

## PCB-CONTAMINATED SEDIMENTS: PERFORMANCE EVALUATION OF SORBENT-AMENDED SEDIMENT CAPS

### Introduction

This paper was presented at the American Chemical Society Division of Environmental Chemistry Symposium on *PCBs in Freshwater and Marine Sediments: Transport, Transformation and Treatment* held in Philadelphia in August 2004. The paper examines the potential of using various sorbent materials (activated carbon, coke and soil) for thin in-situ caps over PCB-contaminated sediments. Laboratory testing and modeling was performed. As expected, activated carbon significantly outperformed both sand and the other adsorbents. A thin layer of activated carbon can be accurately deployed using a Reactive Core Mat.

**PCBs IN FRESHWATER AND MARINE SEDIMENTS:  
TRANSPORT, TRANSFORMATION, AND TREATMENT**

**Organized by**

**D.A. Dzombak and G.V. Lowry**

Symposia Papers Presented Before the Division of Environmental Chemistry  
American Chemical Society  
Philadelphia, PA August 22-26, 2004

**In Place Management of PCB-Contaminated Sediments: Performance Evaluation and  
Field Placement of Sorbent-Amended Sediment Caps**

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**Introduction**

The proper management of PCB contaminated sediment has proven to be a wide spread, complex, and costly issue. A National Research Council (NRC) committee on the remediation of PCB contaminated sediment proposed a risk management framework, which attempts to minimize short and long term risk to human and ecological endpoints.<sup>1</sup> Reible et al. have proposed the Surface Area Weighted Average Concentration (SWAC) as a useful surrogate risk metric.<sup>2</sup> SWAC is the average concentration in the biologically active portion of the sediment, this surficial zone in fresh and salt water systems is estimated to have a mean depth of 10 ±5cm.<sup>3</sup> SWAC considers the biologically available fraction of PCBs in assessing exposure pathways and resulting risk. This surrogate risk metric assumes that PCBs buried below the biologically active portion of sediment are less likely to enter the aquatic food chain.

In-situ capping (ISC) is a commonly employed risk management technology to minimize SWAC. This technology eliminates contact between the benthic community and contaminated sediment with a physical barrier of clean material, usually sand. The objective of ISC is to minimize SWAC by isolating contaminants, stabilizing the contaminated sediment, and reducing contaminant flux into the biologically active portion of the sediment. ISC manages the risk of contaminated sediment without many of the disadvantages associated with dredging, including the generation of large volumes of dredged wastewater requiring treatment, contaminated sediment resuspension and transport, residual contamination, and the creation of new exposure pathways during ex-situ treatment, transport, and disposal.

Thin sand caps can isolate contaminants for years and decrease the flux rate by increasing the required transport length.<sup>4</sup> Adding sorbents to sand caps will prolong contaminant isolation by retarding contaminant movement. Potential sorbents include organic rich soils and sediments, thermally altered carbonaceous material (TACMs), and engineered sorbents such as activated carbon. The tendency for hydrophobic organic compounds (HOCs) to strongly adsorb to TACMs and activated carbon is well documented.<sup>5,6</sup> Sorption provided by organic rich soils or by TACMs will retard contaminant transport and delay contaminant breakthrough, allowing more time for inherently slow natural attenuation processes (e.g. deposition of clean sediment and biodegradation of contaminants buried in sediment). Previous work suggests that contaminants associated with TACMs may not be bioavailable, another potential benefit.<sup>7</sup> Both sorption strength and capacity are important parameters affecting a sorbent's ability to retard contaminant transport.

Thin layers (cm) of TACMs may provide sufficient capacity and retardation to meet management goals, but traditional placement methods, e.g. particle broadcasting, can not accurately deploy such thin layers. Fines, and low specific gravity materials (e.g. coke and activated carbon) that are resistant to settling present an additional placement concern. Geotextiles are porous, synthetic fabrics that may allow for the accurate placement of thin material layers. Bentonite clay filled geotextiles are commonly used as landfill liners. The use of geotextiles to deploy thin layers of TACMs is promising, but field experience in subaqueous placement is limited.

