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Dewatering of Mine Tailings Slurries Using Superabsorbent Polymers (SAPs) Reclaimed from Industrial Reject of Baby Diapers: A Preliminary Study †

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Abstract: Traditional deposition of tailings slurry in a tailings storage facility (TSF) can create risks of dike failure. In order to minimize these risks and slurry spillage, the surface deposition technique of densified tailings (DT) through dewatering of the slurry has emerged. The DT technique has the potential to maximize water reuse, improve the shear strength of surface tailings, and reduce the ecological footprint of TSF. The consistency of DT covers a continuum ranging from thickened state, to paste state, to dry state. Despite its efficiency and economic feasibility, DT densification using thickeners sometimes proves unable to achieve the design target solids mass concentration ($C_{w\%}$). Hence, the use of superabsorbent polymers (SAPs) seems to represent a promising alternative, owing to their higher water absorbent capacity. In this paper, superabsorbent polymers (SAPs) reclaimed from industrial reject of baby diapers (Na-polyacrylates) are explored as a promising alternative to mine tailings slurries dewatering. To this end, laboratory-scale dewatering tests have been performed using two grades of Na-polyacrylate SAPs (grade 1 SAP = SAG-A06P coarse-grained, and grade 2 = SAG-M01P-100 medium-grained) for the tailings slurries densification. A higher water absorbency (or swelling capacity) was observed using the coarser SAPs (SAG-A06P) compared to the finer SAPs (SAG-M01P-100). The preliminary results showed that a SAP volume dosage in the range 10–13 kg of SAP/m^3 of slurry allowed achieving a final solids mass concentration ($C_{w\%\_final}$) ≥ 70%, despite the occurrence of gel-blocking phenomenon.

Keywords: tailings storage facility (TSF); tailings slurry; tailings dewatering; superabsorbent polymers; industrial reject baby diapers; thickened tailings; paste tailings; filtered tailings

1. Introduction

Mining activity generates large amounts of solids wastes such as waste rocks and tailings. Waste rocks are stored in waste rocks pile while mine tailings are commonly stored as slurry in tailings storage facilities (TSF), surrounded by embankment dams [1]. Traditional deposition in TSF can create risks of dike failure [2–7] due to slope instability following excessive stress in the foundation soil, excessive stress in the embankment dam, and inadequate control of water pressure leading to liquefaction (static or dynamic) [8]. In order to minimize the risks of dike failure and slurry spillage, the surface deposition technique of densified tailings has emerged, even if thickening requires a huge dewatering capacity of dewatering capacity of the slurry. The thickened tailings technology has the potential to maximize water reuse, improve the shear strength of surface tailings, and reduce the ecological footprint of TSF by taking up a smaller area and volume [9,10]. The consistency of dewatered—or densified—tailings covers a continuum ranging from slurry state to thickened state (like molasses), to paste state (like toothpaste), and finally to dry state (like soil) [11]. In the mining industry, this consistency is usually defined according to the pulp mass density or the solids mass concentration ($C_{w\%} = 100 \times M_{dry\text{-}tailings}/M_{slurry}$). Thus, the thickened tailings would have a final $C_{w\%}$ of between 45% and 70%, the paste tailings with a final $C_{w\%}$ of between 70% and 85%, and the dehydrated tailings with a final $C_{w\%}$ of greater than 85% [11,12].

When the operation is underground, an alternative or supplement to the surface storage would be returning to the voids created up to 50% of the tailings in the form of cemented paste backfill [1,10,13–15]. When sulphide minerals in mine waste stored in surface are exposed to air and in the presence of water and their acid neutralization potential is not sufficient, or has been exhausted [1], these waste can produce acid mine drainage (AMD). Due to the stringent environmental regulations, these large amounts of wastes must be managed adequately. More often than not, the mining industry is forced to constantly improve their waste management practices. Indeed, densified tailings offered a good response to large tailings impoundments problems by reducing the volume of waste and eventually allowing the risk prevention of tailings dam failure [16,17]. Figure 1 outlines the conventional management of fine tailings by the mining industry.

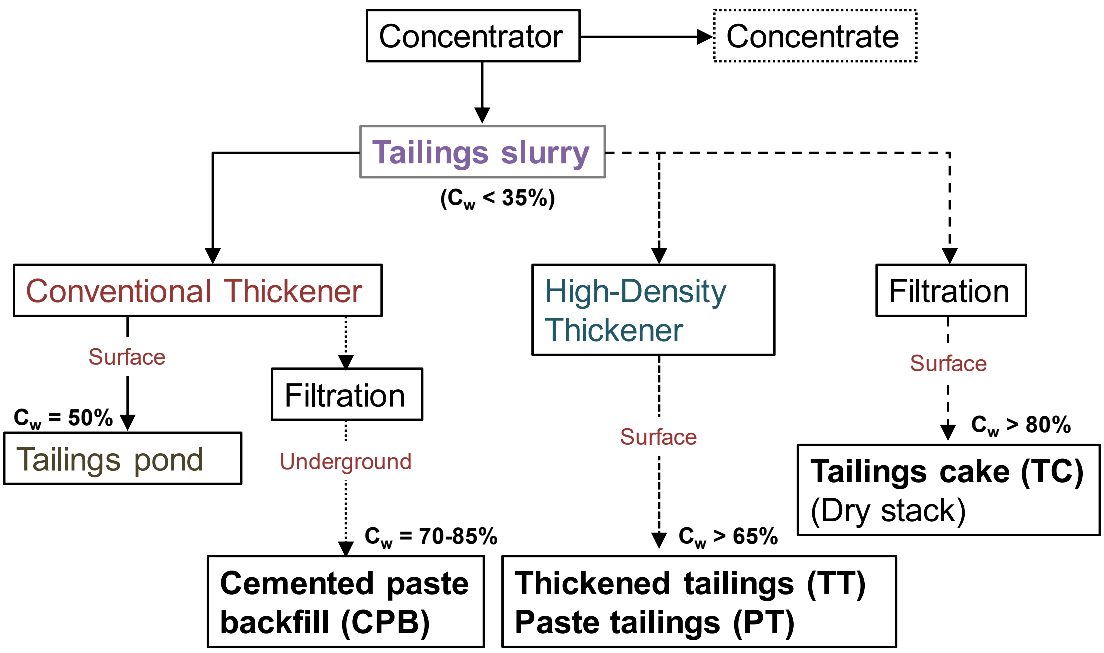

Figure 1. General scheme of conventional methods of the tailings management.

Accordingly, dewatering/densifying techniques aimed at increasing the tailings solids mass concentration. Various conventional techniques exist such as hydrocyclones, high-rate, high-density, and deep cone thickeners. Despite their efficiency and economic feasibility, these techniques prove sometimes unable to achieve the targeted design solids mass concentration (i.e., low water content). Hence, the use of superabsorbent polymers (SAPs) could represent a promising alternative, owing to their higher capacity of water absorption. SAPs are salt polyacrylates (e.g., sodium or Na), capable of absorbing and retaining from 100 to 1000 times their mass in deionized water [18]. The SAPs are commonly in the form of hydrophilic polymer chains that can absorb and retain aqueous fluids through swelling process [18–21]. Figure 2 presents the SAP in dry and swollen states and its molecular interactions (case of Na-polyacrylate).

Superabsorbent polymers are widely used in many fields, such as hygienic products, horticulture, gel actuators, drug-delivery systems, and coal dewatering [22]. Recently, SAPs have

Superabsorbent polymers are widely used in many fields, such as hygienic products, horticulture, gel actuators, drug-delivery systems, and coal dewatering [22]. Recently, SAPs have been used for dewatering and densifying oil sands mature fine tailings [23–25]. Besides, their absorption capacity will depend on various physico-chemical parameters such as temperature, pH of the slurry, composition and concentration of the chemical elements in the tailings slurry, presence of salts and/or cations, etc. [18,26–28].

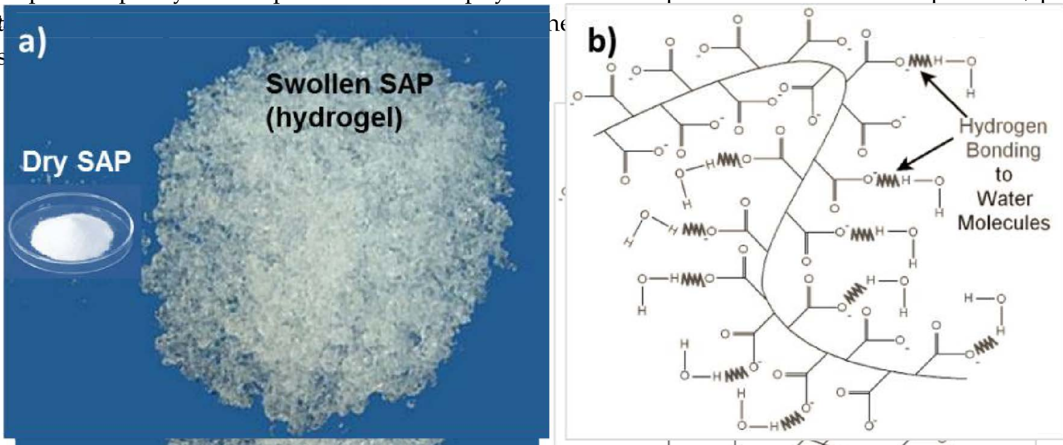

Figure 2. Superabsorbent polymer (SAP): (**a**) dry and swollen SAP (hydrogel), (**b**) molecular interactions of Na-polyacrylate.

