GCLs for use in covers over arsenic-contaminated mine wastes

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ABSTRACT
Between the 1860s and mid-1940s, gold mining and milling in Nova Scotia generated approximately three million tonnes of tailings containing arsenic and other potentially toxic elements. In the case of publicly accessible gold mine sites in Nova Scotia, placing a geosynthetic clay liner (GCL) as a cover may provide a means of minimizing the release of arsenic. In order to investigate the performance of GCLs, a test cover involving three different types of GCL was constructed at Montague Gold Mines in the summer of 2009. This paper presents the characteristics of Montague tailings and describes the test cover construction details. In addition, the paper describes a parallel laboratory testing program.

RÉSUMÉ
Entre les années 1860 et moiti une partie des années 1940, les mines d'or et de fraisage en Nouvelle-Écosse ont généré environ trois millions de tonnes de résidus contenant de l'arsenic et d'autres éléments potentiellement toxiques. Un revêtement d'argile géosynthétique (GCLs) a été identifié comme étant une solution possible pour réduire le rejet d'arsenic dans les mines d'or accessibles au public en Nouvelle-Écosse. Afin d'étudier la performance de GCL, un test de couverture impliquant trois différents types de GCL a été construit à Montague Gold Mines pendant l'été 2009. Cet article présente les caractéristiques des résidus de Montague et décrit les détails de construction du test de l'écran. De plus, cet article décrit un programme parallèle pour les tests en laboratoire.

1 INTRODUCTION

Covers, like other types of hydrological barriers, are used to protect the environment against exposure to contaminants enclosed within waste disposal sites (Daniel and Koerner, 1993). Geosynthetic clay liners (GCLs), which have been used frequently in base liners in landfills, are frequently being used as the preferred clay barrier material in covers. This is because GCLs have very low hydraulic conductivity to water (Rowe et al. 2004), the capability of maintaining a low hydraulic conductivity at relatively high strain (Bouazza et al. 1996), high self healing capacity (Didier et al. 2000), resistance to freeze-thaw effects when hydrated with water not containing significant cations (Rowe et al. 2008), and relative ease of installation (Bathurst et al. 2006). One of the key functions of the GCLs used in cover systems is to limit the infiltration of water into the underlying waste and hence to minimize generation of contaminated water (Aubertin et al. 2000). GCLs are increasingly being used as low permeability liners to control subsurface contamination from mine tailings containing sulphidic minerals (such as pyrite) where the GCL acts both as a water infiltration barrier (Bussière, 2009) and a gas diffusive barrier (Harries and Richie. 1985; Nicholson et al. 1989) to control acidification of the drainage waters. The use of GCLs in applications involving mine tailings has also been reported by previous research (e.g. Olsta and Friedman, 2002; Renken et al. 2005). Thus, GCLs which have primarily been employed as leachate barriers in landfill have, in recent times, seen an increase in the range of applications, including applications in mining industry.

One serious environmental issue in Canada, and elsewhere, is pollution from abandoned mine sites. For example, between 1860s and mid-1940s, gold mining and milling in Nova Scotia generated approximately three million tonnes of tailings containing arsenic, mercury, and other toxic elements (Wong et al. 1999). Today, historical gold districts throughout Nova Scotia commonly have high arsenic concentrations in tailings and nearby streams and groundwater as a result of poorly controlled waste disposal and natural arsenic mineralization. In the case of publicly accessible gold mine sites in Nova Scotia, where arsenic is much higher than the recommended Canadian soil quality guideline (12 mg/kg), placing a GCL as part of a cover over the tailings may provide a means of minimizing the release of arsenic. However, the performance of GCLs will depend on the extent to which there is chemical interaction with cations in the surrounding soil under local climatic conditions (Benson et al. 2007).

Although previous research has characterized the behaviour of GCLs with various leachates (Petrov et al. 1997a, b), including metal-bearing permeants (Lange et al. 2007, 2010) for base liner applications, the interaction of GCLs with mine waste when used in cover applications has received relatively a little attention.

