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Tailings filtration: integrating process design with geotechnical outcomes

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Abstract

With the number of high-profile tailings storage facility incidents over recent years, filtration and dry stacking has received unprecedented attention as a viable option for the management of tailings. Due to regulatory pressures, both new and existing operations are at the very least evaluating or re-evaluating the cost-benefit balance offered by tailings filtration. Consequently, there has been a significant increase in the amount of evaluative test and design programmes in the area. However, the quality of this work may not always meet a level of technical rigour commensurate with the higher cost and associated risk of the filtration approach.

One key risk in the filtered tailings design process lies in the interface between the tailings processing and materials handling/geotechnical disciplines, which typically operate in isolation of each other. This risk is in part due to different terminologies and technical bases used for describing similar properties, but more so is due to this divide preventing development of a holistic picture of the behaviour of the material (e.g. dewatering rates, achievable versus target moistures, rheological behaviour, material variability) across thickening, pumping, filtration, cake handling and ultimate placement. If available as early as possible in the design process, this information can save money and reduce risk by allowing well-informed decisions around design criteria, equipment choices (type, size, dewatering pressure, operational targets) and ongoing detailed test programmes.

Using indicative data (Compressibility/permeability, rheology, filter sizing, Atterberg limits, unconfined compressive strength, flow moisture point) this paper illustrates how a testing and evaluative approach integrating both process and geotechnical considerations can assist in clearly and quickly identifying critical flow sheet design information, operational windows, design and operational risks and highlight avenues for optimisation. Importantly much of this information can be obtained with relatively small sample sizes, early in the evaluation process and at lower cost. The strong interlinkage between material properties is also discussed. Whilst the focus of this paper is on filtration, this approach is equally valuable across all methods of tailings dewatering and disposal, and in particular assists with the early identification of the most suitable approach for an operation.

Keywords: *cake moisture, cake handling, process design, flow sheet optimisation*

1 Introduction

In response to the recent spate of high-profile tailings dam failures, filtration and dry stacking of tailings has been receiving unprecedented attention and is often touted as the gold-standard for tailings management. Whether true or not, due to regulatory pressures, both new and existing operations are at the very least evaluating or re-evaluating the cost-benefit balance offered by tailings filtration. Consequently, there has been a significant increase in the amount of evaluative test and design programmes in the area. However, with the higher cost and complexity of a filtration approach comes greater risks during the test and design process. In particular a key risk in the assessment and design process arises from the multi-disciplinary nature of this, and indeed any tailings management system.

Development of a dewatered tailings management system spans a wide range of specialist disciplines including:

- Thickening, clarification, flocculation and chemical conditioning.
- Slurry rheology and pumping.
- Filtration.
- Materials handling equipment, conveyor design.
- Geotechnical engineering.
- Environmental engineering, geochemistry and hydrology.

In addition to the engagement of an adequality skilled team within each discipline, the design of a successful system that meets the requirements of all stakeholders requires careful development and clear communication of critical design criteria that are inputs or outputs across inter-disciplinary boundaries.

Identification of the best tailings management system for a given operation should ideally be a process approached with limited preconceptions or pre-disposition to a specific outcome. In particular it is best to make no assumptions and be led through the design process by the material properties in conjunction with site, operational and legislative constraints.

Material property, process, test and design information is critical to this assessment, and for a successful outcome it is important to have process design criteria which are informed by measured data at level of accuracy commensurate of the project stage. In particular, project risk is amplified where disciplines operate largely in isolation to each other and disciplinary interfaces have arbitrary, poorly informed inputs or outputs, which can then lead to unrealistic (high or low) targets for upstream or downstream operations. Whilst loose assumptions of behaviour at early project stages may appear tolerable, if they turn out to be unrealistic, they can lead to negative technical or economic shock events later in project. Alternatively, they can lead to overdesign which, in the worst case could lead to an incorrect assessment of a project as sub-economic.

This type of risk can be mitigated by the following strategies:

- Better identification of the critical data required at different project stages across all disciplines.
- Ensuring that targeted test programmes are conducted for their evaluation.
- Ensuring the data are distilled into a commonly understood form that facilitates a clear, integrated picture of the behaviour of the material (e.g. dewatering rates, achievable versus target moistures, material variability) across the entire process including thickening, pumping, filtration, cake handling and ultimate placement.