The study objectives are to i) measure the physical properties relevant to advective-dispersive transport through 4 types of material (e.g. equilibrium partition coefficient, effective porosity, sorption capacity), ii) compare the relative PCB transport through a capping layer of each material under flow conditions expected in a sediment environment, and iii) develop and test a method to place thin layers of capping media. This work finds that very thin TACM layers (~1cm) can isolate PCBs for decades to centuries. Geotextiles effectively and accurately deploy thin layers (1.25 cm) of sorbent into sediment caps.

## **Materials and Methods**

### Sorbents

The properties of the four sorbents used in this analysis: Coke (U.S. Steel Clairton Works, Clairton Pa), F-200 Activated Carbon (Calgon Carbon, Pittsburgh Pa), Soil (3.9% OC) (Sestili Nursery, Pittsburgh, Pa), and Sand are given in Table 1.

### Sorption Isotherms

Sorbents were pulverized, sieved, and dried for 12 hours at 105°C to remove H<sub>2</sub>O ( $d_p < 0.5\text{mm}$ ). A specified mass of sorbent was added to 120 ml of DI water, 10 ml of 1,2 DCB saturation solution (~120mg/L), and 30 ml of headspace. The initial aqueous concentration of 1,2 DCB was 9.3mg/L. Samples were hand shaken once a day and allowed to reach equilibrium (5 days) in a covered 25 degree C bath. A 200  $\mu\text{L}$

Sorbents	Sand	Soil	Coke	AC
Carbon (%)	~0	3.80%	92	90
Porosity (eff)	0.29	0.47	0.48	0.53
Size (mm)	~0.3	0.4-2.0	0.4-2.0	0.3-2.0
Particle Density (g/cm <sup>3</sup> )	2.5	2	1.5	1.4
BET SA (m <sup>2</sup> /g)*	<1	6.6	2 to 12	919
R (retardation)**	6 x 10 <sup>2</sup>	1.6 x 10 <sup>5</sup>	2.3 x 10 <sup>5</sup>	1.8 x 10 <sup>7</sup>

\* N<sub>2</sub> BET

\*\*  $R = \frac{\rho_b K_d}{\eta_e} + 1$  where:  $\rho_b$  - bulk density,  $\eta_e$  - effective porosity,  $K_d$  - equil. partitioning coef. [cm<sup>3</sup>/g]

headspace samples were manually injected onto a Hewlett Packard 6890 Gas Chromatograph (GC) with HP-5 column and  $\mu$ ECD. The dimensionless Henry's Constant for 1,2 DCB in DI water at 25°C was determined appropriate using a previously described method.<sup>8</sup> An external standard curve was run with each isotherm.

### Column Studies

Sorbent filled columns were used to assess the sorption capacity (1, 2 DCB) and effective porosity (sodium chloride tracer) of each material. Influent (~20 ppm) and effluent 1,2 DCB samples were extracted into hexane and analyzed by GC/ $\mu$ ECD with HP-5 column. Tetrachloroethylene was used as an internal standard. The capacity of each sorbent was then determined by numerical integration of the area between the influent and effluent 1,2 DCB measurements until complete breakthrough. A conductivity meter (Fisher Scientific, accumet model 20) was used for tracer studies. Effective porosity was determined by measuring time until 50% sodium chloride breakthrough, flow rate, and the empty column volume (eq. 1) where  $Q$  is the flow rate,  $t_{50}$  is the time until 50% breakthrough,  $V$  is the column volume.

$$\eta_{eff} = \frac{Qt_{50}}{V} \quad (\text{eq.1})$$

### Modeling

Equilibrium partitioning coefficients ( $K_d$ ) for 2,4,5 PCB were extrapolated from measured 1,2 DCB  $K_d$  values using equation 2.