The main objective of this paper is to assess the potential use of superabsorbent polymers (SAPs) for mine tailings slurry dewatering and to obtain densified tailings for surface storage. To do so, the aim is to eliminate all the conventional dewatering systems by replacing them with SAPs (as shown in Figure 3). This objective should be reached through the assessment of the SAP mine water absorbent capacity and the dosage optimization to allow reaching a solids mass concentration set at 68% that is targeted by Mine A. In this preliminary study, instead of using commercially purchased polymers, SAPs reclaimed from industrial reject of baby diapers by a recycling company Recyc PHP inc. (Québec, QC, Canada) were used.

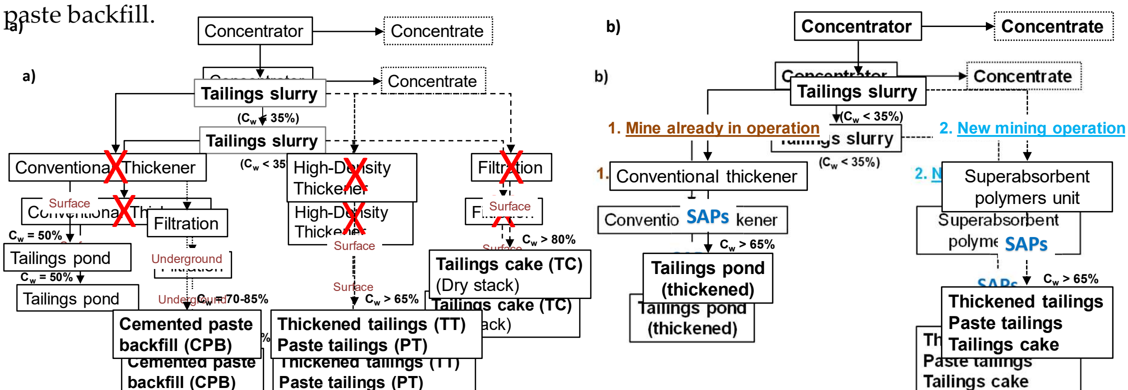

Figure 3. The use of SAPs to obtain densified tailings: (**a**) eliminating all conventional dewatering systems; (**b**) replacing all conventional dewatering system with SAPs, either for a mine already in operations or for new mine operations.

For a mine already in operation (Figure 3b, case 1), it would be possible to obtain thickened tailings at the deposit point of the storage area by adding progressively the SAPs using, for example, a particle projection gun (case of a single use of SAPs). On the other hand, in the event that the recycling of the water absorbed by the SAPs is required, the use of geotextile or other textile bags would be recommended in order to recover the swollen SAPs and recycling them by the most appropriate desorption technique.

In the case of a new mine (Figure 3b, case 2), SAPs can be added directly to the tailings slurry to obtain densified tailings (i.e., thickened and paste tailings or tailings cake) or to produce cemented paste backfill.

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2. Materials and Methods

2.1. Materials

2.1.1. Tailings Sample and Slurry Supernatant Water

The tailings slurry used in this study was sampled from Mine A located in Abitibi area (Quebec, Canada). This sample was collected from the ore processing plant, and was stored in plastic barrels. After transferring to the lab, the slurry was first homogenized, and of which a representative quantity was sampled for different characterizations. Physical and mineralogical characterizations were performed. The grain size distribution of the tailings was determined using a Malvern® Mastersizer S2000 Laser particle size analyzer (Malvern, United Kingdom). The tailings mineralogy was determined by X-Ray diffraction using the D8 Advance model of Bruker A.X.S (Madison, WI, USA). The relative density of the tailings (D_r or G_s) was determined to be 2.7, using the helium pycnometer AccuPyc 1330 from Micrometrics® (Norcross, GA, USA).

The tailings grain size distribution (GSD) is presented in Figure 4, while the tailings gradation parameters determined from the GSD in Figure 4 and the mineralogical properties are listed in Table 1. It should be mentioned that the as-received slurry solids mass concentration ($C_{w\%}$) was 50%.

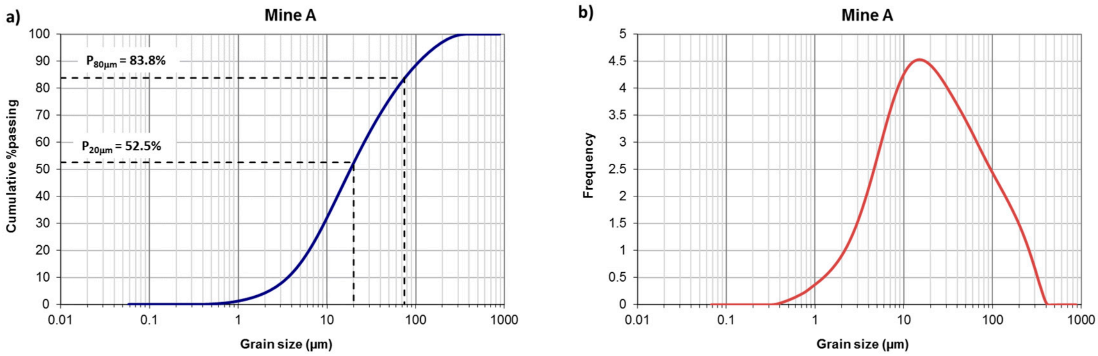

Figure 4. Grain-size distribution curves of the tailings sample (Mine A): (a) cumulative distribution; (b) incremental distribution.

Table 1. Physical and mineralogical properties of tailings sample from Mine A.

Parameter	Value	Mineral	Grade (%)
D_{10}	3.2 µm	Quartz	28.14
D_{30}	9.8 µm	Chlorite	4.3
D_{50}	21.7 µm	Albite	30
D_{60}	31.6 µm	Oligoclase	4.8
D_{90}	112.1 µm	Labradorite	6.2
C_U	9.8	Orthoclase	14
C_c	0.9	Biotite	6.4
$P_{20\ \mu m}$	52.5%	Calcite	3.2
$P_{80\ \mu m}$	83.8%	Pyrite	1.62

Table 1 shows that the values of D_{10} and D_{60} (diameter corresponding respectively to 10% and 60% passing on the cumulative grain-size distribution) correspond respectively to 3.2 and 31.6 µm. These values are typical of hard rock mine tailings [1]. The results of the mineralogical analysis presented in the same table (the two columns on the right) show that the tailings are composed mainly by silicates (quartz, chlorite, albite, oligoclase, labradorite, orthoclase, and biotite) that correspond to 93.8% of total mineralogy; carbonate and sulfide represent 3% and 1.6% of total mineralogy, respectively.

(quartz, chlorite, albite, oligoclase, labradorite, orthoclase, and biotite) that correspond to 93.8% of total mineralogy; carbonate and sulfide represent 3% and 1.6% of total mineralogy, respectively.

Mine A water used in this study was the supernatant (or bleeding water) collected from the top of the slurry barrels after the tailings settlement. The absorbency tests were performed in order to determine the capacity of the SAPs to absorb this mine water.

2.1.2. Superabsorbent Polymers (SAPs) Reclaimed from Industrial Reject of Baby Diapers

Two grades of Na-polyacrylate SAPs from our partner and supplier, Recyc PHP Inc., were tested in this study with the aim at evaluating their water absorbent capacity (or degree of swelling) in mine water: larger size particles grade 1 SAP, SAG-A06P and medium size particles grade 2 SAP, SAG-M01P-100 (see Table 2).

Table 2. Particle gradation of the two Na-polyacrylate SAP grades (SAG-A06P and SAG-M01P-100).

Particle Gradation	Grade 1 SAP = Grade SAG-A06P (Larger Size Particles)	Grade 2 SAP = Grade SAG-M01P-100 (Medium Size Particles)
>1200 µm	0%	0%
between 600 and 1200 µm	4%	≈1%
between 300 and 600 µm	91%	78%
between 150 and 300 µm	≈5%	20%
between 75 and 150 µm	trace	≈1%
<75 µm	0%	trace

2.2. Methods

The methodology adopted consists in preliminary optimization of the SAP dosages to be used for the tailings slurry dewatering tests in relation with the residence time. It should be mentioned that the goal is to achieve a final solids mass concentration ($C_{w\%\_final}$) varying between 68% and 90%. Laboratory experiments were carried out in two stages: (*i*) supernatant mine water absorption tests by adding the SAP to water (direct addition mode), and (*ii*) the tailings slurry dewatering tests by soaking the SAP contained in geotextile bags (indirect addition mode). Figure 5 illustrates the three steps inherent to the indirect addition mode using a geotextile bag containing dry SAPs [29].

