EXECUTIVE SUMMARY

Evaluating the Efficacy of Bioaugmentation for In-Situ Treatment of PCB Impacted Sediments

ESTCP Project ER-201215

SEPTEMBER 2018

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1.0 INTRODUCTION

This report describes the laboratory treatability studies and field demonstration performed for ESTCP Project Number ER-201215, "Evaluating the efficacy of bioaugmentation for *in situ* treatment of PCB impacted sediments". The purpose of the project was to demonstrate and validate a recently developed *in situ* treatment for degrading polychlorinated biphenyls (PCBs) in contaminated sediments under field conditions at Abraham's Creek located on the grounds of Marine Corps Base Quantico, Virginia (MCBQ). The treatment utilizes an activated carbon agglomerate, SediMite™, as a delivery system for deploying PCB degrading microorganisms into PCB impacted sediments to accelerate the reduction of PCB levels in sediment and in the sediment porewater within a period of months. The project demonstrates the first successful treatment of PCB impacted sediments using a combination of in situ treatment with PCB degrading microbes and activated carbon (AC). The activated carbon is effective in reducing the bioavailability of the PCBs in sediments and also facilitates efficient delivery of the bioamendments into sediments, which facilitates mass reduction of PCBs in the treated zone. This combined remedy is particularly effective in environmentally sensitive sites where there is a need to reduce contamination of the aquatic food web from exposure to sediment-bound PCBs with minimal disruption to the environment. In addition to evaluating the performance of the treatment, the demonstration project provides estimates on the cost of deploying the technology in the field and provides data for assessment of its regulatory acceptance.

The commonly accepted methods for treatment of sediments impacted with PCBs are dredging and disposal or capping. Dredging is effective for reducing PCB levels in sediments, but it is costly, disruptive to the ecosystems, and increases the potential risk of PCB release into the water. Capping with passive materials such as sand or gravel is an effective treatment approach for containment of PCBs in sediment, but because it is subject to potential abiotic and biotic disruption, it does not completely eliminate the risk of later exposure and can be disruptive for the existing ecosystem. A recently developed method that is gaining acceptance is the application of AC to PCB impacted sediments to sequester PCBs, thereby decreasing the bioavailability of PCBs to minimize the risk of exposure to the food chain. However, none of these methods accelerate the degradation of PCBs beyond the rates observed for natural attenuation. Biological degradation of PCBs in the environment occurs by anaerobic dechlorination of highly chlorinated congeners followed by the aerobic degradation of the dechlorination products. A key bottleneck is the low native abundance of PCB dechlorinating bacteria in sediments at levels that will only support low rates of degradation. Thus, enhancing this natural process with bioaugmentation to accelerate degradation is a potential treatment strategy for PCB impacted sediments. Development of a tractable microbial *in situ* treatment system would provide a cost-effective and environmentally sustainable means of treating PCBs in sediments.

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2.0 OBJECTIVES OF THE DEMONSTRATION

The objective of the project was to demonstrate and validate a recently developed *in situ* treatment for degrading polychlorinated biphenyls (PCBs) in contaminated sediments under field conditions. Department of Defense (DoD) facilities across the country are impacted with persistent pollutants such as PCBs and the DoD is challenged with the remediation of these sites. This work addresses the DoD need for cost effective, *in situ* remediation technologies for PCBs and can be applied in principle to other persistent organic pollutants (POPs) such as pesticides. Most importantly, this work will enable extensive *in situ* treatment at DoD sites that include both shallow and deep sediments with minimum impact to environmentally sensitive areas. This integrated approach utilizes activated carbon to serve concurrently as an agent to sequester PCBs from the food chain and as a delivery system and solid substrate to enhance both anaerobic and aerobic microbial processes for complete *in situ* degradation. This technology demonstration project was conducted in a 7.8-acre ponded waterbody in Abraham's Creek, Marine Corps Base Quantico, located in the southeastern portion of Chopawamsic Creek near the confluence with the Potomac River. The treatment utilizes an activated carbon agglomerate, SediMite™, as a delivery system for deploying PCB degrading microorganisms into PCB impacted sediments to accelerate the reduction of PCB levels within a period of months. In addition to evaluating the performance of the treatment, the demonstration project provides estimates on the cost of deploying the technology in the field and provides data for assessment of its regulatory acceptance.

