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Iron Ore Tailings Dewatering: Measurement of Adhesion and Cohesion for Filter Press Operation

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Abstract: Globally, mining operators focus increasingly on tailings filtration to recover process water and store tailings more safely. Generally, required water contents below 20-w% are reached by using filter presses. To maintain high efficiency, complete cake detachment is needed because incomplete discharge reduces plant performance. However, filter cake discharge can occur in different ways, mainly influenced by adhesion of the filter cake to the filter cloth as well as by cohesion of the cake. Therefore, this study points out different major detachment behaviors and a theoretical approach to describe them. Furthermore, investigations on iron ore tailings filtrations were carried out to show the influences of different filter media, different filtration pressure and cake post-treatment on adhesion and cohesion.

Keywords: tailings filtration; mineral processing; filter press; cake detachment; adhesion; cohesion; regeneration

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1. Introduction

Due to the steadily growing demand for raw materials, the amount of mined material is also increasing [1]. Therefore, metal ores are extracted in large open pit mines around the world. Since only a small fraction of the mined rock consists of valuable product [2], an increasing amount of waste rock has to be handled, which is present as tailings at the end of the process. However, tailings management has been a major challenge for the industry for some time now [3]. Storage in tailings ponds has been increasingly replaced by dry storage (dry stacked tailings) due to process water loss and the risk of dam breaks. Increasing mechanical dewatering using thickeners and subsequent filtration can reduce the water content of the tailings, thus recovering a large part of the process water and enabling dry stacking [4]. Improved process water management and safer storage reduce costs and are an impossrtant aspect in terms of sustainable mining. For this reason, the number of filtered tailings solutions is steadily increasing [5] and larger and larger plants are being operated [6].

Due to the process-related characteristics of the tailings, their filtration is non-trivial and an existing challenge in solid–liquid separation. During the processing of valuable material, rock has to be crushed to a particle size below 100 µm. However, the particle size distribution is broad, and there is a significant clay content in the lower micrometer range [7]. These particles form a compressible filter cake [8] and influence the filtration process drastically. Therefore, high pressure difference in the form of mechanical pressure is crucial for dewatering. From an engineering point of view, chamber filter presses are suitable for this purpose [9]. These are operated in batch mode, i.e., they must be regenerated after each filtration. This happens by opening the individual press chambers, followed by detachment of the cakes from the filter medium caused by their weight and falling down on a conveyor belt placed below the filter press. Economical handling of the large process streams is given by a parallel connection of large presses (e.g., chamber dimensions of 5 m · 3 m and 160 plates) [10]. However, it is obvious that trouble-free operation is necessary in order not to represent the bottleneck of the entire process chain. Common problems concerning filter presses are the correct selection of the filter media, mechanical wear or blinding of the filter cloth [11] and detachment problems of the cakes. In the latter case, completely adherent cakes or partial drop-off can occur due to partial reaching of the yield limit and breaking, respectively. Remaining cake parts reduce the available process space and thus reduce throughput or lead to leaks and damages if they are attached in the sealing area. This paper therefore presents practical test procedures for determining the adhesion of the cake to the fabric and characterizing the strength of the particulate network (cohesion), as well as investigates relevant parameters (filtration pressure, cake post-treatment, fabric).

2. Theory

Analogous to the time sequences of the tailings filtration process in chamber filter presses, this section provides a brief insight into the relevant fundamentals and interrelationships of cake filtration. Furthermore, the properties of the network of solid particles after filtration are discussed. Finally, the prerequisites for cake detachment are outlined.

2.1. Filtration

Recessed plate filter presses operate on the principle of cake filtration. At the beginning of filtration, particle breakthrough occurs because the pores of the filter medium are usually selected to be larger than the particle diameter in order to reduce hydraulic resistance. If the particle concentration is sufficient, bridging over the pores occurs after a short time and afterwards the approaching particles are progressively deposited on the network of solid particles. Thus, the cake grows. Since the pressure drop within the cake is reciprocal to the pressure of the consolidated network of solid particles, mechanical support is provided behind the filter cloth by means of backing cloths or drainage structures.

The filter cake is a network of solid particles whose structure and properties are strongly dependent on the particle size distribution of the slurry. Clay-sized particles, for example, cause compressible behavior [8]. Normally, tailings have a relevant content of clay and corresponding filter cakes are therefore compressible [5,7,12–14]. In order to ensure achieving crucial residual moisture contents, compaction of the network of solid particles by sufficient filtration pressure is necessary. For this reason, filter presses are used in a lot of applications [5,9,10,15,16]. Furthermore, mechanical dewatering by applying gas differential pressure can be implemented in filter presses with little constructive effort to reduce cake moisture by decreasing pore saturation even more. The adjusted differential pressure dewaters filter cake pores with a corresponding and lower capillary entry pressure [17,18].

The strength of a wet network of solid particles depends strongly on its saturation S (proportion of voids filled with liquid to entire void volume). In the saturation range between 0.3 and 0.9, liquid bridges are present, and capillaries are increasingly filled, i.e., capillary forces act; therefore, the largest tensile forces can be transmitted [19–21]. A maximum is to be expected for S = 0.8 to 0.9 [22,23].

2.2. Approach to Describe Cake Detachment

For the description of the detachment behavior of filter cakes, four stresses are relevant [21], which are shown in Figure 1. A distinction must be made between adhesion as the stress between two different systems (e.g., filter medium and cake) and the cohesion of the cake itself. In each case, a further subdivision can be made into shear stress τ and tensile stress σ. The volume on which the force acts is depicted in blue, whereas the surface associated with the stress is shown in orange. The sketched stresses and their abbreviations in this paper are as follows:

(1) Shear adhesion (adhesion (shear)): τ_{Cloth}.
(2) Tensile adhesion (adhesion (tensile)): σ_{Cloth}.

(3) Shear cohesion (cohesion (shear)): τ_{Cake}.
(4) Tensile cohesion (cohesion (tensile)): σ_{Cake}.

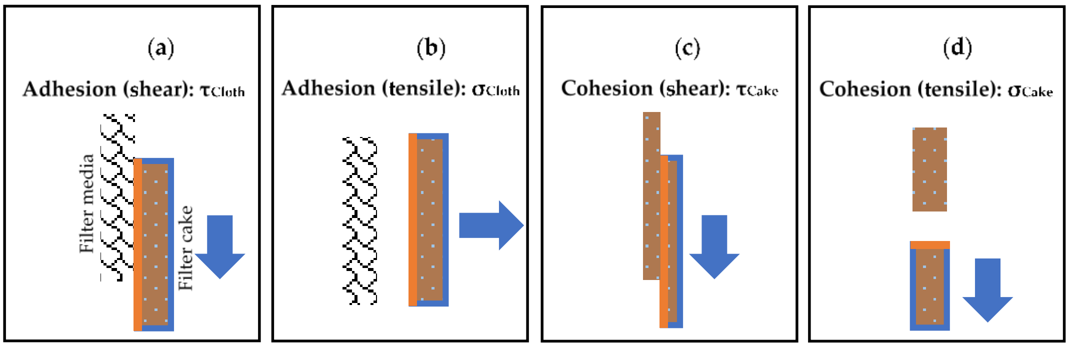


Figure 1. Schematic representation of important stresses for the description of cake detachment. (**a**) Shear adhesion: τ_{Cloth}. (**b**) Tensile adhesion: σ_{Cloth}. (**c**) Shear cohesion: τ_{Cake}. (**d**) Tensile cohesion: σ_{Cake}. Blue: volume on which the force acts. Orange: stress area.

