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Effects of the mineralogical composition and particle size distribution on the rheology of gold and copper tailings

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Abstract

Globally there is an upward trend by mining operations to opt for tailings dewatering technologies to reduce water consumption, minimise surface disturbance (footprint), increase the stability of tailings deposits and, overall, to operate sustainably.

The properties of the mine tailings are largely dictated by the type of ore and the process necessary to liberate the metal values. In other words, it depends on the beneficiation process and the mineralogy of the gangue. Due to the importance of selecting the correct strategy for the management of mine tailings, designing a disposal strategy based solely on the requirements of ore processing may overlook opportunities to maximise the viability of the mining operation, especially when dewatering technologies are being considered. As an example, accepting a coarser grind may reduce overall metal recovery; however, the loss in revenue may be offset by improved dewatering performance and lower capital and operating cost to manage the tailings. Therefore, the design of the ore beneficiation process should consider the requirements for tailings disposal, specifically tailings dewatering and storage facility design, in order to obtain more efficient and sustainable mining operations.

This paper will discuss the effects of mineralogical composition and particle size distribution of gold and copper tailings on rheological properties, which provides an indication of what can be achieved in thickener underflows. The present paper is based on laboratory tests performed by Golder Associates on mine projects around the globe.

Keywords: *rheology, thickening, mineralogy*

1 Introduction

Water is one of the most important inputs when designing ore beneficiation plants, and tailings dewatering is an important system that helps reducing fresh water consumption (i.e. the recovery of water for recycling prior to the disposal of tailings in surface impoundments). How much water can be recovered is a function of how readily the tailings can be thickened. This will have an impact, not only on thickener selection (affecting both type and size), but also on the design of the tailings pumping system and storage facility. The reason is that the factors that affect the tailings dewatering characteristics also affect the slurry density (solids concentration) that can be obtained out of a thickener and therefore the rheology of the tailings.

There are many tailings properties that influence rheology and therefore impact the performance of the mine dewatering operation (Scales et al. 1999; Burdukova et al. 2008). Within these properties, particle size distribution (PSD), pH, mineralogy and process water quality are some of the properties highlighted as key in influencing tailings rheology. Literature demonstrates theoretically that mineralogy can have a strong effect on the viscosity of mineral slurries and mineralogy is a function of the mineral constituents in the sample (Jewell & Fourie 2006). This paper examines the effects that PSD and mineralogy have on the rheology (yield stress) and on the dewatering characteristics of tailings of different gold and copper projects around the globe.

2 Minerals in rheology

Many authors have highlighted the influence of different types of minerals on slurry behaviour referring to their chemical composition, surface charge, particle size and shape of the solid particles. Rheology is one slurry behaviour where some minerals have a greater influence relative to others. When examining the effects of minerals on rheology, two characteristics have an influence – particle shape and size, both of which depend on the mineral's base structure.

For the large mineral families, and as it is in the case with igneous rocks that comprise about 90% of the Earth's crust (Klein & Hurlbut 1993), silicates are the ones that are found in higher percentages in gold and copper tailings, while carbonates, sulphides, sulphates and oxides are minor constituents. Silicates are composed of a base unit of silicon cation (Si^{4+}) surrounded by oxygen anions (O^{2-}), forming a tetrahedral compound. From this key building block, different kinds of silicates can be found, depending on how the tetrahedral units are linked together (Burdukova et al. 2008). Nesosilicates are isolated tetrahedral units connected by cations, inosilicates are linked in long simple or double chains, phyllosilicates are connected by three vertices forming sheets and tectosilicates are linked by four vertices being tridimensional frameworks. Almost three-quarters of the Earth's stony crust is constituted of tectosilicates (of which quartz is an example), making them an important constituent in mine tailings.

Particle shape is one of the most important characteristics influencing tailings rheology; it is because the particle-particle interaction in platy minerals is significant. While tectosilicates are the main mineral that composes tailings, they have tridimensional frameworks where each tetrahedral is attached to four tetrahedral resulting in a stable structure with low water retention, with little influence on rheology. Platy phyllosilicates particles have high aspect ratio, which increases the thickness of their double diffuse layer making particle interaction forces stronger. Tailings rheology also depends on the pH, ion concentration and type of cation found in the layer (Sridharan & Jayadeva 1982). Even though phyllosilicates are platy, and the base structure is the same, there are different kinds of phyllosilicates and each will behave differently because their tetrahedral sheets are bonded together in different ways creating micas, serpentines, chlorites and clays. Clays have been determined to have strong effects on rheology, especially the swelling type such as montmorillonite (Farrokhpay & Ndlovu 2013). Swelling is produced because of their interlayer cations between the particle sheets that are monovalent and strongly hydrated ions like sodium (Na) or lithium (Li) that attract water causing particles to swell (Klein & Hurlbut 1993; Luckham & Rossi 1999; Burdukova et al. 2008).

It is also important to state that PSD is a key parameter when assessing the effects of minerals on rheology. The reason is basically that as the particles get smaller in size they all tend to revert to the base mineral structure. As a result, for example, when phyllosilicates get finer due to their near perfect cleavage, more of the sheets break off in flakes and in consequence, the mineralogy effects could be more evident in fine tailings than in coarser ones.