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3.0 TECHNOLOGY DESCRIPTION

This project is the culmination of more than a decade of laboratory research on PCB dechlorination (Sowers and May) and *in situ* remediation of PCBs (Ghosh) that was ready for implementation in the field. The innovative aspect of the technology is the application of "bioamended" SediMite™ as a solid substrate for delivery of microorganisms into sediments and concentration of hydrophobic PCBs in close proximity to the biofilm of PCB transforming bacteria. Recent laboratory mesocosm scale experiments demonstrated the long-term activity of the microorganisms delivered with SediMite™ and the overall feasibility of the approach.

Based on the optimal loading cell titer and carbon loading rates determined from a mesocosm study, we conducted a pilot-scale field application of bioamended AC in Abraham's Creek (Marine Corp Base Quantico) with the following objectives: 1) demonstrate the scalability of growing PCB respiring microorganisms for field application, 2) develop and test the application of PCB halorespiring and degrading bacteria using pelleted AC as a delivery system, 3) assess the benefits of bioamended AC treatment on concentrations of PCBs in sediments and porewater, 4) assess the fate of the bioamendment over time, and 5) evaluate the impact of treatment on the indigenous microbial populations (**Figure 1**).

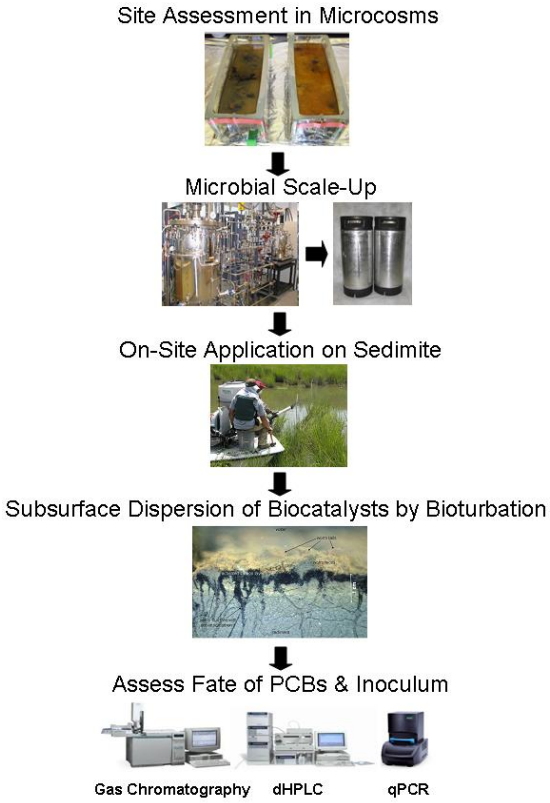

Figure 1. Graphic Scheme for In Situ Treatment of PCB Impacted Sediments Using Bioamended SediMite.

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4.0 PERFORMANCE ASSESSMENT

Key performance objectives of the project included demonstration of reduction of total PCB concentration and PCB bioavailability in sediment after bioamendment. The project was conducted in two phases. In the first phase, a laboratory treatability study was conducted to evaluate performance in laboratory mesocosms using sediments from the field site and evaluate application methods. The treatability study demonstrated that:

- Levels of both higher and lower chlorinated congeners were reduced indicating that both anaerobic reductive dechlorination and aerobic degradation occurred concurrently.
- Total PCB levels were reduced by a mean of 78% after 375 days compared with no significant change in untreated sediments (**Figure 2**).
- The overall toxicity was reduced by up to 90% after treatment based on toxic equivalency of dioxin-like congeners in the sediments.
- Porewater concentrations of all PCB homologs were reduced after bioaugmentation by up to 88% after 120 days and up to 97% after 375 days.

