



The Drivers of Hydraulic Conductivity in Green Liquor Dregs Amended Till: Application to Reclamation of Acid Generating Mine Sites

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Abstract

The mining industry produces massive amounts of waste that in contact with oxygen can result in leaching of metals. Access to a suitable cover-material for the mine waste is sometimes limited, creating a driving force for recycling industrial residues for these purposes. Green liquor dregs (GLD), an industrial residue from paper and pulp production, has the potential to be used in a sealing layer as an amendment to till. Though hydraulic conductivity is commonly used to evaluate the quality of the sealing layer, field application from laboratory investigations is challenging as many factors, apart from vast variations in the physical properties of both the till and the GLD, control hydraulic conductivity. In this study, 5–20 wt.% of GLD from two different paper mills, with different total solid contents and particle size distributions, were mixed with a silty till with varying total solid contents to investigate how the materials' dry density, initial water content, and compaction affects the hydraulic conductivity. We found that the initial water content of the materials was the most important factor. With a drier till and GLD, more GLD should be added to attain the lowest hydraulic conductivity possible. The compaction was not found to notably affect the mixtures' hydraulic conductivity.

Keywords Industrial residue · Circular economy · Sealing layer · Optimum water content · Compaction effort

Introduction

Mining is one of the biggest producers of waste. In Sweden, 104 million tons of mine waste was generated in 2018, accounting for 75% of all waste generated that year (Avfall Sverige 2020). Approximately 70% of Sweden's mine waste contains sulfide minerals (SGU and Swedish EPA 2017) with the potential to produce acid rock drainage (ARD) by chemical and biochemical oxidation (Egierbor and Oni 2007) if the waste is in contact with oxygen and humidity (Saria et al. 2006). ARD is a major long-term threat to the environment as metals and metalloids may become mobile (Saria et al. 2006). The GARD (global acid rock drainage) guide (Verburg et al. 2009) categorizes different methods to prevent ARD after closure into two main categories; engineered barriers and water covers. Engineered barriers can be divided into liners and dry covers. Liners are typically

designed to act as a barrier for contaminant flow from the overlying waste into the receiving environment, while dry covers are usually designed to limit the ingress of water and oxygen into the underlying waste. Under the relatively humid climatic conditions in Sweden where precipitation exceeds evaporation, a dry cover is preferably used to reduce the oxygen flux to the underlying reactive wastes, and thus reduce ARD (Bussière et al. 2003; Collin and Rasmuson 1990; Dagenais et al. 2006). The sealing layer is the key element of a dry cover and consists of a fine-grained material applied just above the mine waste. It is followed by a protective layer, which protects the sealing layer from frost and root-penetration. A vegetation layer on top protects the protective layer from erosion. The main function of the sealing layer is to limit oxygen diffusion through the cover into the waste dump, thereby preventing the oxidation of sulfides and the generation of acidic drainage and release of metals (Höglund et al. 2004). Another function of the sealing layer is to limit the infiltration of precipitation into the waste dump, which according to Swedish standards, requires a hydraulic conductivity below 10^{-8} m/s. In addition to a low hydraulic conductivity, a sealing layer generally has good water retention properties leading to a high

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degree of water saturation (Höglund et al. 2004) reducing the oxygen flux to a level comparable to that of a water cover (Aachib et al. 2004; Yanful 1993). Due to challenges measuring oxygen diffusion, mainly due to oxygen leakage from the atmosphere, hydraulic conductivity is often used to estimate the quality of a sealing layer. Several factors control the hydraulic conductivity of a material. Studies by Leroueil et al. (2002) and Watabe et al. (2000) on glacial till have shown that hydraulic conductivity is highly dependent on the degree of compaction, with significantly decreasing hydraulic conductivity as the void ratio during loading decreases. Furthermore, the molding water content in the material affects the hydraulic conductivity (Benson and Trast 1995; Leroueil et al. 2002); a study conducted by Benson and Trast (1995) on compacted clays showed that the lowest hydraulic conductivity was reached at a molding water content 1–2% wetter than the optimum water content for the material.

Hargelius et al. (2008), Mäkitalo et al. (2015a, b), Nigéus et al. (2023), and Virolainen et al. (2020) have shown that a residue from pulp production, green liquor dregs (GLD), has potential to be used in a sealing layer as an amendment to till. The GLD consist of a fine material that can fill up the pores of the till and potentially decrease its hydraulic conductivity. GLD is an alkaline, inorganic waste originating from the recycling process at sulfate pulp and paper mills. The main solid compounds of GLD consists of CaCO_3 , $\text{Mg}(\text{OH})_2$, C, and metal sulfides, especially FeS (Jia et al. 2014; Sanchez and Tran 2005). The liquid phase of the GLD consists of Na_2CO_3 and NaOH, which generates its characteristic high pH. GLD is generally inert (Mäkelä and Höynälä 2000) and has the same grain size distribution as silt (Mäkitalo et al. 2014). Other characteristics of GLD are its high pH (10–11), relatively high porosity (73–82%), a bulk density of 0.44–0.67 g/m^3 , a compact density of 2.47 to 2.60 g/cm^3 , a low hydraulic conductivity (10^{-8} and 10^{-9} m/s), and a high water retention capacity (Mäkitalo et al. 2014). Sequential extraction performed on GLD has shown relatively low bio-availability of metals in general (Mäkelä and Höynälä 2000; Nurmesniemi et al. 2005), though Bandarra et al. (2019) denoted a "possible hazard" based on the chemical analysis of GLD and because biotests in their study indicated high ecotoxic effects for three out of five organisms. However, when GLD is used as an amendment to till, only a small amount of GLD is required in the mixtures (< 20 wt.%), and the mixtures are in a sealing layer that retains the water reaching it. This means that there should not be much chemical leachate from the GLD reaching the biosphere. However, this needs further investigations.

