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Prediction of the long-term performance of green liquor dregs as a sealing layer to prevent the formation of acid mine drainage

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Abstract

One of the mining industry's main concerns is the management of waste rock and tailings generated by sulfide ore extraction. Upon exposure of atmospheric oxygen, iron sulfides oxidize generating acidity. Infiltrating water form a metal-rich acidic leachate called acid mine drainage (AMD), that can cause serious environmental problems. Green liquor dregs (GLD) is a material that resists the passage of oxygen and water and could thus be used to seal mine wastes, preventing their oxidation and AMD formation. To enable its use in dry mine waste covers, the long-term efficiency of such GLD sealing layers must be evaluated. In this study, fresh GLD and GLD aged for 3 to 13 years was collected from two sites and analysed to determine how aging affects its chemical and physical properties. Aged and fresh GLD were very similar with respect to all the properties important in a sealing layer. In particular, there was no evidence of calcite dissolution in aged GLD samples. Aged GLD also exhibited high water saturation (>91%) and chemical stability, both of which are important for effective long-term sealing. The shear strength of GLD deployed in the field increased over time but not sufficiently to ensure the long-term physical integrity of a pure GLD sealing layer. The development of hybrid materials with improved shear strength will therefore be necessary.

Keywords: Sulfidic mine waste; oxidation; water retention capacity; dry cover; remediation

1. Introduction

Tailings and waste rock generated by the mining of sulfidic ores must be managed and disposed of in a way that guarantees the protection of the environment as well as human health and safety. A major problem associated with sulfidic mine waste is the formation of acid mine drainage (AMD) a metal-rich acidic leachate formed by the waste's oxidation that causes serious environmental problems [1]. A common technique for preventing its formation is to bury the waste underneath a dry soil cover whose purpose is to prevent oxygen from reaching the waste and thereby retard its oxidation [2]. The dry cover usually consists of a sealing layer with a high degree of water saturation to prevent oxygen influx and low hydraulic conductivity to limit water infiltration, thereby reducing the amount of drainage water reaching the waste. A protective layer is applied above the sealing layer to protect its integrity. Unfortunately, there is a lack of sealing materials that are both inexpensive and capable of efficiently preventing oxygen and water from reaching the stored waste in the long term. Clayey glacial till is often used as the sealing layer [3] when possible but many mines are not located in close proximity to tills with the necessary properties, creating a need for alternative solutions. Recent studies have shown that certain industrial wastes and residues could potentially be useful in this context [4-7].

One material that has shown particular promise in preventing oxygen and water ingress is green liquor dregs (GLD) [8], which is the largest waste fraction generated during the chemical recovery cycle at sulfate pulp mills and is classified as non-hazardous chemical waste by the Swedish EPA [9]. This alkaline inorganic waste contains calcite, brucite, amorphous phases and insoluble solids, and is known to have low hydraulic conductivity ($<10^{-8}$ m/s) and a high water retention capacity [8]. Previous studies have shown it could be a viable alternative to traditional materials for the construction of sealing layers [8, 10-11]. However, there is a lack of information on its long-term performance, which is required before it can be considered a general solution.

Four main properties have been determined to affect the long-term performance of a dry cover: hydraulic conductivity, water retention capacity, degree of saturation and physical integrity [12].

Identifying how these properties changes as the material ages will make it possible to predict a sealing layer's long-term performance at preventing water and oxygen ingress.

In this study, GLD aged for 3 to 13 years originating from two paper mills was collected from two landfill sites and compared to fresh GLD of the same origin. The aim was to assess how the four key cover performance properties listed above changed as the GLD aged and to thus predict its long-term performance as a barrier to oxygen and water in dry cover applications for sulfidic mine waste.

2. Materials and methods

2.1 Material

Fresh GLD was kindly provided by the Smurfit Kappa (SK) and Iggesund sulfate pulp and paper mills, both of which are located in northern Sweden.

Aged GLD originating from Iggesund was collected at the Iggesund paper mill landfill. GLD has been stored at this site since 1998 in an organized pattern, making it possible to collect GLD of 3, 8 and 13 years of age. Aged GLD (6 years old) originating from SK was sampled at the Rönnskär landfill at Rönnskärsverken, Sweden, where it had been placed as a sealing layer on top of oxidized tailings (applied in 2006). The site had also been used for disposal of snow from large parts of the surrounding industrial area.