$$K_{d\ 2,4,5PCB} = K_{d\ 1,2DCB} * \frac{K_{ow\ 2,4,5PCB}}{K_{ow\ 1,2DCB}} \quad \text{Eq. 2}$$

Column tracer studies were fit to the Van Genuchten (VG) solution of the advection, dispersion, with retardation (ADR) transport equation to quantify hydrodynamic dispersion and breakthrough vs. time for each capping material.<sup>9</sup> The VG solution can also be used to estimate PCB breakthrough for each material by assuming linear sorption and ignoring sorption capacity. This could lead to substantial error so Freundlich isotherms are currently being applied to nonlinear isotherms to address nonlinear sorption and capacity issues.

## Results and Discussion

### Sorption Isotherms and Capacity Measurements

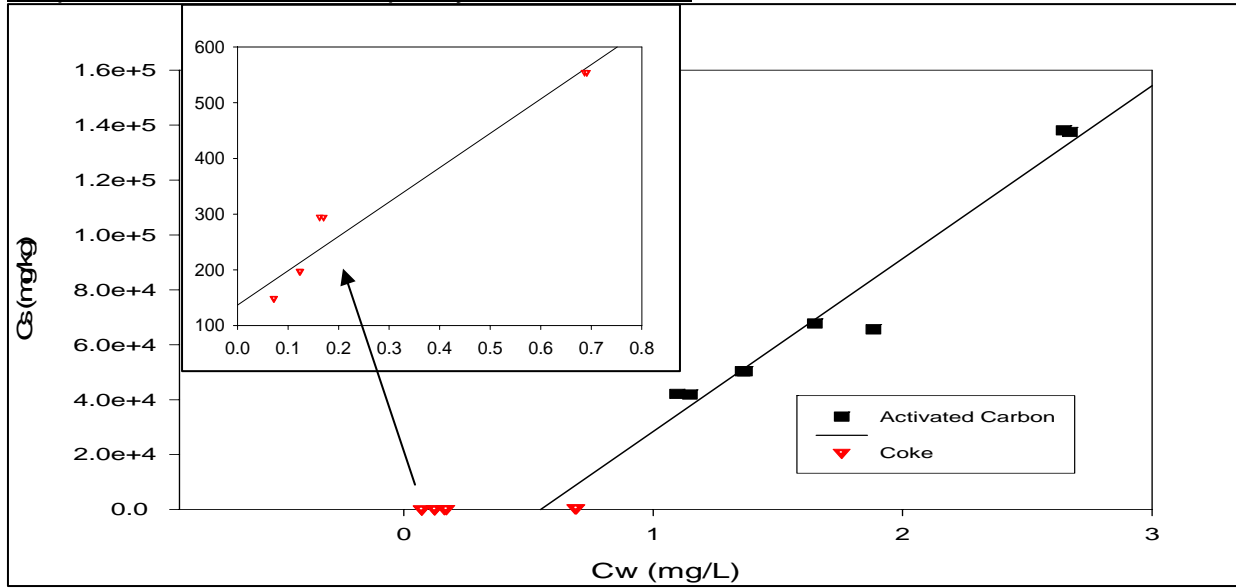


Figure 1. Sorption Isotherm with 1,2 DCB for Coke and Activated Carbon

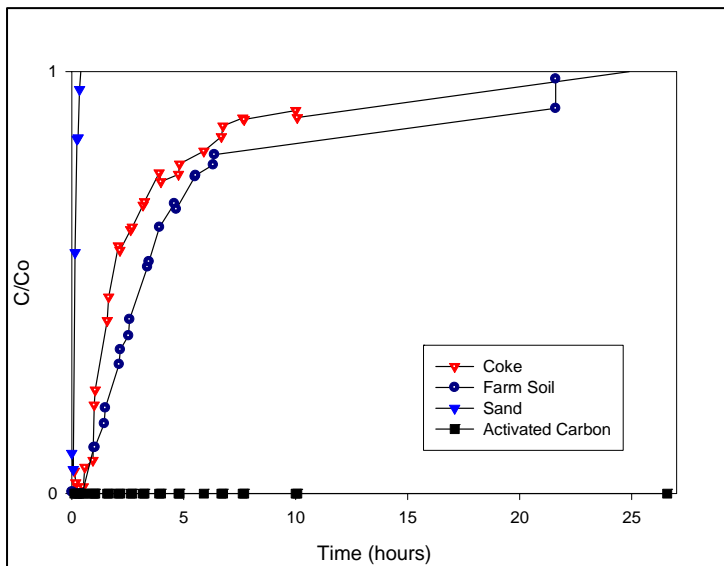
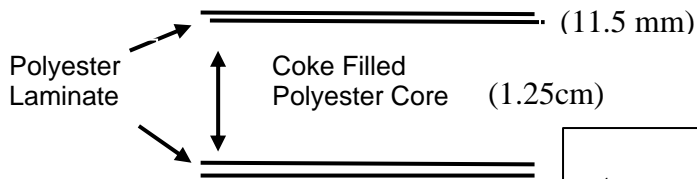


Figure 2. 1,2 DCB Breakthrough Plots for each Sorbent.  $C_o \sim 20$  ppm