3 Methodology

3.1 Laboratory testing

The data used for this investigation has been collected over many years of studying the rheological properties of tailings from different copper and gold projects around the globe. The characterisation includes the PSD, mineralogical composition, pH, specific gravity (SG), viscosity and yield stress. For each sample tested, PSD was determined using mechanical sieving and a laser particle size analyser according to ASTM D4464 (ASTM International 2015). The rheological parameter examined in this paper is the static yield stress, which is defined as the minimum force required to initiate flow in a pipeline or the solids bed in a thickener. It is determined using a slow-moving vane spindle attached to a torque spring with measurements taken at various tailings densities. Static yield stress was determined using unflocculated material previously decanted to a 178 mm slump; the material is mixed and then the yield stress measurements are taken. Decanted process water is added in increments to lower the solids content and measurements taken. The procedure is repeated until the solids content is too low to keep the solids in suspension. The material is mixed between measurements.

Mineralogy was obtained using X-ray diffraction (XRD) techniques obtaining semi-quantitative mineralogical composition.

3.2 Results analysis

Mineralogical composition was analysed in groups of minerals for the oxides, sulphides, sulphates and carbonates, whereas for the silicates, due to their abundance, they were divided in subgroups to differentiate between different phyllosilicates, tectosilicates, inosilicates, nesosilicates and phyllosilicates. Although the laboratory mineralogy test results show different composition for the phyllosilicates, indicating micas (muscovites, phlogopites) and chlorites, no other phyllosilicate minerals were identified. No further mineralogical analysis was carried out to identify the possible presence of clay minerals that could have been included in the mica or chlorite percentages due to the mica/smectite and chlorite/smectite interstratifications (Tomita & Takahashi 1985). Ouellet and Brunet (2010) had found in the Pinos Altos Mine tailings that when performing additional XRD analysis in the 5° to 19° region, almost one hundred per cent of phyllosilicates that were identified as chlorites and muscovites with XRD, were actually montmorillonite, illite and kaolinite. For this reason, the phyllosilicates are all grouped together, with no further differentiation made.

The pH of the tailings analysed were slightly basic with an overall variability in values near 1. To be able to compare the effect of mineralogy in different tailings samples, the samples were grouped according to similarities on their PSDs. With respect to PSD, a similar exercise was performed comparing samples with similar mineralogical composition. To eliminate effects of SG, volumetric concentration (C_v) was considered.

4 Laboratory results

The tailings for each of the projects examined have been numbered without reference to the mining project where they originated. Each tailing sample has also been assigned a different colour, so they can be easily identified in each table or graph.

4.1 Gold tailings projects

The PSD results for gold tailing projects are shown in Table 1.

Table 1 Particle size distribution for gold tailings projects in microns

Project number	SG	pH	-20 µm	D_{10}	D_{30}	D_{50}	D_{60}	D_{80}
Project no. 1	2.83	9.3	42%	3	10	27	44	151
Project no. 2	2.67	8.8	28%	4	22	54	91	145
Project no. 3	2.86	9.2	52%	2	6	18	28	56
Project no. 4	2.67	8.7	37%	3	15	29	37	66
Project no. 5	2.70	8.3	28%	4	22	63	110	162
Project no. 6	2.73	8.8	31%	5	19	36	50	110
Project no. 7	2.68	9.7	51%	2	7	19	26	52
Project no. 9	2.75	9.6	43%	2	10	25	36	109
Project no. 8	3.33	-	48%	3	10	21	27	46
Project no. 10	2.60	9.0	44%	2	8	25	39	131
Project no. 11	2.67	9.4	46%	2	9	23	31	55
Project no. 12	2.74	9.3	37%	3	15	30	39	72
Project no. 13	2.65	8.6	37%	3	13	32	49	129
Project no. 14	2.77	9.1	28%	5	22	39	50	93

The mineralogical compositions of the gold tailings projects are shown in Figure 1. The graph shows the cumulative and partial percentage of composition per mineral in each sample.