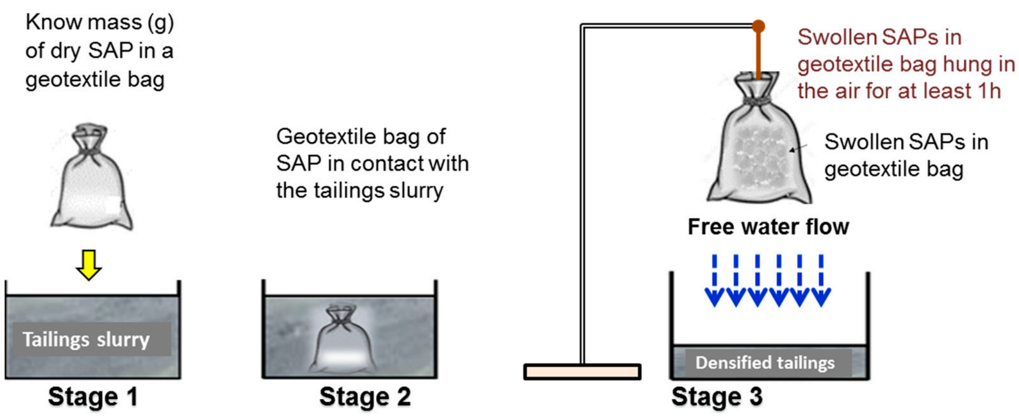

Figure 5. Diagram illustrating the three steps leading to the absorption test using dry SAPs in a geotextile bag by the indirect addition mode (contact with the slurry).

2.2.1. SAP Dosages Calculation and Expression for the Absorbency Parameters

The SAPs dosages can be done either by mass dosage (D_{mSAP}), or by volume dosage (D_{vSAP}). These dosages can be achieved either in relation to the slurry or in relation to the water alone/contained in the slurry. The mass dosage of the SAP can be defined as the ratio of the dry mass of any type and grade of SAP ($M_{dry\text{-}SAP}$) to the mass of the slurry (M_{slurry}) or of the initial water (free or contained in the slurry) (M_{water}) as follows [29]:

grade of SAP ($M_{\text{dry-SAP}}$) to the mass of the slurry (M_{slurry}) or of the initial water (free or contained in the slurry) (M_{water}) as follows [29]:

$$D_{mSAP-s} = \frac{M_{dry-SAP}}{M_{slurry}}, \tag{1}$$

$$D_{mSAP-w} = \frac{M_{dry-SAP}}{M_{water}}, \tag{2}$$

The volume dosage of the SAP can be defined as the ratio of the dry mass of any type and grade of SAP ($M_{\text{dry-SAP}}$) to the volume of the slurry (V_{slurry}) or of the initial water (free or contained in the slurry) (M_{water}) as follows [29]:

$$D_{vSAP-s} = \frac{M_{dry-SAP}}{V_{slurry}} = \rho_{slurry}\left(\frac{M_{dry-SAP}}{M_{slurry}}\right) = \rho_{slurry} \times D_{mSAP-s}, \tag{3}$$

$$D_{vSAP-w} = \frac{M_{dry-SAP}}{V_{water}} = \rho_{water}\left(\frac{M_{dry-SAP}}{M_{water}}\right) = \rho_{water} \times D_{mSAP-w}, \tag{4}$$

where ρ_{slurry} is the slurry density (in g/cm^3, kg/m^3, or t/m^3). The water density ρ_{water} (or ρ_{w}) is 1 g/cm^3 (or 1000 kg/m^3, or 1 t/m^3) and the tailings slurry density is calculated as follows:

$$\rho_{slurry} = \left(\frac{C_w}{\rho_{s-tailings}} + \frac{1 - C_w}{\rho_w}\right)^{-1}, \tag{5}$$

where $\rho_{\text{s-tailings}}$ is the tailing grains density (in g/cm^3, kg/m^3, or t/m^3). The possible dosage units are as follows:

- D_{mSAP}: in kg of SAP/ton of slurry/water (is equivalent to g/kg), or in g of SAP/g of slurry/water (or in kg/kg, ton/ton).
- D_{vSAP}: in kg of SAP/m^3 of slurry/water (is equivalent to g/L), or in ton of SAP/m^3 of slurry/water (is equivalent to g/mL). In the following, only the units in kg/m^3 for D_{vSAP} are used for the presentation of the obtained results.

In order to quantify the SAPs absorbency, three main parameters can be calculated [29]:
The percentage of absorbed water, W_{SAP} (%)

$$W_{SAP}(\%) = \frac{M_{absorbed-water}}{M_{initial-water}} \times 100 = \frac{M_{swollen-SAP} - M_{dry-SAP}}{M_{initial-water}} \times 100, \tag{6}$$

The absorbency ratio, K_{SAP}, i.e., the number of times the mass of the SAP

$$K_{SAP} = \frac{M_{swollen-SAP}}{M_{dry-SAP}}, \tag{7}$$

The degree of swelling, swelling ratio or swelling capacity, Q (e.g., [18])

$$Q = \frac{M_{swollen-SAP} - M_{dry-SAP}}{M_{dry-SAP}} = \frac{M_{absorbed-water}}{M_{dry-SAP}} = (K_{SAP} - 1) = \frac{M_{initial-water} \times W_{SAP}(\%)}{100 \times M_{dry-SAP}}, \tag{8}$$

Figure 6 presents the results of deionized water absorbency tests using the two grades of SAP used in this study: grade 1 SAP, named SAG-A06P (large size particles), and grade 2 SAP, named SAG-M01P-100 (medium size particles, which is finer than SAG-A06P). Figure 6a shows the absorption kinetics of both grades of SAP where 100 mg of SAP is added directly to 200 mL of deionized water. It can be observed that after 1 h of contact between SAP and deionized water, the equilibrium of their swelling is reached. This is called the equilibrium degree of swelling (or equilibrium absorbency), Q_{eq}.

It can also be observed that the Q_{eq} is higher with grade 1 SAP (224 mL/g) than with grade 2 SAP (151 mL/g). Grade 1 has a water absorbent capacity 1.5 times greater than that of grade 2. According to the work done by [28], this could be due directly to the gradation of the polymer particles. Buffer solutions with pH in the range 1–13 were used to assess the pH sensitivity of SAP hydrogels. The desired acidic and basic pHs were adjusted by hydrochloric acid (HCl) and sodium hydroxide (NaOH) solutions, respectively. The pH values were precisely checked using a Fisher Scientific accumet® XL Meter Series pH-meter. The pH dependence of equilibrium degree of swelling Q_{eq} is shown in Figure 6b where 80 mg of SAP is added directly to 200 mL of deionized water, and which confirms the results seen in the literature (e.g., [18]).

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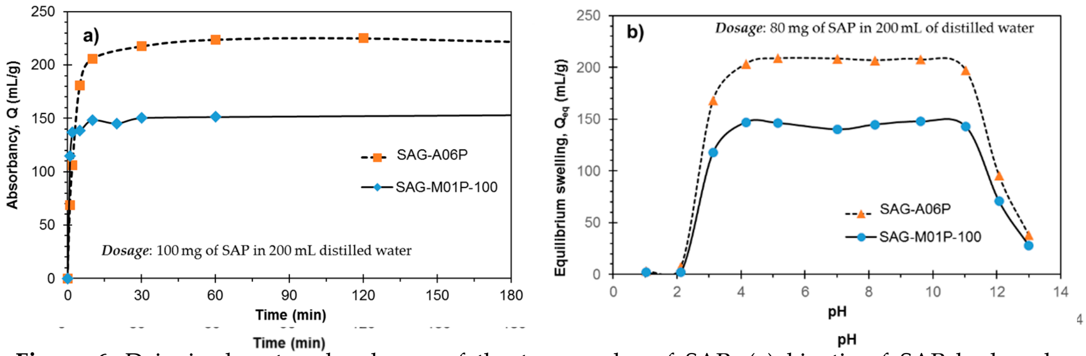

Figure 6. Deionized water absorbency of the two grades of SAP: (**a**) kinetic of SAP hydrogels formation and absorbency Q, (**b**) equilibrium degree of swelling (Q_{eq}) as a function of pH.

Three series of tests are carried out: (*i*) mine water (= tailings slurry supernatant water) absorbency tests using beakers (series #1), (*ii*) mine tailings slurry dewatering tests using Pyrex dishes (series #2), and (*iii*) mine tailings slurry dewatering tests using plastic bins (series #3). Series #1 tests are intended to further understand the absorption kinetics of the tailings slurry supernatant water. Series #2 and #3 tests are designed to understand the dewatering of tailings slurry by varying the volume tested.