Lange et al. (2004) examined the performance of a GCL permeated by neutral-pH, arsenic-rich solution typical of porewaters found in gold mine tailings. Results of permeability tests carried out using rigid wall permeameters, under a stress of 25 kPa, showed a slight increase in the hydraulic conductivity from 1.6×10^{-11} m/s to 5×10^{-11} m/s after 21 pore volume of permeation with mine water. This is encouraging but more work needs to be done to examine interaction with different gold mine pore fluids for cover applications where the applied stress is lower and where in addition to chemical interaction there may be freeze thaw cycles.

In order to investigate the performance of GCLs at Nova Scotia gold mine sites, a test cover was constructed at the site of the Montague Gold Mine in summer of 2009 and a continuous sampling plan was developed. The objective of this paper is to: (a) present the characteristics of Montague tailings, (b) describe the test cover construction details, and (c) show the initial properties of the different GCLs used in this study. In addition, the paper describes a parallel program of laboratory testing being conducted to investigate the effects of freeze-thaw, effective stress, initial tailings moisture content, and tailings chemical composition on GCL performance.

2 MONTAGUE GOLD MINE

The Montague gold mine is located near the city limits of Dartmouth, Halifax County, Nova Scotia, about 7 km from the Atlantic Ocean and about 61 m above the sea level. Thompson (1978) reported that the area is underlain by a cambro-ordovician metasedimentary series of rocks. The upper 4 km is a Halifax formation, which is comprised of soft graphitic, ferruginous slates and minor quartzite, followed by 5 km of Goldenville formation which is comprised of Metagraywacke with feldspathic quartzite and minor slates. This formation contains quartz veins formed from silica rich solutions released during regional metamorphism and these veins contain large amounts of arsenopyrite (FeAsS) in addition to gold.

Gold was discovered at Montague in 1862 and the area was proclaimed a gold district and was mined from 1863 to 1927 by a variety of companies (Malcolm, 1976). During processing the ore, material was crushed to the size of sand or silt in stamp mills and then free gold particles were recovered by dissolving them in liquid mercury which was later boiled off to refine the gold (Dale and Freedman, 1982).

The remaining crushed material was often deposited directly into local rivers, swamps, lakes and the ocean. At Montague, the tailings extended over an area of 12 ha (O'Sullivan and Merchant, 1997). In general, up to 10-25% of the mercury used for amalgamation was lost to tailings. In addition, because arsenic occurs naturally in the gold ore and surrounding bedrock, it can usually be found in high concentrations in mine tailings. Dale and Freedman (1982) showed that arsenic in the tailings is very heterogeneous with arsenic concentration ranging from 0.1% to 7.2% by weight. This heterogeneity arises from both a difference in the processed ore composition and different ages of the tailings.

3 MATERIALS

Three different GCL products were used in the construction of a test cover at Montague gold mine and in the laboratory work described herein. The first product is a Bentofix Thermal Lock "NSL" (GCL A). This is a needle-punched reinforced GCL comprised of a layer of granular sodium bentonite between a slit-film woven carrier geotextile and a staple fibre nonwoven cover geotextile. The second product is Bentofix Thermal Lock "NWE" (GCL B). This is a needle-punched reinforced GCL comprised of a layer of polymer enhanced, granular sodium bentonite encapsulated between scrim reinforced nonwoven carrier and a staple fibre nonwoven cover geotextiles. Bentofix Thermal Lock "CNSE" (GCL C) was also used. It has a structure similar to GCL A, but it has a polymer enhanced sodium bentonite and has a low permeability polypropylene sheet bonded to the woven carrier geotextile to lower the hydraulic conductivity. In all three products, the needle-punched fibres are thermally fused to the carrier geotextile to enhance the reinforcing bond.