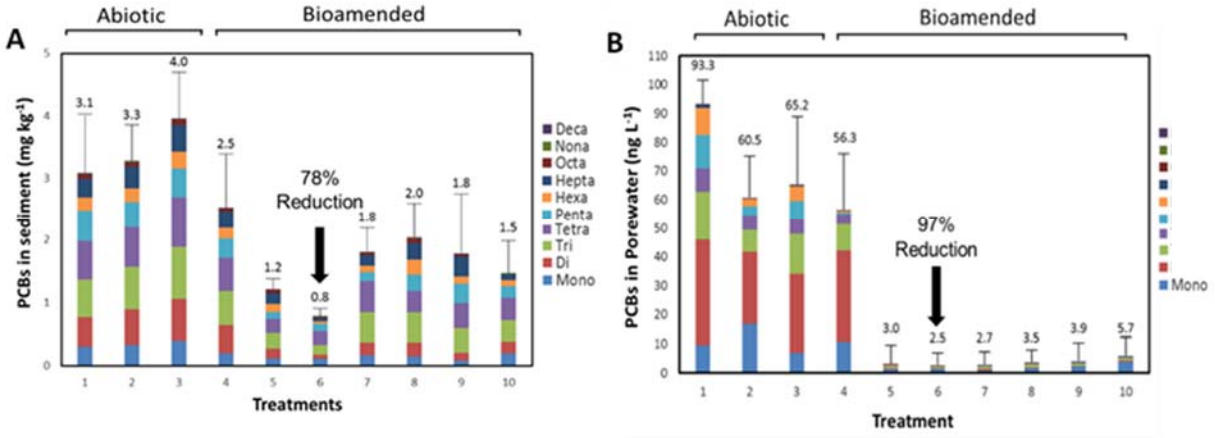

Figure 2. Treatability Studies in Sediment Mesocosms Showing the Effect of Treatments on Total PCBs in Sediments (A) and Dissolved PCBs (B).

Treatments included: (1) no treatment, (2) AC only, (3) AC+ electron donor (ED), (4-6) AC+ED+different titers of DF-1+LB400, (7) AC+DF-1+LB400, (8-10) AC+ED+different halorespiring bacteria.

- PCB levels were reduced throughout the 10 cm sediment column including both the aerobic and anaerobic zones.
- Overall results indicate that SediMite™/cellulose with DF1 and LB400 at 10^5 g^{-1} sediment was most effective for PCB mass reduction for the field demonstration project.
- Sufficient amount of bioamendments were produced to complete the proposed pilot study.

- The Venturi Horn Induction device (VHI) was successfully calibrated to deliver 10^7 cell g^{-1} SediMite™ with no significant loss of inoculum during pellet inoculation.
- There was no significant loss in viability during storage, transport, and passage of bioamended SediMite™ through a 1 m water column.

Based on the treatability study results, a decision was made to move forward with the pilot-scale demonstration in the field and a demonstration work plan was developed. Field testing was performed in close coordination with the RPMs and after approval of the demonstration plan by ESTCP and Naval Facilities Engineering Command (NAVFAC). The testing involved three phases: 1) initial baseline sampling, 2) application of treatment amendments in the field, and 3) subsequent monitoring visits to collect post-treatment samples. The treatment design involved four plots, each approximately 0.1 acres (400 m^2) in area. The four treatments included: 1) control plot with no amendment, 2) SediMite™ as an electron donor, 3) SediMite™ with cellulose and microorganisms, and 4) replicate plots treated with microorganisms applied to SediMite™ (**Figure 3**). The application of treatment amendments was completed in 3 days and each sampling visit was performed within a day. The pilot demonstration was implemented safely and within the target timeline. Key outcomes of the field demonstration are provided below:

