The application of geotextile and granular filters for PCB remediation

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ABSTRACT: The application of a surface, permeable reactive barrier has been implemented at a remote site in the Canadian Arctic for the remediation of soils and water contaminated with polychlorinated biphenyls (PCBs). The initial barrier system was installed in July 2003. Preliminary work in both the field and the laboratory suggested that geotextiles alone may not be adequate for this particular Arctic barrier system, owing to issues related to survivability (specifically the effects of high UV and freeze–thaw) and clogging. Subsequent field and laboratory work demonstrated that granular materials trapped the majority of PCB-contaminated soil without impeding hydraulic performance; however, fines were escaping. Extensive column testing in the laboratory has shown that a nonwoven geotextile filter can be applied with success with a granular permeable reactive barrier system. This paper presents the results of laboratory experiments and field research used in the design of this barrier system.

KEYWORDS: Geosynthetics, PCBs, Geotextiles, Filters, Remediation, Column tests, Batch tests

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1. INTRODUCTION

Geosynthetic barrier systems that contain contaminants by virtue of their low permeability are now well established (Rowe 2005; Southen and Rowe 2005; Barroso *et al.* 2006; Bouazza and Vangpaisal 2006; Dickinson and Brachman 2006; Touze-Foltz *et al.* 2006). In sites with contaminated drainage pathways, a more permeable system may be required. However, little research has been conducted on the use of permeable barrier systems to contain contaminants. This paper describes such an application, and provides the results of laboratory studies and field research aimed at establishing the efficacy of such systems.

A permeable reactive barrier was implemented at a remote site in the Canadian Arctic (Resolution Island, Nunavut, Canada) for the remediation of soils and water contaminated with polychlorinated biphenyls (PCBs). This work is being carried out to support the long-term monitoring plan on Resolution Island, a former Cold War era radar site. This barrier system has incorporated several filter materials over the years in an effort to improve the design and meet site compliance concentrations. Laboratory testing, including permittivity testing, batch tests and column tests, was conducted to assess the suitability of geosynthetic sorbents, geotextiles and granular filters for removing PCBs from water.

This paper presents the results of three laboratory studies and three seasons of field research supporting barrier filtration at Resolution Island, Nunavut, Canada, located at 60° 35′ N, 60° 40′ W. The first laboratory study investigates the effects of stresses (including UV exposure and freeze–thaw conditions) on geotextile permittivity. The second laboratory study compares adsorption isotherms of two promising sorbents identified during the 2003 field season: granulated activated carbon (GAC), and a hydrophilic geosynthetic adsorbent. The final laboratory study, using a horizontal stainless steel column apparatus, measured the fines escaping a variety of permeable filter systems. The field research results from 2003 describe challenges with clogging in a combined geotextile–geosorbent–GAC system. The 2004 results show an increase in permeability in a system using granular materials alone. Finally, the 2005 field research summarises the remaining challenges in the design of this barrier system. Conclusions are drawn for both research and practice, and limitations to the design are described.

1.1. Funnel and gate barriers on site

Subsurface permeable reactive barriers have been used successfully to remediate contaminated groundwater for the past decade (Starr and Cherry 1994; Blowes *et al.* 1999; McGovern *et al.* 2002; Birke *et al.* 2003; Lai *et al.* 2006). There are many advantages to using this particular technology in treating contaminated water. After the initial installation, there are very few costs associated with the operation and maintenance of the barrier system, beyond site monitoring (EPA 2001). The barrier system offers a passive system for treatment of groundwater, using no external energy source. Reactive barrier systems have the potential to remove contaminants from groundwater to meet regulatory levels (EPA 2001).

In order to remediate a plume successfully, the reactive barrier wall must be large enough that the entire plume passes through it. If a contaminant plume extends to great depth, or is very wide, the necessary dimensions for the reactive barrier may be so large as to become impractical, and alternative remediation technologies may be required. McMurty and Elton (1985) originally discussed a design concept in qualitative terms that could enable a barrier to deal with these large contaminant plumes, which was later implemented by Starr and Cherry (1994). This is commonly known as a funnel-and-gate system.

At Resolution Island the field season is short, access to the site is difficult, and climatic conditions are harsh. Remediation of the PCB-contaminated soil under these conditions required the development of a unique cleanup strategy and a novel remediation technology. The contaminated soil was excavated and either destroyed through incineration if levels were > 50 ppm or landfilled on site if concentrations were between 1 and 50 ppm. However, because of the difficult terrain and the fractured bedrock of the site, some PCB-contaminated soil remained on site. Long-term remediation goals were established to minimise PCB migration into the Arctic ecosystem. A technology to demobilise movement of PCBs in sediment and surface water was subsequently developed to meet these goals. Surface funnel-and-gate permeable reactive barriers were designed and constructed on site.

PCB contamination was not present at depths below 1 m, and generally there was little surface soil above bedrock. There is essentially no groundwater owing to the shallow depth of the permafrost, and therefore subsurface remediation was not necessary. The barrier was designed to trap contaminated soils in the funnel portion and to filter fines in the gate portion, with a final polishing step involving the use of an adsorbent to remove aqueous PCBs.

This approach is particularly important when excavation during remediation mobilises contaminated soil. In Canada, cleanup criteria for former military sites in the north stipulate that PCB concentrations in soil exceeding 1 ppm must be isolated from the Arctic ecosystem. Excavation is a cost-effective approach to achieve this goal, but the mobilised sediment can clog geotextile-based permeable systems. Therefore permeable reactive barriers can be used during excavations to trap mobile particles in the drainage pathway, and can be complemented in subsequent years with geotextiles as sediment loading decreases.