Meer and Benson (2007) reported cases where GCLs used in low stress cover applications involving wet-dry cycles combined with the cation exchange between the sodium bentonite in the GCL and divalent cations in the pore water of the adjacent soil, experienced an increase in the hydraulic conductivity (by several orders of magnitude in some cases) and a loss in swell capacity and the ability to self-heal when rehydrated. In cover applications for gold mine wastes where metal-rich tailings may be in direct contact with the GCLs, cation exchange could potentially have a similar effect on the performance of the GCLs. Thus, the current study seeks to examine not only a standard GCL (GCL A) but also GCLs with a polymer enhanced bentonite (GCLs B and C) and one with low permeability polypropylene membrane in direct contact with the tailings (GCL C) to allow an assessment of how these improved GCLs perform relative to the conventional GCL A in this application.

The concept behind the use of the polymer-enhanced bentonite is that when the bentonite takes up water and begins to swell, the bentonite forms a network of chemical bonds with the dissolved polymer to create a strong, dense hydro-gel structure. Thus water transport processes in the mixture are strongly retarded by the polymer and so a lower hydraulic conductivity and less cation exchange can be anticipated.

The initial properties of the GCLs used in this study are summarized in Table 1. Atterberg limits and swell index tests were conducted in accordance with ASTM D4318-05 and ASTM D5890-06, respectively. The hydraulic conductivity tests, using flexible wall permeameters under an effective stress of 15 kPa, were conducted according to ASTM D5084-03. Table 1 also shows the average bonding and peak peel strength of virgin GCLs.

4 FIELD WORK

In the summer of 2009, a test cover involving three different types of GCLs (GCLs A, B, and C) covered with up to 1 m of clean soil was constructed at the Montague gold mine site. First, the three GCL products specified in the previous section (Table 1) were placed directly over the tailings within an area of 10 m x 8 m as shown in Figure 1. Both the GCLs beneath the 1m of fill and those with less fill on the side slopes will be examined.

Table 1. Initial properties of virgin GCLs.

		GCL A	GCL B	GCL C
Avg. bentonite mass/area (g/m^2)	Measured	4393(SD[b]; 410)	5306(SD[b]; 250)	4349(SD[b]; 240)
	MARV[a]	3660	4340	3660
Carrier GT	Type	W	NWSR	W
	Mass (g/m^2)	123	253	125
Cover GT	Type	NW	NW	NW
	Mass(g/m^2)	231	235	232
Structure	Needle punched	Yes	Yes	Yes
	Thermally treated	Yes	Yes	Yes
Initial thickness (mm)		7.7 (SD[b]; 0.6)	8.9 (SD[b]; 0.8)	7.9 (SD[b]; 0.6)
Initial water content (%)		5.0	8.0	6.3
Swell index (ml/2g)		26	24	25
CEC (cmol/kg)		81	80	75
Liquid limit (%)		553	610	555
Plastic limit (%)		123	155	115
Bentonite activity		5.89	8.27	6.98
Avg. bonding peel strength (N/m)		662(SD[b]; 88.1)	1380(SD[b]; 268.3)	1120(SD[b]; 115.1)
Avg. peak peel strength (N)		93.8(SD[b]; 16.5)	172.6(SD[b]; 31.6)	132.2(SD[b]; 8.5)
Hydraulic conductivity (m/s)		4.0×10^{-11} m/s	1.9×10^{-11} m/s	5.0×10^{-12} m/s

Where NWSR = nonwoven scrim reinforced, NW = nonwoven, W = woven
GCLs B and C contains polymer enhanced bentonite
GCL C is coated with a thin-low permeable polypropylene membrane
[a] Manufacturer published minimum average roll value
[b] Standard deviation