2.2.2. Series #1: Mine Water Absorbency Tests Using Beakers

These tests consisted of introducing a known mass of SAP into a beaker containing a certain amount of mine water (here, 100 mL for grade 1 SAP and 200 mL for grade 2 SAP based on the results in Figure 6a) for a residence time of 24 h by direct addition mode (Figure 7). The SAP dosages ranged between 8 and 40 kg/m³ of mine water for grade 1 SAP and between 8 and 20 kg/m³ of mine water for grade 2 SAP.

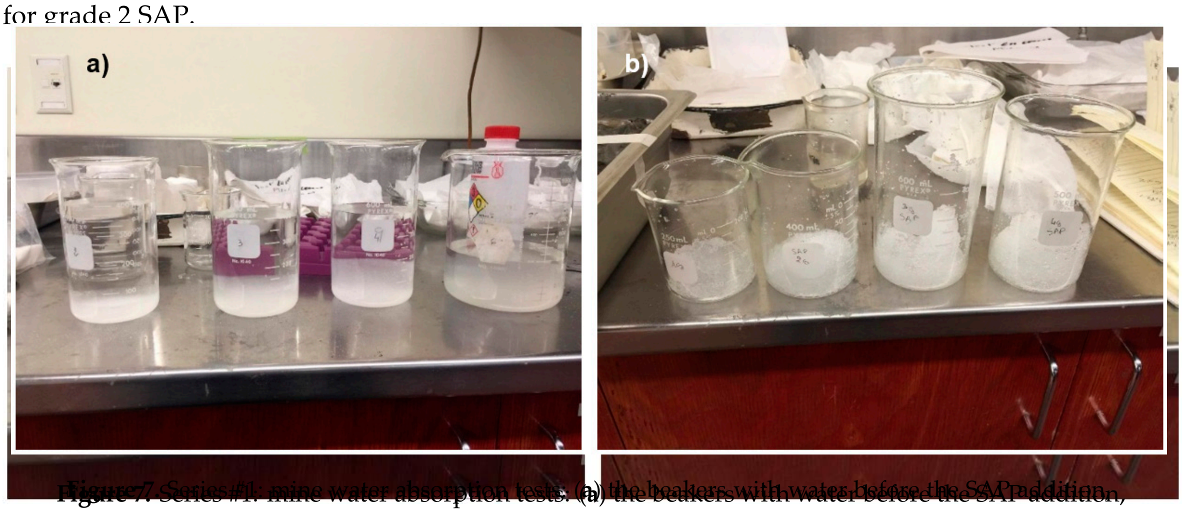

Figure 7. Series #1: mine water absorption tests: (**a**) the beakers with water before the SAP addition, (**b**) after the SAP was added directly.

2.2.3. Series #2: Mine Tailings Slurry Dewatering Tests Using Pyrex Dishes

These tests consisted of soaking the SAP contained in geotextile bags (indirect addition mode) in order to densify the tailings slurry. For this purpose, a known mass of SAP is introduced into geotextile bags (see Figure 8a), which are then soaked into the tailings slurry (with an initial mass M_{Slurry}) previously placed in Pyrex dishes (see Figure 8b). The Pyrex dishes were then covered with

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2.2.3. Series #2: Mine Tailings Slurry Dewatering Tests Using Pyrex Dishes

These tests consisted of soaking the SAP contained in geotextile bags (indirect addition mode) in order to densify the tailings slurry. For this purpose, a known mass of SAP is introduced into geotextile bags (see Figure 8a), which are then soaked into the tailings slurry (with an initial mass M_{Slurry}) previously placed in Pyrex dishes (see Figure 8b). The Pyrex dishes were then covered with plastic foil to avoid any evaporation. These tailings slurries dewatering tests were performed for understanding the impact of the SAP dosages and residence time on their water absorbent capacity. Different SAP dosages (Table 3) were used with tailings slurry having a known initial solids mass concentration $C_{w\%\_initial}$. The $C_{w\%\_initial}$ was set arbitrarily at 50% (gravimetric water content w = 100%) for grade 1 SAP, and at 43% (w = 133%) for grade 2 SAP. Three soaking times (or residence times) were tested: 24, 48, and 72 h. After each residence time, the final gravimetric water content $w\,(\%)_{final}$ and the corresponding final solids content ($C_{w\%\_final}$) of the resulting densified tailings were determined using one or the other of the following equations (according to the determined parameters):

$$C_{w\%\_final} = C_{w\%\_initial} \times \frac{M_{slurry}}{M_{slurry} - \left(M_{swollen-SAP} - M_{dry-SAP}\right)}, \tag{9}$$

$$C_{w\%\_final} = 100 \times \left(1 + \frac{w(\%)_{final}}{100}\right)^{-1}, \tag{10}$$

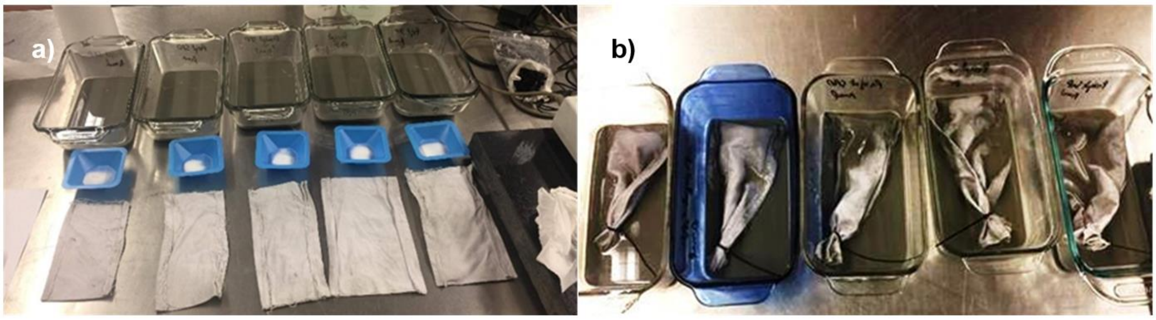

Figure 8. Series #2: tailings slurry in Pyrex dishes: (**a**) before the SAP addition and SAPs in separate dishes next to the geotextile bags (indirect addition mode), (**b**) 24 h after the placement of geotextile bags containing the SAPs into the tailings slurry.

Table 3. Series #2: SAP dosages for the tests using Pyrex dishes.

Test#	Grade 1 SAP		Grade 2 SAP	
	$M_{dry\text{-}SAP}$ (g)	* $D_{vSAP\text{-}s}$ (kg/m³)	$M_{dry\text{-}SAP}$ (g)	* $D_{vSAP\text{-}s}$ (kg/m³)
#1	0.8	5.8	0.8	5.5
#2	0.85	6.2	0.85	5.8
#3	0.9	6.6	0.9	6.2
#4	0.95	6.9	0.95	6.5
#5	1	7.3	1	6.8
#6	1.1	8.0	1.05	7.2
#7	1.5	10.9	1.1	7.5
#8	1.6	11.7	1.15	7.9
#9	1.7	12.4	1.2	8.2
#10	1.8	13.1	1.25	8.6
#11	1.9	13.8		

* M_{slurry} = 200 g; for grade 1 SAP: $C_{w\%\_initial}$ = 50%, ρ_{slurry} = 1457.4 kg/m³ and V_{slurry} = 0.137 L; for grade 2 SAP: $C_{w\%\_initial}$ = 43%, ρ_{slurry} = 1369.4 kg/m³ and V_{slurry} = 0.146 L.

2.2.4. Series #3: Mine Tailings Slurry Dewatering Tests Using Plastic Bins

The tailings slurry dewatering tests using the plastic bins were carried out for evaluating the effect of the slurry initial solids mass concentration ($C_{w\%\_initial}$) on the SAP absorption capacity (Figure 9). This was investigated by adding three SAP masses (4, 7, and 9 g of SAP/1 kg of slurry) to 30 kg of

2.2.4. Series #3: Mine Tailings Slurry Dewatering Tests Using Plastic Bins

The tailings slurry dewatering tests using the plastic bins were carried out for evaluating the effect of the slurry initial solids mass concentration ($C_{w\%\_initial}$) on the SAP absorption capacity (Figure 9). This was investigated by adding three SAP masses (4, 7, and 9 g of SAP/1 kg of slurry) to 30 kg of tailings slurry having different $C_{w\%\_initial}$ values. The corresponding volume dosages are given in Table 4. The initial solids mass concentration was varied from 7% to 74%. After 72 h of residence time (or soaking time), the final gravimetric water content w $(\%)_{final}$ and the corresponding final solids mass concentration ($C_{w\%\_final}$) of the densified tailings were determined.