Table 2. Measured Sorption Strength and Capacity

Sorbent	Log $K_d$	Log $K_d$	Capacity
Units	(L/kg)	(L/kg)	(mg DCB/g)
Sorbate	1,2 DCB	2,4,5 PCB	1,2 DCB
AC	4.80	7.16	>1000
Coke	2.79	5.15	0.6
Soil	2.49	4.85	0.7
Sand	0.78 <sup>10</sup>	3.15	Negligible

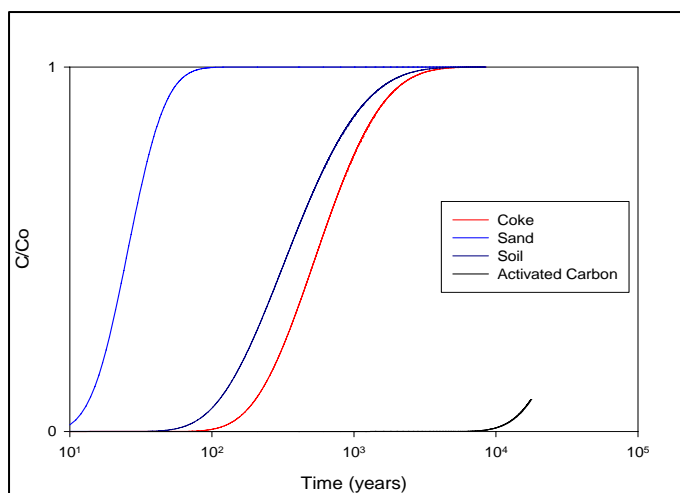
Coke and the soil (3.8% OC) exhibited similar equilibrium partitioning coefficients and total sorption capacities (Table 2). As expected, activated carbon significantly outperforms both sorbents (Figures 1 and 2). Using the VG solution as a first approximation, thin TACM layers (~1cm) can potentially isolate PCBs in typical sediment systems (seepage = 1cm/day) for decades to centuries (Figure 5). The simulations in Figure 5 assume 1) sorption capacity is not exceeded 2) linear sorption is occurring and 3) that competitive sorption, and colloidal transport are negligible. These assumptions are not likely to be valid and are currently being assessed.