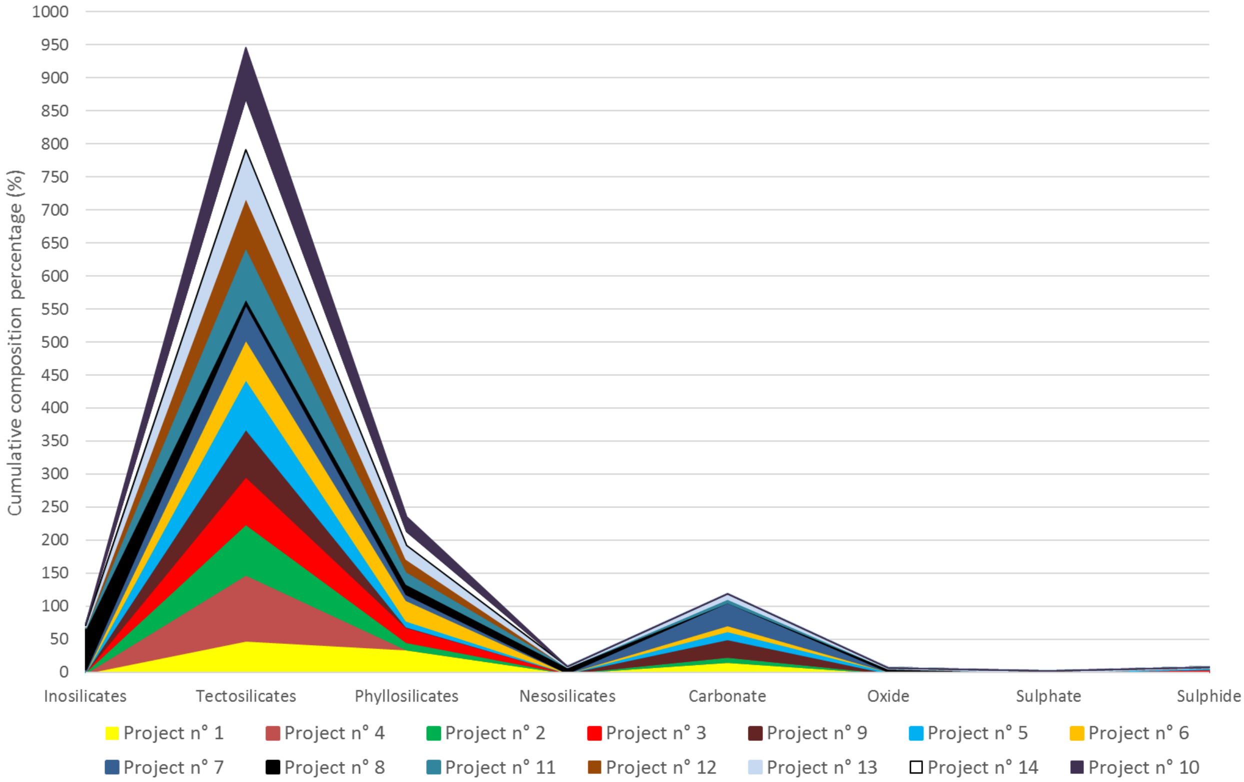

Figure 1 Mineralogical composition of gold tailings projects

The rheological curves, C_v versus yield stress for the gold tailings projects are shown in Figure 2.

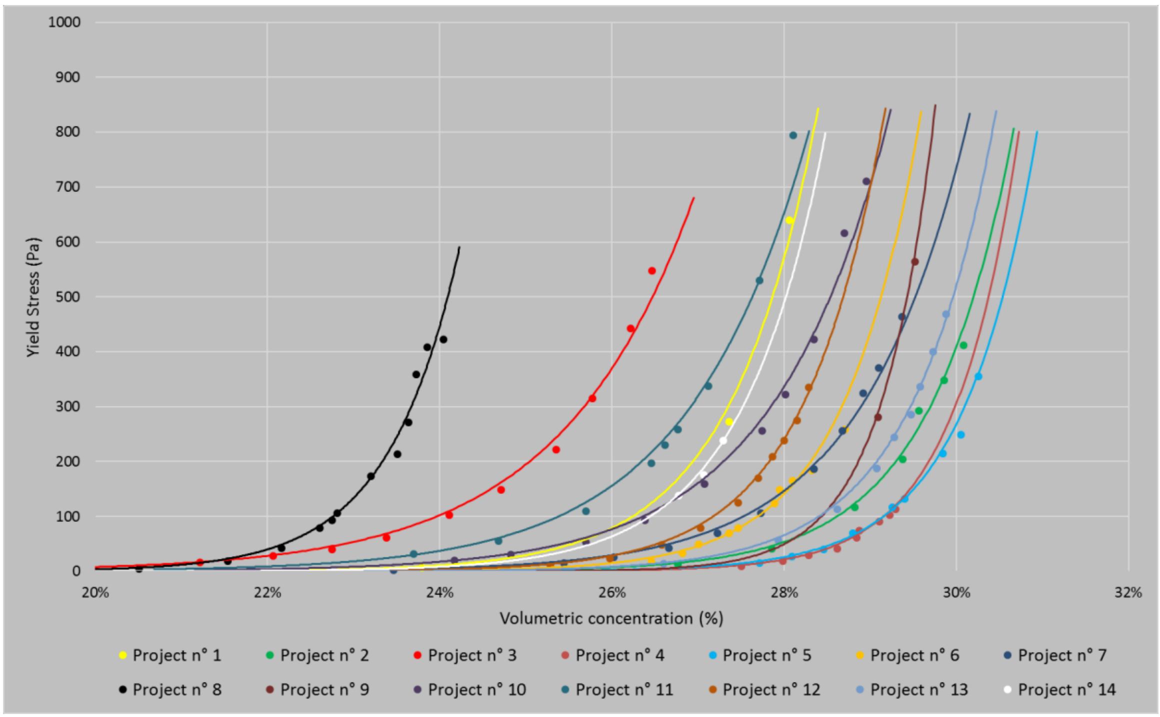

Figure 2 Rheological curves for gold tailings projects, volumetric concentration versus yield stress

4.2 Copper tailings projects

The PSD results for the copper tailing projects are shown in Table 2.