2.2 Methods

2.2.1 Sampling

GLD from SK was sampled at a test plot at the Rönnskär landfill using a plastic shovel. In addition, intact soil cores were collected by slowly pushing a 15 cm long cylinder with an internal diameter of 7 cm horizontally into the sealing layer until it was completely filled with GLD. The collected samples were stored at 8 °C until analysis.

GLD from the Iggesund site was collected by drilling using a mobile drill rig (Georig 607, Geotech Ltd, Askim, Sweden). Samples were taken with an auger to enable sampling at different depths and the acquisition of material of different ages. The samples were then placed in diffusion bags. Pictures were taken of frozen GLD collected from the upper part of the landfill.

2.2.2 Physical properties

Water retention capacity (WRC) was measured on aged and fresh GLD in duplicate. The samples were packed into cylinders and saturated from below. The cylinders were then placed on a ceramic plate and pressurized from below using a pressure plate apparatus (Soilmoisture Corp., USA). The volume of the loose samples was calculated from their bulk density, which was determined from the weight of the dried samples (105 °C for 24 h) divided by the cylinder volume. The total porosity of the GLD samples was calculated according to the following equation: Total porosity = (Particle density – Bulk density) / Particle density. The bulk density of the GLD sealing layer at the Rönnskär landfill was measured in the field by means of a Balloon Densometer Test (n=1). A multivolume helium pycnometer (Pycnometer 1305, Micromeritics, Nercross, GA, USA) was used to determine the compact density of fresh and aged GLD originating from Iggesund (n=2) and aged GLD originating from SK (n=3). The compact density was then used to calculate the GLD's porosity (n), pore number (e) and degree of saturation (S_r).

Ground penetrating radar (GPR) is a geophysical technique for imaging the shallow subsurface by transmitting high-frequency electromagnetic waves into the ground [13-14]. GPR surveys were carried out across the Rönnskär landfill to characterize the integrity of the sealing layer. A RAMAC GPR system (Malå Geoscience, Sweden) was used with 800 MHz and 500 Mhz monostatic shielded antennas (Malå Geoscience, Sweden). GPR profiles were obtained by manually towing the antenna along measured survey lines across the landfill. A “hip chain” was used to trigger each measurement and keep track of distance along the profiles. The sampling frequency was 2500 MHz and a trace interval of 2 cm was used. The number of stacking was set to 8. After acquisition, the profiles were subjected to post-survey

processing including time zero adjustment, subtraction of DC-shift and dewow, gain function, bandpass filter and background removal using the Reflex2Dquick software package (Sandmeier scientific software).

Cone Penetration Test (CPT) measurements were performed at both landfills according to a standard procedure [15] to determine each tested material's undrained compressive strength (τ_{fu}) and angle of internal friction (ϕ).

Cylindrical specimens (5 cm x 10 cm) of fresh GLD from Iggesund (n=2) and aged GLD (n=3) collected at the Rönnskär site were tested under uniaxial compression with an air-hydraulic apparatus. Compression tests were carried out at a deformation rate of 1.5 mm/s.

The dry matter content of fresh and aged GLD from Iggesund and SK was determined (n=3) according to the standard method [16]. Paste pH was analyzed on fresh and aged samples (n=3) with a pH meter (Metrohm Ltd, 704 pH Meter, Herisau, Switzerland) as described previously [17].

Hydraulic conductivity tests on fresh and aged GLD (n=3) from SK were carried out with the Constant Rate of Strain (CRS) method according to a standard procedure [18]. Cylinders measuring 15 cm x 7 cm in diameter were filled with GLD. The samples were then placed under a 30 kPa load for 28 days to mimic the conditions encountered in a 1.5 m protective cover. The cylinders were placed in an oedometer and subjected to a progressively increasing induced stress. Drainage was only allowed from the top. The hydraulic conductivity was calculated based on the deformation and the pore pressure from the lower surface. Hydraulic conductivity tests on Iggesund GLD of 0 (fresh), 3, 8 and 13 years of age were performed in duplicate by the Constant Head Permeability (CHP) method according to a Swedish standard [19] and their results were interpreted using Darcy's equation. Water was pressed through the column from below and collected in sampling bottles using a constant water head. The amount of permeated water was monitored continuously. The samples' density was then calculated, enabling their water content to be determined after drying at 105 °C for 24h.