If available as early as possible in the design process, this information can save money and reduce risk by allowing better-informed decisions around process design criteria, equipment choices (type, size, dewatering pressure, operational targets and envelopes), risk management or design optimisation strategies, and ongoing more detailed test programmes.

A key issue encountered at early project stages is that representative sample availability is limited, whilst many common test methods employed across tailings flow sheet design require large sample masses. This paper seeks to address this issue by highlighting how a carefully designed test and assessment programme can obtain sufficient information to allow development of this holistic picture of tailings behaviour with relatively small sample sizes.

Whilst the focus of this paper is on filtration, and environmental and geochemical issues are not considered, this approach is equally valuable across all methods of tailings dewatering and disposal, and in particular assists with more rigorous comparison of different options at early project stages to identify of the most suitable approach for an operation.

2 Key test methodologies typically employed

A high-level overview of the key test methods utilised across all areas of a tailings assessment process, and their common outputs, sample requirements and type of test provider, is listed in Table 1. It must be noted that the list presented is by no means exhaustive, nor does it take account of environmental and geochemical factors and testing, which have been omitted for the purposes of the current discussion. It is also acknowledged that there are many other test methods used across the wide range of dewatering and tailings handling technologies, however the information is a good snapshot of the more common small- and large-scale methods employed across the key disciplines involved.

A number of key observations can be made from the information in Table 1:

- Many of the test methods outlined require significant amounts of material for their application, particular in the case where a standardised test method exists, which is common within the geotechnical discipline. Whilst accredited test data is required for final design purposes and vendor guarantees, for many test methods, they can be conducted with significantly less material, whilst still delivering fit-for-purpose data suitable for use at early project stages (subject to reasonable limitations associated with factors such as particle size or unusual behaviour such as ageing etc.).

  Alternatively, there are methods which, due to limited fundamental insight, require larger sample masses for conduct of multiple runs to obtain design-related insights (e.g. feed solids variability, thickener flux or filter cycle stage and time adjustments). Such insights can be obtained from smaller-scale material property-focused testing in conjunction with model-based simulations if required.

- A general comment is also made that that some technologies, e.g. shear enhanced processes such as belt press filtration, decanter centrifuges, screw presses, have limited evaluative capacity at bench scale making it harder to accurately evaluate/size equipment with limited sample availability, or methods utilised involve significant proprietary, experience-based empiricism.

- A clear divide is evident between the test providers that operate and generate data in the largely process-oriented space, and those in the geotechnical/materials handling space. This highlights a key interface which generates project risk, and this has been borne out in the authors' experience.

- The most critical observation from Table 1, is that, despite the disciplinary partitioning evident, there are intrinsic links between most of these properties assessed as they are all related to fundamental processes of shear, compression and fluid flow, governed by underlying factors such as moisture level, particle size, shape, mineralogy and interparticle forces (electrostatic, polymer, capillary etc.). Typically, most of these factors are relatively invariant across the tailings management process with the exception of the interparticle forces and degree of aggregation which are impacted by coagulation, flocculation or water chemistry changes due to washing processes and shear effects.

The next section presents examples of both these inter-dependencies, and how consideration of test data across disciplines from a holistic perspective can assist in identifying realistic process criteria and equipment or optimisation strategies that can achieve them. Importantly the assessment uses data that was largely obtained using test methods that required only small to medium masses of solids. The results/trends presented are based on real testwork results, however absolute numbers have been removed from axes due to confidentiality considerations.

Table 1 Key test methods and design data commonly used in a filtered tailings system design process. Sample sizes: VS = very small <0.5 kg solids, S = small 0.5–2 kg, M = medium 2–10 kg, L = large 10–100 kg, VL = very Large >100 kg.