This layer of GCLs was covered with 15 cm of clean (uncontaminated) soil with a low concentration of cations (e.g. at full saturation, the concentrations of Ca^{2+} and Mg^{2+} were 97 mg/L and 12 mg/L, respectively). Based on grain size distribution tests carried out according to ASTM D422-63, this soil is classified as sand and gravel, with some silt and trace clay with 38% gravel, 46% sand, and 12% silt. The water content of the clean soil at the time of construction ranged between 6% to 10%. This layer is intended to serve as a foundation layer for a second set of GCLs. Figure 2 shows the installation of the second layer of the GCLs using the three GCLs used in the first layer. The purpose of this GCL layer is to examine the effect of presence of 15 cm clean foundation soil between the GCL and the tailings on the long term performance of the GCL. The layer of clean foundation soil is expected to provide pore fluid with a lower concentration of cations for GCL hydration than the tailings and also to reduce diffusion of cations from the tailings to the GCL. Note that the layer of GCLs is outside the zone where the GCLs were in direct contact with the tailings to avoid any interaction between the two layers. The fill material was then used to increase the total cover thickness to 1m in the central region. The north and south side slopes were constructed at 4H:1V while the east and west slopes were constructed at 3H:1V. This cover soil provides an effective stress over the GCLs to minimize the swell during the hydration and help self- healing under wet-dry cycles, and to minimize the effect of freeze-thaw cycles on the GCLs. The configuration of the two layers is shown in Figure 3.

The location of the field tests site was selected primarily based on accessibility. Thus while the tailings at this location are representative of part of the site, they do not represent the most extreme conditions at the site (although arsenic concentrations are still two orders of magnitude higher than the recommended maximum value of 12 mg/kg).

Thus 1.5 m^3 of tailings were extracted from three locations (denoted 1, 2 and 3) for use in laboratory test being conducted to examine the effect of different tailings composition on GCL performance as described below.

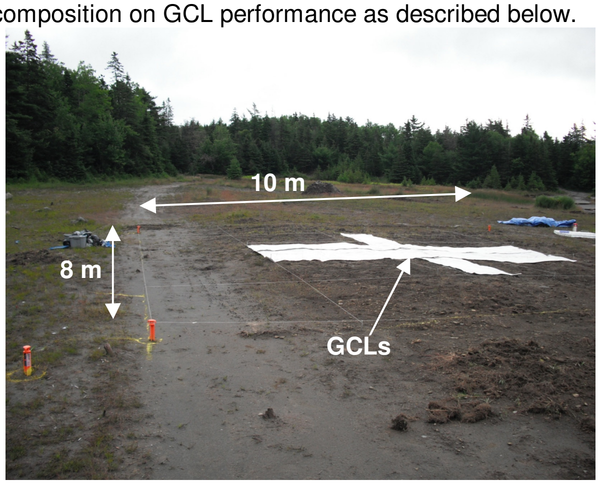

Figure 1. Installation of the first layer of GCLs

Figure 2. Installation of the second layer of GCLs

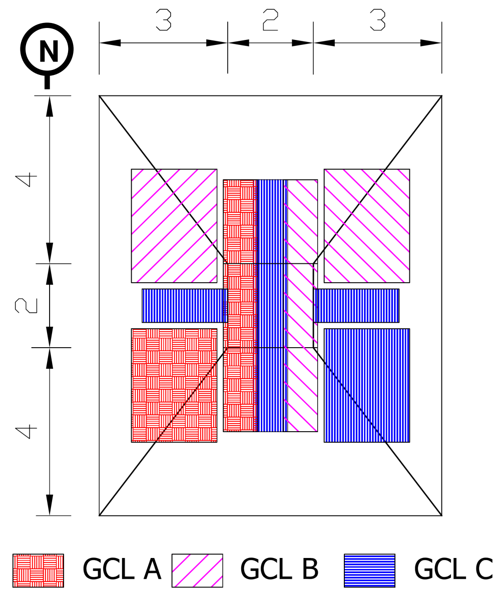

Figure 3. Plan view for the GCLs in the test cover (units in meter)

Location 1 was just beside the test cover location and is representative for the tailings below the GCLs placed in the test cover. The tailings at this location had the lowest arsenic concentrations relative to other locations at the site but two orders of magnitude higher than the recommended Canadian soil quality guideline of 12 mg/kg. Location 2 was the location with the highest observed arsenic concentration within the site. Location 3 has the median arsenic concentration within the site.