2.2.3 Chemical properties

Batch leaching tests on fresh GLD from SK and Iggesund were performed in duplicate according to a modification of the Swedish Standard SS-EN 12457-4 [20]. Samples containing 20 g of GLD on a dry matter basis were placed in 250ml centrifuge bottles (Beckman coulter) and 200 ml of Milli-Q water with pH of 6.3 (matching that of the local snow) was added to achieve a liquid/solid (L/S) ratio of 10. The mixtures were then shaken with an end-over-end shaker for 24 hours and centrifuged at 4000rpm for 10 min, after which 20% of the supernatants were removed and filtered through a 0.22 μ m filter. The leachates' pH, electrical conductivity (EC) and redox potential (E_h) were analyzed immediately using a Voltkraft PH-100ATC pH meter, a WTW Multi 350i multimeter (type Level 1 with WTW 323 electrode, Weilheim, Germany), and a pH/ion meter (Radiometer, Copenhagen, Denmark) with an Ag/AgCl electrode, respectively. E_h values were obtained by adding 207 mV to the readings obtained with the pH/ion meter. Chemical analyses were conducted by an accredited laboratory (ALS Scandinavia AB, Luleå, Sweden). After the leachate's removal, the bottles were topped up with additional Milli-Q water to restore an L/S ratio of 10, and the leachate collection and analysis procedure was repeated as described above on day 3 and day 25 after the establishment of the experiment.

Another series of batch leaching experiments were performed in duplicate using fresh GLD from Iggesund according to a previously described method [21]. Samples containing 10g of GLD on a dry matter basis were placed in a 150 ml polypropylene bottle together with 100 ml of Milli-Q water to establish an L/S ratio of 10. The resulting mixtures were agitated on a shaker at 6 rpm for about 24 hours, which was previously shown to be sufficient time to establish near-equilibrium conditions when dealing with fine-grained residues [22]. The mixtures were then left to stand for 2 days, after which the supernatants were collected and filtered through a 0.22 μ m filter. Their pH was measured with a Voltkraft PH-100ATC pH-meter and their alkalinity was calculated by titration with 0.1M HCl. The bottles were then refilled with the same amount of Milli-Q water to restore an L/S ratio of 10, and the procedure was repeated. After 13 such cycles, the samples were transferred to 1L polypropylene bottles and the

experiment continued with increasing L/S ratios over 13 further cycles, terminating at an L/S ratio of 1800.

3. Results and Discussion

3.1 Changes in physical properties

Hydraulic conductivity tests showed no significant difference in hydraulic conductivity between fresh and aged GLD originating from Iggesund (Table 1). However, the hydraulic conductivity of aged GLD from the Rönnskär site was one order of magnitude higher than that of fresh GLD. This was probably because the GLD at the Rönnskär site had reacted with the underlying tailings, since it has been shown that the tailings below the GLD sealing layer had undergone extensive oxidation and were very acidic when the sealing layer was applied [23]. However, the measured hydraulic conductivity of $10\text{E-}8$ m/s did not appear to affect the sealing layer's function since aged GLD from the two sites exhibited high levels of water saturation (91-100%; see Table 2). This can be related to the material's high ability to hold water (Fig. 1), which is expected to minimize the passage of oxygen by ensuring that the GLD layer remains saturated or almost saturated. High water retention also reduces the risk of shrinkage and cracking due to desiccation, which is a common problem with clay minerals and can have significant adverse effects on sealing layer performance. The material's high water retention capacity may be due to the ionic charges on its constituent particles' surfaces [24-25]. Earlier studies showed that the rate of oxygen diffusion decreases significantly as the degree of saturation increases above 85% [26]. A pressure of -20kPa was required to reduce the S_r of GLD of 13 and 8 years of age to 85% (Fig. 1), while GLD aged 0, 3 and 6 years exhibited a S_r of 92% at the same pressure. At the field capacity of soil (-10kPa), the GLD samples exhibited a S_r of 94-98%. The high water content of GLD and the strength of its binding to water are major advantages for a sealing material because they encourage the formation of a water-saturated layer that will prevent oxygen penetration.

The use of frost-sensitive materials in sealing layers presents a risk of ice lens formation, which could damage the sealing layer via frost heaving if it is close to the ground surface in a cold region. Moreover, when ice lenses melt, they form channels that can potentially allow water and oxygen to pass through the sealing layer and reach the underlying tailings, thus impairing the sealing layer's function. Channel propagation is a common problem in silty soils [28]. Analyses of frozen GLD samples originating from the Iggesund landfill revealed only minor segregated ice growth, producing pieces of ice that are ~1 mm wide (Fig. 2). These would be expected to thaw during the summer and would not cause remaining channels because of GLD's high plasticity [10]. It has previously been shown that subjecting GLD to repeated freeze-thaw cycles did not affect its hydraulic properties [10].

