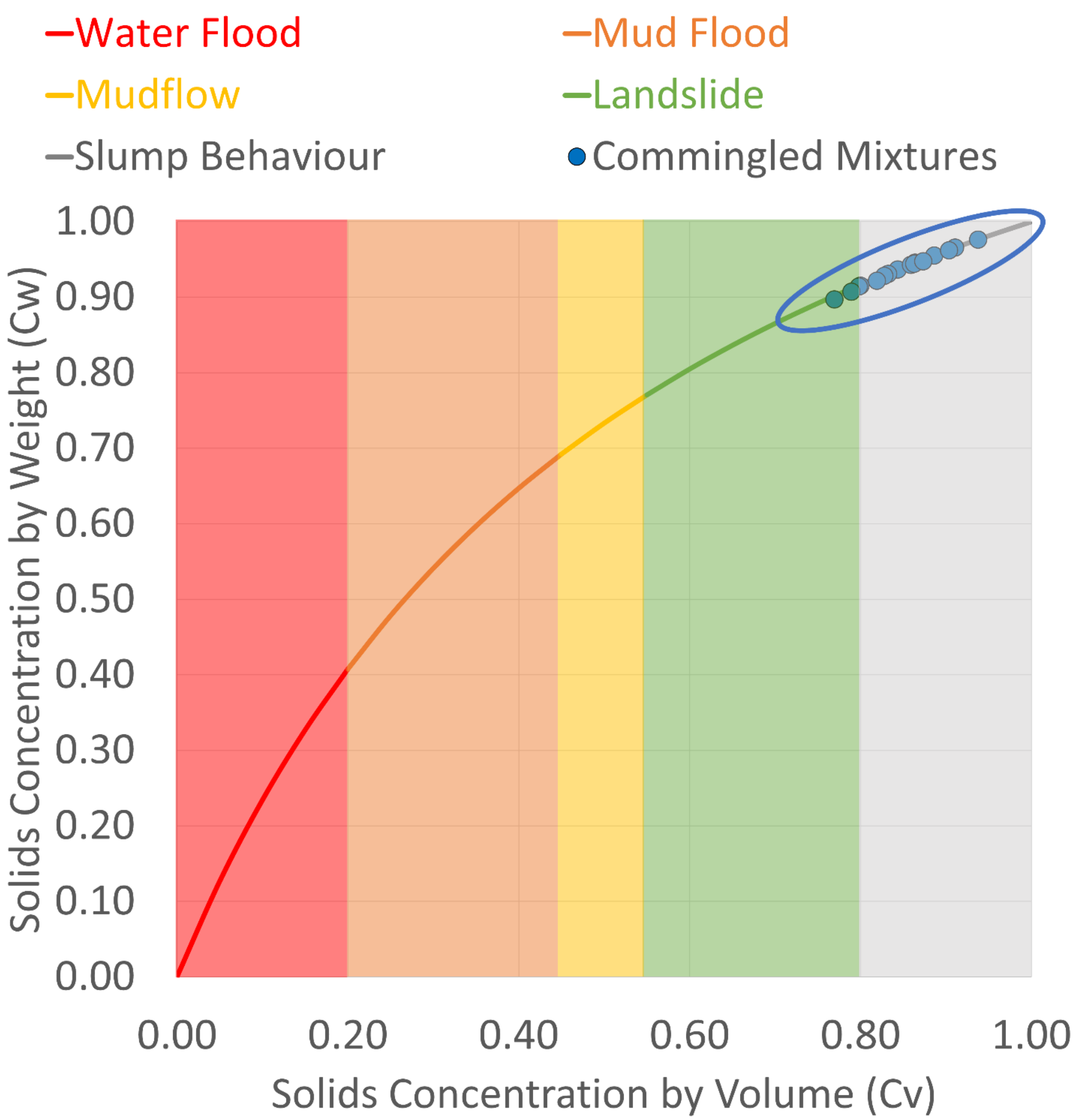

Figure 10 Material flow prediction chart based on O'Brien (1986)

4 Applications

Despite there being few large-scale test cases of commingled waste rock and tailings, valuable design tools have already been developed. These range from elementary laboratory tests to advanced experimental methods, all of which can be paired with predictive methods to understand material behaviour. Readily available laboratory tests include the PSD, hydraulic conductivity, density, specific gravity, and SWCCs. More-specialised testing includes the use of a large shear box, slurry consolidometer, large SWCC, CAT scans, and/or large diameter triaxial cell. Data gathered in the laboratory can be used to predict parameters such as the mix ratio, flow behaviour, and seepage characteristics.

While there is not yet a proven design methodology for commingled materials, an example of such a process could include the following elements:

- Lab tests of rock and tailings for specific gravity, moisture content, and rock porosity, allowing for the prediction of an optimum mix ratio (and the associated just-filled line).
- Development of a property boundary chart and/or ternary diagram. This will provide an early understanding of tailings dewatering requirements.
- Lab tests for PSD, Proctor density, and ksat of the optimum mix, and SWCC of the tailings. Additional mix ratios can also be tested.
- Prediction of flow behaviour from flow behaviour charts.
- Measured density values plotted on property boundary chart to understand material behaviour at deposition.
- Utilise PSD and ksat data to examine seepage potential. Early determinations if material sizing or crushing will be required.
- Examine ksat and SWCC data for a general understanding of the material saturation and how the geochemistry may be affected.
- Large shear box tests for determining the friction angle.
- Slurry consolidometer tests to determine appropriate loading rates that correspond to acceptable pore pressure responses.
- Large SWCC and CAT scans to better understand the saturation and drainage of more-representative samples.
- Large-scale triaxial tests to determine the critical state properties and understand the liquefaction potential, if any.

Even without the data from advanced testing, there can easily be enough measured and predicted data to begin the design process for deposits made from commingled materials. This includes determining an optimum mix ratio, and then measuring or calculating properties for that specific mixture. It is important to remember that the desired mix ratio may not always be the same as the optimum. If it is found that the optimum mix ratio does not have a favourable PSD, or it does not efficiently use up waste rock and tailings volumes, a different mix ratio can be chosen and new calculations can be made. This process could go through several iterations until an acceptable mixture is determined.

5 Conclusion

The use of commingled materials in mine waste management is still under-utilised in practice. However, it is potentially a very versatile material not just for waste covers, but for full depth deposits. Decades of research and advancements in tailings dewatering technologies have generated an effective toolset for the design and construction of commingled deposits. Material properties can be measured and predicted using well-known laboratory techniques. PSD, hydraulic conductivity, compaction, and SWCCs can be used to determine appropriate mix ratios and deposition plans. Specialised laboratory testing can provide even more data, such as slope friction angles, pore pressure responses, and critical state parameters.

Despite this, there is only so much that can be learned at a laboratory scale. By utilising existing methods for measuring and predicting the material properties of commingled mine waste materials, it is possible to start building new deposits at pilot-scale or full-scale. These are important next steps, as only at large-scale can the next set of challenges be revealed and solved. The challenges related to traditional mine waste management practices are well known after decades of practice and research. The solutions to these problems continue to get costlier and more complex as mines get larger and larger. The use of commingled materials may offer a new approach that can mitigate physical and chemical stability issues, while generating more natural landforms. With the tools and methods available, large-scale testing can begin now.

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