5 LABORATORY WORK

The grain size distribution of the three types of tailings, according to ASTM D422-63, to depth up to 30 cm is presented in Figures 4 to 6. Based on their grain size, the tailings in locations 1 and 3 are classified as silty sand, while the tailings at location 2 is classified as sand. Nine tailings samples representing the tailings at locations 1 to 3 to a depth of 30 cm were taken in 10 cm intervals and tested for the metal and metalloid concentrations in both solid and aqueous phase. The total metal concentration in the samples, using aqua regia digestion followed with analysis by Inductively Coupled Plasma-Mass Spectrometer (ICP-MS), are shown in Figures 7 through 9. The metal and metalloid concentrations were highly variable both spatially and with depth. This is consistent with the findings from Dale and Freedman (1982). The maximum arsenic concentration was 12.7 wt.% (127,000 mg/kg) at location 2 (top 10 cm) and the minimum arsenic concentration was 0.45 wt.% (4,500 mg/kg) at location 1 (top 10 cm).

A shake flask extraction technique, as described by Price (1997), was used to analyze the readily extractable elements from tailings at different locations and depths. The mass of extractable elements divided by the volume of pore fluid present at full saturation is shown in Table 2.

This represents an upper bound on the pore water concentration assuming all readily leachable elements are initially in solution. This may not be the case but it does represent the mass of the element that is available to come into solution. The highest concentrations were found in the tailings at Location 3.

As the purpose of laboratory work is to study the effectiveness of GCL as a cover for arsenic rich gold mine tailings, tailings extracted from the site were reconstituted and compacted to a similar density and moisture content as in the field into 72 PVC pipes with an internal diameter of 10 cm, 6 cells with a height of 30 cm and internal diameter of 60 cm, and 3 cells with a height of 30 cm and 40 cm internal diameter.

The reconstituted tailings from the three locations were covered with the three different GCL products used in the field test cover. In one series of experiments the GCL was covered with a rubber membrane and then a stress of either 7.5 or 15kPa was applied. This represents a worst case situation where the GCL is forced to uptake moisture from the underlying tailings.

In other experiments a 15 cm foundation layer and/or 30 cm cover of clean soil were placed below and above the GCL to mimic the GCL-soil contact conditions for the upper GCL layer in the test cover.