Shear adhesion causes the sticking of filter cakes to filter media and must be overcome for cake detachment [21]. Corresponding to the apparatus used this can, e.g., be proceeded by compressed air blowing (vacuum disc filters), back washing (candle filters), filter media movement (tower filter presses) or gravity (chamber filter presses).

The driving force for cake detachment in tailings filtration in chamber filter presses is the weight force acting on the cake. The condition of complete detachment requires the following relationship in Equation (1), which assumes sufficiently high cohesion of the cake and an infinitely extended plate, i.e., neglecting support at the sealing edge and other chamber structures as well as detachment of the cake with subsequent wedging between two adjacent plates. Besides cake dimensions (thickness T_{Cake}, width W_{Cake} and height H_{Cake}), its porosity ε and saturation S, as well as the density of the solid ρ_{Solid} and the fluid ρ_{Fluid}, are decisive for the weight force.

$$T_{Cake} \cdot W_{Cake} \cdot H_{Cake} \cdot ((1-\varepsilon) \cdot \rho_{Solid} + \varepsilon \cdot S \cdot \rho_{Fluid}) \cdot g = F_{Gravitation} > F_{Adhesion} \quad (1)$$

A common problem is an incomplete cake detachment (complete sticking or partial detachment). There are several cake detachment scenarios where the loading parameters mentioned in Figure 1 are crucial. Figure 2 shows these scenarios. It can be divided between the requested detachment (a) and the problematic cases (b–d). In detail, these can be described as follows:

(a) The weight of the cake is sufficient. The cake falls off in one piece. Assumption: cohesion sufficient, no breaking.
(b) The weight force is too low; the cake adheres. Assumption: cohesion sufficient, no breaking.
(c) The tensile stresses transmitted during plate moving rupture the cake. If there are several fractures, partial falling may occur. Assumption: insufficient shear strength of the cake and low weight force.
(d) A higher adhesion (tensile) than cohesion (tensile) splits the cake. If there are several fractures, partial falling may occur. Assumption: low weight force and local saturation/compaction differences.

It can be taken advantage of the interdependency of the four stresses mentioned. A relationship between cohesion (tensile) and adhesion (tensile) ($\sigma_{Cake}/\sigma_{Cloth}$) can be derived from the theory of contact points. Using a bulk solids mechanics approach, the ratio between cohesion (shear) and cohesion (tensile) ($\tau_{Cake}/\sigma_{Cake}$) can be determined. Therefore, measurements of shear adhesion and shear cohesion allow the determination of all relevant stresses.

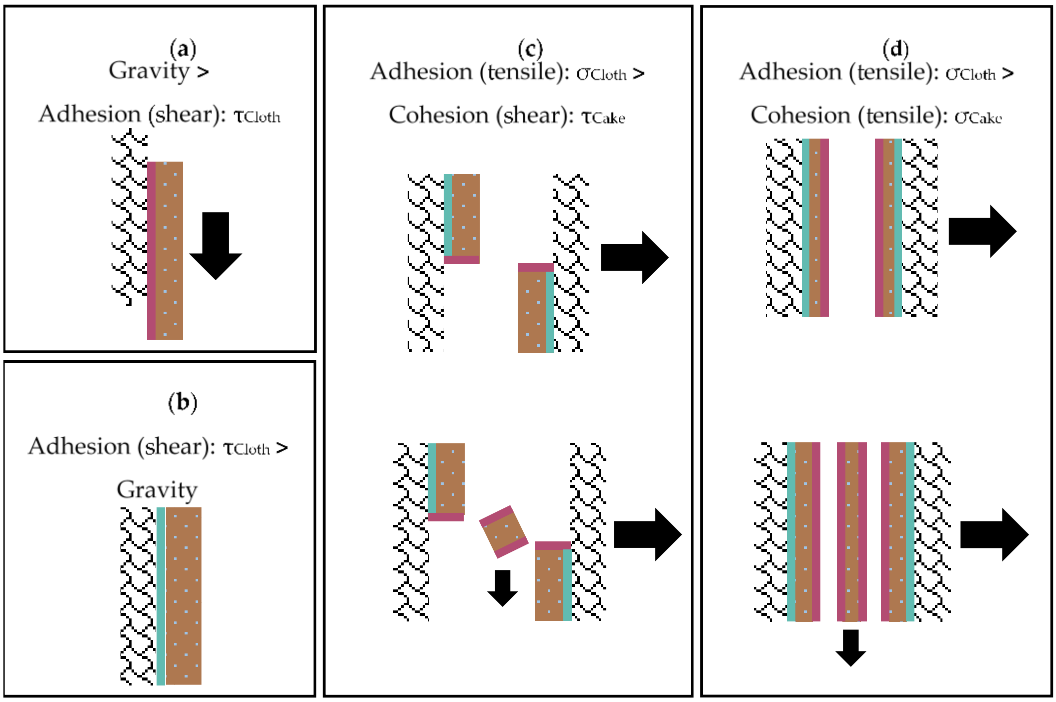


Figure 2. Schematic representation of different detachment behaviors regarding underlying mechanisms. (**a**) The weight of the cake is sufficient. The cake falls off in one piece. (**b**) The weight force is too low; the cake adheres. (**c**) The tensile stresses transmitted during plate moving rupture the cake. If there are several fractures, partial falling may occur. (**d**) A higher adhesion (tensile) than cohesion (tensile) splits the cake. If there are several fractures, partial falling may occur. Green: stress area without detachment. Red: stress area with detachment.

2.3. Theory of Contact Points

Using close-packed structure theory, it is obvious that the number of contacts to a wall is smaller than the number of contacts within a network of solid particles. Based on theoretical approaches combined with measurements of real polydisperse systems, the ratio of tensile strength in an undersaturated wet network of solid particles to tensile strength of the same network to a wall can be approximated with 1.15 according to Douglas [24]. Translated into the application and the nomenclature of this investigation, it is referred to as the ratio between the transmissible tensile cohesion inside the cake and tensile adhesion between cake and cloth ($\sigma_{Cake}/\sigma_{Cloth}$) in the following Equation (2):

$$\frac{\sigma_{Cake}}{\sigma_{Cloth}} \approx \frac{3.6}{\pi} \approx 1.15 \tag{2}$$

However, it should be noted that a network of solid particles deviates from an ideal packing structure if it is compressible (e.g., tailings). Here, the state of compression (e.g., corresponding to filtration pressure) plays an important role. For compressible structures, a higher filtration pressure leads to an increase in the number of contact points, and it becomes closer to the approximation of ideal packings.