The smallest particle size of soil contains the highest amount of PCBs (ASU 2002). The barrier was designed to capture these highly contaminated fine particles of soil, and to provide at least partial treatment of runoff water containing PCBs. In the design employed at Resolution Island, contaminated drainage water flowed first between a funnel constructed of gabions, and then over a geosynthetic liner in order to trap particulate matter by reducing the flow of the water. Water and entrained particulate matter would then be contained by the ‘funnel’ and forced to pass through the filter box, or ‘gate’.

1.2. Filters for remediation

The soil to be remediated at Resolution Island is a sand with 20% gravel and classified as SP under the Unified Soil Classification System. It has no plasticity, a d_{85} (particle size in which 85% of the soil sample is finer than) of 5 mm, a d_{50} of 0.6 mm, a d_{10} of 0.075 mm, a coefficient of curvature (C_c) of 0.83, and a coefficient of uniformity (C_u) of 11.3. The grain size ranges from 75 μm to 25.4 mm, with a gently changing slope. This section will describe the application of various filter technologies in remediating this type of contaminated soil.

Filters, by removing particulate matter from water, play a critical role in potable and waste water treatment (Reddi 1997). In each application, the filter provides an economical particle separation process that can achieve a desired water quality level with respect to particulate matter and, in some cases, with respect to specific contaminants that are often found in colloidal or particulate phases. Filters can be used in barrier systems exposed to liquid carrying particles in suspension (Faure *et al.* 2006; Liu and Chu 2006; Muthukumaran and Ilamparuthi 2006; Wu *et al.* 2006). Though this design is an atypical use of geotextiles, it acts in a similar manner to a ‘silt fence’ application (Stormont *et al.* 1997; Theisen 1992; Henry *et al.* 1999).

There are various filter design criteria, depending on the application. The two most important functional criteria for filter design are soil retention and permeability (Luettich *et al.* 1992; Luettich 1993; Giroud 1996; Mlynarek and Fannin 1998). However, these criteria have conflicting requirements: as retention increases, so does the likelihood of clogging, and as clogging increases, permeability drops.

Geosynthetic adsorbents, both hydrophilic and hydrophobic, were used in the original field filtration design at Resolution Island, but have since been discarded in favour of granular activated carbon (GAC), which can both act as a filter for contaminated fines and adsorb aqueous PCBs. Sorptive removal can be a good solution for the attenuation of hydrophobic organic contaminants in water (Simon *et al.* 2003), and has been shown to be effective in cleaning up PCBs in the environment (Carroll *et al.* 1994). Therefore its application in this scenario was investigated. GAC is an adsorptive material that has been used in many PRBs (Lorbeer *et al.* 2002, Birke *et al.* 2003) as well as being a suitable sorption material for PCB remediation (Ghosh *et al.* 2003). The use of a passive material that will be able to withstand the harsh Arctic conditions has great appeal. Table 1 describes the various filter materials and their relevant properties.

In addition to the field trials on Resolution Island, the various filter and absorbent materials used on site have been examined in various laboratory studies. Batch tests were conducted on the two most promising sorbents from the 2003 field data results: GAC, and the geosynthetic hydrophilic absorbent boom. Sorption kinetics were evaluated and compared between these two materials. The geotextiles were also tested for permittivity and permeability after being subjected to freeze–thaw and UV stresses to simulate the harsh conditions in the Arctic environment and evaluate the survivability and durability of the materials.

1.3. Batch studies

Batch studies screen potential materials rapidly for reactive barriers. The results from these studies can be used to quickly select which materials are best suited for the contaminant/geochemical situation, and these materials can then selected for further laboratory testing (Powell and Powell 1998). Batch tests are usually faster, cheaper and simpler to set up than column studies (Crittenden *et al.* 1985, Powell *et al.* 1995). This study used batch adsorption isotherm tests. In these tests, a controlled amount of medium was added to water with known concentrations of contaminant, and then shaken for a specified interval. These studies were used to compare the two most promising adsorbent filter materials used in the 2003 field: GAC and the hydrophilic geosynthetic adsorbent.

1.4. Column studies

Column studies provide a means to mimic field conditions. Column studies were conducted to assess permeability, breakthrough and effective residence times. These tests involved pumping a feed solution that mimicked contaminated runoff passing at varied rates through a column of reactive material. Breakthrough occurs when the reactive medium thickness is too small, and in the field would result in the barrier failing to meet the compliance point (Powell and Powell 1998). Column studies provide a means of assessing which filter materials trapped the maximum amount of fines without clogging.

Table 1. Filter materials examined

Filter	Type	Relevant properties
W1	Woven polypropylene geotextile	EOS = 0.6 mm $k = 3.3 \times 10^{-4}$ m/s $\mu = 82$ g/m^2 $t_{GT} = 0.61$ mm
W2	Woven polypropylene geotextile	EOS = 0.6 mm $k = 1.0 \times 10^{-4}$ m/s $\mu = 210$ g/m^2 $t_{GT} = 0.67$ mm
NW1	Nonwoven, polypropylene needle-punched geotextile	$k = 1.5 \times 10^{-3}$ m/s EOS = 50–150 μm $\mu = 730$ g/m^2 $t_{GT} = 4.65$ mm
NW2	Nonwoven, polypropylene needle-punched geotextile	$k = 1.9 \times 10^{-3}$ m/s EOS = 50–150 μm $\mu = 690$ g/m^2 $t_{GT} = 4.24$ mm
Hydrophilic geosorbent	Booms, 7.6 cm diameter, polypropylene	–
Hydrophobic geosorbent	2.54 cm shredded blue polypropylene	–
GAC1	Granulated activated carbon	2–3.35 mm particle size
GAC2	Granulated activated carbon	2 mm particle size
Gravel	Granular	2–8 mm particle sizes 6.4–12.7 mm particle sizes

k = hydraulic conductivity, EOS = equivalent opening size, μ = mass per unit area, t_{GT} = thickness of geotextile from Terrafix (1997).

