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Modelling of filtration properties of representative standards of tailings based on quantitative phase analysis

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Abstract

The large demand for mineral resources and large-scale mining operations produce significant quantities of mining waste, e.g. tailings. One of the most important environmental considerations is how to manage these large volumes of waste to minimise impacts and maximise benefits. Dewatering technologies, e.g. thickening and filtration, can reduce its footprint. Through the filtration process, it is possible to obtain a final residue with solid-like behaviour. The filter press is one of the most popular pieces of equipment for these purposes, thanks to high performance achievable in terms of dewatering efficiencies and solid throughputs.

Since clay minerals are a challenge in the design of filtration and de-watering processes, it is necessary to describe quantitative relationships between the filterability parameters and the contents of mineral phases; in particular those clay minerals that determine the structure, porosity and inner properties of filter cakes.

Several standards were prepared according to the classification of fine-grained clastic sedimentary rock units. The main minerals that were mixed in different concentrations were quartz, carbonates and clay minerals, swelling and non-swelling, such as smectite and kaolinite. The concentrations of clay minerals vary from 0.1–40% and the particle size distribution is about 1–20 µm. According to the German guideline VDI 2762-2 (VDI Verein Deutscher Ingenieure e.V. [VDI] 2017), the filtration process has been simulated at the laboratory-scale using a Nutsche filter with a filter area of 20 cm². High-resolution X-ray tomography was used to investigate the filter cake microstructures, the arrangement of the clay particles and the porosity.

The specific resistances of cake were correlated with clays contents and with the properties of cake, such as packing structure.

From the results, it is clear how clay phases play a crucial role in affecting the throughput achievable by a filter press, how they influence the inner characteristics of the cake and the amount of water recovered. Predicting the behaviour of the material during the filtration process would allow to design a filtration plant with optimised capital expenditure and operating expenses.

Keywords: *clay minerals, specific resistance of cake, Nutsche pressure filter, cake properties, X-ray tomography*

1 Introduction

There is a global trend of increasing tailings production. This is due to 2 main causes: the rising global demand for critical minerals and declining average ore grades. Many tailings filtration projects are currently processing 50,000 tonnes per day throughput, while a few feasibility studies reach even higher values, up to 450,000 tonnes per day. These materials are usually discharged as a slurry to a storage area commonly known as a tailings storage facility. The lack of knowledge on tailings behaviour and the poor performance of monitoring, management and construction processes can be considered as the main predisposing factors of

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dam failures (Piciullo et al. 2022). Tailings dam failures have resulted in disastrous environmental and human tragedies (Piciullo et al. 2022).

Filtered tailings disposal presents a promising alternative for safer and more sustainable mining operations. Tailings dewatering can take place using pressure or vacuum force and pressure filtration can be carried out on a much wider spectrum of materials (Davies 2011). The use of pressure filters for tailings dewatering is currently being evaluated and often selected as preferred technology where filtered stacked tailings is the elected solution for residue disposal. This is mainly due to some objective benefits, such as high throughput and achievable cake dryness. Filtration technology enhances deposit stability, reduces the risk of catastrophic failures, and lowers long-term environmental liability. The approach also supports water recovery and better control of leachate, reducing both the demand for fresh water and the burden on downstream treatment infrastructure. These improvements contribute to a smaller environmental footprint and can support stronger regulatory and social license outcomes (Kaswalder et al. 2023).

Filtration performance is generally assessed by the filtration rate and the moisture content of filter cake which are dependent on the specific cake resistance (m kg^{-1}). The filtrate volume increases with the time-to-volume ratio. The slope of the straight line formed by these 2 parameters is the specific cake resistance. This parameter depends on numerous factors such as mineralogy, particle size distribution, particle shape and chemical environment (Basnayaka et al. 2018). The presence of fine particles significantly reduces the filtration efficiency. They reduce the capillary diameter of flow channels in filter cakes built up during the filtration process (Besra et al. 1999). The higher amount of fines influences the generation of particle–particle interactions at the microscopic level and leads to a shift toward a throat-dominated inner pore structure and smaller pore sizes. This pore throat-dominated structure favours the formation of many but very small hydraulic isolated areas, which hinder the cake structure's dewatering and lead to high saturation levels (Löwer et al. 2021). In large-scale operations filtration of fines is an inhibiting factor to increasing throughput and decreasing filtration rates.