2.4. Bulk Solid Mechanics

In contrast to rheology describing stress states of flowing systems, bulk solid mechanics characterizes the flow behavior of dry or undersaturated wet networks of solid particles [25]. After consolidation, they deform or rearrange at certain yield stresses due to internal friction caused by particle contacts. The flow properties, especially of initial flow, are depending on several parameters, for example, solid volume fraction, applied normal stress and stress at preshearing [26].

Relationships and derivable quantities can be depicted in a plot out of experimental shear measurement data, which are referred to as the yield locus and schematically illustrated in Figure 3. Consolidated bulk material starts to deform or rearrange under stresses above the yield locus. Such networks (e.g., filter cakes) have a positive shear stress of $\sigma = 0$, which is referred to as cohesion (shear) in this paper. The tensile strength of cohesive networks at $\tau = 0$ occurs for negative normal tensions, which is referred to cohesion (tensile) in this paper. The yield locus for tensile fracture ends vertical to the abscissa [27].

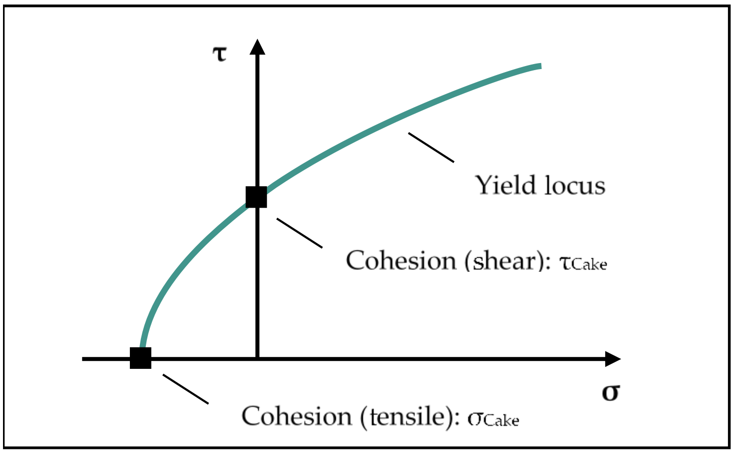


Figure 3. Schematic representation of yield locus, τ_{Cake} and σ_{Cake}.

The ratio of $\tau_{Cake}/\sigma_{Cake}$ describes the brittleness of the network of solid particles in simplified terms. As can be seen in the literature, a prediction of $\tau_{Cake}/\sigma_{Cake}$ is not possible. However, it can be stated that $\tau_{Cake}/\sigma_{Cake}$ is in general between one and five, but even ratios below one and up to 25 are reported [21]. Regarding undersaturated limestone particle networks, Rumpf mentioned $\tau_{Cake}/\sigma_{Cake} > 2$ leads to a brittle breaking behavior [28]. Stitch-proof-to-brittle properties are stated to be crucial for cake detachment [21], as well as the fact that cake texture changes in a small range of residual moisture, as reported by Tittel [29]. Generally, $\tau_{Cake}/\sigma_{Cake}$ increases due to the progressive decreasing of saturation of the network of solid particles [28]. However, slurries at concentrations of the gel point or higher are also able to transfer forces, e.g., wet filter cakes after filtration [30]. Since they theoretically have a saturation of one, this work extends the method of the yield locus for this specific case. This assumption is justified since in the literature brittle behavior is also mentioned for full-saturated networks of solid particles [21].

2.5. Shear Breaking

It is important to note that the acting forces are always proportional to the area where they are acting. This is to be exemplified in Table 1 by scenario c using realistic chamber dimensions (2 m · 2 m · 0.05 m) and a cohesion/adhesion ratio ($\sigma_{Cake}/\sigma_{Cloth}$) of 1.15 (see Section 2.3). If the shear strength of the filter cake is too low, the cake becomes ruptured by shearing due to the adhesion of the cake parts sticking to the cloths. The area ratio of the attaching cake part in relation to the shear area is important and is therefore defining a critical ratio of $\tau_{Cake}/\sigma_{Cake}$ needed for the avoidance of rupture by shearing. If $\tau_{Cake}/\sigma_{Cake}$ is sufficient (over 17.4), no rupture of the cake is possible.

If incomplete detachment occurs, in addition to manual cleaning, there are some ways developed over time to remove the cake or remnants of it. Weigert lists some patents for this, using the following ideas: stretching medium, plate tilting, vibration, shaking, scrapers and nozzles [21]. However, it would be optimal if an autonomous detachment of the complete cake could be achieved by systematic process parameter control. Therefore, it is obvious that not only filtration tests with regard to separation efficiency and hydraulic properties of the filter media are necessary for the design of filter presses. In addition, knowledge of the stresses and the parameters influencing them is of enormous importance. Therefore, beside presentation of a suitable, application-related measurement method for relevant variables, this paper aims to show the impact of various process parameters (e.g., filtration pressure and dewatering).

Table 1. Exemplary calculation of critical $\tau_{Cake}/\sigma_{Cake}$ ratio whose undercutting causes shear breaking.

Assumptions: Cake 2 m · 2 m · 0.05 m, $\sigma_{Cake}/\sigma_{Coth}$ = 1.15	
Area ratio one cake parts is adhering to	0.5
Area adhesion (tensile) acts	1 m · 2 m
Area cohesion (shear) acts	0.05 m · 2 m
Ratio area $_{\text{Adhesion (tensile)}}$/area $_{\text{Cohesion (shear)}}$	20
Resulting critical ratio of $\tau_{Cake}/\sigma_{Cake}$	17.4

3. Materials and Methods

Test equipment and procedures used are described in this section. Furthermore, investigated process parameters are discussed.

3.1. Properties of the Tailings

The study considered iron ore tailings having a size distribution and a mass concentration typical for tailings. Detailed properties are listed in Table 2. As referred to in Section 2, a high fraction of fine particles can be stated. The elemental composition measured by angle dispersive XRF can be found in a previous publication [31].

Table 2. Properties of the iron ore tailings.

Iron Ore Tailings		
Solid density		3050 kg·m^{-3} *
Slurry concentration		30 Vol-%
Particle size distribution	$x_{10,3}$	7.2 µm *
	$x_{50,3}$	38.2 µm *
	$x_{90,3}$	120.8 µm *

* [31].

3.2. Procedure

It would be ideal if a characterization of the stresses could be realized with the least possible effort while at the same time providing sufficient information. In the following, a possibility is therefore presented. The idea is to combine filtration tests and shear tests using one apparatus (a cylindric one-chamber frame filter press) and, in addition, commercial standard equipment with minimal adjustments (a tensile testing machine).

The tests in this paper used a laboratory frame filter press provided by FLSmidth, also used in previous investigations [31]. It consists of a cylindrical frame element (inner diameter 10 cm, height 4 cm) with a suspension inlet at the top and pressed by a spindle between two end plates. These end plates have drainage channels and four filtrate outlets, one at the top and at the bottom (Figure 4a). The four filtrate outlets are equipped with valves. Closing the lower filtrate outlet on one side and the upper filtrate outlet on the other side and introducing compressed air at the open upper filtrate outlet thus enables gas differential pressure dewatering of the filter cake (Figure 4b). Filling of the chamber is carried out using a stirred pressure vessel with a riser pipe overlaid with compressed air.