2. METHODS

2.1. Barrier

In 2003 a trial barrier system was installed on site (Figure 1). The filter box, or gate, consisted of four pairs of slots into which filters or cassettes containing absorbing material were placed (Figure 2). The filter box was made from 0.16 cm stainless steel panels. The lids of the boxes were painted black to increase the temperature within the barrier through sunlight exposure, so that any frozen material would melt more quickly.

To allow changing of the filter cartridges, the lids of the barrier were removable. Cartridges were placed in each filter slot. Geotextile filters were installed by fitting the geotextile on a wood frame and placed in the slots furthest upstream (Figure 2). Window screen material with an aperture of 2 mm was used to contain granular materials. Details of the filter materials used are given in Table 1.

2.2. Column

The column apparatus was constructed of stainless steel, and comprised an entrance drain, filter sections and an exit drain (Figure 3). Each middle section can be interchanged, providing for greater flexibility in testing varying filter thickness. Water flow was controlled using a programmable water pump. Once testing was completed, contaminated exit water passed through a sand and charcoal filtration system prior to being discarded or reused. For the purposes of this particular paper, breakthrough was considered evident when fines exited the column apparatus. The filter materials and water were tested periodically to ensure that exiting waters were PCB free. The column apparatus was designed to allow for both vertical (preferential for kinetics testing) and horizontal (preferential for mimicking field conditions) orientation of testing. Prior to running adsorption experiments, it was important to evaluate whether a mass balance could be achieved on the new apparatus.

The PCB-contaminated soil used for experiments was excavated from the site and stored at 4°C. Different concentrations of soils were combined and homogenised to create a sample of uniform soil concentration with a PCB concentration approaching 50 μg/g. Soil with a higher PCB concentration was used for experiments to facilitate subsequent analysis. The soil was mechanically mixed for two days using a tumbling apparatus to obtain reasonable homogeneity. Three subsamples of this soil mixture were analysed using Soxhlet extraction to evaluate its PCB concentration. A level of PCBs in soil of 44 $\pm$ 3.3 μg/g was achieved.

To establish a mass balance, a known quantity of this PCB-contaminated soil was flushed through the column at a constant flow rate as a slurry, sourced from a glass

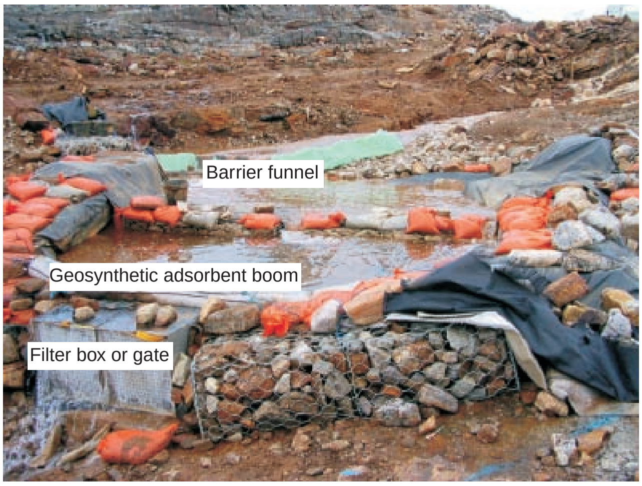

Figure 1. Downstream view of barrier system installed at Resolution Island, Nunavut, July 2003

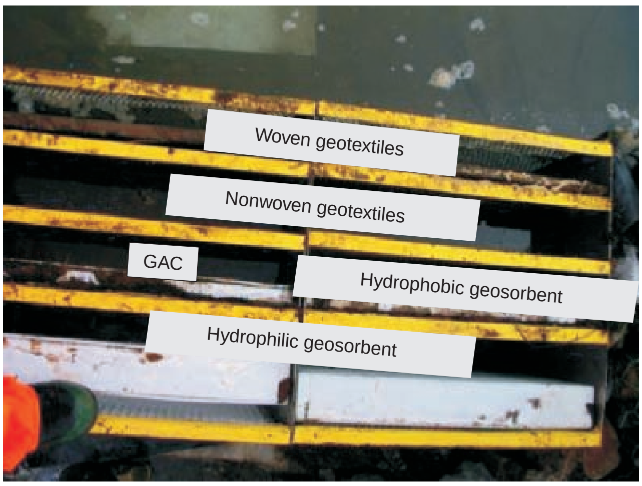

Figure 2. Barrier filter slots and filter materials used in 2003. Flow of water through barrier filter system is from top to bottom of figure