**Figure 4a.** Schematic of RCM



**Figure 4b.** Picture of RCM



**Figure 5.** Concentration of 2,4,5 PCB at top of 1cm of capping media vs. time. Advection = 1cm/day

### Anacostia Field Demonstration

A reactive core mat (RCM) has been developed with CETCO (Arlington Heights, IL) (Figure 4a,b) to accurately deploy thin layers (1.25 cm) of sorbent. A coke filled (1lb/ft<sup>2</sup>) RCM was placed in the Anacostia River in Washington D.C. in March 2004. The RCM sunk readily, was placed without incident (unrolled using crane and diver), and fines were not visually detected. A sand layer (12”) was placed above the RCM to secure it and to provide a habitat for benthic organisms to colonize without compromising the integrity of the cap. Organics and metals found in solid coke and leachate were below the appropriate federal regulations (NOAA’s Effect Range Low and EPA’s Criterion Maximum Concentration, respectively). Sediment cores from this capping demonstration site will be used to assess the performance of sorbent (contaminant isolation) and RCM (placement, sustained permeability, and structural integrity).

## Conclusions

The performance of all sorbents analyzed is superior to that of sand, the traditional cap material used. The alternative sorbents evaluated can isolate contaminants from the biologically active zone for decades to centuries, allowing more time for the deposition of clean sediment and the biodegradation of buried contaminants. Thin layers of alternative sorbents can be accurately deployed in RCMs. These thin layers may provide sufficient capacity and retardation to meet management goals.

## Acknowledgements

This work was funded by the Hazardous Substance Research Centers through a research grant to Dr. Lowry (R139634) and by Alcoa, Inc. (Pittsburgh, PA). The authors also thank Jim Olsta and Chuck Hornaday of CETCO for constructing the RCMs.

## References

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8. McAuliffe, C.D.; *Chem. Tech.* 1971, 1, 46-51
9. Van Genuchten, M. Th. and W. J. Alves. 1982. *Analytical Solutions of the One-Dimensional Convective-Dispersive Solute Transport Equation*. United States Department of Agriculture, Agricultural Research Service, Technical Bulletin 1661.
10. Schwarzenbach, R., Gschwend, P., Imboden, D., *Environmental Organic Chemistry*. John Wiley and Sons, Inc., New York, 1993.

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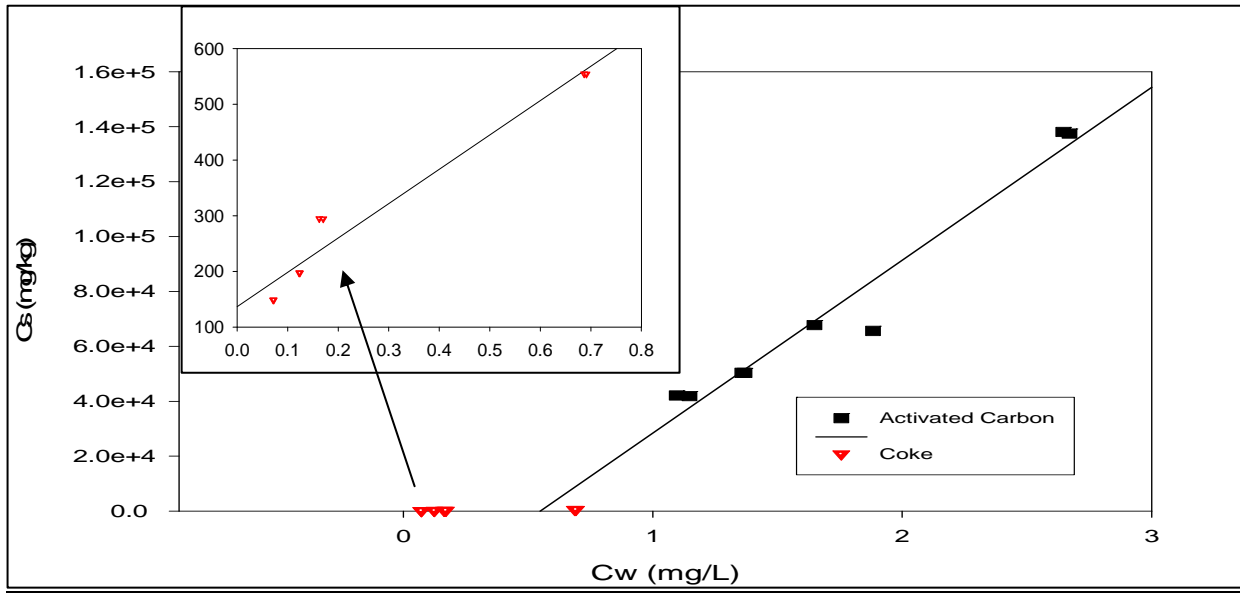