Nigéus et al. (2023) studied how the hydraulic conductivity of a mixture of GLD and till was affected by different amounts of fines/clays and found that the clay content played a major role in determining the final hydraulic conductivity of the mixture. The higher the clay-content, the lower the

hydraulic conductivity. That study also suggested that there might be other factors, such as initial water content, dry density after compaction, and degree of compaction, that could affect the hydraulic conductivity of the GLD-till mixtures. In this follow-up study, 5 to 20 wt.% GLD from two different paper mills, with different total solid content (TSC) and particle size distributions (PSD) were mixed with a silty till with different TSCs. The purpose was to investigate how the initial water content, compaction effort, and dry density after compaction affect the hydraulic conductivity. A maximum of 20% naturally wet GLD was added as a mixture with a higher GLD content can cause liquefaction and compaction difficulties.

The hypothesis was that a lower initial water content of the till and GLD would lead to less hydraulic conductivity when higher amounts of GLD was added. The final water content after compaction would then be closer to the optimum water content. The mixtures were expected to reach the lowest hydraulic conductivity at a water content a few percent higher than the optimum water content and the addition of small amounts of GLD to the mixtures was expected to yield a higher dry density and lower hydraulic conductivity, due to the added fines decreasing its porosity. However, as the amount of GLD increases, other properties of the GLD, such as its low shear strength and high water content, could also influence the hydraulic conductivity of the mixtures. The objectives of this experimental study were to find out: (i) how the initial water content of a silty till and GLD respectively affects the hydraulic conductivity of the mixtures; (ii) how the dry density after compaction correlates with the hydraulic conductivity of a silty till and its mixtures with GLD; and (iii) how compaction effort affects the dry density and hydraulic conductivity of the silty till-GLD mixtures.

Materials and Methods

Materials

A silty till (SiT) from a till quarry (Brännkläppen in Boden, Sweden) was used as the bulk material. The till was air dried and sieved through a 20 mm sieve and the particles above 20 mm removed, which is praxis for a material that is to be used in a sealing layer as these particles could negatively affect the effectiveness of the sealing layer.

GLD from two different paper mills (GLD1, the Smurfit Kappa paper mill, Piteå, Sweden and GLD2, the Billerud Korsnäs paper mill, Kalix, Sweden) were used in the experiments. The GLDs were collected in sealed plastic containers to preserve the water content of the materials.

The till was mixed with 5, 10, 15, and 20 wt.% of GLD. The weight percentage was calculated towards a dry till and

a naturally moist GLD. The GLD was kept naturally moist in sealed containers, as previous unpublished studies had shown it to be difficult to affect its physical properties by rewetting. The mixing was carried out by hand with a small shovel until the mixture appeared to be homogenized.

Particle Size Distribution

The till was washed and dry sieved according to SS-EN 933–1:2012 to obtain the weight percentage of fines in the material. A mechanical sieve tower (Retsch AS 200) with an amplitude of 2.2 mm/g was used. The cut-off sizes were 12.5, 10, 8, 5, 4, 2, 1, 0.5, 0.25, 0.125, and 0.063 mm.

Particle size distribution (PSD) for the fines and the two GLD were determined by laser diffraction analysis on triplicate samples of each material by a CILAS Granulometer 1064 (CILAS, Orléans, France). The PSD was then calculated using CILAS software. The results are presented in Fig. 1.

Particle Density

The particle density of the materials was determined using an AccuPyc II 1340 Pycnometer and the results are presented in Table 1.

Total Solid Content

The total solid content (TSC) of each material and mixture used for the hydraulic conductivity analysis were evaluated by drying them in an oven (105 °C for 24 h) according to the SIS standard SS-EN 14,346:2007 and are presented in Table 1.

Proctor Compaction

Proctor compaction (PC) was carried out according to standard SS-EN 13286-2:2010. Also, a lighter compaction weight compared to standard PC and drop length was used in this study. For the light Proctor compaction (LC), a 2.5 kg weight was dropped from a height of 30 cm onto the sample. The PC tests were started with triplicates, but the first results showed very little variation, so only one or two repetitions were made thereafter. The PC was done on air-dried till and naturally moist GLD (TSC 43% for GLD 1 and 58% for GLD 2; Table 1).

Hydraulic Conductivity

Hydraulic conductivity was measured on a moist (SiTm; TSC 91 ± 1%, n = 24) and a drier till (SiTd; TSC 96%) with 5, 10, 15 and 20 wt.% addition of GLD. The constant

Fig. 1 Particle size distribution (PSD) of the silty till (SiT) and the two different GLD (GLD1 and 2)

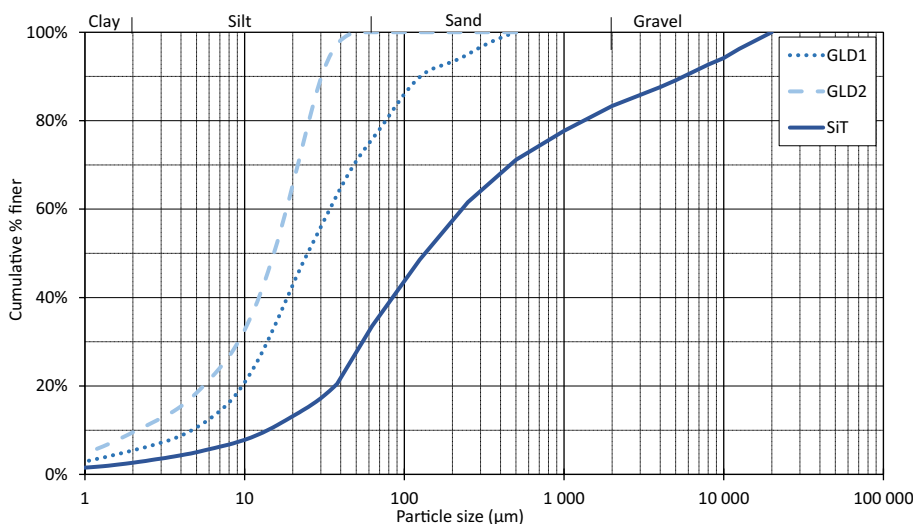


Table 1 Particle density (g/cm³), total solid content (TSC), percentage of fines and clays in the two tills (SiT-moist and dry) and GLDs (GLD1 and 2), N = number of analyzed sets