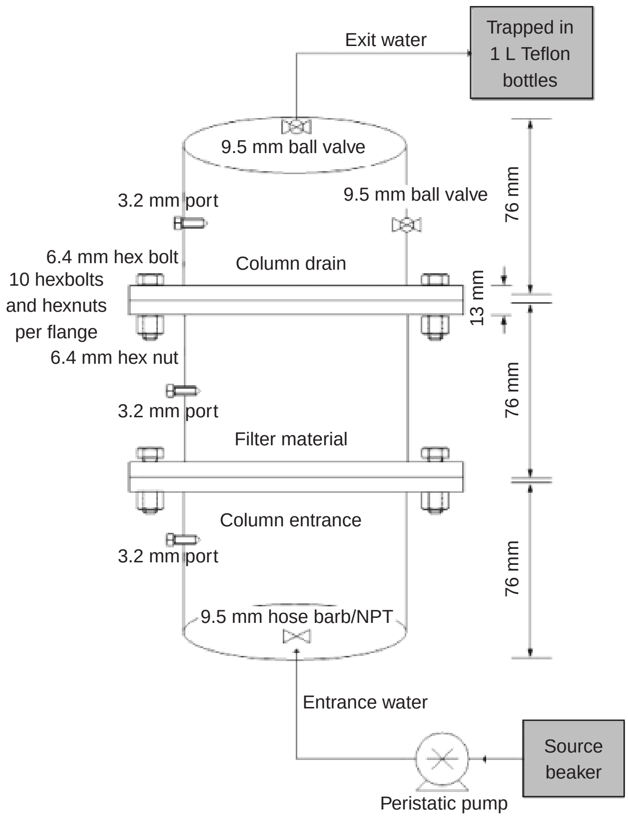

Figure 3. Stainless steel column apparatus schematic used for column experiments

beaker. The effluent was collected and carefully filtered through filter paper with an opening of 0.45 μm. The source beaker was rinsed, and the effluent was also filtered through filter paper with an opening of 0.45 μm. Air was blown through the column to dry the material inside for 12 h. The column was then carefully taken apart to ensure that each fraction of PCB-contaminated soil remained within the sections (i.e. entrance drain, filter section, exit drain; see Figure 3.) After emptying the column, it was wiped down with gauze, and DCM and all samples were analysed using Soxhlet extraction (EPA 1996) and GC/ECD (gas chromatography with an electron capture detector). Concentrations were converted to percentages, to enable comparison between the experiments. It was possible to use these numbers to establish a mass balance on the column. Across 14 experiments an apparatus error was established of ±10%. This mass balance added confidence that results obtained using this column apparatus reflected good performance and meaningful results.

Discrepancies in filter porosity can lead to large variations in results. A larger degree of pore space within the filter compartment translates to more fines escaping. Tests were performed for samples at the same porosity. Data reported are from column runs within acceptable error limits of ±5%.

2.3. Filter analysis of filters in field gate

Three geotextiles (W1, W2, NW; see Table 1) were examined. The effective opening size (EOS) of the filters was obtained from the manufacturers' literature, using the ASTM D4751 standard. After a period in the barrier gate (the filters were either left on site during the summer field season or 'over-wintered' during the winter and spring seasons), they were removed and sampled by cutting out three 7 cm by 7 cm squares, cut across the top, the middle and the bottom of the filter. This was done so that the values in each area could be averaged, and applied to give an appropriate value for each section of filter (top, middle, bottom) as well as averaged for the whole filter. The hydrophobic geosorbent shredded material was sampled in two rows down the sides of the filter from top to bottom, totalling six samples with two samples taken from the top, two from the middle region and two from the bottom region of the filter box. Because the granules of the activated carbon (GAC) shifted during transport back to the laboratory, the granulated carbon was poured into several large containers and thoroughly mixed. In total, nine samples were taken for extraction, and the results were averaged. In the case of the absorbent booms, there were four booms in each filter box. One sample was taken per boom from the filter boxes. These four boom samples were subdivided into top, top middle, bottom middle and bottom. The results for the two middle booms were pooled. The samples were then analysed for PCBs using Soxhlet extraction and GC-ECD analysis.

2.4. Batch tests

Distilled, deionised water (800 mL) was added to a 1 L Teflon bottle. To this water, PCB as Aroclor 1260 (1000 μg/mL) was added, in varying amounts to obtain concentrations ranging from 25 to 1000 ppb in water. The resulting solution was tumbled in a revolving box, at a rate of 30 ± 2 rev/min, as per Ontario Leachate Testing Regulations 558/00 (Government of Ontario 2000). After one hour of tumbling (to allow time for the solution to mix thoroughly), the bottles were removed and 1.0000 ± 0.0005 g of pre-measured sample (sorbent) was added to the solution. The bottles containing 1260 Aroclor, water and geosynthetic were allowed to tumble for various periods of time: 12 h, one day, three days, and one week. At the end of the allotted period of time the samples were then filtered through pre-weighed filter paper (Q8 Fisher) into separatory funnels. PCB analysis was performed on the resulting water. The bottles were rinsed, and rinsate was poured through the funnels, to ensure that all material was retrieved. The solid samples were then allowed to dry before Soxhlet extraction.

2.5. PCB analysis

All dried, pre-weighed samples were placed in a glass thimble and spiked with a 100 μL aliquot of DCBP, a surrogate standard. Samples were extracted with 250 mL of methylene dichloride. Extracts were concentrated using a rotoevaporator, and the solvent was exchanged for hexane before cleanup of the sample, accomplished by flushing the hexane containing PCBs through a Florisil silica column and making the resultant eluent up to 10 mL with hexanes. Approximately 1.5 mL of sample was then transferred from the 10 mL volumetric into a labelled GC vial and sealed. Each sample was analysed using an HP 5890 Series II Plus gas chromatograph equipped with a Ni^{63} electron capture detector (GC/ECD), a SPBTM-1 fused silica capillary column (30 m, 0.25 mm ID × 0.25 μm film thickness) and HPChem station software. A 10 ppm 1260 Aroclor standard was run with the samples, blank and spike along with three DCBP standards, used to calculate percentage recovery. A hexane blank was also run with the samples.

2.6. Permittivity testing

Four different geotextiles were tested for their permittivity and permeability: woven W1 and W2 and nonwoven NW1 and NW2. A second set of these geotextiles was exposed to freeze–thaw cycles to mimic the Arctic environment. This procedure ran for 150 days. Each morning, the filters were submerged in water and placed in a freezer. At night (after approximately 10 h) the filters were removed and allowed to thaw at room temperature (26 ± 3°C). These steps were repeated every 1–2 days for a total of 100 continuous freeze–thaw cycles. Another set of these same geosynthetics were exposed to ultraviolet light for 5 months during spring and summer. The materials were secured to a wooden board and placed flat on the southern side of the roof of the five-storey Biosciences building at Queen's University, Kingston, Ontario, Canada (latitude 44° 14′ N, longitude 76° 30′ W). The filters were monitored and continually exposed to the elements. After completing exposure conditions, the geosynthetics were tested using the ASTM D4491 standard. The flow rates through the woven and nonwoven filters were recorded, along with the water pressures on either side of the geotextiles.