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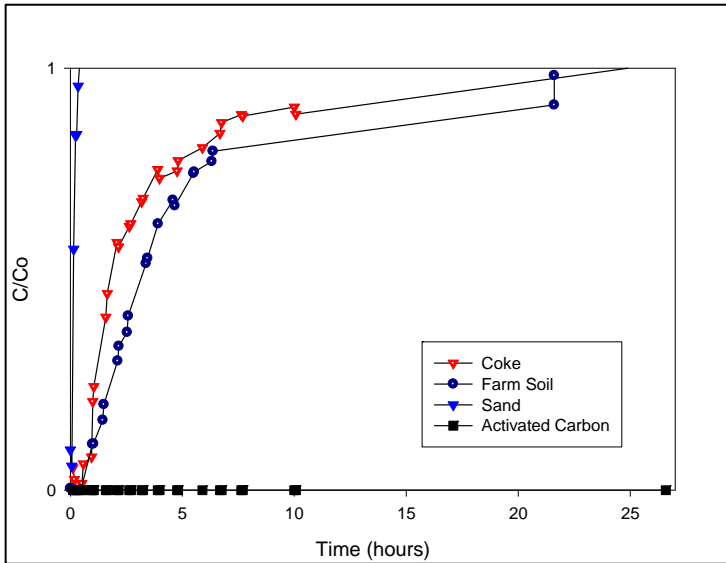
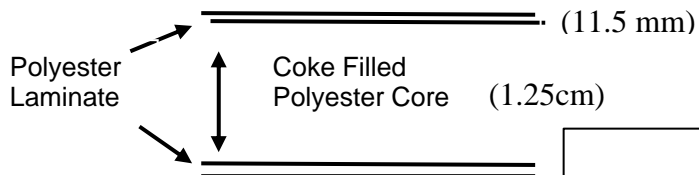


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**Table 2. Measured Sorption Strength and Capacity**

Sorbent Units	Log $K_d$ (L/kg) 1,2 DCB	Log $K_d$ (L/kg) 2,4,5 PCB	Capacity (mg DCB/g) 1,2 DCB
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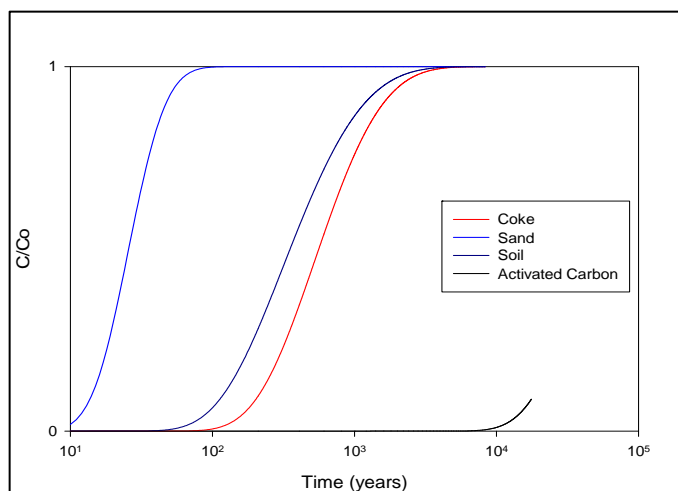
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