The focus of this paper is to investigate the influence of clays on the filtration performance. Two clays with distinctly different characteristics, a non-swelling clay mineral, kaolinite, and a swelling clay mineral, smectite, which are common in mining tailings, were selected for the study. For this work, standards which simulate mineralogical composition of real samples have been analysed. The contents of clay minerals were correlated with filtration parameters such as specific resistance of cake, and properties of filter cakes, such as porosity, pore size distribution and capillary pressure, in order to highlight the huge influence that they have on the filtration process. These data could be used to develop a model to predict the behaviour of tailings and the features of filtration plant according to mineralogical properties. The parameters in terms of filterability and dewaterability of real cases could be estimated.

2 Methodology

Several standards were prepared according to the classification of fine-grained clastic sedimentary rock units (Lindner 2016). Each sample is composed by the same ratio of quartz, calcite and muscovite and a different concentration of clay minerals, swelling and non-swelling, such as smectite and kaolinite as shown in Figure 1. Swelling clay minerals absorb water molecules into the interlayers and the basal spacing increases. The basal spacing of a mineral is the distance between 2 parallel crystallographic planes (typically in layered minerals), measured perpendicular to the planes. The content of clay minerals varies from 0.1–40%. According to the laser diffraction analyses, these particles have a diameter between 1 and 18 µm. The D_{50} of the particles has a diameter below 7 µm.

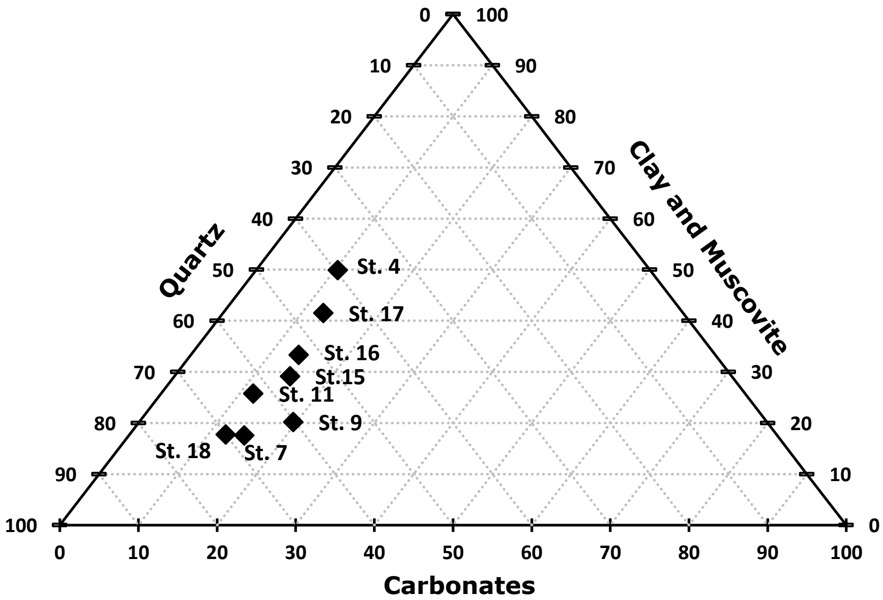


Figure 1 Triangular diagram which shows the mineralogical composition of different standards