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Figure 9. Series #3: plastic bins dewatering tests (**a**) the empty plastic bin, (**b**) almost dry tailings slurry obtained using geotextile bags with SAP (72 h residence time), (**c**) SAP in a geotextile bag (after 72 h).

Table 4. Series #3: grade 1 SAP dosages for the tests using plastic bins.

Test#	$M_{dry\text{-}SAP}$ * (g)	ρ_{slurry} (kg/m³)	$C_{w\%\_initial}$ (%)	$D_{vSAP\text{-}s}$ (kg/m³)
#1	120	1049	7	4.2
#2	120	1078	11	4.3
#3	120	1121	17	4.5
#4	120	1457	50	5.8
#5	120	1717	66	6.9
#6	120	1873	74	7.5
#7	210	1252	32	8.8
#8	210	1326	39	9.3
#9	210	1426	47	10.0
#10	270	1153	21	10.4
#11	270	1325	39	11.9
#12	270	1434	48	12.9

* M_{slurry} = 30 kg; grade 1 SAP used; 120 g of SAP = 4 g/kg of slurry; 210 g of SAP = 7 g/kg of slurry; 270 g of SAP = 9 g/kg of slurry.

3. Results

3.1. Equilibrium Degree of Swelling of SAP (Q_{eq}) Using Mine Water (Series #1 Tests)

Figure 10 presents the equilibrium degree of swelling (Q_{eq}) of the SAP when placed in contact with mine water directly for 24 h residence time. For both SAPs, Q_{eq} increases and reaches a maximum value for a SAP dosage between 10 and 15 kg/m³. Beyond 15 kg/m³, Q_{eq} seems to decrease. It can be observed that the maximum Q_{eq} using the grade 1 SAP (SAG-A06P) is 53 mL/g and 43 mL/g using the grade 2 SAP (SAG-M01P-100). These maximum Q_{eq} values correspond to 24% and 28% of the absorbency in deionized water using grade 1 and grade 2 SAPs, respectively. If for deionized water the grade 2 SAP absorption capacity is 67% of that of grade 1 SAP, for the Mine A water the grade 2 SAP absorption capacity is 81% of that of the grade 1 SAP.

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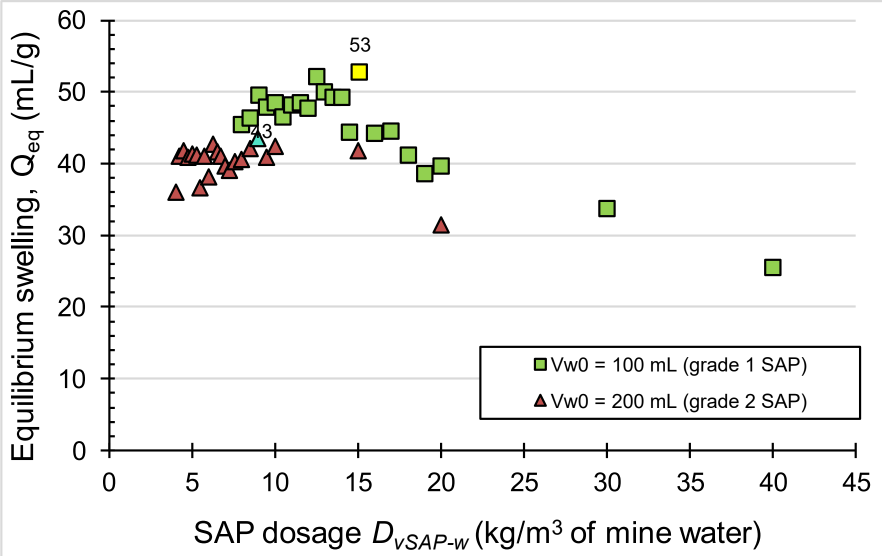


Figure 10. Mine A water absorbent capacity of SAP after 24 h residence time (Q_{eq}) by using grade 1 SAP (SAG-A06P) and grade 2 SAP (SAG-M01P-100).

3.2. *Dewatering of Tailings Slurry Using SAP Geotextile Bags*

3.2.1. Pyrex Dishes Tailings Dewatering Tests (Series #2 Tests)

Figure 11 presents the results of densifying a tailings slurry at $C_{w\%\_initial}$ at 50% using grade 1 SAP geotextile bags for different polymer dosages and residence times. Figure 11a presents the change in SAP equilibrium degree of swelling (Q_{eq}) and Figure 11b presents the calculated $C_{w\%\_final}$. It can be noted that for D_{vSAP-s} in the range 5.8–8.0 kg/m^3, $Q_{eq} > 40$ g/g while above this range of dosage $Q_{eq} < 40$ g/g. The maximum $Q_{eq} = 53$ g/g without any obvious and clear trend (see Figure 11a). At the end of the tests, the SAP geotextile bags were very swollen (see Figure 9c). This is because the polymer particles swell due to the tailings slurry free pore water absorption. Indeed, due to higher osmotic pressure difference between the inside and outside of the SAP (mine water) the polymer particles

of the average value (45 mL/g) obtained with dosages in the range 5.8–8 kg/m^3. This reduction in Q_{eq} value can be related to the gel-blocking phenomenon and is discussed in Section 3.2.2 (see Figure 11).

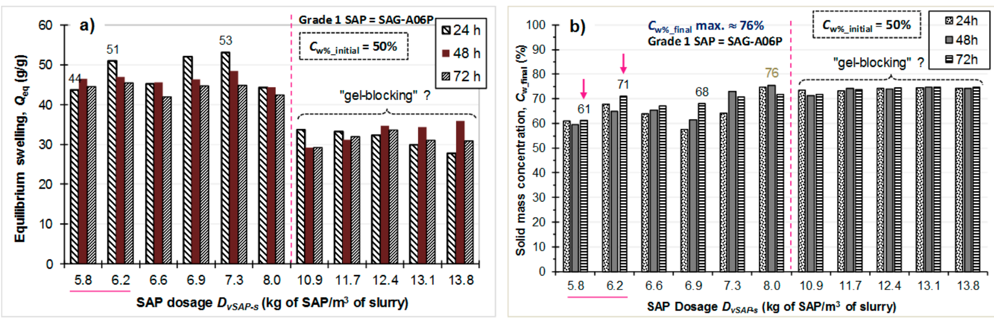
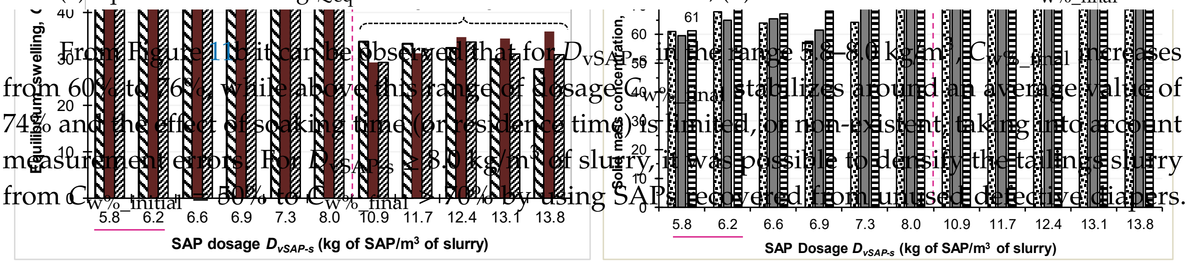


Figure 11. Tailings slurry at $C_{w\%\_initial}$ = 50% dewatered at different dosages of grade 1 SAP (SAG-A06P): (**a**) equilibrium swelling Q_{eq} for three different residence times, (**b**) final solids concentration $C_{w\%\_final}$.



From Figure 11b it can be observed that for D_{vSAP-s} in the range 5.8–8.0 kg/m^3, $C_{w\%\_final}$ increases from 60% to 76%, while above this range of dosage $C_{w\%\_final}$ stabilizes around an average value of 74% and the effect of soaking time (or residence time) is limited, or non-existent, taking into account measurement errors. For $D_{vSAP-s} \leq 8.0$ kg/m^3 of slurry, it was possible to densify the tailings slurry from $C_{w\%\_initial}$ = 50% to $C_{w\%\_final} > 70\%$ by using SAPs recovered from unused defective diapers.

Above 8 kg/m^3, the Q_{eq} value becomes lower and its average value (35 mL/g) is approximately 78% of that of the average value (45 mL/g) obtained with dosages in the range 5.8–8 kg/m^3. This reduction in Q_{eq} value can be related to the gel-blocking phenomenon and is discussed in Section 3.2.2 (see Figure 11).

Figure 12 presents the results of densifying a tailings slurry at $C_{w\%\_initial}$ = 43% using grade 2 (SAG-M01P-100) SAP geotextile bags for different polymer dosages and residence times. From Figure 12a it can be observed that for Q_{eq} > 30 g/g, regardless of the residence time, the highest degree of swelling using $D_{vSAP\text{-}s}$ of 36 g/g was achieved after 24 h. From Figure 12b it can be observed that $C_{w\%\_final}$ increases from 55% to 66% after 72 h.