Material	Particle density (g/cm ³)	TSC (%)	Fines (% < 63 µm)	Clay size (% < 2 µm)
SiTm	2.71	91.5 ± 0.4% (N = 9)	34 ± 5 (N = 9)	2.6
SiTd	2.71	96%	34 ± 5 (N = 9)	2.6
GLD1	2.49	43 ± 4% (N = 12)	76 ± 29 (N = 3)	5.4 ± 4.1 (N = 3)
GLD2	2.63	58 ± 0.3% (N = 3)	100 ± 0 (N = 3)	9.5 ± 1.6 (N = 3)

head-method was used (Sandoval et al. 2017) in airtight cylinders with a volume of 996 cm^3 . The walls of the cylinders were coated with a thin layer of bentonite to prevent preferential wall flow. The mixtures inside the cylinder were compacted with standard PC. Silty till with an addition of 5–20 wt.% of GLD1 was also compacted with a LC. Water was connected to the bottom of the cylinder with a hydraulic gradient of 8.7. The water passing through the cylinders were collected in plastic bottles, sealed from the top to prohibit evaporation. The plastic bottle was weighed regularly, and the time was noted to measure the velocity of the water passing through the sample. The hydraulic conductivity was calculated using Darcy's law and the analysis was done with three sets of each sample.

Results and Discussion

The Effect of Initial Water Content on Hydraulic Conductivity

A lower initial water content of the till and GLD was expected to decrease the hydraulic conductivity when more GLD was added, as the final molding water content of the mixture would then be closer to the optimum water content. This hypothesis was confirmed in this study. The mixture with the wetter till (SiTm-GLD1) decreased from 3- to $2 \times 10^{-8} \text{ m/s}$ with an addition of 5 wt.% of GLD, and then increased with further addition of GLD (from 2- to $7 \times 10^{-8} \text{ m/s}$; Fig. 2A; Table 2). In the drier

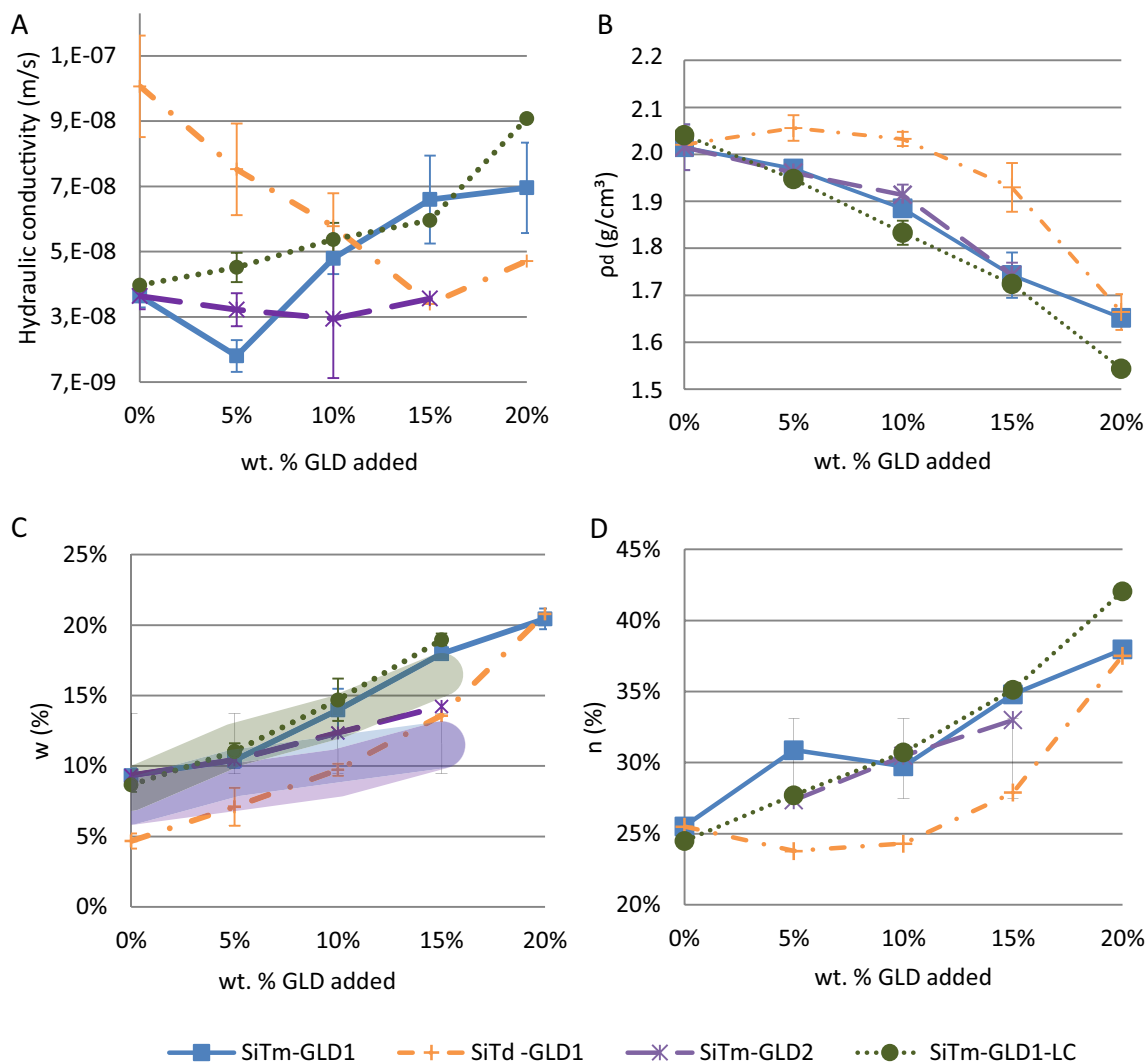


Fig. 2 A Hydraulic conductivity, B dry density after compaction (ρ_d), C water content (w), and D) porosity (n) in the different mixtures of till and GLD. *SiTd* represents a till with half the water content that was used in *SiTm*. *SiTm-GLD1-LC* is compacted with less compac-

tion effort (lower weight and drop height) than a standard Proctor compaction. The transparent thick lines in fig C are the 1–2% wet of optimum w for each mixture

Table 2 Hydraulic conductivity, dry density (ρ_d), compaction degree (R_D), water content (w), if the mixtures are wet of optimum w , porosity (n), void ratio (e), maximum ρ_d and optimum molding water content (omw) of the different mixtures are presented