3. RESULTS AND DISCUSSION

3.1. Permittivity testing

Permittivity testing was conducted on the geosynthetics to evaluate the effects of the harsh conditions of the Canadian Arctic on the hydraulic performance (Table 2). The pressure differences across the geosynthetics were recorded when different flow rates were applied. The temperature was also recorded for each run, as the viscosity of water changes with temperature.

The effect of different gradients on the flow through the geotextiles was also investigated. Exposure to UV light and freeze–thaw cycles significantly (at the 95% confidence level based on Student's *t*-test) affected the flow through all geotextiles tested. Specifically, UV affected W1 and NW2; freeze–thaw affected both NW1 and NW2. In some cases the material was stretched, which allowed greater permittivity and permeability values. In other cases the pores of the materials were damaged and collapsed, giving lower permittivity and permeability values. This shrinking action in the field could reduce permeability, while stretching could impact the effectiveness of soil retention.

3.2. Batch studies

3.2.1. *Sorbent*

For all periods of time and concentrations (25 to 1000 ppb in water) of PCB, the hydrophilic geosorbent proved to be very effective at adsorbing the PCBs under these static conditions. Recovery of the PCBs in the sorbent, averaged over 39 samples, was 96% ± 13%. In all cases, the amount of PCB detected in the water was below detection levels ($<$ 3 ppb). PCBs, especially 1260 Aroclor, which is made up primarily of hexa- and septa-chlorobiphenyls, have very low solubilities in water (Hutzinger *et al.* 1983). It was noted that there was no significant difference between the varying periods of time of tumbling, which indicated that the reaction reached equilibrium by 12 h.

Additional batch tests were conducted to assess the maximum sorption capacity of the sorbent, and to establish whether efficiencies changed when a greater concentration of PCB was present in the solution. It was found that, as amounts of PCB approached 600 ppm for 1 g of sorbent, efficiencies were significantly decreased (Figure 4). However, there has been no evidence to suggest that the materials would be exposed to these levels of PCB in such a short period of time in the field. These findings were therefore promising, since they indicated that the hydrophilic geosorbent booms selected from 2003 were capable of accommodating high concentrations of PCBs.

3.2.2. *GAC*

GAC was tumbled for two different durations, 12 h and 24 h, at varying concentrations (25 to 1000 ppb in water). Similar to the findings from the hydrophilic geosorbent boom batch tests, there was no detectable PCB in the water and recovery for the GAC (92% ± 6%, $n = 14$), demonstrating that GAC was as effective a sorbent as the geosynthetic booms under the conditions examined.

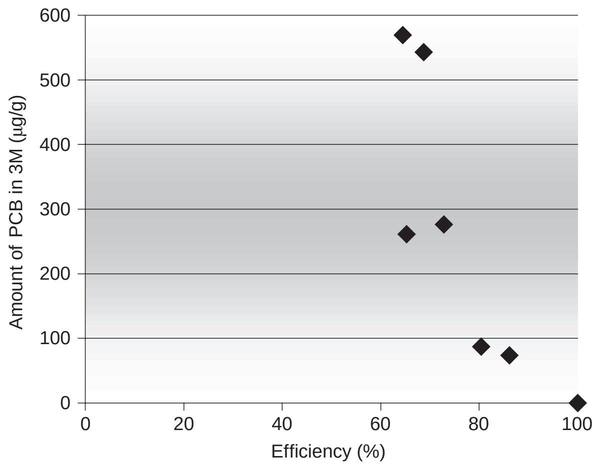

Figure 4. Efficiency at capturing PCB in hydrophilic geosorbent boom material from batch test results

Table 2. Permittivity results of geotextiles evaluated for use in barrier filter system

Geotextiles	Permittivity (s^{-1})	σ	Permeability (cm s^{-1})	σ
NW2				
Literature	0.58	–	0.23	–
Control	0.62	0.08	0.25	0.03
Freeze–thaw	0.45	0.14	0.19	0.05
UV	0.75	0.27	0.30	0.12
NW1				
Literature	0.25	–	0.15	–
Control	0.19	0.07	0.11	0.04
Freeze–thaw	0.38	0.10	0.23	0.06
UV	0.28	0.08	0.17	0.05
W1				
Literature	0.17	–	0.03	–
Control	0.37	0.08	0.07	0.03
Freeze–thaw	0.34	0.12	0.07	0.03
UV	0.73	0.39	0.15	0.08

σ = standard deviation. Literature results taken from manufacturer guidelines (Terrafix 1997).

Although GAC may retain PCB-contaminated soil by acting as a granular filter, the ability of the granular material to treat PCB-contaminated water in the field may be greater than that of the hydrophilic geosynthetic sorbent owing to its more permeable nature as a granular material, exposing greater surface area to the contaminant. In batch studies, the maximum sorption capacity of the GAC was not reached. As the PCB amount increases, levels of sorption efficiency will decrease as the maximum sorption capacity is reached. Even at levels of 800 ppm, 100% of PCB was adsorbed. These levels of PCB contamination were not observed in the field, because the more highly concentrated soil was removed via excavation. Contamination at levels tested in the laboratory is unlikely to be found in field sites, reducing concerns about sorption capacity.