After filtration, it is possible to remove the cylinder together with cake and adhere filter media from the press. This allows subsequent positioning in a commercial tensile testing machine (velocity 10 mm·min^{-1}) with minimal modification (Figure 5). First, the adhesion (shear) of the filter media was measured by a crescent-shaped clamp, as proposed by Ginisty [32], by pulling of the fabric. Then, the cake was pushed halfway out of the cylinder using a disc spacer and afterwards the top half was sheared off with a lid to determine the cohesion (shear) of the cake analogues to a Jenike shear cell [33]. The maximum of the force-displacement curve related to the shear area represents the respective measured stress value. If the filtration is considered as preconsolidation and thus as preshearing of the network of solid particles, each shearing test value describes one point of the yield point, depending on the associated pair of values from normal stress and resulting shear stress. Different normal stresses can be realized by weight disks on the lid. In this way, a yield locus is obtained for each pressure and each cake post-treatment [26].

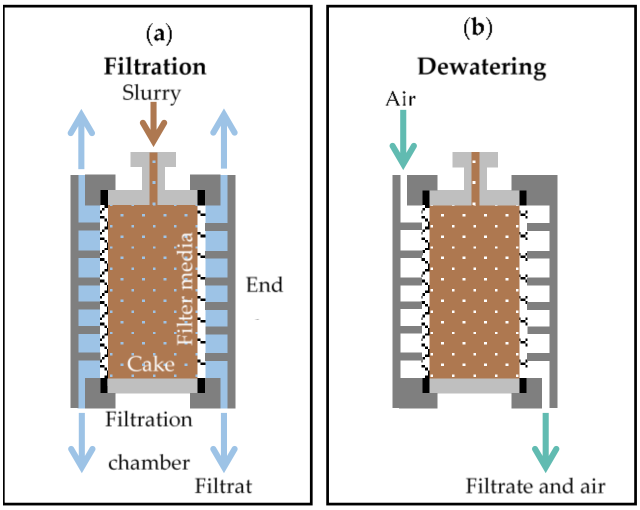


Figure 4. Schematic side view cross-section representation of lab filter press filtration (**a**) and dewatering procedure (**b**).

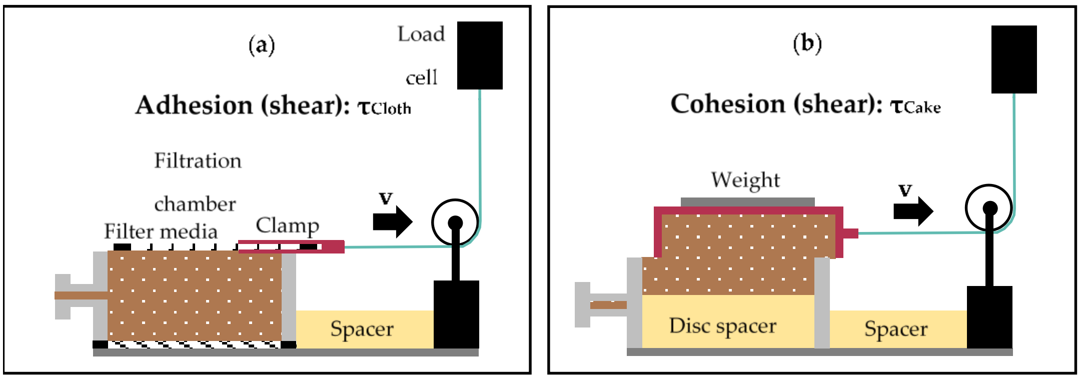


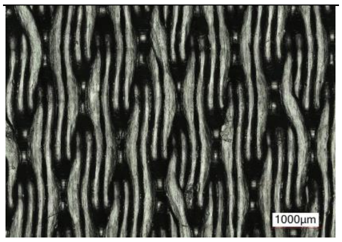
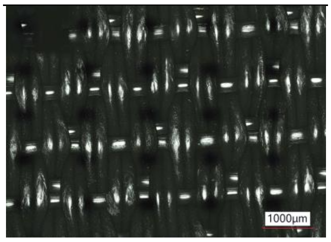
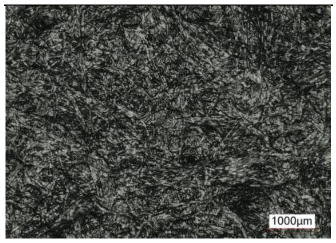
Figure 5. Schematic side view cross-section representations of the shear adhesion test (**a**) and the shear cohesion test (**b**).

3.3. Process Parameters

Filtration tests were carried out with three filter media typical for tailings filtration application. Two cloths of polypropylene (PP) and nylon (NY) as well as a PP felt media were compared. These were chosen to be able to compare two fiber materials and a cloth to a felt media. Their properties are listed in Table 3. Filter media resistance measurements were carried out in a pressurized filter cell according to VDI guideline 2762 [17].

To investigate the influence of compaction, filtrations were performed at 250 kPa and 1250 kPa. For each pressure, there were tests with filtration only and tests with a dewatering cake post-treatment, as can be seen in Figure 6. This was a gas differential pressure dewatering at 250 kPa for filtrations at 250 kPa and at 550 kPa for filtrations at 1250 kPa. A pressure of 550 kPa is an industrially used value for gas differential pressure dewatering. However, gas differential pressure is limited by the filtration pressure (danger of cake back flow). So, 250 kPa was the maximum pressure usable for 250 kPa filtration pressure.

Table 3. Properties of the three tailings filtration filter media.

	PP Cloth	**NY Cloth**	**PP Felt**
Image			
Weave type	Twill	Plain	-
Fiber type	Mono/mono	Mono/mono	-
Fiber diameter (warp/weft)	180 ± 10/330 ± 30 µm	280 ± 20/310 ± 20 µm	-
Resistance	$2.6 \pm 0.6 \cdot 10^8$ m^{-1}	$1.8 \pm 0.1 \cdot 10^8$ m^{-1}	$7.4 \pm 0.9 \cdot 10^8$ m^{-1}
Thickness	1.1 ± 0.1 mm	1.0 ± 0.1 mm	2.2 ± 0.2 mm

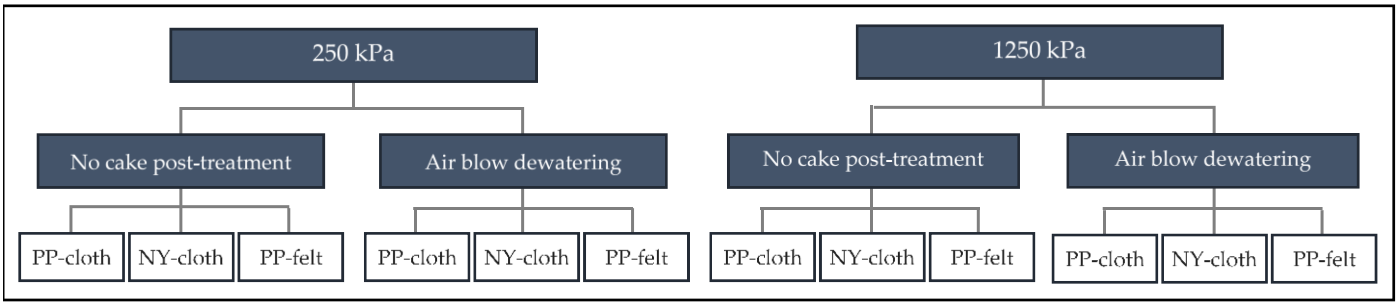


Figure 6. Overview of filtrations made for subsequent adhesion and cohesion tests.