According to the German guideline VDI 2762-3 (VDI 2017) filtration experiments were carried out with a Nutsche pressure filter, which simulates in a small-scale the filtration process (VDI 2017). The device is shown in Figure 2. The Nutsche pressure rig consists of a vertical cylindrical vessel into which the suspension is filled. The value of the filling volume is 0.029 l and the filter area is of 0.0019 m^2. The solution was formed by 40 grams of sample, which has a solids specific gravity of 2.7 and 27 ml of distilled water. The ratio of solid volume to volume is 0.35. At the bottom, the filter cloth closes Nutsche pressure filter. The filter cloth used was a semi-permeable membrane made of poly propylene with a satin weave, an air permeability (approximate values) of 5 $l/m^2/s$ at 20 mm of water column (169 Pa) and an air permeability (approximate values) of 3 cfm/ft^2 at 1/2 inch of water column (125 Pa) equivalent to 15.24 $l/m^2/s$. At the top, a pressure-tight lid covers it. After the lid and the filter cloth are mounted and the suspension is filled in, the vessel is pressurised to 2 bar. A scale measures the filtered volume, and the particles settle on the filter cloth building a filter cake. From the slope of the straight line formed by the filtered volume and the ratio of time to volume, the specific resistance of the cake can be measured according to Svarovsky´s law, which derives from Darcy´s law (Svarovsky 1977):

$$\frac{t}{V} = \frac{\alpha\mu c}{2A^2\Delta p}V + \frac{\mu R}{A\Delta p} \tag{1}$$

where:

t = time of filtration (s)

V = filtered volume (m^3)

α = specific resistance of cake ($m\ kg^{-1}$)

µ = viscosity of filtrated ($Ns\ m^{-2}$)

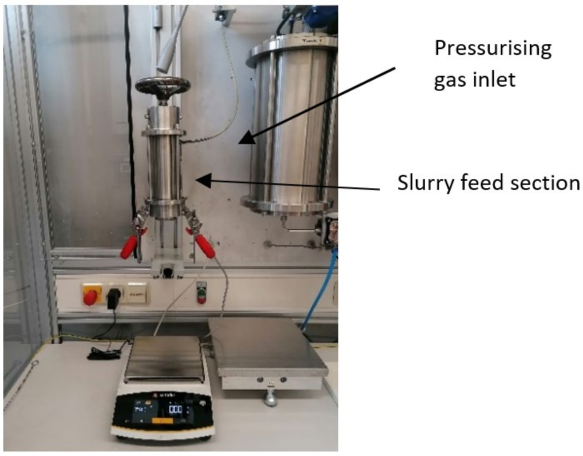
c = concentration of solids in suspension ($kg\ m^{-3}$)

A = filter area (m^2)

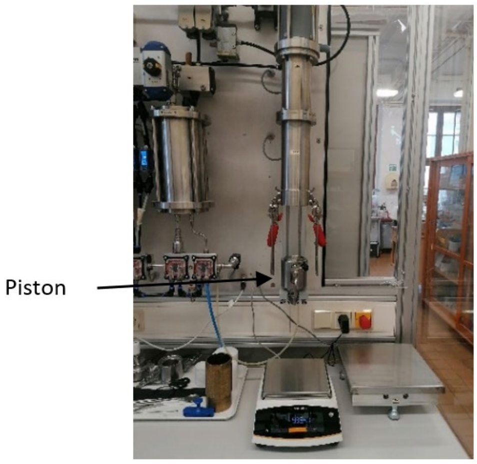
Δp = feeding pressure ($N\ m^{-2}$)

R = filter cloth resistance (m^{-1}).

The Nutsche pressure filter was also used to perform the capillary pressure tests. For these measurements, a semi-permeable membrane made of polyvinylidene fluoride (Merck Durapore PVDF, average pore size of 0.1 µm) was used. Filtration tests stop at complete saturation (S = 1), where liquid still fills all voids within the cake. This point is determined by the time when the reflection on the surface of the filter cake disappears. The filter cakes are then slightly mechanically consolidated with a perforated piston and dewatered. They were compressed with a gradient pressure of 0.25–0.5bar/600 s. The range of pressure varied from 0 bar up to 5 bar while the filtered volume was measured. The capillary pressure was the value of pressure at which the cake started to be desaturated, when all the water is lost, and air enters the cake.