3.3. Column studies

A particle size of 2–3.35 mm was selected for the GAC filter. It was expected that the bridging mechanism that occurs during clogging of pore spaces would reduce pore throats (Giroud 1996), thereby retaining a greater quantity of PCB-contaminated fines. Inevitably, some fines will escape through the three-dimensional pore network structure of the granular filter. Modelling of granular filters has shown that, over time, granular filter material is unstable, which can lead to washing out (Locke *et al.* 2001). In an application where the goal is to trap contaminated fines, and the filter is likely to receive seasonal loading, this can become a problem. In this study, laboratory tests were conducted using a horizontal column apparatus that was capable of mimicking site conditions such as dynamic seasonal loading.

Column test results were conducted to compare 7.6 cm thick gravel, and 2.5 cm and 7.6 cm thick GAC filters. There are two types of GAC filter, of varying size partitions: GAC2 has a uniform particle size of 2 mm, and GAC1 consists of particle sizes ranging from 2 mm to 3.35 mm. The sand had an angular shape, and a uniform particle size of 2 mm. The gravel was sieved to a particle size range of 3–6 mm.

Results are given in Table 3 and Figure 5. 'Trapped by filter' refers to PCBs that are trapped either in front of the filter or within the filter. 'Trapped within filter' refers to PCBs in the filter material. 'Escaped' refers to PCB fines exiting column and collected in 1 L Teflon bottles. From these results, it is apparent that the thicker GAC filter performs better than both types of thin GAC filter or the thick gravel, in terms of the amount of fines escaping the filtration system. It was found that the thick gravel filter performs similarly to a thin GAC filter. This result is particularly interesting, primarily because gravel is a much more cost-effective filter material. Provided that there was enough space to make a thick enough gravel filter in the field, one could use less GAC material, and reserve it for a fine polishing step.

Although nonwoven needle-punched geotextiles were prone to clog, and hence performed poorly hydraulically as a full-size filter, they performed very well in trapping PCB-contaminated fines owing to their fine pore structure. These filter materials were reintroduced as final polishing steps, after the granular filters. The filters were redesigned as half-height filters, covering from the bottom to the middle of the filter chamber. If clogging occurs, water can flow over the top of the geotextile filter, without hindering the overall hydraulic performance of the barrier system.

In column studies, the half-height geotextile filters did not make a noticeable difference to the amount of fines trapped when used with the finer GAC (GAC2). However, when used with the larger particle-size GAC (GAC1), the half-height geotextile filter reduced the fines escaping the system. It was found that increasing the thickness of

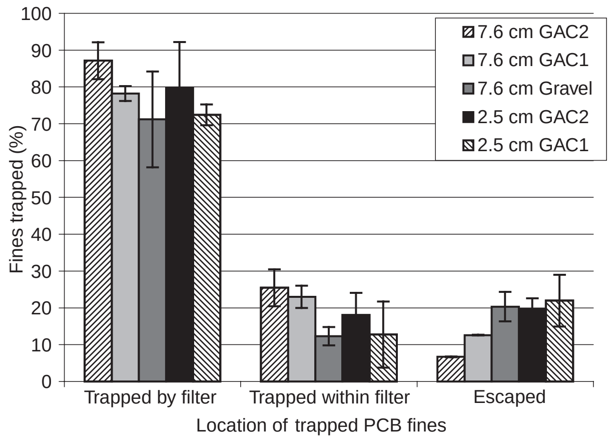

Figure 5. Column test results of GAC and thick gravel. Figure depicts trapped percentage of PCB fines in various portions of column

Table 3. Column test results

Filter	% Trapped by filter	% Trapped within filter	% Escaped
GAC2 (7.6 cm, thick)	87 ± 5	25 ± 5	7 ± 1
GAC2 (7.6 cm, thick) with 1/2 NW2	87 ± 3	25 ± 3	7 ± 0.4
GAC1 (7.6 cm, thick)	78 ± 2	23 ± 3	13 ± 0.1
GAC1 (7.6 cm, thick) with 1/2 NW2	70 ± 5	12 ± 2	8 ± 3
Gravel (7.6 cm, thick)	71 ± 13	12 ± 0.2	20 ± 4
Sand (2.5 cm, thin)	64	15	20
GAC2 (2.5 cm, thin)	80 ± 13	18 ± 6	20 ± 3
GAC1 (2.5 cm, thin)	72 ± 3	13 ± 9	22 ± 7

Table depicts trapped PCB fines in various portions of column.

the charcoal filters (Figure 6) provided the best performance in terms of trapping PCB-contaminated fines. As is seen in the field results (presented later in this paper), much of the soil gets trapped prior to entering the filter chamber. This occurs because the water flow is not great enough to push the soil along the bottom through the window screen mesh into the granular filter. These studies were short-term (2 min), pumping the soil slurry through the column only once, followed by flushing the system for the remaining period of time. Further studies will be needed to investigate the role of the polishing half-height geotextile over longer periods of time, and with dynamic loading of soil through the column. The column study results were beneficial in demonstrating that a geotextile filter, used in the form of a half-height filter, can be used together with a granular reactive medium to provide effective trapping of PCB-contaminated soil without hindering hydraulic performance

3.4. Fieldwork

The initial filter box, or gate, installed in 2003 consisted of four pairs of slots into which filters (or 'cassettes') containing absorbing material were placed (Figures 1 and 2). In 2003 two separate sets of filters were installed. The first set experienced summer rain conditions, and the filters were shipped south for sampling and analysis. The second set of filters experienced over-wintering and spring runoff conditions. Filters were sampled on site at the beginning of the field season, and replaced soon after with a new set of filters. For subsequent years filters were installed at the end of the field season, 'over-wintered', and sampled at the beginning of the subsequent field season (Table 4).