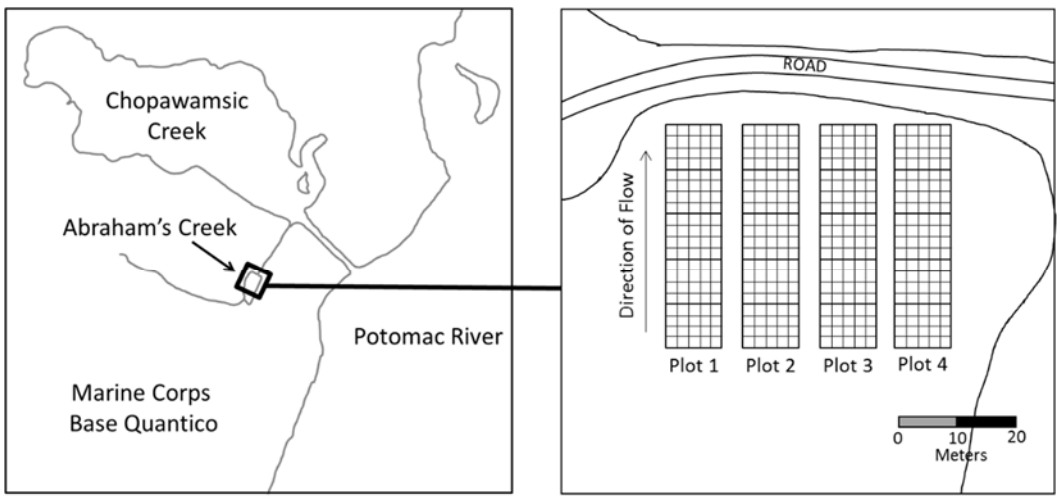

Figure 3. Schematic of (A) Abraham's Creek in Marine Corps Base Quantico and (B) Positions of the Treatment Plots 1 (no treatment), 2 (Granulated activated carbon [GAC] only), 3 and 4 (bioamended GAC).

Pre- and post-treatment sediment samples were taken from random positions from each of five areas (bold grid lines) within the treatment plots. Arrow shows direction of water flow.

- Both anaerobic halorespiring and aerobic biphenyl degrading bioamendments were mass cultured, transported to the site and delivered through a water column to sediments without significant loss of viability using a compressed air powered modified VHI system (**Figure 4**).

Figure 4. Flat Bottom Boat Loaded with VHI System, Hoppers Filled with Bioamended SediMite and 20 L Buckets of Bioamended SediMite for Refilling Hoppers (Left Panel); Application of Bioamended SediMite™ at Abraham's Creek (Right)

- Treatment with the bioamendment mixture on 3% bioamended SediMite™ reduced the mean total PCB concentration by 30% in Plot 3 and 52% in Plot 4 based on 5 sediment cores (**Figure 5A**). Even after excluding two outliers in plot 4 that had exceptionally high concentrations of black carbon (15.3 and 16.6%) due to variability in application, the decrease in total PCB concentration was 43% instead of 52% compared with Day 0 and was still statistically significant ($p>0.05$) confirming the effect was due to the bioamendment and not excess AC.
- The tri+ PCB congeners in sediment porewater were reduced by 84% and 95% in the two bioamended field plots after 409 days (**Figure 5B**). Co-planer congener levels were reduced by up to 80% in the sediment and were undetectable in the porewater.

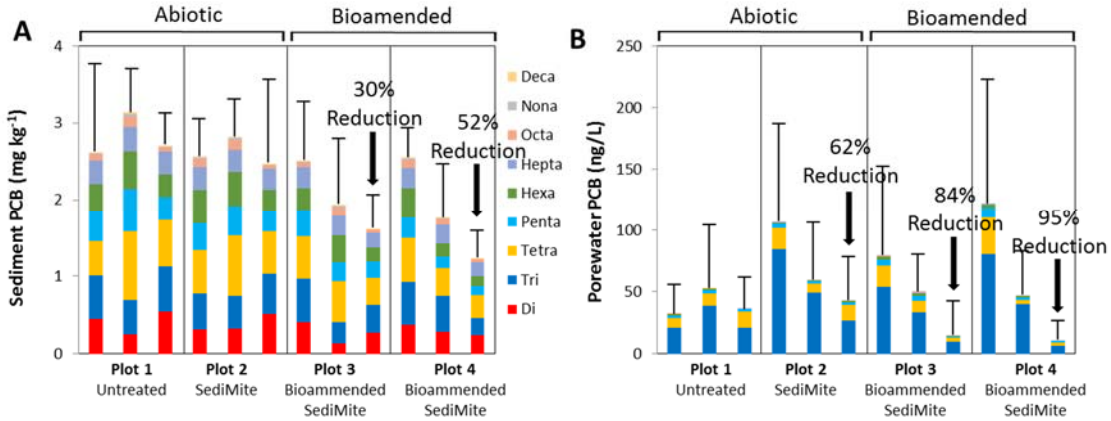

Figure 5. Field Study Showing the Effect of Treatments on PCBs in Sediment (A) and on Freely Dissolved PCBs in Porewater (B).