Discipline	Details	Typical design data	Sample	Test provider
Thickening	Floc screening tests	Settled densities, settling flux, feed dilution, reagent doses	S to M	Vendors, Met labs
	Dynamic Rig	Underflow density versus flux/floc dose, paste estimations	M	Vendors, Met labs
	Pilot thickener	Underflow density versus flux/floc dose, paste sizing data	L to VL	Vendors, Met labs
	Consolidation-permeability (C-P)	Stress-solids, permeabilities, thickening limits	S to M	Specialist labs
Rheology	Shear yield stress	Shear yield stress versus solids	S	Met labs, Specialist labs
	Steady shear tests (Couette)	Shear stress-shear rate, viscosity, thixotropic assessment	S	Met labs, Specialist labs
	Pipe loop studies	Pressure versus flow rate, scale-up, large-scale flow assessment, coarse/settling slurry data	L to VL	Specialist labs
Filtration	Batch filter cell	Stress-solids, permeability, desaturation (pressure or vacuum) data, model-based sizing and optimisation	S to M	Vendors, Specialist labs
	Buchner test kit	Solids versus drying time, throughput, cake thickness effects	S to M	Vendors, Met labs
	Pressure filter test rigs	Solids versus press (or air blow) time, throughput, cake/chamber thickness	S to M	Vendors, Met labs
	Pilot pressure/vacuum rigs	Solids versus press (or air blow) time, throughput, cake/chamber thickness	M to L	Vendors, Met labs
Materials handling	Atterberg limits	Plastic, liquid limits, plasticity index	VS to S	Met labs, Geotech
	Flow moisture point	Conveyability/handling moisture limit	S to M	Geotech, Specialist labs
	Shear strength testing	Bulk strength, friction angles for materials handling design	S to M	Geotech, Specialist labs
Tailings storage	Proctor compaction	Optimum compaction moisture, design density, trafficability moisture limits	S to M	Geotech
	Shear, compressive strength	Vane shear versus solids, Unconfined compressive strength versus solids/compaction pressure	M	Geotech
	Air drying	Shrinkage and dry density limits	S to M	Geotech
	Settling/C-P/Rowe cell	Settled density limits, Water recovery, consolidation-permeability data	S to M	Geotech, Specialist labs
	Triaxial testing	Detailed geotech design parameters, seismic stability, target filter cake moistures	M	Geotech

3 Tailings filtration system design

Full design of a tailings filtration and dry stacking system, or the evaluation of it against other candidate management strategies, requires testwork across all the areas outlined in Table 1. For illustrative purposes, the discussion in this section is confined to filtration, materials handling and placement. Integration of thickening and slurry rheological considerations is touched on in the following section, although the importance of integrated consideration will also be clear from the discussion in this section.

Before filtration testing is even undertaken, thickener tests should have already been conducted to:

- Generate material for filtration testing with a representative treatment history.
- To define realistic feed solids concentrations for filtration assessment.

Once material is available, filtration testwork is generally conducted by equipment vendors or metallurgical labs. A standard test programme (ignoring washing studies) would typically cover the following:

- Assessment of both pressure and vacuum filtration if considered viable.
- Limited number of feed time/cake thickness tests, typically at fixed pressure.
- Limited number of pressing or air-drying time tests, typically at fixed pressure.
- A single feed solids concentration unless instructed otherwise.

Such an approach, whilst delivering data useful for the vendor’s sizing and to obtain an idea of the ideal equipment, has a number of key limitations in the context of a holistic approach, which include:

- A narrow focus, often tailored to a vendor’s specific equipment design, with an inability to readily identify behaviour at conditions outside of those explicitly tested. This prevents revision of operating parameters in response to downstream process requirements identified subsequently, without further testing.
- In particular, a systematic exploration of absolute dewatering limits under different operational conditions is often not conducted.

An alternative approach to filtration testing is the performance of compressibility-permeability assessment using a small-scale filtration cell. Such an approach, when analysed appropriately (e.g. Wakeman & Tarleton 1999; de Kretser et al. 2001) delivers compressibility and permeability data which can yield the same information as a traditional vendor test programme, with significant further advantages. Example data are presented in Figures 1a and 1b for two different substrates; a fine neutralisation residue (Material A) and a coarse, fines-containing leach residue (Material B). This type of data is significantly more versatile in that it can be used:

- To clearly define absolute moisture limits as a function of pressure. For a given pressure the fine residue achieves significantly lower cake solids concentrations than the coarser residue (Figure 1a). i.e. it exhibits a compressive strength that balances the applied pressure within the filter at a lower solids concentration.
- To quickly assess the viability of moisture reduction via increased squeeze or feed pressure. The shape of fine residue curve in Figure 1a illustrates greater compressibility, highlighting high pressure squeezing as an optimisation strategy. This is not the case for the coarser residue for which there is limited increase in cake solids at higher pressures.
- To perform detailed sizing and throughput calculations including optimisation assessments e.g. variable feed solids, changing filter chamber. The permeability behaviour drives the filtration rate and the significantly poorer permeability of the fine residue is evident in Figure 1b.