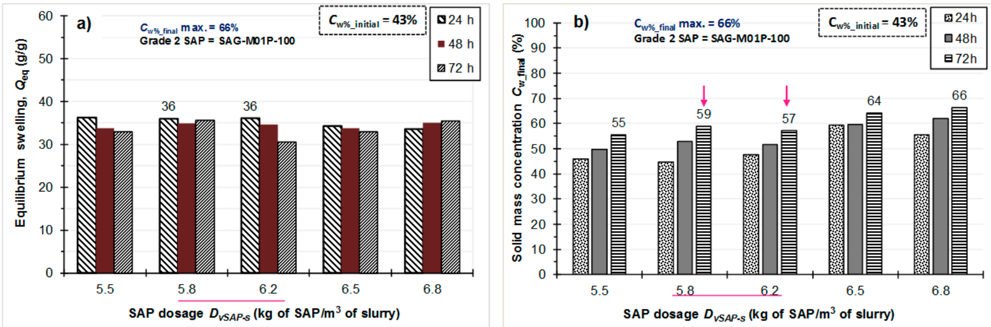


Figure 12. Tailings slurry at $C_{w\%\_initial}$ = 43% dewatered at different dosages of grade 2 SAP (SAG-M01P-100): (**a**) equilibrium swelling Q_{eq} for three different residence times, (**b**) final solids concentration $C_{w\%\_final}$.

To compare the performance of the two grades of polymer used (grades 1 and 2), only the two identical $D_{vSAP\text{-}s}$ values of 5.8 and 6.2 kg/m^3 are considered (values underlined in the abscissa axes). For these two dosages and comparing Figures 11a and 12a at the residence time of 24 h for example, it can be seen that Q_{eq} is 44 and 51 g/g when using the grade 1 SAP, while Q_{eq} = 36 g/g when using the grade 2 SAP. In addition, by comparing Figures 11b and 12b at the residence time of 72 h, it can be observed that $C_{w\%\_final}$ is 61% and 71% using grade 1 SAP, while $C_{w\%\_final}$ is 59% and 57% using grade 2 SAP. From these results, it can be concluded that the equilibrium degree of swelling (or water absorbent capacity) of the grade 2 SAP is lower compared to the grade 1 SAP. This can be explained mainly by the difference in particles gradation (see Figure 6a). Indeed, grade 1 SAP is coarser than grade 2 SAP (see Table 2).

3.2.2. Plastic Bins Tailings Dewatering Tests (Series #3 Tests)

Figure 13 presents all the results obtained following different tailings slurry dewatering tests according to SAP dosages presented in Table 4.

From Figure 13 it can be seen that $C_{w\%\_initial}$ influences the efficiency of the dewatering process of the tailing slurries using SAP (grade 1, coarser). Indeed, for low $C_{w\%\_initial}$ tailings slurry (7%, 11%, and 17%), the use of SAP at dosages in the range 4.2–4.5 kg/m^3 allowed achieving $C_{w\%\_final}$ of 21%, 29%, and 34%, respectively (corresponding to an increase of 20%, 25%, and 80%, respectively). Conversely, for high $C_{w\%\_initial}$ tailing slurries (namely, 66% and 74%), the use of SAP at dosages of 6.9 and 7.5 kg/m^3 allowed achieving $C_{w\%\_final}$ of 78% for both (corresponding to an increase of 17% and 5%, respectively). Considering the most common $C_{w\%\_initial}$ of tailings slurry in the mining industry, which is about 50%, a SAP dosage of 5.8 kg/m^3 yielded densified tailings at $C_{w\%\_final}$ of 67% (an increase of 34%). This $C_{w\%\_final}$ generally corresponds to the target for the surface storage of the thickened tailings.

For $C_{w\%\_initial}$ tailings slurry of 32%, 39%, and 47%, the use of SAP at dosages in the range 8.8–10.0 kg/m^3 allowed achieving $C_{w\%\_final}$ of 38%, 49%, and 50%, respectively (corresponding to an increase of 20%, 27%, and 6%, respectively). This low level of dewatering could be due to a possible gel-blocking phenomenon. Gel-blocking (see Figure 14) occurs when the wetted surface of an SAP particle swells

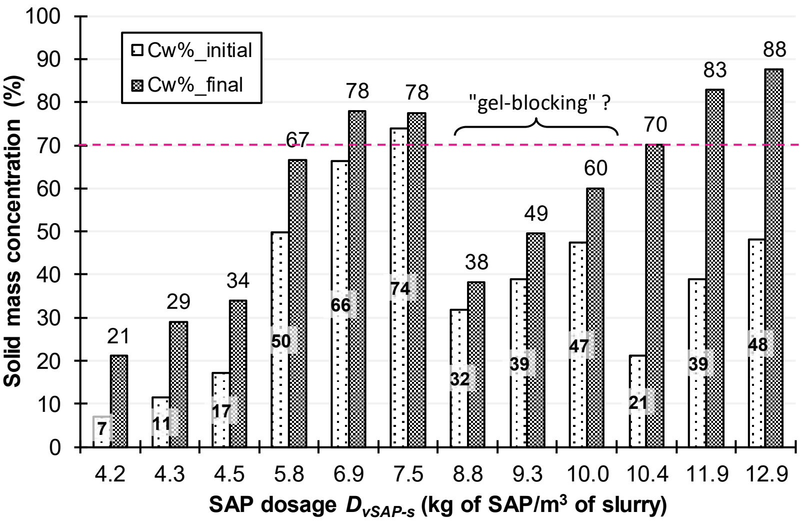


Figure 13. Results of tailings slurry dewatering using $D_{vSAP\text{-}s}$ in the range 4.2–12.9 kg/m³ of grade 1 SAP and after 72 h residence time.

For $C_{w\%\_initial}$ tailings slurry of 32%, 39%, and 47%, the use of SAP at dosages in the range 8.8–10.0 kg/m³ allowed achieving $C_{w\%\_final}$ of 38%, 49%, and 50%, respectively (corresponding to an increase of 20%, 27%, and 6%, respectively). This low level of dewatering could be due to a possible gel-blocking phenomenon. Gel-blocking (see Figure 14) occurs when the wetted surface of an SAP particle swells and impedes flow of liquid into the interior of the SAP particle, and frequently occurs with high absorbency SAPs that also have low percolation rate or permeability [30,31]. In fact, it is believed that this phenomenon is inherent to the soaking method using the SAP in geotextile bags or to the direct addition mode in the case of a probable overdosing (see Figure 11a for $D_{vSAP\text{-}s} > 8$ kg/m³). Indeed, after absorbing a certain amount of water, the polymers can form a gel on the surface of the geotextile bags that prevents water from penetrating deep. This formed "gel-screen" drastically reduces access of water to the rest of the polymers in the geotextile bags (Figure 14).

Figure 13. Results of tailings slurry dewatering using $D_{vSAP\text{-}s}$ in the range 4.2–12.9 kg/m³ of grade 1 SAP and after 72 h residence time.

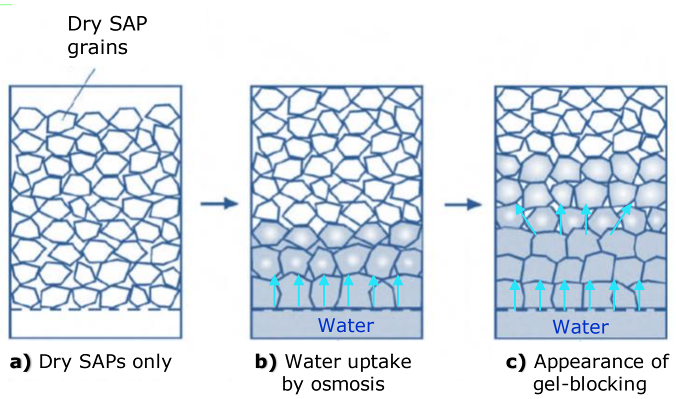


Figure 14. Schematic illustration of the mechanism of gel-blocking (modified from [30]).

For $C_{w\%\_initial}$ tailings slurry of 21%, 39%, and 48%, the use of SAP at dosages in the range 10.4–12.9 kg/m³ allowed achieving $C_{w\%\_final}$ of 70%, 83%, and 88%, respectively (corresponding to an increase of 233%, 113%, and 82%, respectively). It can be noted that gel-blocking did not occurred and the reason could simply be due to a better placement of the geotextile bags with the SAPs in the tailings slurry. The results show a very good performance of tailings slurry dewatering with SAP at $D_{vSAP\text{-}s}$ in the range 10.4–12.9 kg/m³. Indeed, within this range of $D_{vSAP\text{-}s}$ it was possible to densify the tailing slurries to a final solids mass concentration ≥ 70%.