Normally, a tailings filtration fabric is used for a thousand or more filtration cycles [34]. During this process, changes occur in the fabrics due to blinding and mechanical abrasion. This is not considered in this work. A new set of fabrics (two pieces) was used for each pressure level. In order to still be able to observe a steady state (e.g., turbidity impact constant), six filtrations were carried out previously with the filter media to soil them before a fivefold determination of each measuring point was made. No post-treatment and post-treatment measurements were carried out alternating.

3.4. Validation

To validate the theoretical description of the cake detachment behavior, various chambers for a laboratory recessed plate filter press (Simex Mini Mobil, Simex Filterpressen GmbH & Co. KG, (Calw, Germany)) were additively manufactured in order to be able to carry out tests with 5, 10 and 15 mm thick cakes. Three filter plates were printed in each case, i.e., two end plates and one intermediate plate with an edge length of 150 mm and a cake dimension of approx. 120 mm in width and height. For this investigation, the PP cloth was used. One set of cloth was used for each pressure level (250 kPa and 1250 kPa). At first, for each pressure level, six filtrations were made to ensure basic contamination of the cloth. At this number, the particle penetration occurring at the beginning of each filtration had decreased to an approximately constant amount. Then, five filtrations were made for each cake thickness.

4. Results

4.1. Adhesion Measurements to Determine Required Cake Thickness for Detachment

First, the shear adhesion values of the different fabrics for two filtration pressures and two cake post-treatments are presented. A plot of the shear stress to be applied for the individual fabrics is given in Figure 7, including the standard errors of the means. The black data series represents the measured values of saturated cakes and the white data series those of dewatered (undersaturated) cakes. The lowest adhesion is found for the lower filtration pressure (250 kPa) and a fully saturated cake (S = 1) for all fabrics. Dewatering after filtration at 250 kPa increases adhesion for all fabrics. The same applies to an increased filtration pressure (1250 kPa). For example, the adhesion of the PP cloth is approximately twice as high after a filtration at 1250 kPa without post-treatment than at 250 kPa without post-treatment, i.e., an almost twice as thick cake would be required to fulfill the detachment condition. Dewatering of the cakes formed at higher filtration pressure further increases adhesion for the PP cloth at 250 kPa and 1250 kPa, the NY cloth at 250 kPa and 1250 kPa and the PP felt at 250 kPa, comparing measurements at the same filtration pressure level. These findings are consistent with theoretical considerations of fewer contact points and literature data on saturation influence. Only the felt filter media for filtrations at 1250 kPa show an exception to this. Adhesion is slightly decreasing after dewatering. This results from the fact of a structure with lower permeability compared to the cloths reducing dewatering performance. Therefore, dewatering after 1250 kPa filtration has no further adhesion-increasing effect. For the iron ore tailings, 5 $kN \cdot m^{-2}$ corresponds approximately to 25 mm cake thickness by assuming a residual moisture of 20 w-%, ρ_{Solid} of 3050 $kg \cdot m^{-3}$, ρ_{Fluid} of 1000 $kg \cdot m^{-3}$, a full saturated cake (S = 1) and no sealing edge.

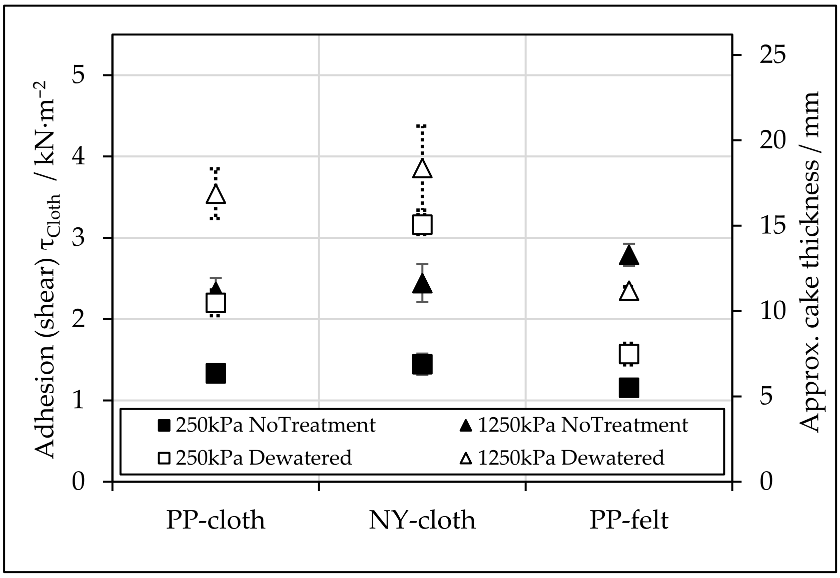


Figure 7. Adhesion (shear) τ_{Cloth} of the three filter fabrics for different process conditions.

In general, the residual moisture of the filter cake is the key parameter in filter press operation. It allows direct conclusions to be drawn about the throughput and is partly used as a target parameter for successful discharge. If only the adhesion of the cake to the fabric is considered, it is obvious that the residual moisture has a decisive influence on adhesion (Figure 8). Even a small change in residual moisture changes adhesion significantly. Considering all data points of filtrations at different filtration pressure levels, with and without cake post-treatment by dewatering, the assumption of a quasi-linear increase in adhesion when decreasing residual moisture is justified. Furthermore, standard error of the mean increases for decreasing moisture, especially for woven filter media.

However, detachment behavior cannot be simply described by only using the adhesion of the cake to the fabric. This is obvious regarding the possible detachment cases mentioned above and the underlying interactions of the different stresses. Further differentiation is necessary, and the structure of the cake must be considered. First, the understanding of the adhesion increase with decreasing residual moisture is useful. In fact, the residual cake moisture is resulting out of two different processes. One is compacting, and the other is dewatering. Therefore, if only the residual moisture is considered, information becomes lost. The effect of the different influences is visible, for example, in the representation of the adhesion referred to in the saturation of the network of solid particles (Figure 9). The networks are completely saturated (S = 1) for all filtrations without cake post-treatment of gas differential pressure dewatering. Depending on the available gas differential pressure (250 kPa or 550 kPa), further undersaturation and even higher adhesions can be achieved.