- To quickly (<1 day) estimate geotechnical parameters suitable for preliminary tailings consolidation assessment (Stickland et al. 2005; de Kretser & Scales 2007). The data can also be used in thickener assessment when interlinked with data from settling and other methods (Scales et al. 2015).

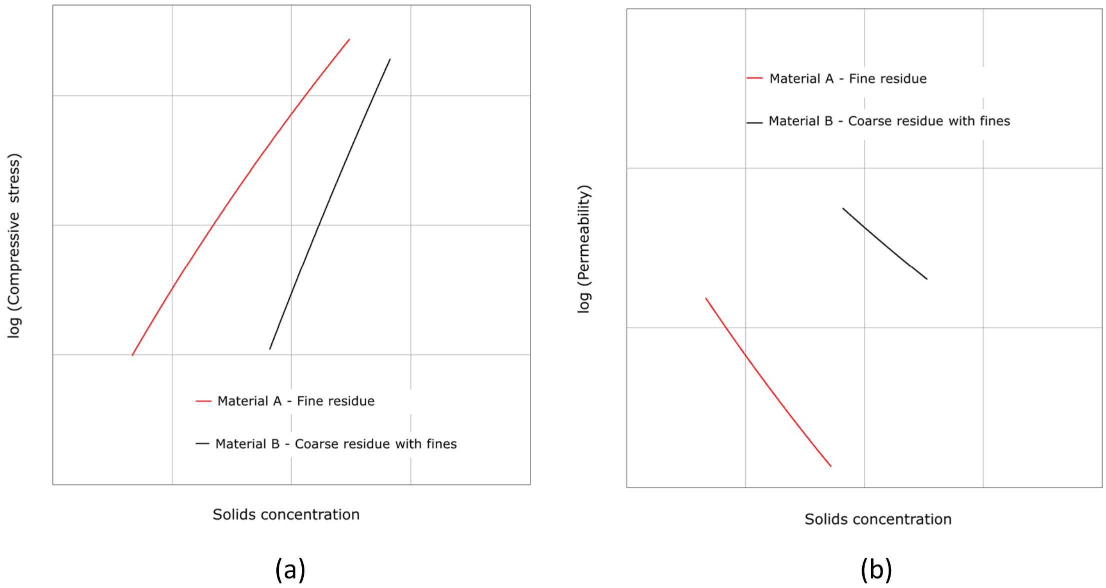

Figure 1 Indicative compressive stress (a) and permeability (b) versus solids concentration data for a fine and coarse residue

Further detail around absolute achievable moisture limits can be obtained by performing air displacement/cake desaturation tests as a function of pressure. When combined with the mechanical expression data, a clear picture can be obtained of the absolute limiting performance of a given filtration technology and whether it will achieve the target moisture levels. Example data for a lead–zinc tailings in Figure 2 illustrates:

- The filter cake is clearly amenable to air displacement dewatering/desaturation, provided a threshold pressure of around 100 kPa is exceeded.
- The target cake solids level can only be achieved with an air blow exceeding 200–300 kPa. This rules out vacuum filtration as an option and mechanical expression alone will not be viable. For this application a pressure filter with an air blow stage was required.