	GLD (wt.%)	Hydraulic conductivity					Compaction properties		
		Hydr. cond (m/s)	ρ_d (g/cm ³)	R_D (%)	w (%)	Wet of omw (%)	n (%)	Max. ρ_d (g/cm ³)	omw (%)
SiTm-GLD1	0	$3 \times 10^{-8} \pm 3 \times 10^{-9}$ ($N=3$)	2.01 ± 0.05 ($N=3$)	97	9 ± 0.5 ($N=3$)	1	26	2.08 ± 0.01 ($N=3$)	6
	5	$2 \times 10^{-8} \pm 5 \times 10^{-9}$ ($N=3$)	1.97 ± 0.02 ($N=3$)	96	10 ± 0.6 ($N=3$)	2	31	2.05 ± 0.01 ($N=2$)	8
	10	$4 \times 10^{-8} \pm 5 \times 10^{-9}$ ($N=3$)	1.88 ± 0.01 ($N=3$)	95	14 ± 1.3 ($N=3$)	5	30	1.99 ± 0.01 ($N=2$)	9
	15	$6 \times 10^{-8} \pm 1 \times 10^{-8}$ ($N=3$)	1.74 ± 0.05 ($N=3$)	90	18 ± 0.4 ($N=3$)	8	35	1.95 ± 0.00 ($N=2$)	10
	20	$7 \times 10^{-8} \pm 1 \times 10^{-8}$ ($N=3$)	1.65 ± 0.02 ($N=3$)		20 ± 0.7 ($N=3$)		38		
SiTm—GLD2	0	$3 \times 10^{-8} \pm 3 \times 10^{-9}$ ($N=3$)	2.01 ± 0.05 ($N=3$)	97	9 ± 0.5 ($N=3$)	1		2.08 ± 0.01 ($N=3$)	6
	5	$3 \times 10^{-8} \pm 4 \times 10^{-9}$ ($N=3$)	1.96 ± 0.02 ($N=3$)	92	10 ± 0.5 ($N=3$)	3	27	2.12 ($N=1$)	7
	10	$3 \times 10^{-8} \pm 5 \times 10^{-9}$ ($N=3$)	1.91 ± 0.02 ($N=3$)	93	12 ± 0.3 ($N=3$)	4	30	2.05 ($N=1$)	8
	15	$3 \times 10^{-8} \pm 2 \times 10^{-8}$ ($N=3$)	1.74 ± 0.03 ($N=3$)	85	14 ± 0.8 ($N=3$)	4	33	2.04 ($N=1$)	10
	20							1.99 ($N=1$)	11
SiTm – GLD1 LC	0	4×10^{-8} ($N=1$)	2.04 ($N=1$)	98	9 ($N=1$)	2	24	2.1 ($N=1$)	7
	5	$4 \times 10^{-8} \pm 4 \times 10^{-9}$ ($N=3$)	1.95 ± 0.02 ($N=3$)	95	11 ± 0.9 ($N=3$)	1	28	2.03 ($N=1$)	10
	10	$5 \times 10^{-8} \pm 5 \times 10^{-9}$ ($N=3$)	1.83 ± 0.05 ($N=3$)	92	15 ± 0.6 ($N=3$)	3	31	1.93 ($N=1$)	12
	15	$6 \times 10^{-8} \pm 1 \times 10^{-8}$ ($N=3$)	1.72 ± 0.02 ($N=3$)	88	19 ± 0.4 ($N=3$)	4	35	1.81 ($N=1$)	15
	20	9×10^{-8} ($N=1$)	1.54 ($N=1$)		25 ($N=1$)		42		
SiTd—GLD1	0	1×10^{-7} ($N=1$)	2.02 ($N=1$)	97	5 ($N=1$)	– 1	26	2.08 ± 0.01 ($N=3$)	6
	5	$7 \times 10^{-8} \pm 2 \times 10^{-8}$ ($N=3$)	2.06 ± 0.02 ($N=3$)	100	7 ± 0.5 ($N=3$)	– 1	24	2.05 ± 0.01 ($N=2$)	8
	10	$5 \times 10^{-8} \pm 1 \times 10^{-8}$ ($N=3$)	2.03 ± 0.04 ($N=3$)	100	10 ± 1.3 ($N=3$)	1	2	1.99 ± 0.01 ($N=2$)	9
	15	$3 \times 10^{-8} \pm 1 \times 10^{-8}$ ($N=3$)	1.93 ± 0.01 ($N=3$)	99	14 ± 0.4 ($N=3$)	4	28	1.95 ± 0.00 ($N=2$)	10
	20	4×10^{-8} ($N=1$)	1.66 ($N=1$)		21 ($N=1$)		38		

The compaction degree (R_D) for the mixtures compacted with light Proctor compaction (SiTm-GLD1-LC) is calculated toward maximum dry density in SiTm-GLD standard compaction. N number of analyzed sets

till mixture (SiTd-GLD1), the initial hydraulic conductivity was greater, 1×10^{-7} compared to 3×10^{-8} m/s in the SiTm (Fig. 2A; Table 2). The hydraulic conductivity then decreased steadily with increasing amounts of GLD (from 1×10^{-7} to 3×10^{-8} m/s) up to 20 wt.% of GLD added to the SiTd (Fig. 2A; Table 2). When the GLD addition to SiTd exceeded 10 wt.%, the hydraulic conductivity was less than

in the moister mixture, 3×10^{-8} compared to $7-8 \times 10^{-8}$ m/s (Fig. 2A; Table 2).