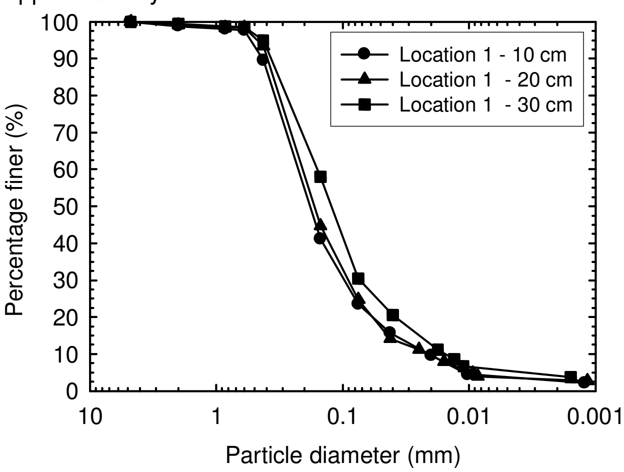

Figure 4. Grain size distribution at Location 1

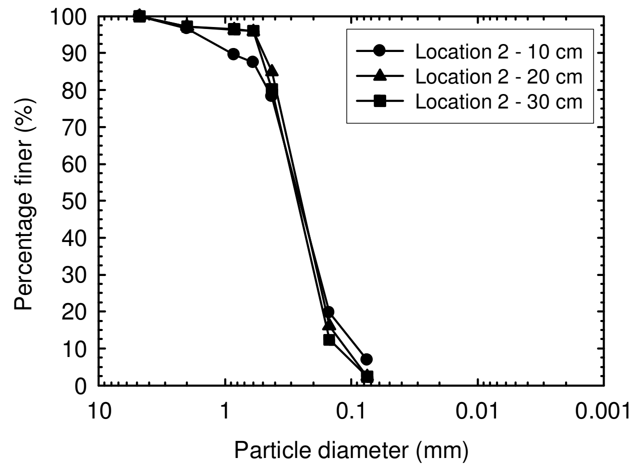

Figure 5. Grain size distribution at Location 2

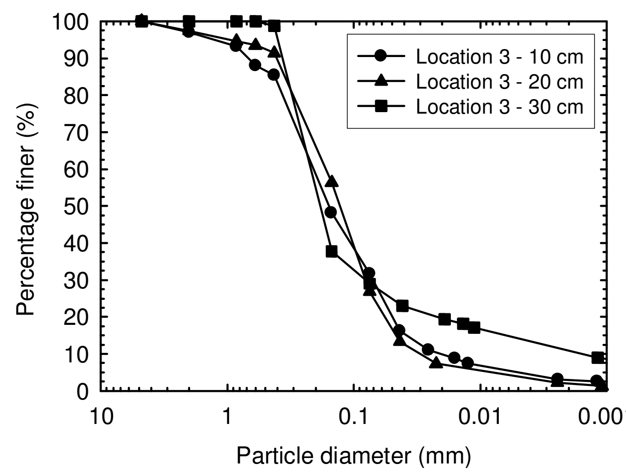

Figure 6. Grain size distribution at Location 3

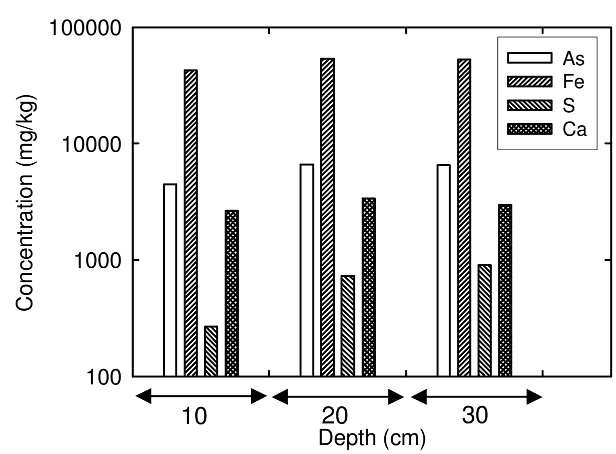

Figure 7. Total metalloid and metal concentrations in tailings from Location 1 at different depths

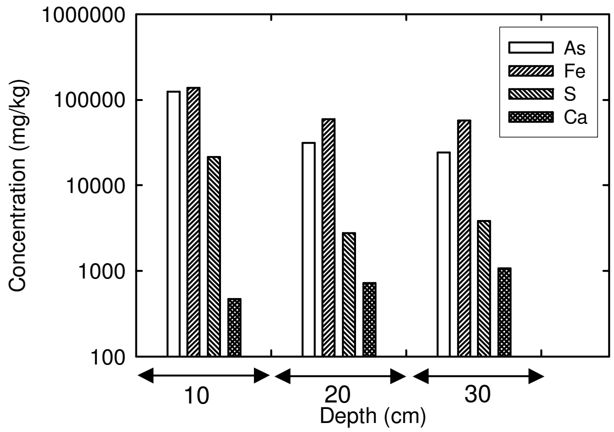

Figure 8. Total metalloid and metal concentrations in tailings from Location 2 at different depths