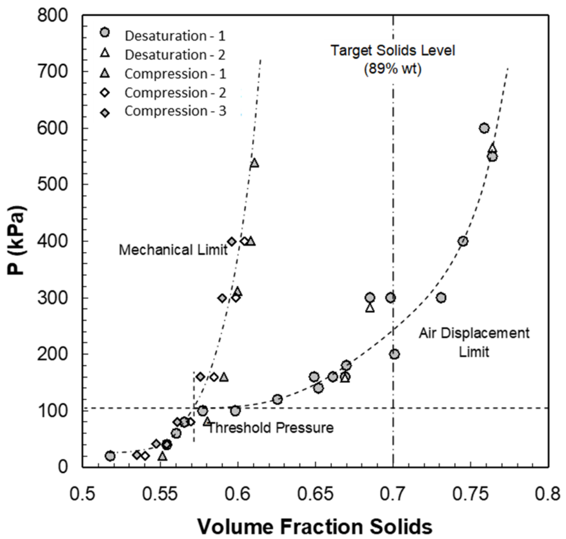

Figure 2 Reference dewatering stress versus solids concentration data for both mechanical and air displacement (desaturation) dewatering of a lead–zinc tailings

A range of measurement techniques were outlined in Table 1 for the evaluation of filter cake handling and stacking properties. Whilst many of these techniques require significant masses of sample or specialist equipment, it is possible to readily obtain fit-for-purpose data to make a high-level assessment of the design requirements for cake handling and stacking with the use of certain key types of measurement, as outlined below:

- The Flow Moisture Point (FMP) for filter cake under low compaction conditions for conveyability/ transfer behaviour assessment.
- A filter cake strength determination under placement compaction conditions e.g. unconfined compressive strength (UCS) or vane shear strength.
- A compacted density determination. This could be a formal Proctor compaction test or inferred from preparation of other test samples.
- Atterberg limits, which provide an excellent overview of the moisture bounds for material behaviour to inform design decisions.

Figures 3 and 4 illustrate examples of this type of data as function of moisture content for low (Material B) and high (Material A) compressibility residues presented earlier. In this testwork strength was quantified using miniature UCS tests, however shear strength could also be used as trends would closely mirror those in compression. Key insights from this data are largely what would be expected in isolation, but offer key insights when integrated with the filtration performance data:

- The plastic index (PI) of the fine residue (Material A) is significantly larger than the coarse residue (Material B) with a more gradual increase in UCS with decreasing moisture.
- In both cases there is a strong correlation between the change in strength with moisture and the liquid (LL) and plastic (PL) limits. At moistures below the PL a strength plateau or even maximum exists, due to the transition to friable solid behaviour – this is more evident for the coarser residue. The peak strength correlates closely with the PL, as typically would the peak compacted density.
- The strength of as-received filter cake samples was similar, even though the actual cake moisture differed – this is a general trend observed over multiple samples. From a mechanical perspective such behaviour is largely to be expected for a constant pressing pressure, as the physical strength of the formed filter cake is largely governed by the pressing pressure employed in filtration (note that this is analogous to a relatively consistent thickener underflow yield stress, irrespective of underflow moisture for a given configuration, bed depth, level of raking etc).
- From a practical design perspective, the fine residue data indicate a cake moisture below the FMP, suggesting acceptable conveyability. However, the safety margin is not great and a lower moisture may be desirable – this would also increase placed residue strength. A ready means of obtaining this would be the use of higher squeezing pressures, as was evident from the limiting cake solids versus pressure data in Figure 1a.
- For the coarse residue data, the low PI value and the fact that the filter cake moisture is above the FMP, indicate design and operational challenges due to the high sensitivity of cake mechanical properties to small changes in moisture. For this material, higher pressing pressures are not a viable strategy, however desaturation tests such as those in Figure 2 indicated a means of markedly reducing cake moistures below the FMP via use of an air blow stage in the filtration cycle.

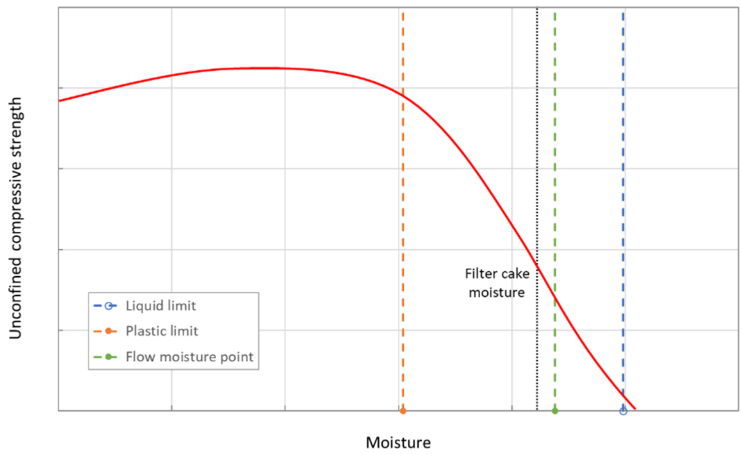

Figure 3 Indicative cake mechanical strength versus moisture – fine residue (Material A)