The decrease in hydraulic conductivity in the drier till-mixture (SiTd) might be explained by the correlation between the hydraulic conductivity and the degree of compaction and molding water content (Benson et al. 1994; Leroueil et al. 2002; Watabe et al. 2000). Compacting a drier till

(SiTd) results in higher dry densities in mixtures with 5–15 wt.% GLD addition, approximately 0.1 to 0.2 g/cm^3 , compared to a wetter till (SiTm; Fig. 2B). However, the hydraulic conductivity in the mixtures where the drier till (SiTd) was used (TSC 96% compared to 91%) only reached lower values than in the wetter mixture (SiTm) with 15–20 wt.% GLD addition (hydraulic conductivity of $3\text{--}4 \times 10^{-8}$ compared to $6\text{--}7 \times 10^{-8} \text{ m/s}$ in the wetter mixture). Adding 15 wt.% GLD to the moist till increased the water content far beyond the optimum water content (SiTm; Fig. 2C; Table 2), leading to a lower dry density and a higher hydraulic conductivity than in a mixture with a drier till. Evidence of a negative correlation between dry density and hydraulic conductivity was only seen in the moist SiTm-mixtures (Figs. 3B and 4B), and not in the drier SiTd-mixtures where only a weak positive correlation can be seen, i.e., increasing hydraulic conductivity with increasing dry density (Figs. 3F and 4B). Benson and Trast (1995) showed that the hydraulic

conductivity is sensitive to the molding water content, where the lowest hydraulic conductivity was reached at a molding water content of 1–2% wet of the optimum water content. About 5 wt.% of GLD1 seems to be a threshold for tills with a TSC content of approximately 91% (SiTm). With an increasing amount of GLD above that, the water content increases beyond the 1–2% wet of the optimum water content (Fig. 2A, C). A drier till can therefore tolerate a higher amount of GLD-addition compared to a wetter till (SiTd). At 15 wt.% of GLD1 addition to SiTd, the 1–2% wet of optimum water content was reached and this was also where the lowest hydraulic conductivity was seen (Fig. 2A). The drier SiTd reached its optimum molding water content when more than 10 wt.% GLD was added (Fig. 2C), which explains the negative correlation between hydraulic conductivity and molding water content seen in these mixtures (Figs. 3D and 4A). The addition of GLD to the drier till (SiTd) increased the molding water content closer to the optimum values,

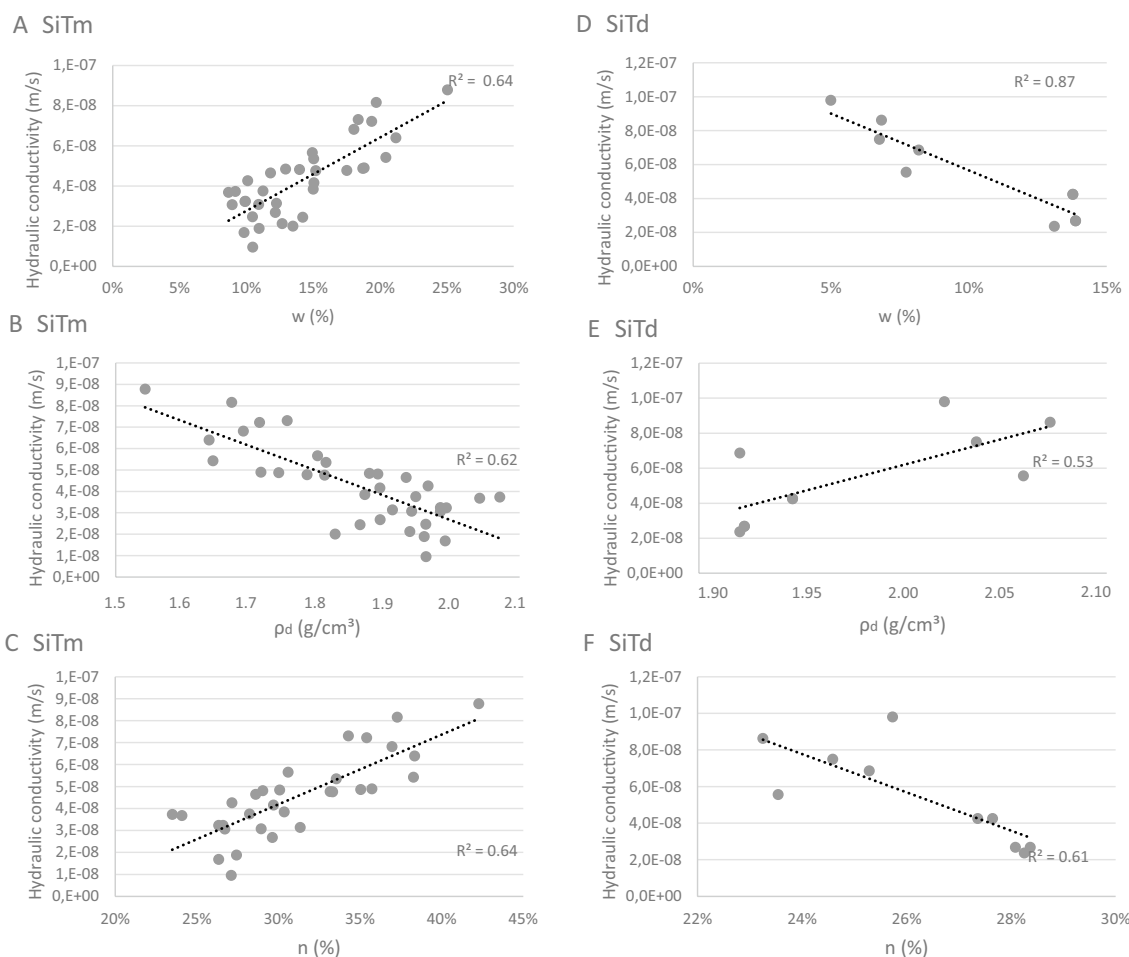


Fig. 3 Correlations between hydraulic conductivity and water content (w), dry density (ρ_d), and porosity (n). **A–C** is the moist silty till-mixtures; SiTm-GLD1, SiTm-GLD2 and SiTm-GLD1-LC, with 0–20 wt.% GLD addition. **D–F** is the dry silty till mixtures (SiTd)

with 0–20 wt.% GLD addition. The dotted line is the linear regression between the data points with the R^2 value presented in the right upper corner