3.4.1. *2003*

In 2003 both nonwoven and woven filters were incorporated into the gate (see Figure 2). From these field results (shown in Table 5 and Figure 6), it was found that all filter materials successfully trapped PCB to varying degrees. GAC proved to be the most effective filter material. Whether this was due to its properties as a granular filter or as a sorbent remains to be established.

Although the geotextile filters successfully retained PCBs, they were found to clog. The woven geotextile filters were replaced in an attempt to reduce the clogging. The W1 and W2 geotextile filters were soil-stained along the bottom half. The nonwoven geotextile (NW1) was completely soil-stained, indicative of high water levels and clogging. Samples were analysed for PCBs, and the results indicate that the filters were successful in trapping PCBs. The results shown in Figure 7 were obtained from averaging and multiplying the concentration of the sample squares by the density and area of the section in question (top, middle, bottom). This yielded total μg of PCB trapped by the filter, allowing for direct comparison of the filters.

From these results, it can be seen that there is a vertical gradient in concentration, with more PCBs trapped at the bottom of the filters than at the top. This gradient is probably due to the fact that most of the soil stayed in the bottom half of the flowing water column. These results confirm that most of the PCBs are adsorbed onto fine soil particles. Pore opening sizes must be chosen carefully to prevent clogging. The NW1 filter was more successful in trapping PCBs than either W1 or W2, owing to both its smaller pore channels and its increased thickness, which gave rise to a substantially smaller EOS for NW1 than W1 or W2 (Table 1). The barrier was designed to filter out fine particles of contaminated soil: these initial field trials indicate that the geotextiles were successful in this task. The total amount of PCBs trapped by the geotextiles was 7.1 mg in the 6-week trial. However, because of clogging, the nonwoven geotextiles were not effective as a filter in this location. However, as noted earlier, they did subsequently prove effective as a half-height polishing filter.

3.4.2. *2004*

In 2004, at the field site, it was found that the soil loading was much greater than previously expected. The barrier, with its current design of geotextiles and geosynthetics, could not cope with the volume of soil. Water was found to be overflowing the barrier before any filters were removed. Once the geotextile filters were removed, a greater volume of water flowed through the barrier. Owing to the performance of geotextiles in the laboratory tests and in the field, it was decided to switch to granular filters in order to improve the design. Half-height gravel was used as the first filter to trap the maximum amount of contaminated soil without clogging the whole system in the first step. This half-height filter could remove the majority of the sediment without clogging, by allowing clean water to flow over the top to the next filter. If the half-height filter clogged, which was inevitable, it would not completely hinder the performance of the rest of the barrier system. Figure 8 shows the filter materials sampled

Figure 6. Geotextile filters used in 2003. Note soil stains

Table 4. History of filters used and field observations at Resolution Island, 2003–2006

Installation/removal	Filters (listed upstream to downstream)	Observations	Conditions
Installed in July 2003 Removed in September 2003 Shipped to Queen's sampled and analysed	Woven and nonwoven geotextiles GAC Hydrophilic geosorbent Hydrophobic geosorbent	Poor hydraulic performance	Exposed to summer rain conditions only Excavation nearby
Installed in September 2003 Removed in July 2004 Sampled on site	Woven geotextiles GAC Hydrophilic geosorbent Hydrophobic geosorbent	Poor hydraulic performance	Overwintered Spring runoff conditions Excavations nearby
Installed in September 2004 Sampled on site Removed in July 2005	Gravel GAC	Better hydraulic performance	Overwintered Spring runoff conditions Excavations and large soil piles nearby
Installed in September 2005 Removed in July 2006 Sampled on site	Gravel GAC	Adequate hydraulic performance	Overwintered Excavations nearby and completed this year
Installed in August 2006	Gravel GAC Nonwoven geotextiles	N/A	Noted need for finer particle retention: hence reintroduction of geotextiles

Table 5. Various filter materials and PCB retained (μg) by the 2003 barrier system

Filter	PCB retained (mg)
W1	0.4
W2	0.2
NW1	6.5
Hydrophobic geosorbent	2.7
GAC2	360

Note performance of PCB retained by GAC, compared with all other materials.

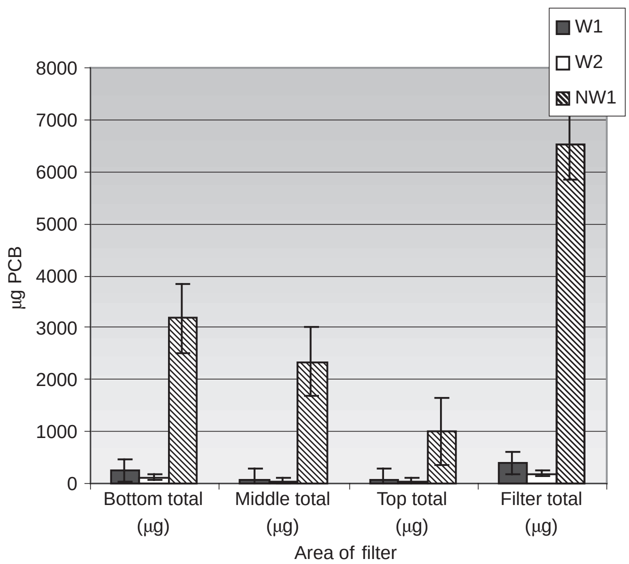

Figure 7. PCB (μg) in geotextile filters

at the beginning of field season 2004 (July), and the switch to new materials.