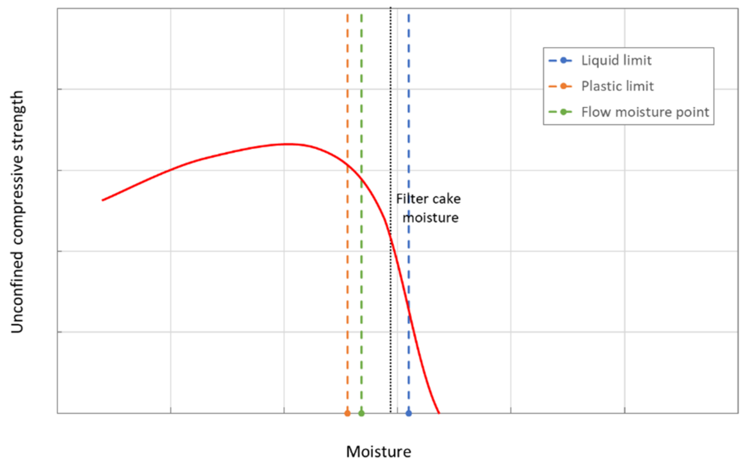

Figure 4 Indicative cake mechanical strength versus moisture – coarse residue (Material B)

Whilst the approach and conclusions presented above may seem obvious, often these trends are obscured due to factors related to the testwork being conducted across different test providers with relatively narrowly defined test objectives. Adopting the approach above allows quick and clear assessment of required cake properties against equipment capability such that design optimisation requirements can be identified.

The discussion above has largely focused on matching achievable cake moistures with the requirements for cake handling and stacking. However, a key aspect of design is the sizing of the filters, for which the permeability data in Figure 1b can be used. A critical factor that impacts filter sizing is the level of pre-thickening of the filter feed (de Kretser 2018). Maximising thickening is critical, as generally it is more cost-effective to remove water in a thickener than a filter. Consequently, integration of thickening and underflow rheological considerations into the holistic approach is also required.

4 Tailings thickening/pumping system considerations

The importance of some type of integrated thickener testing was highlighted earlier in terms of defining realistic inputs to filtration test conditions, however enhancement of the level of thickening is also a key lever for filter throughput improvement. As such, understanding the operational limits of thickening is preferable, something which is also intrinsically linked to underflow rheological behaviour.

The fundamental links between the yielding behaviour of particulate suspensions in shear and compression are well established (e.g. Zhou et al. 2001) given that the shear and compressive strength both originate from the same physico-chemical phenomena. In the case of thickener design and operation both shear and compressive yielding play a critical role.

Figure 5 illustrates the compressive and shear yield stress behaviour for three different mineral composite slurries. Note that the compressive yield stress data are a hybrid of high solids concentration data determined using C-P type testing and low solids concentration data from cylinder settling tests.

Key points to note from Figure 5 are:

- The data illustrates the same ranking of the composites in terms of solids concentration for a given stress for both the compressive and shear yield behaviour – similar rankings would also be evident in the steady shear behaviour.
- The shear and compressive yield stress data both tend towards zero at a common solids concentration, the gel point. The gel point is a strong function of particle size and level of flocculation and can reasonably be considered a lower bound for the achievable solids concentration for a thickener (although this would only be indicative, as the gel point of a flocculated suspension is highly sensitive to shear and matching sample shear conditions in a simple test to operational shear levels is almost impossible).
- The theoretical limiting achievable solids for a given bed depth in a thickener, assuming long residence times, can be estimated from the data in Figure 5 using compressive load generated by the bed, which can vary from less than 1 kPa up to more than 5 kPa. This can provide an indication of the maximum achievable solids concentration as a function of bed depth (or thickener type – conventional, high compression or paste).
- However, operational limits exist related to both rake torque or underflow pumpability. In this case, the shear yield stress can provide a ready gauge of the handleability limits for either centrifugal (typically 50 to 100 Pa) or positive displacement pumping (>100 Pa).
- It is important to note that whilst thickener bed depth defines absolute thickening limits possible at long residence times, the permeability behaviour governs how close the thickener can approach the limit at practical fluxes (and the level of flocculation required).