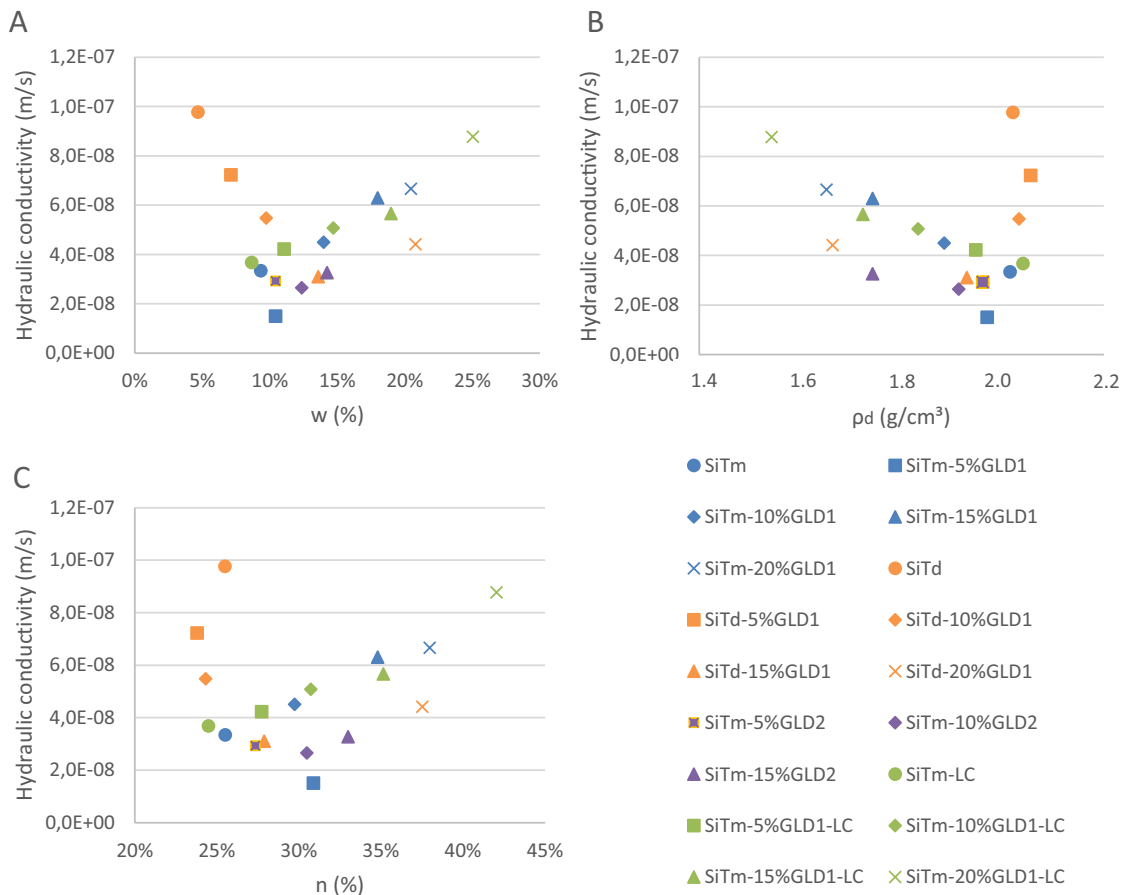


Fig. 4 Correlations between hydraulic conductivity and water content (*w*), dry density (ρ_d), and porosity (*n*) in the different separate mixtures. The blue dots represent the moist silty till (SiTm) and 5–20 wt.% GLD1 amendment, the orange dots represent the dry silty till

(SiTd) with 5–20 wt.% GLD 1 amendment, the purple dots represent the moist silty till with 5–15 wt.% GLD 2 amendment, and the green dots represent mixtures with moist silty till and GLD1 that has been compacted with a low compaction effort (SiTm-LC)

leading to a decrease in hydraulic conductivity (Fig. 2). The moist till (SiTm) on the other hand already had a high moisture content and the addition of higher amounts of GLD (> 10 wt.%) increased the values beyond the optimum water content, which led to an increase in hydraulic conductivity with ≥ 10 wt.% GLD-addition (Fig. 2).

An addition of the drier GLD2 to the till was expected to decrease the hydraulic conductivity of the mixture, as it should have a water content closer to the optimum. In this study, the hydraulic conductivity stayed around 3×10^{-8} m/s with the addition of up to 15 wt.% of the drier and more fine-grained GLD2 and did not follow the same u-shaped trend as when using GLD1 (Fig. 2A). As with the drier till-mixture, there seems to be a higher tolerance of how much drier GLD2 can be added to SiTm compared to the wetter GLD1. This is also likely due to the optimum water content, which for 10–15 wt.% addition of GLD1 reaches 5–8% wet of the optimum water content after compaction; for GLD2, the corresponding number is 4% (Fig. 2C). This higher tolerance of GLD-addition is of interest when considering a

study conducted by Jia et al. (2019), who concluded that drying the GLD before mixing it with the till did not seem to affect its properties. This means that if the GLD is dry, higher amounts can be added to the till without exceeding the optimum water content. A higher amount of GLD in the mixture likely increases the water retention capacity of the material, improving its sealing layer properties by deterring oxygen diffusion (Nigéus et al. 2023). However, the low shear strength of the GLD (Mäkitalo et al. 2014) needs to be considered, since greater amounts of GLD in the mixture can lead to decreased slope stability.

Another explanation is that GLD2 is more fine-grained than GLD1 (Table 1). Even if the dry density decreases with the addition of more GLD, the increase of fine-grained material decreases the porosity and levels out the expected increase in hydraulic conductivity. The porosity increases with more GLD in both mixtures but is slightly lower in the SiTm-GLD2-mixtures than in the SiTm-GLD1-mixtures (Table 2 and Fig. 2D). This also might be due to the water content increasing beyond the optimum water content, with

the increasing GLD addition leading to an increasing porosity, as discussed previously.

The hydraulic conductivity in this study does not reach below the common requirement of $< 10^{-8}$ m/s in Sweden, which might be explained by the formation of agglomerates when the GLD is mixed with the till. Evidence of this is seen in the porosity increasing instead of decreasing (as expected) with the GLD addition (Table 2). Agglomeration might mean that the fine particles of the GLD did not fully fill the pores of the till. This agglomeration was observed while mixing the materials and was also observed by Virolainen et al. (2020) when studying till-GLD mixtures. When correlating the porosity with hydraulic conductivity, a positive correlation was found in the SiTm-mixtures (Fig. 3C), with decreasing hydraulic conductivity with decreasing porosity. This might suggest that if it is possible to mix the GLD and till properly without agglomeration, a lower hydraulic conductivity might be reached. If the GLD is dried before being transported to the mine site, proper mixing might be possible and lower porosity and hydraulic conductivity might be reached. This should be investigated further.