Gate design amendments included a move to more permeable substances, such as granulated activated carbon (GAC), instead of adsorbent geosynthetics. The particle size used in 2003 was deemed too fine and broad a distribution of particle sizes (0.425 μm to 2.0 mm) to function as a granular filter after examining granular filter criteria. In using such a small particle size of GAC there was the added fear of losing highly contaminated GAC fines outside the system. The new particle size distribution used in the GAC filter for the 2004 field season comprised fewer fines and a narrower distribution (GAC1, 2–3.35mm). The GAC had the added benefit of acting as a soil retention filter as well as being potentially able to treat PCB-contaminated water. Larger particle size gravel filters (2–8 mm) were placed in front of the GAC to trap soil and help protect the more expensive GAC filters.

Some of the water flowed in between and around the geosynthetic sorbent materials, rather than through them. Water levels in the hydrophilic geosorbent boom slot did not appear to exceed 30 cm, as water quickly flowed between and around the booms. Again, this indicates that the materials chosen were not permeable enough to allow water to flow freely, and that the preferential flow path was around these materials. From this observation in the field it was concluded that geosynthetic sorbent materials, like geotextile filters, may have a use in a barrier system, but not without design modifications.

3.4.3. *2005*

The barrier system was inspected at the start of the field season (July). Large volumes of sediment (7 m^3) had been trapped, but water was still flowing through the filters in the filter box. Fines were seen to be escaping from the box through the filter gates, although not enough to visibly increase the volume of soil deposits downstream. Monitoring points downstream from the barrier did not show an increase in PCB concentration.

The new particle distribution (2–3.35 mm) in the GAC filter was sampled in 2005 to evaluate its success. The

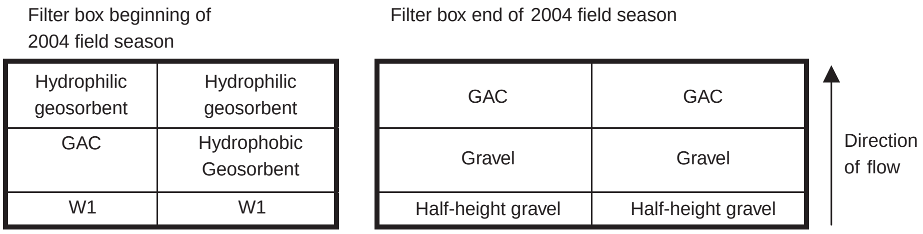

Figure 8. Arrangement of filters in gate in 2004. Note change from geosynthetics to granular materials

larger particle size GAC trapped contaminated soil but did not clog. The thickness of the GAC filters was increased (from 7.6 cm to 15.2 cm) in 2005 to ensure that breakthrough of contaminant did not occur. Gravel particle size was increased in the filter system (6.4–12.7 mm), largely to accommodate constraints on time: this change was related to logistics rather than design considerations.

Column tests were comparable to what is seen in the field: although the granular filters were not clogging, fines were still escaping the barrier system. The granular filters cannot be made to be thicker within the space allotted in the current design. The GAC must maintain its present thickness of 15.2 cm in the field to be able to adsorb PCBs from water. In this remediation scheme, a final polishing step in the form of a half-height geotextile filter provides the perfect option for helping to refine the remediation process.

Although a full-size nonwoven geotextile filter clogged when used as a lead filter in the system (as discovered in the 2003 field trial), it was also found to be the most successful geotextile filter for trapping PCB-contaminated fines. However, by placing it at the end of the system, after most of the particulates have been removed, the potential for clogging can be substantially reduced. Furthermore, by using a half-height filter, it can clog without impeding the overall hydraulic performance of the barrier system. In the future, half-height (26.5 cm) nonwoven needle-punched geotextile filters will be placed at the end of the gate system, in order to act as a final, polishing step. It is proposed to use several of these final polishing filters in series, allowing water to flow over top the first, with the second filter catching what the first filter missed.

Excavation work at the site was completed in 2005. The barriers constructed at the site will, in future years, have a much lower sediment loading.

4. CONCLUSIONS

Based on data from a remote site in northern Canada, we can conclude that the use of suitable geotextiles in a surface permeable reactive barrier is necessary to minimise the escape of PCBs to the environment via drainage pathways. Although a granular filter medium is preferable from the perspective of permeability, survivability and durability, a nonwoven geotextile is ideal for small particle retention in this particular use of barrier technology and should be included in the filtration system as a final, polishing step. As seen in the 2003 field season data, the nonwoven filter outperforms the W1 and W2 filters in PCB retention. This is an important contrast to the laboratory permittivity testing results, which show an advantage to woven filters in terms of performance extreme UV and freeze–thaw stress conditions.

The geosynthetic hydrophilic adsorbent was as effective an adsorbent as GAC up to 600 μg for 1 g of adsorbent in the batch studies. By contrast, the GAC enabled excellent PCB uptake while maintaining an adequate flow in the field studies. In these field conditions, water tended to flow around and between the hydrophilic sorbent booms, rather than through the material itself.

Horizontal column studies demonstrated that the use of a nonwoven geotextile in conjunction with a more permeable GAC could reduce the loss of contaminated fines. The column studies showed that if thickness of the barrier was not limited, it would be possible to replace the finer GAC material with a less expensive alternative, such as gravel, to trap contaminated particles. However, this would hinder remediation of PCB in water by decreasing the residence time of the contaminant in the reactive portion of the barrier. Through both field and column work it has been shown that, to meet remediation goals, a nonwoven geotextile filter can be applied to remove PCB-contaminated fines when used together with a granular, permeable reactive barrier system.

Further studies will be needed to investigate the role of the polishing half-height geotextile over longer periods of time, and with dynamic loading of soil through the column. Evaluation of the GAC material and its performance with respect to adsorption versus particle retention is currently ongoing. The results will help decide whether a more economical material with the same particle size and distribution could be substituted in lieu of GAC. Column studies must be conducted under varying temperatures to examine the effects of PCB adsorption in a colder climate.

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