- All homolog groups were reduced in sediment and porewater indicating that both anaerobic halorespiration and aerobic degradation occurred within the benthic zone of the field sediments

- The effectiveness of bioamended SediMite™ for reducing concentrations of total and soluble PCBs was affected by the homogeneity of the application. Although the mean values in bioamended plot 4 met the performance objectives, this was not the case for identically treated Plot 3. However, there was also wide variation within each bioamended plot and maximum values exceeded the performance objectives for total and porewater concentrations of PCBs in both bioamended plots.
- In the bioamended plots, there was a direct relationship between the extent of degradation and the amount of black carbon detected in an individual sediment sample, which indicated that for full-scale treatment more consistent application would be required to achieve consistent degradation throughout the site. The VHI device is appropriate for application in water margin areas, wetlands, and difficult to access areas such as below piers and under overhanging trees. For larger areas, methods that ensure even distribution such as a boat mounted belt spreader or land based telebelt are required to evenly distribute the bioamendments and obtain target effectiveness consistently.
- The titer of the bioamendments decreased over two orders of magnitude but were still detectable after 409 days in the field. Indigenous microbial diversity was not significantly different between any other sites, time points, or depths. Therefore, bioaugmentation and the addition of activated carbon did not significantly alter total microbial diversity on a macroscale.
- The bioamended SediMite™ was stable and did not migrate downstream of the treatment area.

The study was limited to two post-assessments 140 and 409 days after treatment. Multi-year post-treatment assessments would be necessary to fully validate the long-term effectiveness of the bioamended AC to reduce total and porewater concentrations of PCBs in sediments. In addition, we observed a gradual reduction in the abundance of the bioamendments over time in the field. Future work should explore the feasibility of a second application to further reduce the concentrations of PCBs achieved with a single application. Our experience with the field application suggests that two applications may be helpful not just in further reducing the total PCB concentrations, but also potentially reducing the spatial heterogeneity in application observed after a single application.

5.0 COST ASSESSMENT

The general approach to addressing contaminated sediment is dredging, removal from the site and disposal with or without treatment. Additional costs associated with the technology often include containment of treated area to prevent release of resuspended PCB contaminated sediments downstream, dewatering of the dredged material before transport, and backfill of clean fill material to restore the site back to the original condition. Development of a tractable microbial *in situ* treatment system would provide a more cost-effective and environmentally sustainable means of treating persistent pollutants. The initial costs for dredging and off-site disposal are very high; however, the long-term monitoring, oversight, and management expenses are low. In situ remediation with bioamended SediMite™ will require post-treatment monitoring to ensure the proper functioning of the bioamendment in reduction of PCB concentrations. In terms of the life cycle assessment, use of bioamended SediMite™ would have a significantly reduced impact compared with dredging by reducing the health risks associated with sediment disruption, reducing overall energy use (reduced carbon footprint), effectively negating the requirement for extensive waste management, and obviating the requirement for substantial habitat restoration. A cost model for treatment of PCB impacted sediments with bioamended SediMite™ is shown in **Table 1**.

Table 1. Cost Model for Bioremediation of PCBs in Sediments with Bioamended SediMite™

Cost element	Data Requirements
Treatability Study	Personnel & labor Materials (Bioamendment, SediMite™, disposable labware) Analytical laboratory costs
Baseline characterization	Pre-treatment assessment of concentrations and distribution of PCBs Post-treatment assessment of bioamendment distribution Post-treatment assessment of bioamendment viability
Materials cost	Unit: cost/lb bioamended SediMite™ Production of SediMite™ Production of bioamendment
Installation	Unit: cost/treatment area Scale-dependent installation method Mobilization cost Personnel and labor
Post-treatment monitoring	Personnel & labor for sampling Analytical laboratory costs

The costs determined for the bioamended SediMite™ technology were compared with costs estimated for other technologies evaluated in the 2008 Feasibility Study conducted for this site. The construction cost of each of the 8 alternatives presented in the Feasibility report are compared to the cost of the construction of the bioamended SediMite™. The costs presented in the 2008 Feasibility report were escalated to present value (2017) using a 3% inflation rate. As shown in **Table 2**, the net present cost for the 8 technologies evaluated in the Feasibility study ranged from $0 for no further action scenario to $25M for full excavation and disposal off-site. Implementation of an isolation cap with or without reactive media is estimated at $4M.

In comparison, the estimated cost of bioamended SediMite™ application is $1.8M and SediMite™ only without bioamendment is $1.1M. The capping design involves an 18" sand cap with a 6" topsoil habitat layer creating a total of 24" of cap thickness. This can have a major effect of altering the nature of the wetland/pond system. In comparison the amount of material to be added as bioamended SediMite™ will barely alter the bathymetry of the pond and wetland system with minimal impact on the existing ecosystem. We anticipate the annual monitoring and maintenance costs for bioamended SediMite™ to be in the range of costs for Monitored Natural Attenuation or capping which are estimated at about $100k/year for the first 5 years. The total annualized cost per acre for each of the alternatives are shown in the last column of **Table 2**.