(a)



(b)

Figure 2 Nutsche pressure filter. (a) Filtration process; (b) Compression and dewatering

The cakes were analysed with mercury intrusion porosimetry (MIP). Mercury (Hg) is a non-wetting liquid and has a contact angle of 140°. If an external force is applied, it can fill pore spaces. Through lower pressure, the Hg can fill larger pores, while applying higher pressure, the liquid also enters the smaller pores. The range of pressure was 0–400 MPa with an increase in speed of 9–36 MPa/min. According to the diameter of pores, the volume of Hg inside the pores was measured. These tests were used to measure the pore size distribution and pore volume through Washburn´s equation:

$$D_p = -\frac{4\gamma \cos\theta}{P} \tag{2}$$

where:

D_p = pore diameter (m)

γ = surface tension of mercury (N/m)

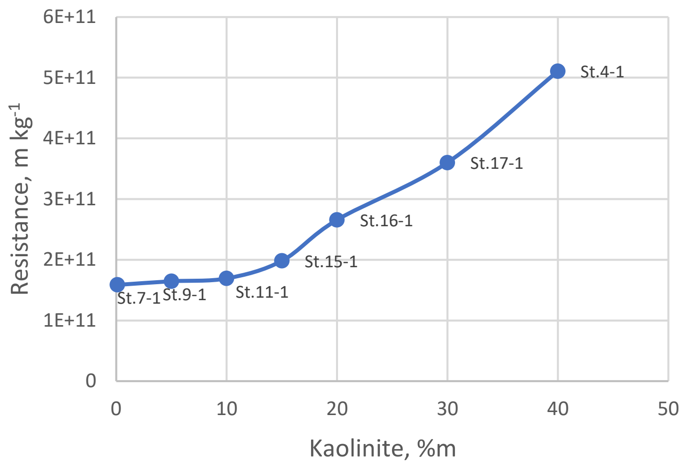
θ = contact angle (°)

P = applied pressure (Pa).

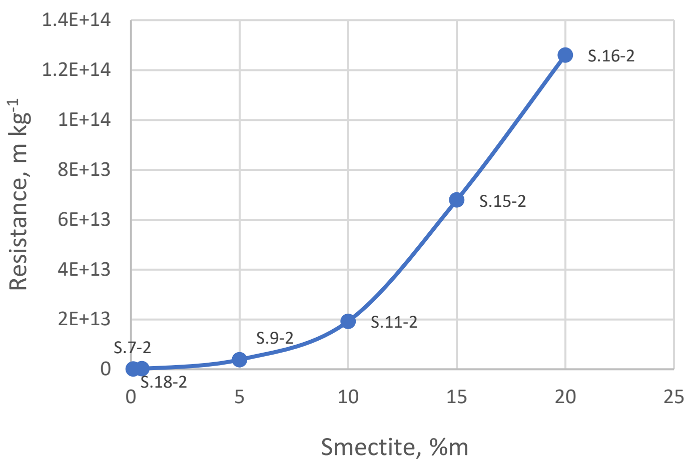
All these data obtained from these measurements were correlated with the content of clay minerals.

3 Results and discussion

The Nutsche pressure filter was used to carry out the filtration test. For each sample, the specific cake resistance was measured and this value was correlated with the clay content (in percent dry mass) as shown in Figure 3.