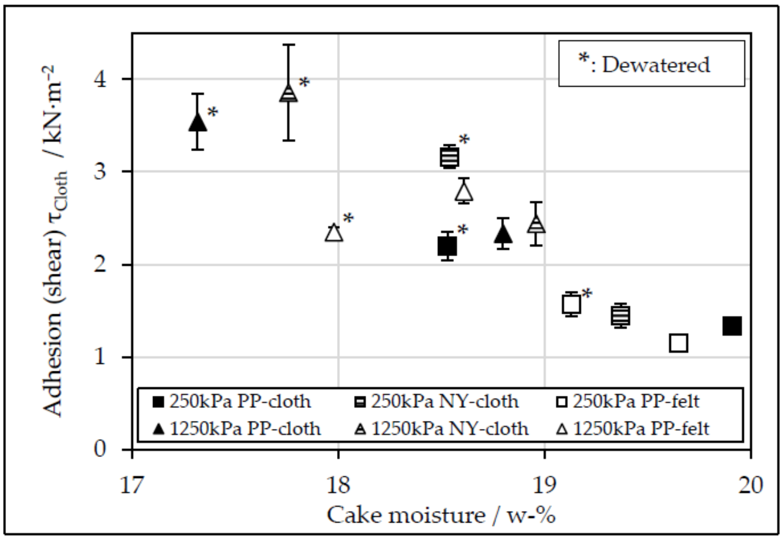


Figure 8. Adhesion (shear) τ_{Cloth} referred to corresponding residual cake moisture of filtrations at different filtration pressure levels, with and without cake post-treatment by dewatering.

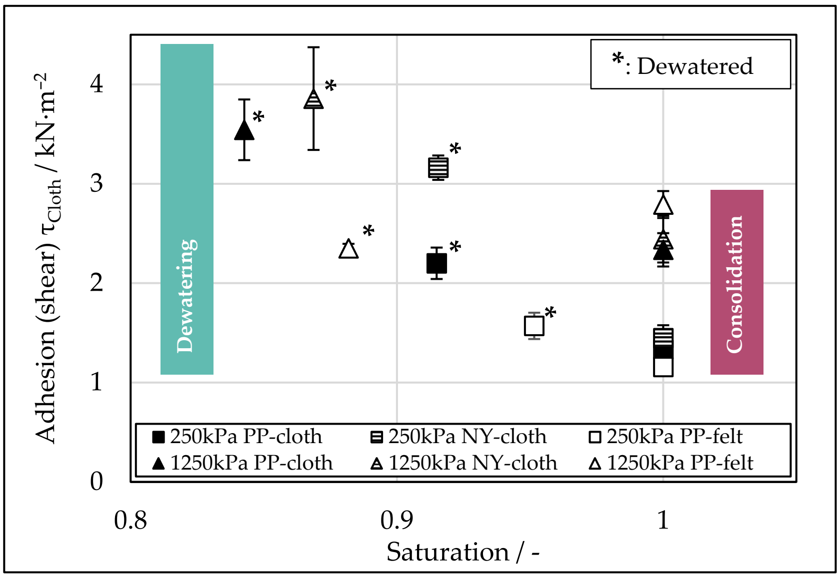


Figure 9. Adhesion (shear) τ_{Cloth} referred to corresponding saturation of the network of solid particles.

However, it should be noted that an increased filtration pressure acts as an antagonist. For compressible cakes and resulting compaction, the pores become smaller; thus, a higher capillary inlet pressure is required for dewatering.

4.2. Cohesion Measurements to Evaluate Shear Breaking Risk

The determination of the adhesion of the cake to the filter cloth helps to determine the required cake thickness for detachment (See Figure 2a,b). However, no statement can be made about the occurrence of the other possible scenarios (See Figure 2c,d). For these, the other stress states on and in the filter cake as well as their relationship to each other play an important role, e.g., the ratio of $\tau_{Cake}/\sigma_{Cake}$, which indicates the brittleness of the network of solid particles in simplified terms. A first step is to determine the shear cohesion, i.e., the shear strength of the filter cake, using the procedure shown in Figure 5. Figure 10 shows the results of these cohesion measurements for the PP felt media over residual moisture. Analogous to shear adhesion, an approximately linear relationship between shear cohesion and residual moisture content is evident, regardless of whether the lower residual moisture content results from increased compaction (due to a higher filtration pressure) or undersaturation (gas differential pressure dewatering)

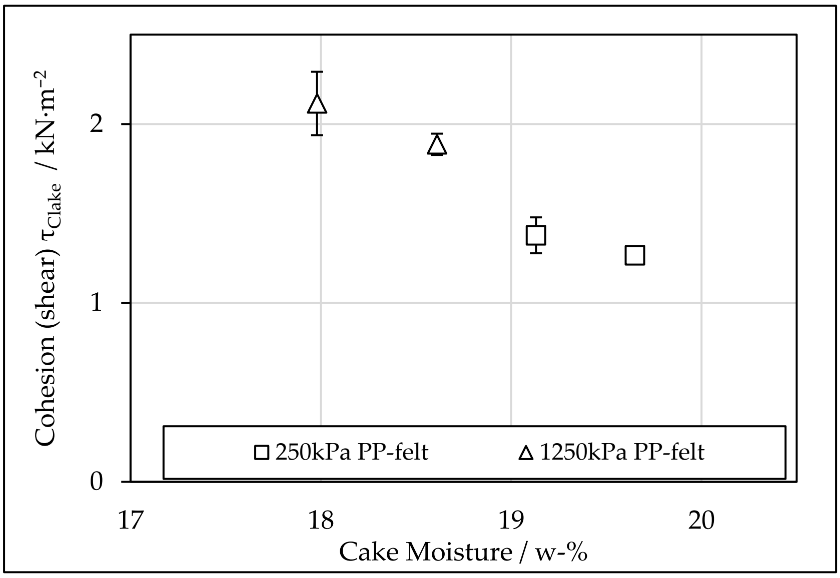


Figure 10. Cohesion (shear) τ_{Cake} referred to corresponding residual cake moisture of filtrations at different filtration pressure levels for the PP felt media, with and without cake post-treatment by dewatering.

Furthermore, the determination of the ratio of $\tau_{Cake}/\sigma_{Cake}$ can be carried out by determining the yield loci and expanding them into negative normal stresses. How these curves are to be expanded is discussed controversially [21]. Linear extrapolation of the yield locus slope at $\sigma = 0$ is a common simplified way to describe the relationship between τ_{Cake} and σ_{Cake}. However, this overestimates the tensile strength and underestimates $\tau_{Cake}/\sigma_{Cake}$, respectively. Nevertheless, a statement about the detachment behavior can already be derived from the ratio of the slopes. This is discussed using the example of the yield loci for filtration at 250 kPa and 1250 kPa using the PP felt media for no post-treatment of the cake and gas differential pressure dewatering (Figure 11). When looking at the linear fit, a higher slope, which is similar to the ratio of $\tau_{Cake}/\sigma_{Cake}$ at a higher filtration pressure, can be observed. Qualitatively, scenario c is thus less probable with filtration at 1250 kPa. A slight impact by cake post-treatment can be stated as well.