Table 2 Particle size distribution for copper tailings projects in microns

Project number	SG	pH	-20 µm	D_{10}	D_{30}	D_{50}	D_{60}	D_{80}
Project no. 1	2.96	9.5	37%	3	14	34	53	206
Project no. 2	2.91	9.2	34%	3	16	38	64	238
Project no. 3	2.83	9.3	42%	2	10	28	43	171
Project no. 4	2.83	9.0	28%	4	24	66	109	177
Project no. 5	2.60	9.4	29%	3	21	82	133	222
Project no. 6	2.89	8.2	29%	3	14	30	41	91
Project no. 7	2.95	8.7	29%	3	10	22	29	57

The mineralogical compositions of the copper tailings projects are shown in Figure 3, the graph shows the cumulative and partial percentage of composition per mineral in each sample.

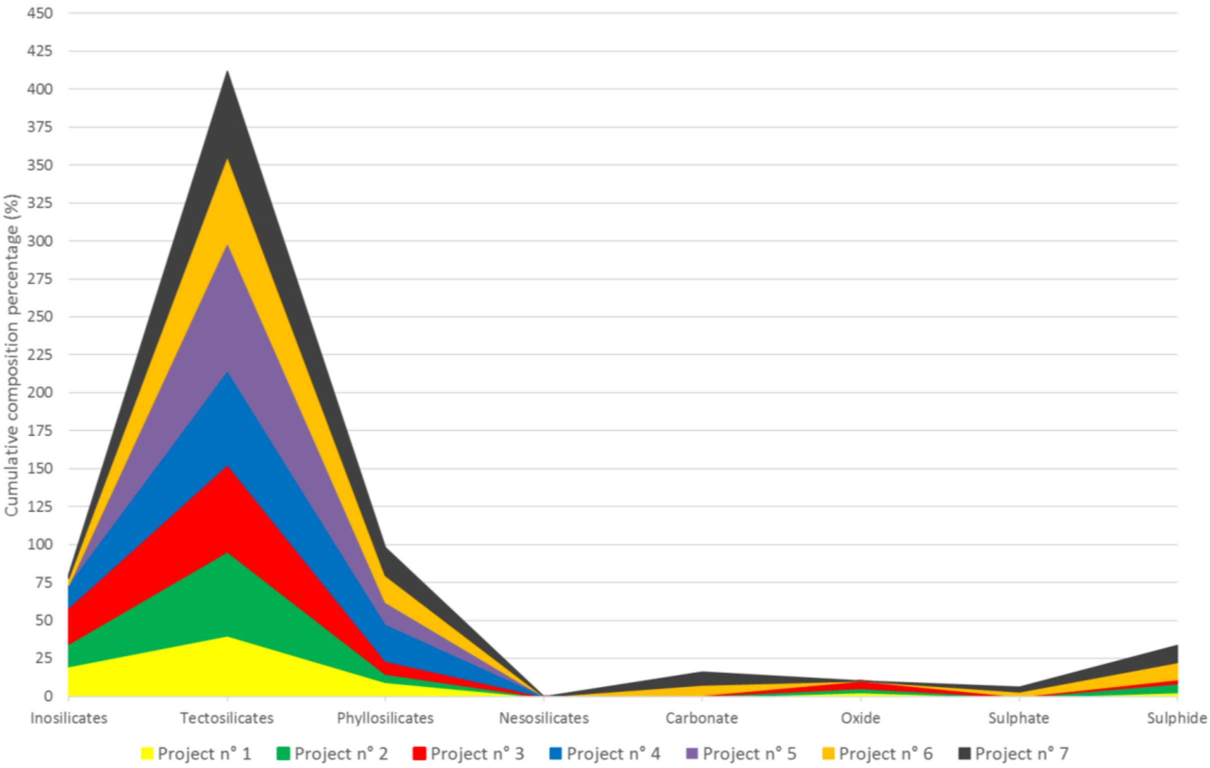

Figure 3 Mineralogical composition of copper tailings projects

The rheological curves, C_v versus yield stress for copper tailings projects are shown in Figure 4.