Field analyses indicated that neither aging nor depth altered the texture of the GLD. The measured CPT parameters revealed only minor differences between the two types of GLD and between samples of different depths and ages. However, uniaxial compression tests on aged GLD revealed its compressive strength to be almost three times higher than that of fresh GLD (Table 3). CPT measurements also indicated that the compressive strength of aged samples in the field was around twice that of fresh material. However, although the shear strength of GLD increases with age in field applications, the GPR studies indicated that even aged material is too soft to be used alone in sealing layers: the buried sealing layer exhibited many vertical dislocations such that the distance between its surface and the ground surface varied between 25 and 40 cm (Fig. 3). The GPR data also revealed a section of the sealing layer that appeared paler than the rest, which was attributed to the accumulation of water above the sealing layer resulting in a weakening of the GPR signal. A rupture of the layer was considered unlikely due to the material's softness and plasticity [10]. In some places, the sealing layer had been compressed or dislocated horizontally, causing its thickness to decline from the original 50 cm at the time of application to 20 cm six years later.

It can be concluded that the physical properties of fresh and aged GLD are similar. The aged GLD had not undergone any physical changes that would be expected to alter its performance as a sealing

layer. Its ability to retain water declined somewhat with age, but even old material exhibited a high degree of saturation (91-100%), suggesting that GLD layers would be effective at limiting the amount of oxygen reaching the underlying mine waste. However, the material's low shear strength may cause problems and reduce its long-term performance as a sealing layer because compression could reduce the layer's thickness and reduce its resistance to the passage of water and oxygen. Blending GLD with till to take advantage of the former's favorable hydraulic properties and the latter's mechanical properties has been demonstrated to produce a cover material with improved shear strength [10]. Adding fly ash has also been reported to increase the shear strength of the GLD [11, 29].

3.2 Changes in chemical properties

It has previously been shown that GLD's chemical and mineralogical composition varies with the origin of the wood used at the pulp mill and the mill's GLD retrieval process [8]. This makes it difficult to directly compare fresh and aged GLD. However, comparing the chemical compositions of such materials can still give an indication of how they respond to aging.

Sulfate is a major constituent of GLD. The sulfur concentrations of fresh and aged GLD differed substantially, indicating that sulfur leaching had occurred in the aged material from both Iggesund (Table 4) and Rönnskär (Table 5). Batch leaching experiments on fresh GLD samples confirmed the high leachability of S from the Iggesund material, which lost 16% of its original sulfur content during the first 24 hours of the experiment (Table 4). This is consistent with the results of a previous study on the leachability of GLD [30]. Conversely, only 0.04% of the original S content was lost from the SK GLD over the first 24 hours. This may indicate that the process used at the Rönnskär mill differs slightly from that used at Iggesund, producing more insoluble sulfur species. The Al and K concentrations of aged GLD from the Rönnskär site were lower than those in the corresponding fresh material (Table 5), whereas the concentrations of these elements in the Iggesund GLD varied unpredictably with age (Table 4). K was the most extensively leached of the elements considered in the batch tests: fresh GLD samples from Iggesund and SK lost 40% and 15% of their original K contents over 24 hours' leaching. In contrast, the rate of Al

leaching from fresh GLD in the batch tests was quite low for both the SK and Iggesund materials. It is therefore possible that the large variation in the Al contents of the aged GLD samples was due to natural variation between samples rather than leaching. The same applies to Mn and Mg, whose concentrations varied widely in the aged GLD samples, especially at the Rönnskär site (Table 5) but which exhibited no appreciable leaching during the batch tests with either material. Some leaching of Cr may have occurred since the concentration of this metal in aged GLD was lower than in fresh material. In the batch leaching experiments, 1.7% of the SK GLD's Cr content was lost over the first 24 hours (Table 5). Other elements whose concentrations in aged Rönnskär GLD were lower than in fresh material and which may therefore have leached included Ni, Cu, Co and Cd. These elements exhibited moderate levels of leaching on day 1 of the batch leaching test (0.01-0.2%). The calcium in the GLD is expected to originate from calcite as previous mineralogical analysis showed the presence of this mineral [8]. Calcite has low solubility in neutral and alkaline water but dissolves more readily in acidic water [31]. The calcium concentrations of the aged GLD at Rönnskär and Iggesund were similar to or greater than those of fresh GLD, indicating that the rainwater that had percolated through the GLD had not dissolved its calcite. The slightly acidic milliQ water (pH 6.3, chosen to match the pH of the melted snow at the site) used in the batch leaching test also did not dissolve the calcite present in fresh GLD. One of the original concerns about using GLD in sealing layers was the potential dissolution of calcite, which could cause free Ca^{2+} to precipitate as gypsum and significantly change the material's texture and structure. If gypsum had formed in this way, the CPT results would have indicated the presence of hard sections, but the GLD was found to be soft all the way from the top to the bottom of the landfill. The cold and only slightly acidic rainwater was thus incapable of dissolving the calcite. In addition, the GLD is alkaline independent of its calcite content [32], which would disfavor calcite dissolution.