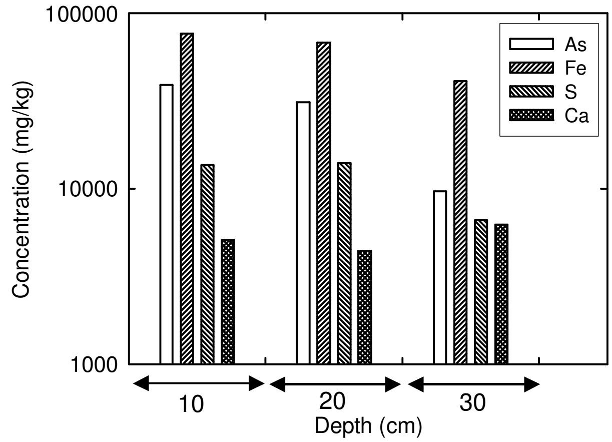

Figure 9. Total metalloid and metal concentrations in tailings from Location 3 at different depths

Table 2. Mass of extractable elements divided by the volume of pore fluid in the tailings at fully saturation (in mg/L except for pH and conductivity).

parameter	Location 1			Location 2			Location 3		
	10 cm	20 cm	30 cm	10 cm	20 cm	30 cm	10 cm	20 cm	30 cm
pH	6.58	6.61	6.30	2.95	3.41	3.49	4.24	5.62	6.45
Conductivity (uS/cm)	74	55	126	1450	457	379	1572	1760	686
Aluminum (Al)	1.31	15.2	7.41	41.0	43.6	87.2	<1.0	<1.0	<1.0
Arsenic (As)	17.7	17.7	18.8	29.6	13.1	12.0	7.41	3.08	9.63
Calcium (Ca)	61.0	42.2	53.0	16.4	20.4	26.6	536	571	392
Iron (Fe)	4.33	33.1	13.7	116	1.71	2.05	<0.05	0.73	<0.05
Magnesium (Mg)	19.5	48.5	29.6	47.0	24.4	19.3	348	573	121
Manganese (Mn)	2.57	4.39	<0.05	8.66	0.91	1.20	80	116	11.6
Potassium (K)	27.5	47.3	50.2	41.5	27.76	24.2	86.6	155.	59.9
Sodium (Na)	27.3	123	95.8	11.8	15.9	19.7	50.0	53.8	26.3
Sulphur (S)	15.5	47.9	103	356	207	225	909	1430	440
Zinc (Zn)	1.94	7.41	0.80	2.96	2.45	3.65	20.4	29.8	<0.01
Chloride (Cl^-)	48.1	46.5	34.4	27.8	26.3	41.3	41.5	52.9	30.9
Sulphate (So_4^-)	42.2	16.7	132	1540	473	583	3770	4780	1500

Another parameter being considered is the moisture content of tailings, foundation and cover soil. Samples from GCL will be extracted regularly and their physical and chemical properties will be tested. Some of extracted GCL samples will be subjected to laboratory freeze-thaw cycles to assess the effect of freeze-thaw and cation exchange on hydraulic conductivity and GCL structure.

6 CONCLUSIONS

Many abandoned gold mine sites across Canada represent both an environmental and health risk. Historical production records show that more than 3 million tonnes of tailings were generated at the various gold districts in Nova Scotia between the 1860s and 1940s where most mine sites have one or more deposits of tailings, which generally contain elevated concentrations of arsenic and mercury. Since the mines closed, ongoing residential development, industrial construction, and recreational activities on these sites have increased the potential for human exposure to these mine wastes. Thus, isolation of these tailings from human use may be required. GCLs used in covers represent one option for reducing infiltration through the tailings and hence potentially reduce arsenic release. However, since the GCLs performance could be affected by cation exchange from the tailings, a field and laboratory investigation has been initiated. Samples from the test cover built at the Montague gold mine site will be extracted in the summer of 2010 and 2011. Samples of the GCLs being studied under laboratory also will be tested over the next three years.

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