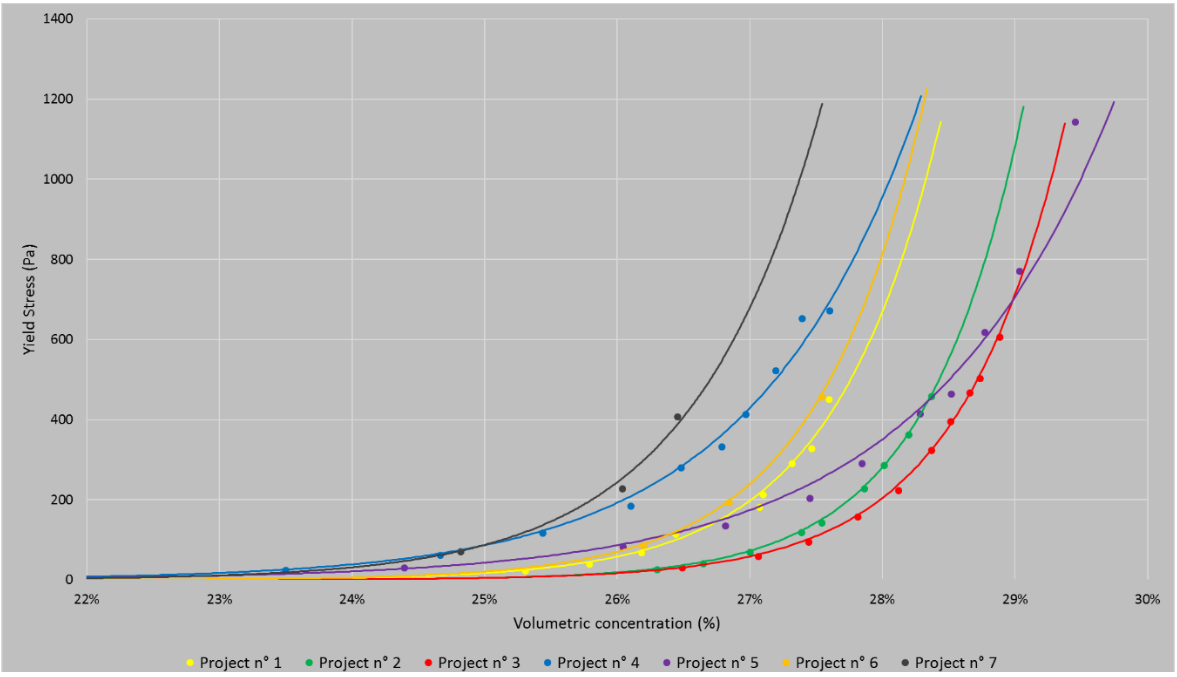

Figure 4 Rheological curves for copper tailings projects, volumetric concentration versus yield stress

5 Data analysis

5.1 Gold tailings projects

To analyse the effect of PSD on rheology and dewatering behaviour, project tailings with similar mineralogy have been grouped, being tailings with phyllosilicates content between 10 and 30%. The rheology curves of C_v versus yield stress of these tailings are shown in Figure 5, each curve shows PSD parameters for each project.

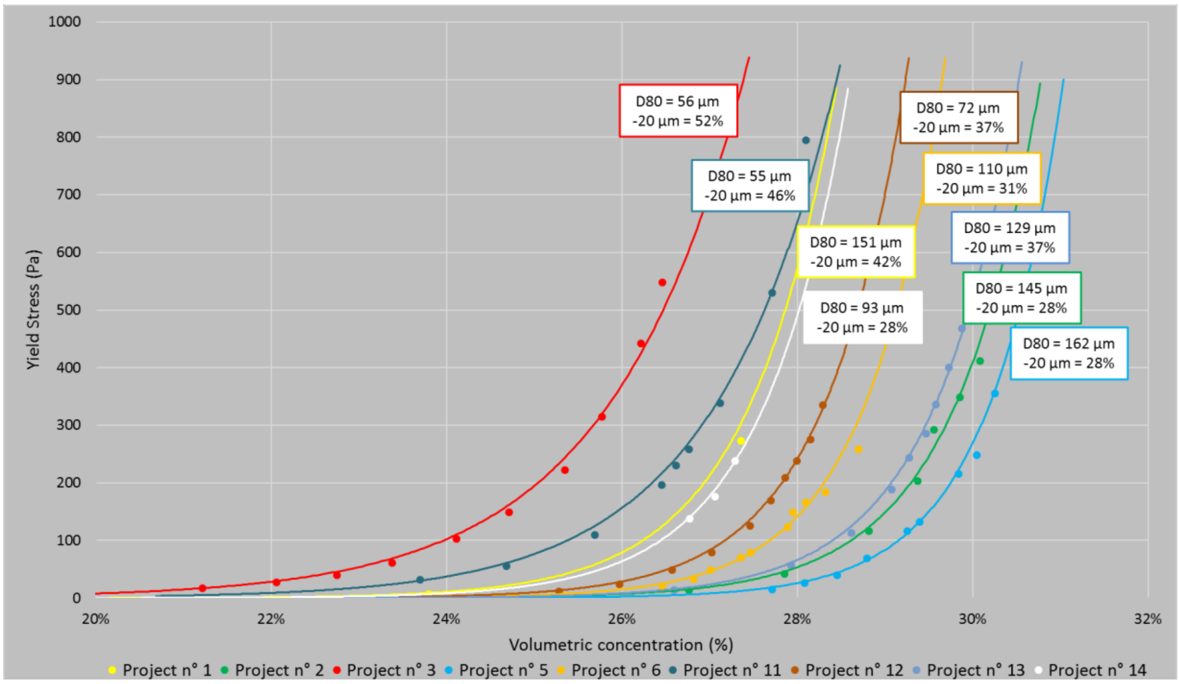

Figure 5 Rheological curves for gold tailings projects with phyllosilicate content between 10 and 30%, volumetric concentration versus yield stress

Figure 5 clearly shows the tendency of decreasing the yield stress as the samples gets coarser and increasing the yield stress as fine fraction (defined as material passing the 20 microns size) increases. When looking from right to left, the order seems logical until the values for project no. 14 is considered. There must be other factors influencing this sample's behaviour. Project 1 presents one of the coarser samples, but it has a percentage of phyllosilicate near to 30% with high percentage of fine particles. Samples with the finer particles are clearly more viscous, exhibiting a measurable yield stress at lower solids concentration, making it more difficult to achieve high solids concentration in a thickener underflow. The analysed range of C_v is approximately 5% (for 100 Pa yield stress) between the finer and coarser tailings samples.