The pH of the GLD at the Rönnskär landfill had decreased from 12.5 to 9.3 over six years (Table 2). At the Iggesund landfill site, the pH of the aged GLD varied between 9.3-11.0 and was lower than that of the fresh material. It is not clear to what extent this variation is due to natural variation between batches or the dissolution of alkaline compounds. The pH and alkalinity of fresh Iggesund GLD decreased

steadily during titration, eventually stabilizing at an L/S of 40 (Fig. 4). The pH stabilized at ~10 and remained at this value until the test concluded at an L/S of 1800. The aged GLD at the Rönnskär landfill had probably already reached this stage whereas many samples from the Iggesund site had not. The samples at the Rönnskär site exhibited greater variation with age. This was attributed to the superficial placement of the GLD at this site and its reactions with the acidic tailings combined with the fact that the site had been used for snow disposal, causing large stress on the sealing layer during snow melt. Deep furrows caused by loaders' wheels were visible at the site. The site also lacked drainage so large quantities of water may have percolated through the sealing layer, which exhibited dislocations in the radiogram image. Based on the slow decrease in pH observed during the sequential leaching of fresh GLD from Iggesund, during which the samples were shaken extensively, the calcite in this material is not expected to dissolve to an extent that would affect its quality as a cover in the long term.

The time required for a GLD cover to become non-functional in the field was estimated on the basis of the materials' density and hydraulic conductivity as well as their performance in the batch leaching experiments. A 30 cm thick GLD sealing layer with a hydraulic conductivity of $1\text{E-}08$ m/s would retain its buffering capabilities (i.e. would not suffer appreciable calcite dissolution) for more than 200.000 years.

4. Conclusions

The effects of aging on GLD largely depend on the amount of water that passes through the material, changing its chemical composition and ultimately its pH. A previous study on fresh GLD showed that while samples varied in their chemical composition, their hydraulic conductivity, buffering capacity, pH, and particle sizes were all rather consistent [8]. This is consistent with our findings, which revealed no great changes in the properties of GLD after several years' use in a sealing layer: the material exhibited a WRC of >85% under field conditions and retained a high degree of water saturation with low hydraulic conductivity independently of its age.

Some elements, primarily sulfur and potassium, can be expected to leach from GLD-based sealing layers over time. However, the loss of these elements does not seem to affect its performance as a cover. The shear strength of the GLD increased over time in the field but not to a degree that would ensure the long-term integrity of the sealing layer. Improving its shear strength is therefore a necessity. It is important for the dry cover to be correctly installed with a 1.2-1.5 m protective layer above the sealing layer to protect the sealing layer from additional stress of the sort observed at the Rönnskär site.

The results indicate that GLD is not expected to undergo any physical or mineralogical changes that will affect its ability to prevent oxygen from reaching underlying mine waste. The major concern is that its major constituent, calcite, might dissolve and fundamentally change its properties. However, there is no indication that this will occur over periods of thousands of years. Therefore GLD is expected to be a viable sealing layer for mine waste in the long term.

While this study examined GLD samples of various ages, it provides no information on the material's responses to climatic changes such as transitions from dry to wet periods. A 400m² pilot scale study using a blend of GLD and till as a sealing layer has been established and is being monitored. This will hopefully provide more detailed insight into the cover system's performance and enable long-term evaluation of its behavior *in situ*.