Table 2. Comparison of Total Capital Costs of Implementation of Remediation Technologies for 7.8-acre Pond in Abraham's Creek.

Costs for Alt 1-8 are based on 2008 Feasibility Study for the site (Battelle 2008).

Treatment Alternative	Total Capital Cost (2017 dollars)	O&M Cost	Total Annualized cost ($/acre)
Alt 1: No further action	0	0	0
Alt 2: Monitored Natural Attenuation	130,000	520,000	83,333
Alt 3: Isolation cap	4,030,000	910,000	633,333
Alt 4: Excavation & on-site confined disposal facility	17,030,000	910,000	2,300,000
Alt 5: Excavate & off-site disposal	25,090,000	0	3,216,000
Alt 6: Partial excavation & off-site disposal	11,570,000	260,000	1,516,666
Alt 7: Capping and wetland creation	5,850,000	910,000	866,666
Alt 8: Reactive cap	4,030,000	910,000	633,333
Alt 9: SediMite™ only	1,096720	910,000	250,640
Alt 10: Bioamended SediMite™ (present study)	**1,767,920**	**910,000**	**343,323**

6.0 IMPLEMENTATION ISSUES

The draft and final Field Demonstration Work Plan was provided to the remedial project manager at NAVFAC and Environmental Restoration Project Manager at Marine Corps Base Quantico (MCBQ) prior to implementation. Although a permit was not required for the pilot scale field test, full-scale implementation would need to comply with the substantive requirements of environmental regulators. Any regulations would be identified by contractors in planning documents prior to fieldwork, which would then be reviewed by state and federal regulators. Dept. of Navy representatives and NAVFAC and MBQ would then review the applicable regulations. The only restrictions encountered during the field implementation and post-treatment sampling was obtaining permission to access the site from the Officer of the Deck (OOD) between Marine Corps Officer Candidates School (OCS) training sessions and ensuring that all equipment did not exceed the maximum height requirement due to proximity of the site to an airfield.

The biggest factor is that the technology is cost effective and capable of producing the desired results. A major concern would be site implementation without impacting training, so staging area(s), traffic, and availability to be on site would need planning. The approval process for possible full-scale treatment would need to fit in to the training schedule of the site. A tele belt or other equipment would need to get approval from the airfield. This is a multi-step process if certain conditions exist but would generally follow: submit plan/equipment to airfield; airfield conducts an Obstacle Evaluation to submit to the Federal Aviation Administration (FAA); waiver granted by FAA; prior to equipment being used in the field a Notice to Airman (NOTAM) is issued. We do not believe extensive examination of the technology itself would be required for the purpose of obtaining or exemption from a permit. Regulatory agencies are familiar with use of SediMite™ in several other projects and the microbes used are not GMO nor pathogenic and are ubiquitous in the environment. Finally, before full scale implementation would be approved, there would be comparison to other technologies during the feasibility stage of process.

In terms of procurement issues SediMite™ is available for order from Sediment Solutions, requiring a lead time of 6 months (for 160 tons) for production and shipment. The microorganisms used as bioamendments are available from either commercial culture collections and/or individual university labs. Scale-up of the microorganisms requires outsourcing to companies with large volume bioreactors with the ability to grow anaerobes in the case of the halorespiring microorganism. However, plans are under way to develop a commercial source for these microorganisms. The VHI used in this study requires slight modification, but other deployment methods (*e.g.*, telebelt, broadcaster) could be used directly without modification. All other equipment used in the study is available commercially. Commercial contractors such as Brightfields Inc. are familiar with the use and application of the material.

Overall, the project demonstrates the potential treatment of PCB impacted sediments using a combination of *in situ* treatment with PCB degrading microbes and activated carbon. The activated carbon is effective in reducing the bioavailability of the PCBs in sediments (as demonstrated in previous studies) and also facilitates efficient delivery of the bioamendments into sediments, which facilitate mass reduction of PCBs in the treated zone. This combined remedy is appropriate and effective for sites that are ecologically sensitive and provide a hydrodynamically stable environment where the amendments will remain embedded in the sediments.