To compare mineralogical content, four similar PSDs were identified, having a D_{80} near 50 microns and a percentage passing 20 microns of approximately 50%. The rheological curves for these projects are shown in Figure 6, and each curve shows the phyllosilicate mineral content (PC). The graph shows the difference in the volumetric concentration between curves for a yield stress of 100 Pa.

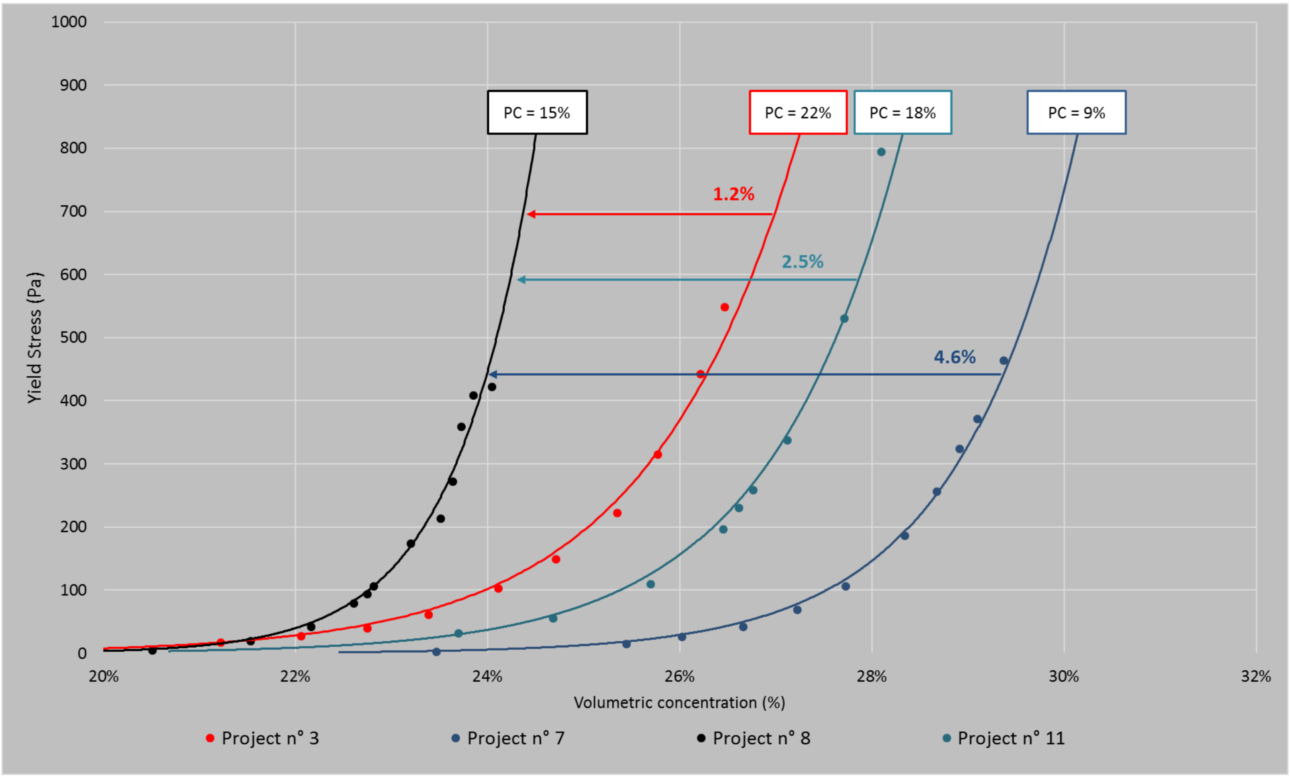

Figure 6 Rheological curves for gold tailings projects with similar fine particle size distribution, volumetric concentration versus yield stress

Project 7 is the one with lower yield stress having the lower PC value, followed by project 11 with higher yield stress and the double of PC value, while project 3 follows the same logic with increased PC value and viscosity. Project 8 is the one with higher yield stress, but with less PC value than projects 3 and 11. A dimensionless phyllosilicate influence (PI) factor can be determined to indicate strength of the phyllosilicate to move the rheological curve; it is the ratio between the C_v difference between two rheological curves at a yield stress of 100 Pa and the difference of PC as shown by Equation 1. Then, calculating the factor with respect to the project with lower yield stress and PC (project 7), PI of 0.76, 0.26 and 0.23 are obtained for projects 8, 3 and 11, respectively. Analysing the phyllosilicates of the samples, the influence of the phyllosilicates on rheology of projects 3 and 11 are similar, while the influence of project 8 phyllosilicate is almost the triple of projects 3 and 11. The higher the PI, the higher will be the gain in viscosity with increasing PC.

$$PI = \frac{C_{vB} - C_{vA}}{PC_A - PC_B} \quad (1)$$

where:

PI = phyllosilicate influence factor.