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Figure Captions

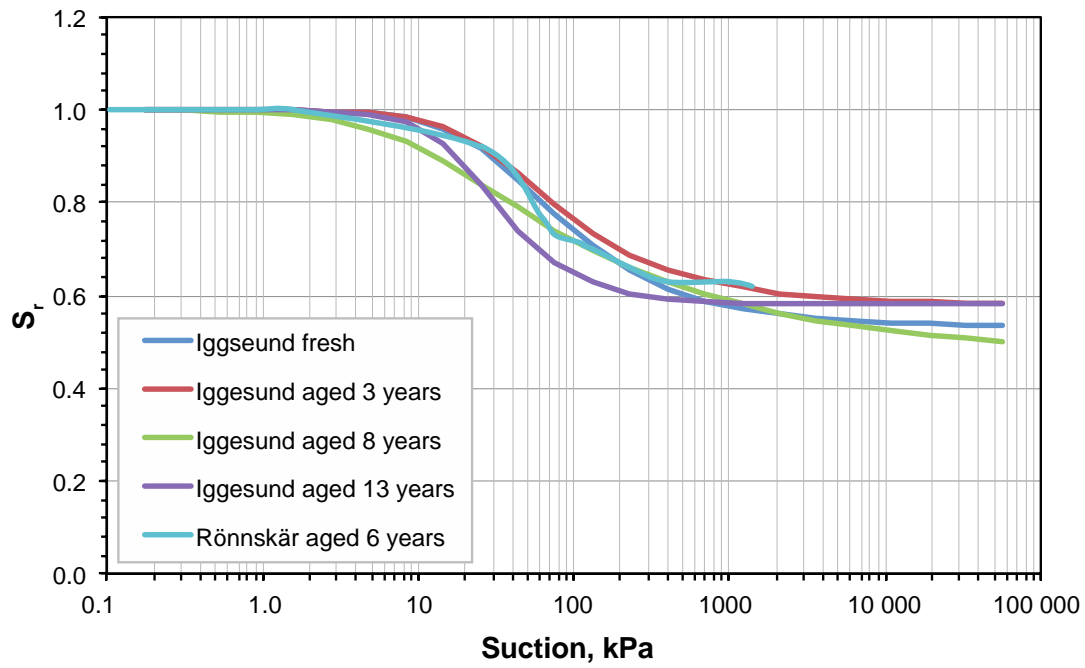


Figure 1. Water retention capacities of aged GLD from the Rönnskär and Iggesund sites and fresh GLD originating from the Iggesund paper mill. Note the variation between GLD samples of different ages.



Figure 2. Small (~1 mm) segregated ice growths (indicated by arrows) visible in frozen GLD sampled from the Iggesund landfill. The white sections are lime mud originating from the filter used during the collection of GLD in the paper mill.

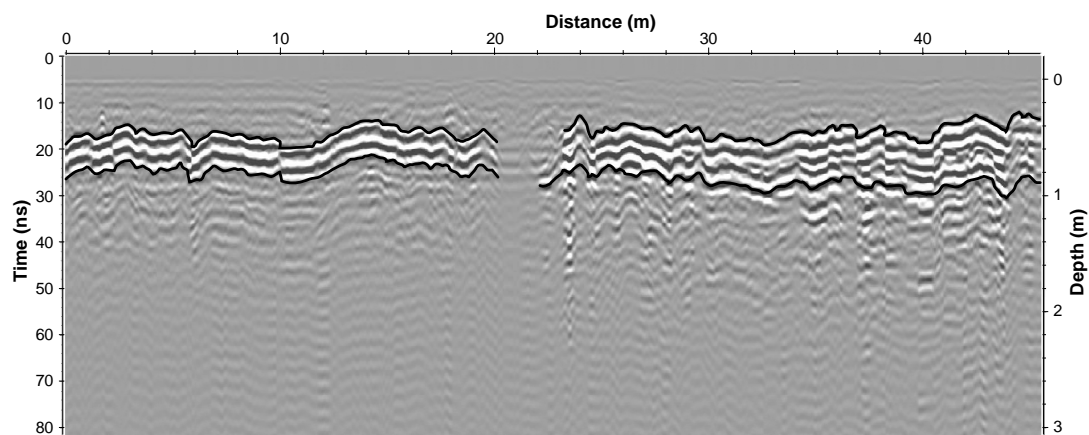


Figure 3. A 45 m GPR profile of the GLD sealing layer at the Rönnskär site showing its integrity after 6 years in operation. Vertical dislocations and variations in the thickness of the GLD sealing layer are visible. The pale spot in the layer at 20-23 m is probably due to the accumulation of water above the surface of the GLD.