In summary, this study showed that the initial water contents of the materials are very important for determining the hydraulic conductivity of the mixtures. It determines the degree wet of optimum and the final porosity of the mixtures that in this and previous studies has been shown to greatly affect the hydraulic conductivity (Benson et al. 1994; Benson and Trast 1995). This study confirms the results from Benson and Trast (1995) that 1–2% wet of the optimum water content is the target to reach the lowest hydraulic conductivity in a material. If the till is dry, a higher amount of GLD would be needed to reach the lowest possible hydraulic conductivity. When more GLD was added, the hydraulic conductivity was independent of the amount of GLD. However, none of the mixtures reached the required (in Sweden) hydraulic conductivity for a sealing layer, $< 10^{-8}$ m/s; this might be explained by the formation of agglomerates when the GLD and till were mixed.

The Effect of Dry Density on the Hydraulic Conductivity of the Till-GLD Mixtures

The hypothesis was that adding small amounts of GLD to the tills would increase the dry density and decrease the hydraulic conductivity due to the higher amount of fine-grained material in the mixtures. However, as the amount of GLD was increased, it was anticipated that other properties of the GLD, such as its low shear strength and high water content, would have more influence on the hydraulic conductivity of the mixtures. A water content above the optimum molding water content of the mixture would make it more difficult to compact. The expected increase in dry density with less GLD added could not be seen in any of the mixtures. The

dry density in the SiT-mixtures decreased and the porosity increased with greater amounts of GLD (Table 2, Fig. 2B, D). The lack of the expected increase in dry density and decrease in porosity is most likely due to the higher water content, beyond the preferred 1–2% wet of optimum water content, as discussed earlier (Table 2, Fig. 2C). The lower particle densities of the GLD also affected the dry density (Table 1). It might also be explained by the formation of agglomerates when the GLD was mixed with the till.

The hypothesized U-shaped trend was confirmed in the hydraulic conductivity samples compacted using the standard PC method. In the SiTm-GLD1 mixture, the hydraulic conductivity reached its lowest hydraulic conductivity (2×10^{-8} m/s) when 5 wt.% of GLD1 was added to the till. It then increased up to 7×10^{-8} m/s with 10 wt.% or more GLD in the mixtures (Fig. 2A; Table 2). The hydraulic conductivity in the drier till mixtures reached its optimum hydraulic conductivity at 15 wt.% of GLD. When using LC, the hydraulic conductivity behaved differently than the rest of the mixtures, and the hydraulic conductivity increased with more GLD ($4\text{--}9 \times 10^{-8}$ m/s; Fig. 2A; Table 2). This cannot be explained by the dry density or porosity as it was similar for the samples compacted with standard PC and LC (Fig. 2B, D). A likely explanation might be the optimum water content. At 5 wt.% GLD addition, the molding water content was very near the optimum water content (Fig. 2C). Benson and Trast (1995) found that the lowest hydraulic conductivity was reached at 1–2% of the optimum water content, suggesting that the mixture used in this study was too dry.

To summarize, the hydraulic conductivity is known to be highly dependent on the degree of compaction, with decreasing hydraulic conductivity at great degrees of compaction (Benson et al. 1994; Leroueil et al. 2002; Watabe et al. 2000). However, this study showed that the dry density after compaction affects the hydraulic conductivity in mixtures of silty till and GLD to some extent but does not appear to be important in determining the hydraulic conductivity.

The Effect of Compaction on the Dry Density and Hydraulic Conductivity of the Till-GLD Mixtures

A lower compaction effort, i.e., LC instead of standard PC, was expected to increase the dry density and decrease the hydraulic conductivity in the GLD-till mixtures. Previous studies indicated that an increased strain on the GLD releases the water that is retained (Mäkitalo et al. 2015b) and this could decrease the compaction degree. Indications of this was observed when mixtures with higher amounts of GLD were compacted. However, the hydraulic conductivity and dry density measurements showed no evidence of the hypothesis (Fig. 2A, B). Comparing LC to standard PC, lower maximum dry densities after compaction were reached

when lighter compaction effort was used in the till-GLD mixtures, 1.81–2.03 to g/cm^3 compared to 1.99–2.12 g/cm^3 with 5 to 15 wt.% GLD added (Fig. 5A, B, Table 2). The difference between the compaction methods increased when greater amount of GLD were added. For further evaluation, the effect of the standard PC, LC, number of compacted layers (three or five), and number of blows with the Proctor hammer per layer was compared (5–25 blows) (Fig. 5C, D). These tests showed that the difference between standard and light Proctor compaction with the same number of compacted layers was negligible. The highest maximum dry densities were reached with 25 blows and five layers (Fig. 5). The decreased maximum dry density in the till-GLD-mixture after compaction due to decreased compaction effort was not expected (Mäkitalo et al. 2015b). However, Benson and Trast (1995) among others give evidence for the results shown in this study, i.e., increased dry density after compaction with increasing compaction effort.

Considering compaction effort and its effect on hydraulic conductivity, the hypothesis was that less compaction effort might also lead to a lower hydraulic conductivity of the till-GLD mixtures (Mäkitalo et al. 2015b). However, the results from this study do not agree with this, as a decreased compaction effort did not significantly affect the hydraulic conductivity (Fig. 2). A difference when LC was used compared

to standard PC was only seen with the addition of 5 wt.% of GLD1, where the hydraulic conductivity was higher, not lower as expected, when using LC (4×10^{-8} compared to 2×10^{-8} m/s; Fig. 2A; Table 2). However, despite the lack of positive effects on hydraulic conductivity when using LC, it might still be worth considering since laboratory tests tend to underpredict hydraulic conductivity compared to actual values in the field (Daniel 1984). Compaction in the field is usually made with less effort than in the lab, leading to increased optimum water content and a lower hydraulic conductivity in a laboratory experiment than in a field study (Daniel 1984). Therefore, when compacting in the field, the material is compacted dryer than the optimum water content, resulting in a higher hydraulic conductivity than expected. Other reasons for underestimating field hydraulic conductivity are desiccation cracks, difficulties in getting a representative sample of soil for a laboratory test, and poor construction (Daniel 1984). The unsaturated properties of a soil in the field are another challenge. The hydraulic conductivity of an unsaturated soil can vary over 10 orders of magnitude, making it difficult to analyze and interpret the results (Fredlund et al. 1994).