C_{vA} = volumetric concentration for a yield stress of 100 Pa in curve A.

C_{vB} = volumetric concentration for a yield stress of 100 Pa in curve B.

PC_A = phyllosilicate content in curve A tailings.

PC_B = phyllosilicate content in curve B tailings.

Figure 7 shows a comparison of another three PSD groups indicating their PC, D_{80} and percentage of particles passing 20 microns (the first one with average D_{80} of 130 microns and average % of particles passing 20 microns of 40%; the second one with 70 microns and 37%; and the third one with 154 microns and 28%).

The graph shows the difference of volumetric concentration between curves for 100 Pa of yield stress and the PI factor.

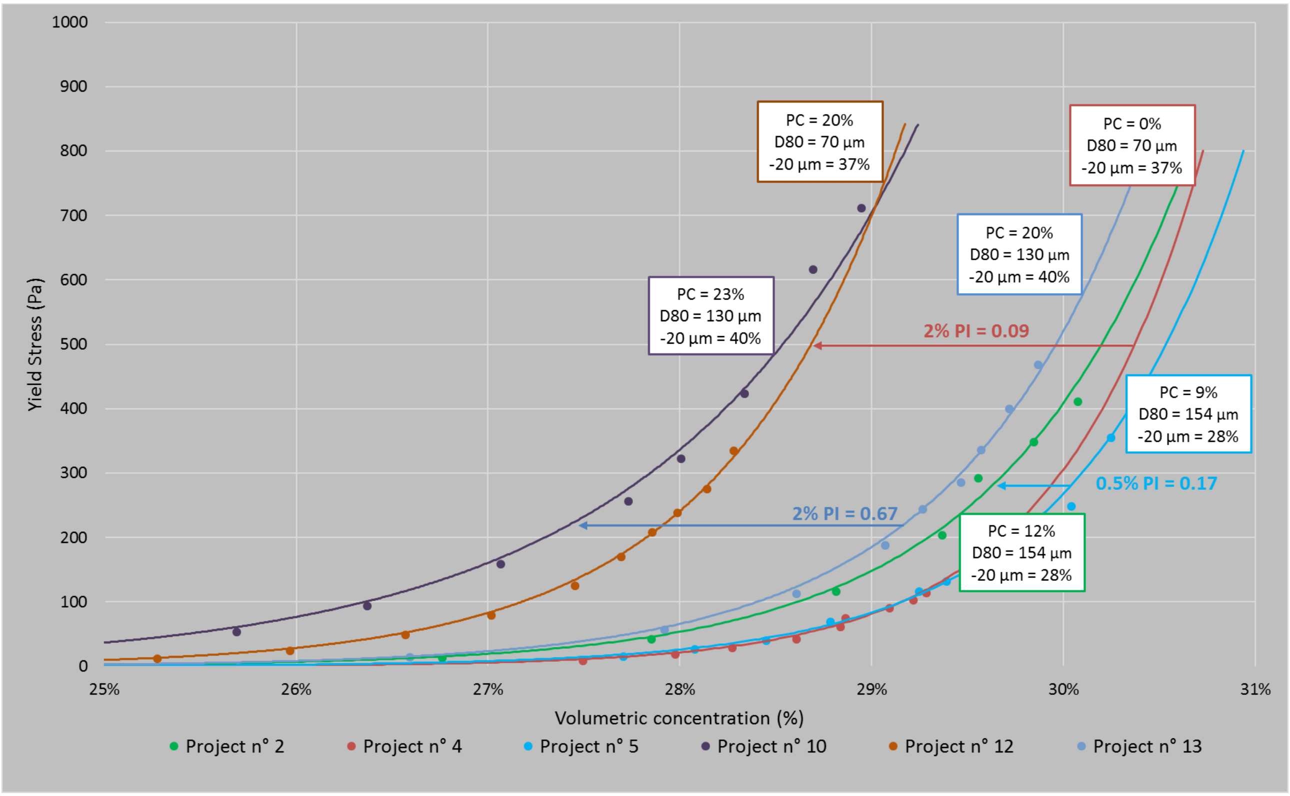

Figure 7 Rheological curves for gold tailings projects with similar particle size distribution, volumetric concentration versus yield stress

In the three PSD groups shown in Figure 7, there is a tendency for increasing viscosity with a higher PC. Different PI values were calculated, likely influenced by the different type of phyllosilicate in each tailing.

5.2 Copper tailings projects

For copper tailings, grouping projects by PSD or mineralogical is more difficult due to a smaller number of samples. For this reason, all samples were analysed together. Figure 8 shows the rheological curves of copper tailings indicating for each of them the PC, D_{80} and percentage of particles passing 20 microns.