(a)



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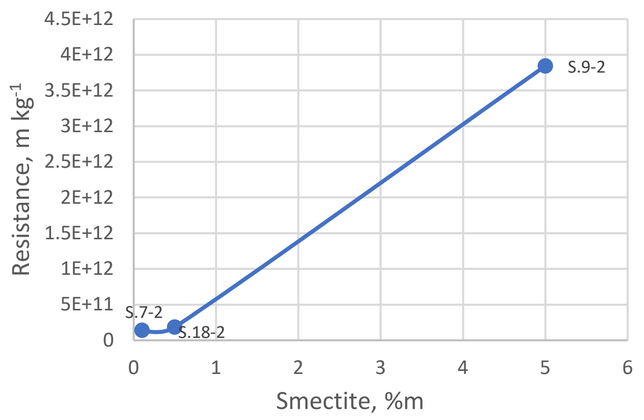

(c)

Figure 3 Correlation between specific cake resistance and content of clay minerals (%). (a) Non-swelling clay mineral, kaolinite; (b) Swelling clay mineral, smectite; (c) Better resolution for standards with low smectite content

Swelling and non-swelling clay minerals seem to have a huge impact on the filtration behaviour. The content of kaolinite below 10% and of the smectite below 5% do not strongly influence the filtration parameters; if their amount increases, the resistance increases, and they will have a higher impact.

After the filtration experiments, the filter cakes were analysed to obtain the value of pore size distribution. Figure 4 shows the results of the MIP measurements.

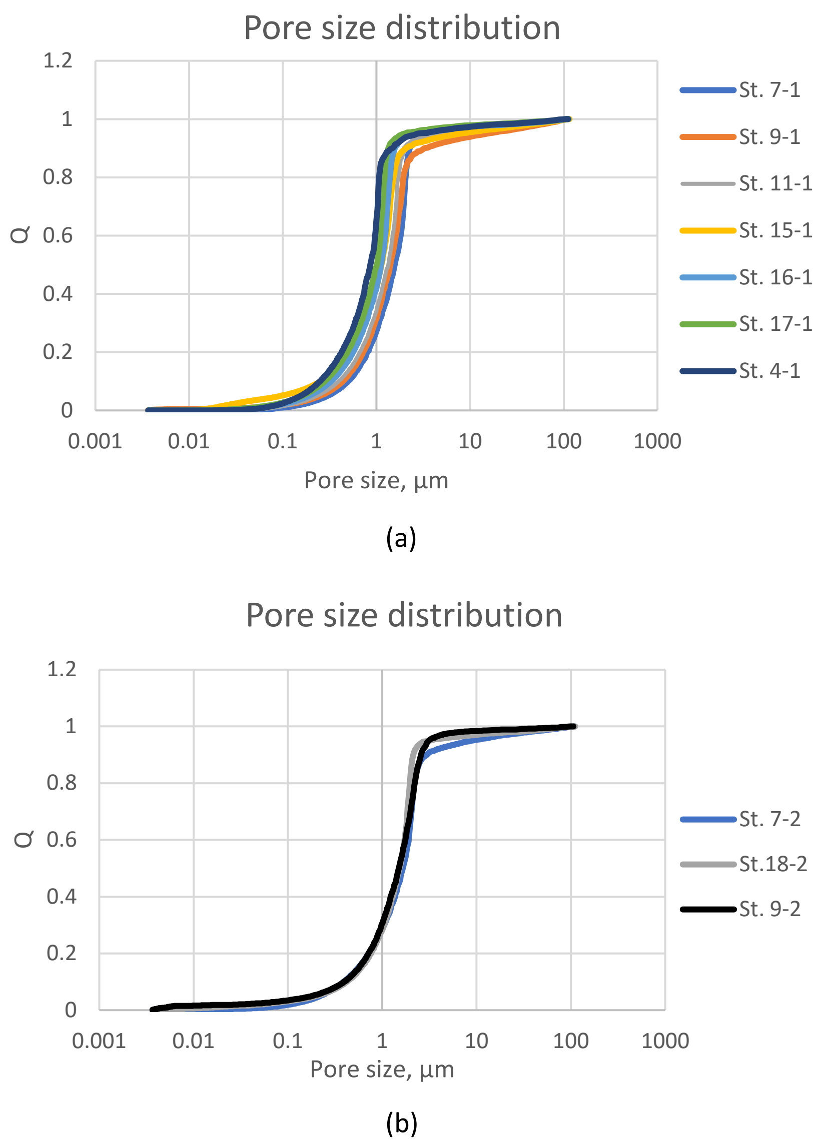

Figure 4 Pore size distribution correlated with clay content. (a) Standards with kaolinite; (b) Standards with smectite

The pore sizes became smaller by increasing the content of clay minerals. The finest particles that compose the material fill all the pore spaces, and a higher amount of pores reach a diameter below 1 µm (Tables 1 and 2).