The comparison of the tests performed using 9.3 and 10.0 kg/m³ dosages ($C_{w\%\_initial}$ of 39% and 47%) to those performed using 11.9 and 12.9 kg/m³ ($C_{w\%\_initial}$ of 39% and 48%) supports the hypothesis of polymers gel-blocking phenomenon (Figures 11a and 13). Despite the high dewatering performance of the SAPs, the gel-blocking phenomenon is still present and represents a challenge when using geotextile bags method. Since the dosages in the range 10.4–12.9 kg/m³ are considered very high, the obtained $C_{w\%\_final}$ in the range 70–88% are expected to be even higher.

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4. Discussion

4.1. Evolution of the Percentage of Absorbed Mine Water

From Figure 15 it can be observed that the apparent maximum rate of absorbed water W_{SAP} (%) was 100% when using grade 1 SAP at dosages ≥ 30 kg/m³ and 60% when using grade 2 SAP at dosages ≥ 20 kg/m³. It should be noted that W_{SAP} = 60% would be achieved with a dosage in the range 10–15 kg/m³ of grade 1 SAP (see Figure 15). The rate of absorbed mine water of grade 2 SAP is lower in comparison to the grade 1 SAP. These preliminary results confirmed that the use of SAPs that are reclaimed from industrial reject of baby diapers results in very good absorbency of mine water.

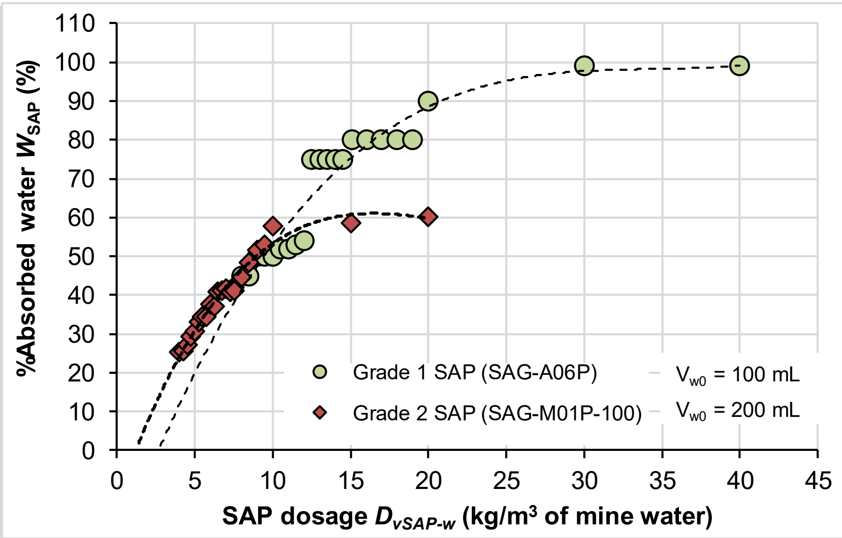

Figure 15. Mine A water absorption capacity of coarser SAP (grade 1 ≡ SAG-A06P) and the finer SAP (grade 2 ≡ SAG-M01P-100).

4.2. Effect of Residence Time on Tailings Dewatering

Figure 16 presents the variation in tailings slurry final solids mass concentration after dewatering at three different residence time (24, 48, and 72 h). It can be observed that the residence time does not have much influence on the effectiveness of the dewatering of tailings slurry using SAPs recovered from unused defective diapers. Indeed, for the same SAP dosage of 6.6 kg/m³, the final solids percentage $C_{w\%\_final}$ obtained with grade 1 SAP is 64%, 65%, and 67% after 24, 48, and 72 h, respectively. In addition, by using grade 2 polymers, the final $C_{w\%\_final}$ values are 59%, 60%, and 64% after 24, 48, and 72 h, respectively.

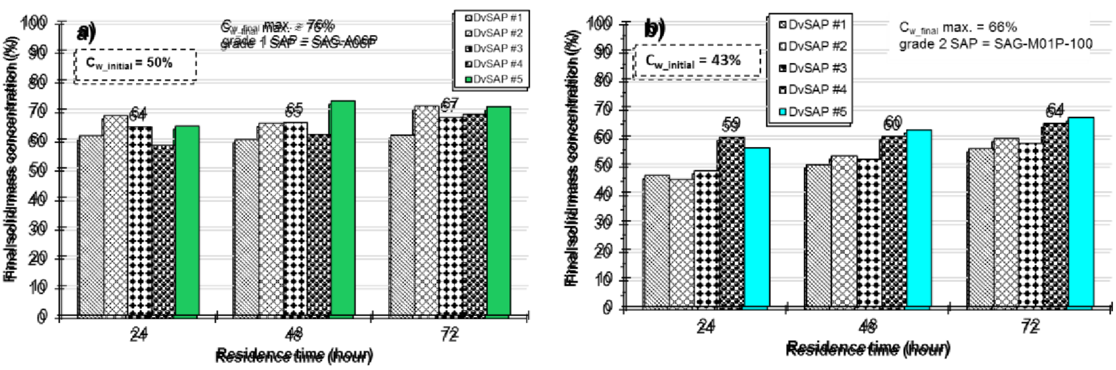

Figure 16. $C_{w\%\_final}$ of densified tailings slurry as a function of residence time for five dosages (#1 to #5 in Table 3) using: (**a**) grade 1 SAP (SAG-A06P), (**b**) grade 2 SAP (SAG-M01P-100).

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Figure 16. $C_{w\%\_final}$ of densified tailings slurry as a function of residence time for five dosages (#1 to #5 in Table 3) using: (**a**) grade 1 SAP (SAG-A06P), (**b**) grade 2 SAP (SAG-M01P-100).

Figure 17 shows that for the same SAP dosage of 6.6 kg/m³, the increase of $C_{w\%\_final}$ using grade 1 polymers is 28%, 31%, and 34% (after 24, 48, and 72 h, respectively), and using grade 2 polymers, it is 38%, 39%, and 49% (after 24, 48 and 72 h, respectively). It can be emphasized that because of the difference in $C_{w\%\_initial}$ (50% and 43%), the grade 2 polymers seem to have absorbed more water than the grade 1 polymers that are likely to be more efficient.

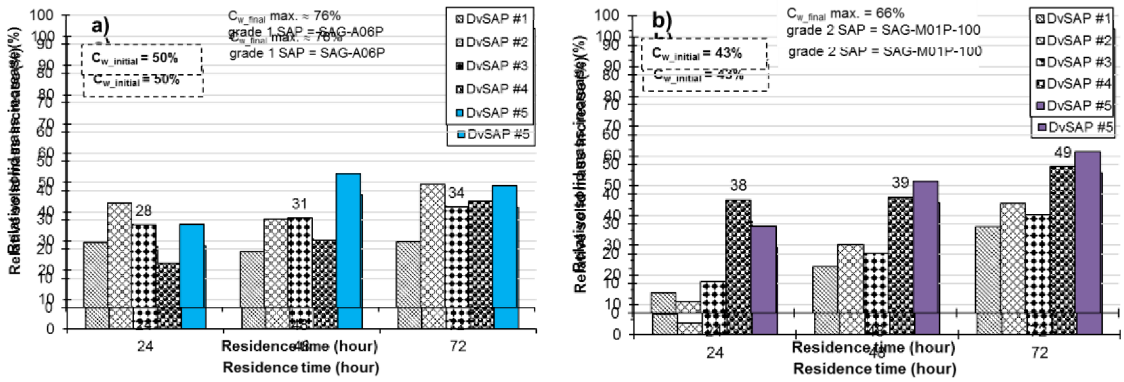

Figure 17. Tailings slurry relative solids mass concentration increase regarding the residence time and five SAP dosages: (**a**) grade 1 SAP (SAG-A06P), (**b**) grade 2 SAP (SAG-M01P-100).

4.3. Empirical Relationship for Tailings Dewatering Using SAPs

Figure 18 shows correlation curves between $C_{w\%\_initial}$ and $C_{w\%\_final}$ for all the tests performed using plastic bins. As a first approximation, a power law exists between the two states (initial and final) depending on the dosage range.