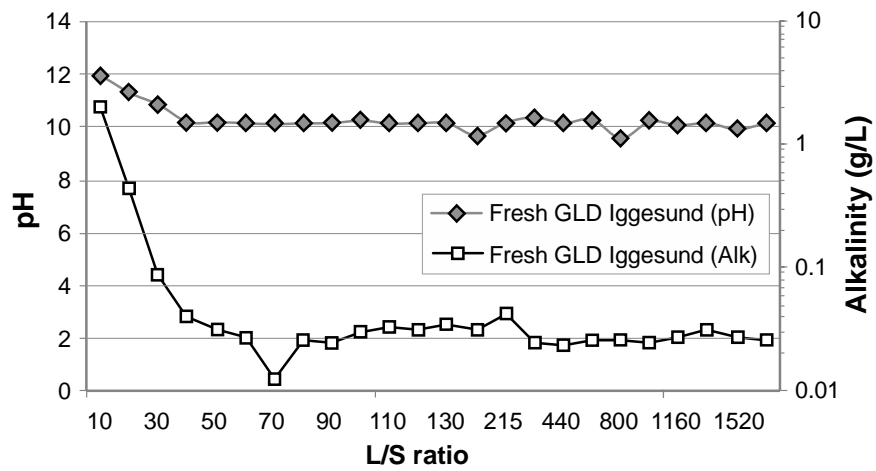


Figure 4. pH and alkalinity (g/L) as CaCO_3 of fresh GLD from the Iggesund paper mill.

Tables

Table 1. Hydraulic conductivity, dry matter content (DM) (n=4), dry density (ρ_d) and water content (w) of aged and fresh GLD. SK Rönnskär refers to GLD originating Smurfit Kappa placed at the Rönnskär landfill whereas SK refers to fresh GLD from Smurfit Kappa. Data for the fresh GLD are included for reference purposes [27]. Fresh and aged Rönnskär GLD samples were analyzed in triplicate.

Sample	Age	Depth (m)	w ₁ (%)	w ₂ (%)	k ₁ (m/s)	k ₂ (m/s)	ρ_{d1} (t/m ³)	ρ_{d2} (t/m ³)	DM
Iggesund	~13	6.7-7.0	54	56	8.69E-09	7.42E-09	0.99	1.01	59±6
Iggesund	~8	4.6-5.0	61	58	1.60E-08	6.80E-08	1.04	1.04	63±3
Iggesund	~3	1.5-2.0	75	78	8.26E-08	1.78E-08	0.93	0.88	62±3
Iggesund	0	0	115	117	2.74E-08	3.31E-08	0.65	0.64	60±4
SK Rönnskär	6	0.5	191	192	3.67E-08±2.9E-09		N/A	N/A	41±5
SK	0	N/A	N/A	N/A	3.23E-09±3.26E-09		N/A	N/A	44±4

Table 2. Properties of aged and fresh GLD. The dry density (Table 1) was used to calculate the porosity (n), pore number (e) and degree of saturation (S_r). Compact density (ρ_s) and pH values are reported as averages of three measurements. SK Rönnskär refers to GLD originating Smurfit Kappa placed at the Rönnskär landfill whereas SK refers to fresh GLD from Smurfit Kappa.

Sample	Age (years)	Depth (m)	ρ_1 (t/m ³)	ρ_2 (t/m ³)	ρ_s (t/m ³)	S_r (%)	e	n (%)	pH
Iggesund	~13	6.7-7.0	1.53	1.58	2.58	91	1.57	61	10.3±0.1
Iggesund	~8	4.6-5.0	1.68	1.63	2.66	100	1.48	60	9.8±0.5
Iggesund	~3	1.5-2.0	1.62	1.57	2.58	100	1.85	65	10.2±1.2
Iggesund	0	0	1.39	1.39	2.56	100	2.99	75	12.5±0.1
SK Rönnskär	6	0.5	1.2	N/A	2.12±0.16	98.6	4.3	80	9.3±0.3
SK	0	N/A	N/A	N/A	N/A	N/A	N/A	N/	12.2±0.2

Table 3. Parameters obtained from the CPT data and uniaxial compressive strength tests.

Material	CPT measurements		Lab measurements
	Median undrained compressive strength, τ_{fu} (kPa)	Angle of internal friction, ϕ (°)	Uniaxial compressive strength, τ_{fu} (kPa)
GLD Rönnskär (aged)	67.5	38.7	27.4±7.8
GLD Iggesund (aged)	55.9	35.2± 2.7	N/A
GLD Iggesund (fresh)	N/A	N/A	11.8±2.2

Table 4. Metal concentrations in GLD from Iggesund (n=1) fresh (n=3) expressed on a dry matter basis. Results from the batch leaching tests on fresh GLD from Iggesund at an L/S ratio of 10 are also shown. Results are quoted in terms of the %age loss relative to the original elemental content.