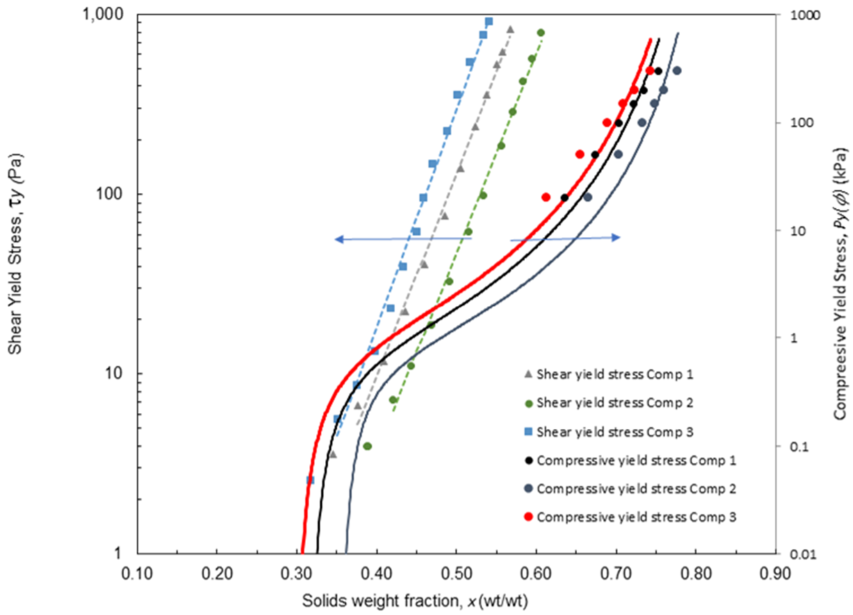

Figure 5 Shear and compressive yield stress versus solids concentration behaviour for three different composite samples

A final note on the analogous behaviour of shear and compression is that it can be exploited to facilitate more informed and streamlined larger scale testing e.g. It can be possible to use simple shear rheology (i.e. yield stress) as a ready ranking tool for filtration behaviour as a function of various process and material parameters (additives, mineralogy, PSD).

5 Practical implications

The key philosophies underpinning the approach outlined in this paper are that the best design outcome can be arrived at most efficiently by ensuring:

- As much design information is available as possible at early design stages.
- Information generated from testing is as versatile as possible to ensure high utilisation efficiency of samples, which are typically in limited supply at early stages.
- As complete a picture as possible is depicted by the test results, due to intrinsic inter-dependencies through the flow sheet.
- Clear definition of process design criteria in commonly understood notation.

Whilst a conventional testing and design approach will eventually work through the challenges to deliver an operational tailings management system, this is usually with significant design iterations, which can add significant project cost, especially when occurring at pre-feasibility study or feasibility study level. The critical point of the approach put forward in this paper is to attempt to bring these iterations, as much as is practicable, into the early stages of design. When moving into later project stages, for detailed design, costing, vendor guarantees or certification by an engineer of record, more in-depth specialised testing is clearly required, however by this stage this work can be completed with greater confidence in the process design criteria and overall flow sheet selected.

Furthermore, whilst the focus of this paper has been on an integrated approach for options selection and identification, the benefits of this small sample size approach are equally applicable for later stage assessments such as process variability testing, or optimisation or modification studies for existing operations, whether or not limited sample is available.

6 Conclusion

A key risk in the design and implementation of any tailings management process lies in the information transfer across the interfaces between the different technical disciplines and service providers involved. This paper, using consideration of a filtered tailings management system design as an example, highlighted how a better integrated, holistic approach to testing and design at early project development stages could address this risk and more efficiently and cost-effectively deliver a viable management solution. Whilst the discussion focused on filtered tailings, the approach and principles are equally applicable to the design of any tailings management system.

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