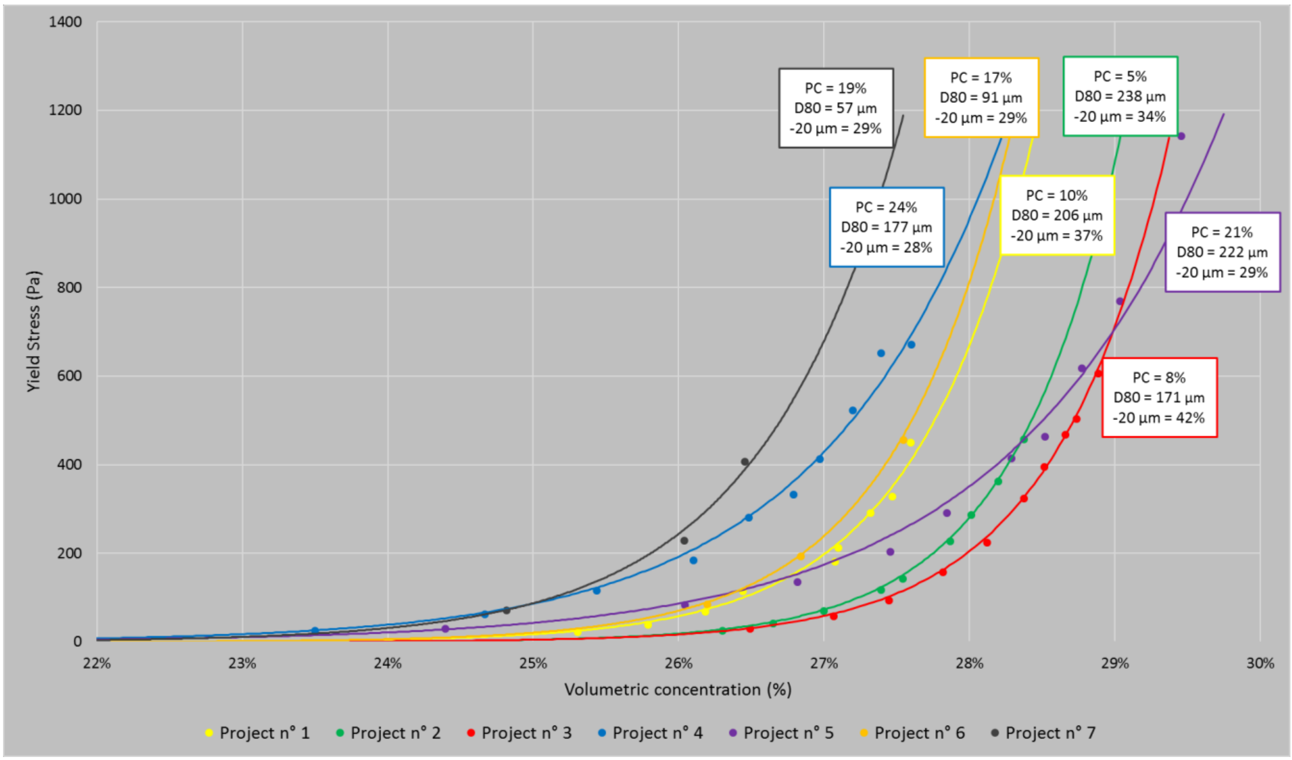

Figure 8 Rheological curves for copper tailings projects with similar particle size distribution and phyllosilicate mineral content information, volumetric concentration versus yield stress

Figure 8 shows that the curves with more viscous behaviour have higher PC, the projects with lower yield stress are the ones with less PC. Project 5, which has a high PC value, is less viscous behaviour, likely due to the coarser particles.

6 Conclusion

An analysis of the rheological behaviour as a function of mineralogical composition and PSD for a variety of different copper and gold tailings projects was examined. Within the minerals, special attention was placed on the presence of phyllosilicates, which according to literature were the ones that directly affect yield stress and include the clay type minerals. When comparing the effects of certain sample properties, samples with similar parameters were selected. This proved difficult due to the unique nature of each tailings sample.

Nonetheless, for both copper and gold tailings, a trend was observed where the samples had a more viscous behaviour with higher percentages of phyllosilicates minerals and would likely result in lower thickener underflow densities. The amount of the shift is variable and cannot be predicted by the percentage of phyllosilicates in the tailings. The PI is variable, ranging from 0.09 to 0.76 in the tailings samples examined. The PI value is likely directly dependent on the type of phyllosilicate. Further analysis would need to be made to identify the influence of different types of phyllosilicates on the PI range of values. Effects of the mineralogical composition on rheology were found even in the coarser tailings samples, as they always contained a significant percentage of fine particles.

PSD had an important effect on rheology when comparing tailings with similar PC; in the sample examined, a change of from 28 to 52% passing 20 microns moved the yield stress curve up to 5% of C_v. Also, SG, which is also a function of mineralogy, was found to be an important parameter. Even though SG was not considered at the beginning as part of the analysis, it had to be included because its effects could not be ignored as the SG shifted the rheological curves. Then, to eliminate its effects, volumetric concentration had to be considered. Again, further analysis would need to be conducted to determine if the higher SG is directly related to a particular group of minerals.

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