Element	Sample batch				Batch leaching at L/S 10		
	0 years (mg/kg)	~3 years (mg/kg)	~8 years (mg/kg)	~13 years (mg/kg)	Day 1 (%)	Day 3 (%)	Day 25 (%)
Dry matter (DM)	57.0±0.8%				N/A	N/A	N/A
Si	3300±490	68.4%	66.3%	62.3%	N/A	N/A	N/A
Al	6700±160	84100	7940	37900	3.8E-3	3.7E-3	-2.3E-3
Ca	295000±540	20800	4440	10700	1.7E-3	3.4E-4	-8.3E-4
Fe	0	236000	339000	310000			
K	7920±910	13200	5380	6790	2.9E-3	1.6E-4	-1.4E-3
Mg	3410±190	8590	2020	6290	40.0	0.2	0.7
Mn	30500±390	29300	20600	16200	8.2E-3	1.6E-3	-5.1E-3
P	17300±390	9370	6890	4980	4.6E-4	1.6E-4	-1.0E-4
LOI 1000 °C	1490±10	2370	3700	3540	N/A	N/A	N/A
	36.1±0.2%	32.8%		36.5%	N/A	N/A	N/A
As	DM	DM	40.3% DM	DM			
Cd	0.19±0.08	0.90	0.24	1.15	0.2	-0.8	0.3
Co	14.7±0.3	5.9	7.8	3.6	4.7E-3	4.8E-4	-5.7E-4
Cr	12.9±0.2	10.7	8.4	5.6	8.7E-3	8.9E-5	-2.0E-3
Cu	97.3±6.7	97.5	93.0	44.1	6.1E-3	3.2E-4	-1.6E-3
Hg	170±2	135	98.3	60.4	5.2E-3	-2.1E-3	3.8E-5
Ni	<0.04	<0.04	<0.04	0.0415	0.3	0.1	0.05
Pb	64.6±0.6	43.2	49.6	29.2	0.2	0.01	0.02
S	26.1±0.3	22.3	46.9	25.4	4.4E-3	7.6E-4	7.7E-4
Zn	22000±400	2900	8030	8450	15.7	3.6E-4	2.1
	2800±40	1810	1430	1110	6.6E-4	0.1	2.2E-4

Table 5. Metal concentrations in GLD from SK (fresh GLD) ($n=5$) and SK Rönnskär (aged GLD) expressed on a dry matter basis. Results from the batch leaching tests on fresh GLD from SK at an L/S ratio of 10 are also shown. Results are quoted in terms of the %age loss relative to the original elemental content.

Element	Sample batch			Batch leaching L/S 10		
	0 years (mg/kg)	6 years a (mg/kg)	6 years b (mg/kg)	Day 1 (%)	Day 3 (%)	Dag 25 (%)
Dry matter (DM)	41.7±5.8%	36.3%	53.0%	N/A	N/A	N/A
Si	44000±39400	6260	3380	N/A	N/A	N/A
Al	122000±144000	3500	2080	0.08	0.01	-9.9
Ca	220000±71600	208000	334000	3.1E-3	6.5E-4	1.6E-3
Fe	8100±5500	6130	2810	2.5E-4	5.0E-5	1.1E-3
K	12600±1600	7360	<750	15.3	-5.6E-3	0.2
Mg	22200±6440	43800	21200	1.0E-4	2.0E-3	1.2E-4
Mn	10000±2900	19400	9060	3.2E-3	4.3EE-5	5.1E-3
P	3770±1130	3240	5540	N/A	N/A	N/A
LOI 1000 °C	59.3±2.6% DM	53.0% DM	45.3% DM	N/A	N/A	N/A
As	2.2±1.9	1.6	<0.1	1.9	0.2	0.1
Cd	8.0±2.2	9.3	5.8	0.01	-4.9E-4	5.2E-3
Co	8.4±2.2	12.2	5.5	0.1	1.8E-3	-6.2E-3
Cr	132.7±117.3	140	71.7	1.7	0.09	0.4
Cu	196.4±144.7	156	69.8	0.2	0.03	0.4
Hg	<0.04	<0.04	<0.04	3.2E-4	0.05	0.05
Ni	77.3±63.3	111	70.1	0.2	4.5E-3	-0.01
Pb	21.0±5.4	16.4	10.4	8.1E-3	-2.89E-4	9.3E-3
S	14100±2130	7150	1760	0.04	-0.7	-2.6
Zn	1390±524	2120	1020	0.03	2.9E-3	0.1