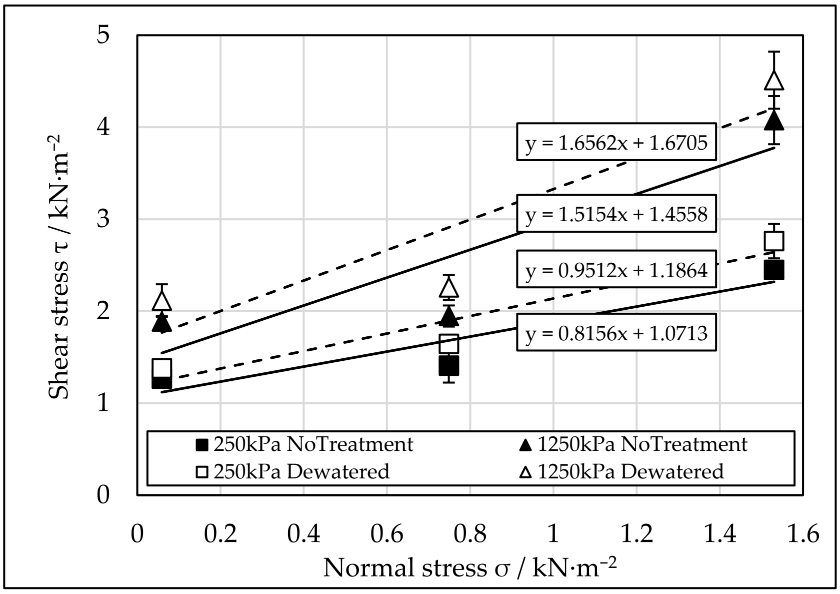


Figure 11. Yield locus excerpt of different filtration process parameters for PP felt media.

4.3. Validation

The presented different scenarios a–d of cake detachments can be observed in laboratory tests. Figure 12 shows images of each scenario after filtration of the iron ore tailings using PP cloths in the laboratory recessed plate filter press. The first image shows scenario a, which is a complete detached cake after a filtration with 5 mm chambers at 250 kPa filtration pressure without cake post-treatment. In the next image, scenario b, a complete sticking cake can be seen after a filtration with 5 mm chambers at 250 kPa filtration pressure and without cake post-treatment. The third image shows a shear breaking (scenario c) after a filtration with a 5 mm cake at 250 kPa filtration pressure and without cake post-treatment. Scenario d is a breaking parallel to the cloth, which could often be observed after filtration with cake dewatering as shown in the image on the right side. This was also taken after a filtration at 250 kPa with 5 mm chambers and air blow.

(**a**) (**b**) (**c**) (**d**)

Figure 12. Different detachment behaviors seen in lab filtration: (**a**) complete detachment (5 mm, 250 kPa, no cake post-treatment), (**b**) complete sticking cake (5 mm, 250 kPa, no cake post-treatment), (**c**) shear breaking (5 mm, 250 kPa, no cake treatment) and (**d**) breaking parallel to cloth (5 mm, 250 kPa, air blow).

Figure 12 shows different scenarios observed for filtrations that do not differ in their chamber thickness. This is due to the fact that each detachment behavior has a certain probability for the respective process conditions. This stochastic distribution results, for example, from local inhomogeneities of the cake due to the broad particle size distribution. For example, shear breaking was observed for seven out of ten filter cakes having a thickness of 5 mm using PP cloths in the laboratory recessed plate filter press (see Table 4). This is the process parameter condition resulting in the highest residual moisture. A five-hold determination of each combination using this two-chamber filter press gave ten detachments that can be observed. Shear breaking did not occur for thicker cakes at filtrations with 250 kPa and without post-treatment or at any other combination.

Table 4. Cake shear breaking probability of filtrations in the laboratory recessed plate filter press using the PP cloths.

Filtration Pressure	Cake Post-Treatment	Shear Breaking		
250 kPa	No treatment	5 mm: 7 of 10	10 mm: 0 of 10	15 mm: 0 of 10
250 kPa	Air blow dewatering	5 mm: 0 of 10	10 mm: 0 of 10	15 mm: 0 of 10
1250 kPa	No treatment	5 mm: 0 of 10	10 mm: 0 of 10	15 mm: 0 of 10
1250 kPa	Air blow dewatering	5 mm: 0 of 10	10 mm: 0 of 10	15 mm: 0 of 10

5. Discussion

In this study, several points are considered in a simplified way. Determination of filter media influences is limited since long-term behavior of the different filter media cannot be studied at the laboratory scale to an application-related extent. In addition, filter media having higher pressure losses reduces available gas differential pressure for dewatering and therefore hampers adhesion and cohesion comparisons. Generally, extensive field data acquisition and comparison between field and laboratory data would be suggested.

In this study, only iron ore tailings are considered. It would be interesting for future work to compare tailings from different mines but also from the same mine at different exploration times. Changes in rock composition are a major challenge for the entire process chain but also explicitly for solid–liquid separation. Larger data sets would then also allow predictive control of this process.

6. Conclusions

First, a detailed view on cake detachment cases as well as underlying forces and tensions was depicted. Afterwards, measurement procedures combining filtration tests and cake-to-cloth shear adhesion as well as cake shear cohesion were presented, and their suitability for iron ore tailings was proven. Thereby, filtration process parameter influences on shear adhesion and shear cohesion could be shown. Increasing compaction of the cake by applying a higher filtration pressure leads to a higher shear adhesion, requiring a thicker cake to reach sufficient cake weight to fulfil the detachment condition as well as to a higher shear cohesion. Furthermore, decreasing cake saturation by cake post-treatment (gas differential pressure dewatering) also increases shear adhesion and shear cohesion. In summary, an approximately linear increase in shear adhesion as well as shear cohesion with decreasing residual moisture can be observed, regardless of whether the decrease results from compaction (higher filtration pressure) or undersaturation (gas differential pressure dewatering). For the regarded amount of filtration cycles (relatively low compared to industrial use), no significant differences between cloth and felt media, as well as PP and NY, can be seen.

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Abbreviations

Saturation	S
Adhesion (shear)	τ_{Cloth}
Adhesion (tensile)	σ_{Cloth}
Cohesion (shear)	τ_{Cake}
Cohesion (tensile)	σ_{Cake}