In addition to compaction, there are several other parameters in the laboratory method that make it challenging to estimate the field hydraulic conductivity from a laboratory

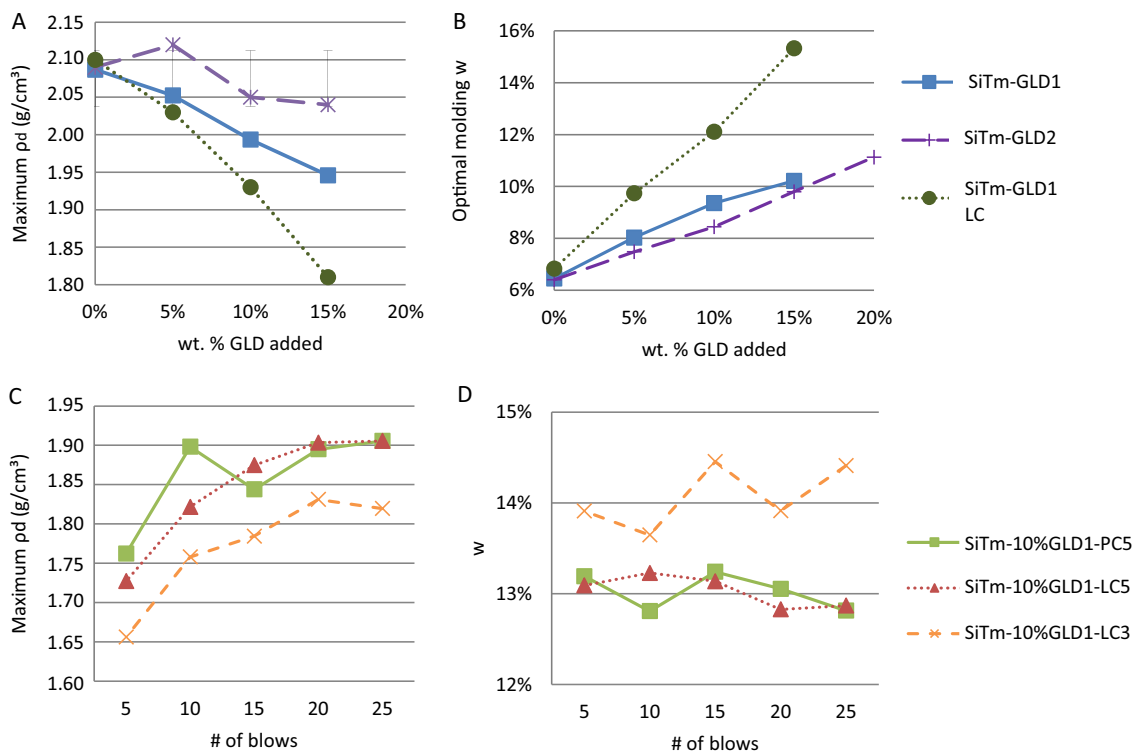


Fig. 5 A Maximum dry density (ρ_d) and B Optimum molding water content (w) after compaction with increasing wt.% GLD added. Changes in max ρ_d (C) and w (D) after compaction with different Proctor compaction efforts (PC=Standard Proctor compaction,

LC=Light Proctor compaction), number of blows with the Proctor hammer (5–25) and number of compacted layers (PC/LC3 or 5) in silty till-10 wt.% GLD1 mixture

test. One is the compaction method itself. The dry density is known to affect the hydraulic conductivity and the dry density depends on how well compacted the material is. Hand compaction is a non-standardized compaction procedure that can lead to differences between samples, and therefore variations in the dry density and hydraulic conductivity. Consequently, a PC method is preferable as it uses the same effort between samples. One downside of the PC method is that the compaction hammer does not reach the sides of the sample cylinder. Therefore, the millimetres closest to the walls are not compacted and there is a risk of preferred wall-flow when measuring hydraulic conductivity. Using a hand-operated compaction hammer attached to a frame enables standardization in the compaction effort between the samples and the hammer can reach the sides of the cylinder. The disadvantage with this method is that it can be challenging to make sure that the whole sample is compacted to the same degree, compared to the PC method with compaction around the sample in a standardized fashion. Another parameter in the hydraulic conductivity method that can affect the outcome is the hydraulic gradient. In geotechnical engineering, it is common practice to apply high hydraulic gradients for quick determination of the hydraulic conductivity, but this can increase the hydraulic conductivity as the increased flow rate at high hydraulic gradients widens the void space by erosion (Al-Taie et al. 2014). High hydraulic gradients can also reduce the hydraulic conductivity if the pressure is high enough to erode aggregates of colloidal size from the flow channels (Al-Taie et al. 2014; Pusch and Weston 2003). However, in this study, the hydraulic gradient of 8.7 was comparable to that in field and much less than 100, which Al-Taie et al. (2014) suggested as a limit, or 30, which is the ASTM-recommended hydraulic gradient.

In summary, this study showed that the compaction effort does not seem to be the driving factor controlling hydraulic conductivity when working with till-GLD mixtures. However, due to the properties of the GLD and the aim to mimic field conditions, a lighter compaction effort than the standard PC is still recommended. Also, the effect of the compaction method on laboratory measured hydraulic conductivity needs to be further investigated, especially comparing manual compaction and the standardized Proctor compaction method.

Conclusions

The initial water content of the materials might be the most important factor determining the hydraulic conductivity of till-GLD mixtures. When using a drier till and GLD in a mixture, more GLD needs to be added to reach the lowest possible hydraulic conductivity. Compaction effort on the other hand did not seem to be important in determining

the hydraulic conductivity of the mixtures in this study. For future studies, it would be of interest to dry the GLD before mixing to investigate if higher amounts of GLD can be added to the till, which might lead to lower hydraulic conductivity values. In this and in a study conducted by Virolainen et al. (2020) an aggregation was seen in the GLD when mixing with till. It would therefore be of interest to evaluate how well the GLD fills the pores of the till. Data from this study is available by email to the corresponding author on a reasonable request.

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Data availability Data is available by email to the corresponding author on a reasonable request.

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