Table 1 Number of pores less than 1 µm: standards with kaolinite

Standard	Kaolinite (%)	% pores <1 µm
St.7-1	0.1	0.28
St.9-1	5	0.32
St.11-1	10	0.36
St.15-1	15	0.42
St.16-1	20	0.43
St.17-1	30	0.49
St.4-1	40	0.72

Table 2 Number of pores less than 1 µm: standards with smectite

Standard	Smectite (%)	% pores <1 µm
St.7-2	0.1	0.28
St.18-2	0.5	0.28
St.9-2	5	0.30

Only 3 samples with smectite were studied, because if its amount is higher than 5%, the cake cannot be obtained and the measurement cannot be performed. Also, when increasing the feeding pressure, the cake cannot be formed, because the smectite particles absorb water and the filtrate volume decreases. It means that clays also below 5% have an impact on the behaviour of the tailings during the filtration process.

The capillary pressure measurements confirm these data. Tables 3 and 4 show the pressure needed to desaturate the filter cakes.

Table 3 Capillary pressure: results of the standards with kaolinite

Standard	Kaolinite (%)	Capillarity pressure (bar)
St.7-1	0.1	0.31
St.9-1	5	1.56
St.11-1	10	1.56
St.15-1	15	1.56
St.16-1	20	2.05
St.17-1	30	2.07
St.4-1	40	2.56

Table 4 Capillary pressure: results of the standards with smectite

Standard	Smectite (%)	Capillarity pressure (bar)
St.7-2	0.1	1.07
St.18-2	0.5	1.07
St.9-2	5	1.57

Also, for these tests, only 3 samples with smectite were studied. Applying higher pressures, the Hg fills finer pores in the samples which are composed by a high content of clays. Lower pressures allow Hg to enter the bigger pores. The presence of fine particles could significantly reduce the filtration and dewatering efficiencies of slurries.

4 Conclusion

Tailings are characterised by a huge variability of mineralogical composition. The results presented here highlight how some minerals, in particular clay phases, play a crucial role in the tailings behaviour in terms of filterability and dewaterability. The presence of clay adversely effects the filtration performance by increasing specific cake resistance and capillary pressure.

Non-swelling clay minerals, such as kaolinite, influence the behaviour of tailings below 10 %m. That value could be considered a threshold value. If the concentration exceeds that amount, the resistance will start to increase and the performance of the filtration process will change. For swelling clay minerals, the threshold seems to be lower, and at smectite contents also below 5 %m this affects the filtration process. Therefore, as expected, it can be stated that smectite inhibits the filtration more than kaolinite. If tailings are composed of clay minerals which are beyond these thresholds, they will become very challenging materials to filter. Only future analyses can highlight its big role on filtration properties and how to improve the performance of this process. A higher amount of clay minerals means high specific cake resistance, long filtration time, low rate of filtration, and consequently increases energy demand for equipment operation. If the cake measures low porosity and higher capillary pressure, more time and pressure will be needed to dewater it.

Knowledge of the type and content variability of clay is one of the main factors that can help to set up the filtration plant. Predicting the behaviour of the material during the filtration process would allow to design a filtration plant with improved performances in terms of lower needs of energy and time and higher volume of water recovered. At the same time, better control and tuning of the process can be achieved, optimising the capital expenditure and operating expenses.

Further properties could be measured, such as surface area or filter cake microstructure, and real samples from mines and quarries could be studied and correlated. These results can be used in order to develop a model or a dataset to describe and quantify the influence of the clay concentration on the filtration process and predict the behaviour of tailings and the performance of filtration plants.

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