References

1. Smidth, F.L. Sustainability Report 2020; UN Global Compact Office. Available online: https://ungc-production.s3.us-west-2.amazonaws.com/attachments/cop_2021/495014/original/flsmidthsustainabilityreport2020.pdf?1616590187 (accessed on 9 April 2021).
2. Concha, F.A. *Fluid Mechanics and Its Applications Volume 105 Solid-Liquid Separation in the Mining Industry*; Springer: Cham, Switzerland, 2014. [CrossRef]
3. Jewell, R.J.; Fourie, A.B. *Paste and Thickened Tailings—A Guide*, 3rd ed.; University of Western Australia: Nedlands, Australia, 2015.
4. Fitton, T.G.; Roshdieh, A. The impact on slurry rheology on tailings and disposal options. In Proceedings of the Four Case Studies, Paper Presented at IIR Slurry Pipelines Conference, Perth, Australia, 20–21 November 2012.
5. Davies, M.P. Filtered Dry Stacked Tailings—The Fundamentals. In Proceedings of the Tailings and Mine Waste, Vancouver, BC, Canada, 6–9 November 2011.
6. Amoah, N. Large-Scale Tailings Filtration and Dry Stacking at Karara Magnetite Iron Ore Operation. In Proceedings of the Tailings and Mine Waste, Vancouver, BC, Canada, 17–20 November 2019.
7. Wang, C.; Harbottle, D.; Liu, Q.; Xu, Z. Current state of fine mineral tailings treatment: A critical review on theory and practice. *Miner. Eng.* **2014**, *58*, 113–131. [CrossRef]
8. Wakeman, R. The influence of particle properties on filtration. *Sep. Purif. Technol.* **2007**, *58*, 234–241. [CrossRef]
9. Gomes, R.B.; De Tomib, G.; Assisa, P.S. Iron ore tailings dry stacking in Pau Branco mine, Brazil. *J. Mater. Res. Technol.* **2016**, *5*, 339–344. [CrossRef]
10. Wisdom, T.; Neumann, R.; Chaponnel, J. Development and Testing of the World's Largest Capacity Tailings Filter Press. In Proceedings of the 23rd International Conference on Paste, Thickened and Filtered Tailings—PASTE 2020, Online, 2–6 November 2020; Gecamin Publications: Santiago, Chile, 2020. [CrossRef]
11. Fränkle, B.; Morsch, P.; Nirschl, H. Regeneration Assessments of Filter Fabrics of Filter Presses in the Mining Sector. *Miner. Eng.* **2021**, *168*, 106922. [CrossRef]
12. Kaswalder, F.; Cavalli, D.; Hawkey, A.; Paglianti, A. Tailings dewatering by pressure filtration: Process optimisation and design criteria. In Proceedings of the 21st International Conference on Paste, Thickened and Filtered Tailings—Paste 2018, Perth, Australia, 11–13 April 2018. [CrossRef]
13. Mamghaderi, H.; Gharabaghi, M.; Noaparast, M. Optimization of role of physical parameters in the filtration processing with focus on the fluid flow from pore. *Miner. Eng.* **2018**, *122*, 220–226. [CrossRef]
14. Wennberg, T.; Stalnacke, A.; Sellgren, A. Commissioning and Operational Experience of a Thickened Tailing Facility with Two Thickeners. In Proceedings of the 23rd International Conference on Paste, Thickened and Filtered Tailings—Paste 2020, Online, 2–6 November 2020; Gecamin Publications: Santiago, Chile, 2020. [CrossRef]
15. Bowker, L.N.; Chambers, D.M. The Risk, Public Liability, & Economics of Tailings Storage Facility Failures, 2015, Earthwork Action. Available online: https://files.dnr.state.mn.us/input/environmentalreview/polymet/request/exhibit3.pdf (accessed on 12 April 2021).
16. Kaswalder, F.; Fritzke, I.; Cavalli, D.; Bassi, A. High Capacity Dewatering Plants, 2020. In Proceedings of the 23rd International Conference on Paste, Thickened and Filtered Tailings—Paste 2020, Online, 2–6 November 2020; Gecamin Publications: Santiago, Chile, 2020. [CrossRef]
17. VDI. *Mechanical Solid-Liquid-Separation by Cake Filtration—Mechanical Deliquoring of Incompressible Filter Cakes by Undersaturation Using a Gas Pressure Difference (VDI 2762 Part 3)*; Verein Deutscher Ingenieure e.V.: Düsseldorf, Germany, 2017.

18. Puff, T.; Stahl, W. Pressentwässerung mit nachgeschalteter Gasdifferenzdruckentwässerung. *Chem. Ing. Tech.* **1992**, *64*, 298–299. [CrossRef]
19. Batel, W. Einige Eigenschaften feuchter Haufwerke. *Chem. Ing. Tech.* **1956**, *28*, 195–200. [CrossRef]
20. Rumpf, H.; Turba, E. Über die Zugfestigkeit von Agglomeraten bei verschiedenen Bindemechanismen. *Ber. Dtsch. Keram. Ges.* **1964**, *41*, 78–83.
21. Weigert, T. *Haftung von Filterkuchen bei der Fest/Flüssig-Filtration*; VDI-Verlag: Düsseldorf, Germany, 2001.
22. Schubert, H. *Kapillarität in Porösen Feststoffsystemen*; Springer: Berlin, Germany, 1982.
23. Ozcan, O.; Ruhland, M.; Stahl, W. The effect of pressure, particle size and particle shape on the shear strength of very fine mineral filter cakes. *Int. J. Miner. Processing* **2000**, *59*, 185–193. [CrossRef]
24. Douglas, A.G. Tensile Strength of granular materials. *Nature* **1967**, *215*, 952–953. [CrossRef]
25. Hammerich, S.; Stickland, A.D.; Radel, B.; Gleiss, M.; Nirschl, H. Modified shear cell for characterization of the rheological behavior of particulate networks under compression. *Particuology* **2020**, *51*, 1–9. [CrossRef]
26. Schulze, D. *Flow Properties of Powders and Bulk Solids*; Dr.-Ing. Dietmar Schulze Schüttgutmesstechnik: Wolfenbüttel, Germany, 2011. Available online: https://www.dietmar-schulze.de/grdle1.pdf (accessed on 9 April 2021).
27. Schwedes, J. *Fließverhalten von Schüttgütern in Bunkern*; Verlag Chemie: Weinheim, Germany, 1968.
28. Rumpf, H. Die Wissenschaft des Agglomerierens. *Chem. Ing. Tech.* **1974**, *46*, 1–11. [CrossRef]
29. Tittel, R.; Borchers, K.O.; Nacken, F. Erfahrungen mit der Entwässerung feinstkörniger Rückstände aus einer Bodenwaschanlage. *Aufarb.-Tech.* **1995**, *36*, 366–371.
30. Stickland, A.D. Solid-Liquid Separation in the Water and Wastewater Industries. Ph.D. Thesis, Faculty of Engineering, Chemical and Biomolecular Engineering, The University of Melbourne, Melbourne, Australia, 2005.
31. Fränkle, B.; Morsch, P.; Nirschl, H. Towards prediction of cake detachment in tailings filtration. In *Paste 2021: 24th International Conference on Paste, Thickened and Filtered Tailings*; Fourie, A.B., Reid, D., Eds.; Australian Centre for Geomechanics: Perth, Australia, 2021; pp. 25–30. [CrossRef]
32. Ginisty, P.; Legoff, B.; Olivier, J.; Vaxelaire, J.; Tabuteau, H.; Paixao, J. Measurement of adhesion strengths and energy between calcium carbonate cake and filter cloth. *Water Pract. Technol.* **2017**, *12*, 211–216. [CrossRef]
33. *ASTM D6128–16*; Standard Test Method for Shear Testing of Bulk Solids Using the Jenike Shear Tester. ASTM International: West Conshohocken, PA, USA, 2016.
34. Wisdom, T. Maintaining high availability and low operational costs for filtered tailings facilities. In *Paste 2019: Proceedings of the 22nd International Conference on Paste, Thickened and Filtered Tailings*; Paterson, A.J.C., Fourie, A.B., Reid, D., Eds.; Australian Centre for Geomechanics: Perth, Australia, 2019; pp. 337–348. [CrossRef]