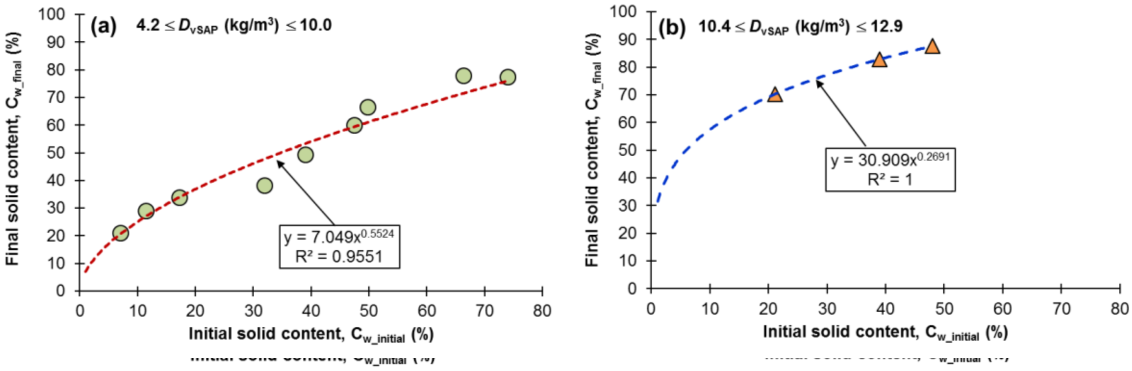

Figure 18. Power law empirical correlations between $C_{w\%\_initial}$ and $C_{w\%\_final}$ using grade 1 SAP (SAG-A06P): (**a**) for $D_{vSAP\text{-}s}$ in the range 4.2–10 kg of SAP/m³ of slurry, (**b**) for $D_{vSAP\text{-}s}$ in the range 10.4–12.9 kg of SAP/m³ of slurry.

This power law relationship is given as follows:

$$C_{w\%\_final} = a \times \left(C_{w\%\_initial}\right)^b, \tag{11}$$

where a = 7.049, b = 0.5524 and r = 0.98 for $D_{vSAP\text{-}s}$ in the range 4.2–10 kg of SAP/m³ of slurry and $C_{w\%\_initial}$ in the range 7–70%; a = 30.909, b = 0.2691 and r = 1.00 for $D_{vSAP\text{-}s}$ in the range 10.4–12.9 kg of SAP/m³ of slurry and $C_{w\%\_initial}$ in the range 10–60%.

4.4. Regeneration of the SAPs for Their Multiple Reuse and Preliminary Economic Analysis

One of the advantages of superabsorbent polymers is the ability to desorb the absorbed water to be returned to the water reuse loop at the mine, while the SAPs could be reused in turn several times (case of indirect addition mode). Indeed, some authors have proved that SAPs can be reused at least five times without losing their water absorbent capacity [24,25]. The regeneration capacity of SAPs (number of water absorption/desorption cycles) shall be evaluated for each type of SAP and for each SAP dosage. The water desorption from the SAPs can be carried out according to different techniques: by heat treatment (drying at T ≤ 180 °C), by pH control (very acidic or basic), by electrolysis, or simply by the use of a saline solution (eg 1 mol/L). However, the economic feasibility analysis of the water desorption method should be done because an industrial desorption and water recovery unit will have to be built in a suitable location. At this stage of the study, there are still many steps before considering industrial application as economic viability has not yet been proven.

One disadvantage of the technique of dehumidification of tailings slurry using SAPs is the fact that it is a physico-chemical process (and not a mechanical one, as in conventional cases) which can therefore be affected by various factors such as the degree of crosslinking of SAPs, the presence of di- or tri-valent dissolved cations, the presence of salts, very acidic or basic pHs and temperature.

To determine the economic feasibility of tailings slurry dehumidification using SAPs, it is essential to be able to compare costs with conventional techniques (thickeners and filtering systems). Table 5 contains comparative cost data for the different existing tailings dewatering technologies. This table also contains the estimated values—by interpolation of the test results—of the SAP dosages allowing obtaining the different equivalent consistencies.

Table 5. Typical relative operating cost (US $/t) of tailings storage for different tailings dewatering technologies [32] and corresponding estimated equivalent SAP dosages.

Tailings Consistency	Initial Solids Content (%)	Typical Solids Content at Deposition (%)	Thickeners & Filtration Systems Costs (US $/t Slurry)	SAP Dosage (kg/t Slurry) *
Slurry	25	45	0.15	11.65
Thickened	25	65	0.23	17.01
High-density	25	70	0.38	18.83
Paste	25	78	1.13	28.97
Filter cake	25	85	3.76	35.15

* Data interpolated from the experimental results.

Mine A, an open-pit gold mine, generates 53,614.00 t/day of dry tailings. If the slurry initial solids content is 25%, this corresponds to a mass of 214,456.00 t/day of tailings slurry to be stored on the surface. On Alibaba trade website, it can be seen that the price of SAPs of the sodium polyacrylate type varies between US $1000 and 2800/t (or US $1.00 and 2.80/kg). Table 6 contains calculations of the quantities of polymers needed per day and their associated costs (in US $ per tonne of slurry and per day). As can be seen, the gross costs are exorbitant because they are between 10 and 77 times higher than those from thickeners and filtration systems (see Table 5). These ratios become between 2 and 15 when the SAPs are used at least five times (absorption/desorption cycles).

Table 6. Dewatering cost of Mine A tailings slurries for different equivalent tailings consistencies using superabsorbent polymers (price of SAP considered: US $1000.00/t).

Equivalent Consistency	Mass of SAP Needed (t/Day)	Cost of SAP (US $/t Slurry)	Total Cost of SAP for 1 Use (US $/Day)	Total Cost of SAP for 5 Uses (US $/Day)
Slurry	2498	11.65	29,107	5821
Thickened	3648	17.01	62,051	12,410
High-density	4038	18.83	76,039	15,208
Paste	6213	28.97	179,985	35,997
Filter cake	8347	38.92	324,851	64,970

For the case of Mine A and with a minimum SAP market price of US $1000/t, it will cost between US $29,000 and US $325,000/day with a single use of SAPs, while it will cost between US $6000 and US $65,000/day for five cycles of use.

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To obtain a ratio of 1 (i.e., equivalent costs between conventional technologies and that of superabsorbent polymers), the price of one tonne of SAPs should vary between US $65/t (for slurry at 50% solids content) and US $485/t (for filter cake at 85% solids content) by assuming five cycles of use. Thus, the average acceptable price would therefore be in the order of US $180 per tonne of SAPs. Figure 19 compares the processing and transport costs of tailings to the ponds for conventional technologies and that using SAPs with an average price of US $180/t. From this figure, it can be seen that at an average price of US $180/t of SAPs, it would be cheaper (compared to conventional technologies) to deposit the tailings in the state/consistency of paste or cake. From there the real question is: would it be possible to get SAPs with the same water absorbent capacity at this price? The answer can only be given by polymer manufacturers.

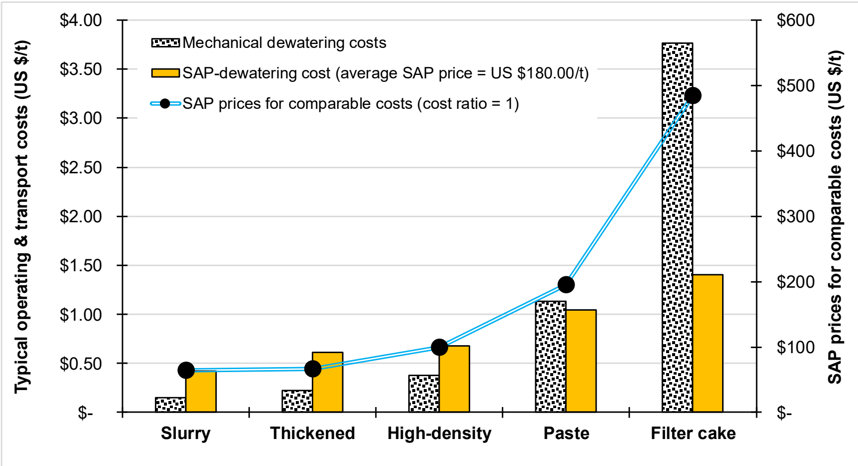

Figure 19. Comparison of the typical operating cost of tailings storage for conventional and SAPs tailings dewatering technologies (the average price of SAPS = US $180/t and 5 cycles of use).

5. Conclusions

The results from this preliminary study show that the use of SAPs reclaimed from unused (virgin) industrial reject of baby diapers should be a promising alternative for tailings slurry dewatering (or densification), owing to their relatively high capacity of water absorption, for surface storage in tailings storage facilities (TSF). The following concluding remarks can be made:

- The target final solids content $C_{w\%\_final}$ of 68% was achieved for the Mine A tailings slurry;
- The coarser super absorbent polymers (SAPs) exhibit a higher absorbency (or equilibrium degree of swelling, Q_{eq}) than the finer super absorbent polymers;
- The contact or residence time of the super absorbent polymers does not have a major impact on the amount of water absorbent capacity;
- Only the SAP dosages ≥ 10 kg/m³ would make it possible to achieve the consistency of thickened tailings with a final solids mass concentration greater than 70%;
- The occurrence of the gel-blocking phenomenon, which is reducing the water absorbent capacity of the super absorbent polymers in geotextile bags, has also been highlighted;
- Preliminary economic analysis has shown that, given the realities of the current SAP market, the costs of dewatering of tailings slurries would be very exorbitant for large-scale application;
- According to the results of this preliminary study, the acceptable price of SAPs would be only 18% of the current minimum market price of US $1000/t (i.e., a price reduction of almost 82%).

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