

Technical Bulletin

Soil Stabilization:

Optimizing Activated Carbon-Based
Adsorbents for Immobilizing PFAS
in Source Zones

Soil Stabilization: Optimizing Activated Carbon-Based Adsorbents for Immobilizing PFAS in Source Zones

SECTION 1.0

Introduction to *In Situ* Stabilization and Solidification

Quick Reference:

Topic

Soil Stabilization: Optimizing Activated Carbon-Based Adsorbents for Immobilizing PFAS in Source Zones

Relevant Technologies



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Known as “forever chemicals”, per and polyfluorinated alkyl substances (PFAS) are highly resistant to biological and chemical degradation due to their having the strongest bond in organic chemistry—the carbon-fluorine bond. This leads to PFAS widely circulating in the environment once released.

For example, the use of PFAS-containing aqueous film-forming foam (AFFF) used to extinguish flammable liquid fires is responsible for a significant amount of PFAS released into surficial soils. PFAS in these “source zones” can migrate through the vadose zone, driven primarily by precipitation events, eventually reaching and contaminating groundwater. Contaminated soils represent one of the largest threats to continuing PFAS groundwater contamination, therefore efficiently treating PFAS in these source zones is essential to protecting groundwater and preventing PFAS plume development.

Two common field-implemented soil treatments for PFAS contamination are excavation/landfilling and stabilization/solidification. [Reference 1](#) Regulatory uncertainty as to whether PFAS-contaminated soils are “hazardous”, the potential for recycling the contaminants back into the environment via landfill leaching, and the overall poor sustainability of the approach make excavation/landfilling less favorable. In contrast, *in situ* stabilization/solidification (ISS) can be more efficient and environmentally sound as PFAS are immobilized in place without long-distance transportation of large quantities of contaminated soils. ISS involves treating contaminated soils with amendments to immobilize (stabilize) contaminants and solidify the soils to reduce water infiltration, a main driver for contaminant transport. When PFAS are tightly bound to adsorbents and soils are impermeable to water flow, PFAS mobility in source zone soils is significantly reduced, therefore reducing the risk of PFAS transport and further exposure downgradient.

SECTION 2.0

In Situ Stabilization Basics:

Evaluating Stabilizing Adsorbents



Choosing the correct adsorbent materials and application dose is critical for effective *in situ* PFAS immobilization. Equally important is determining the soil PFAS immobilization objectives for a site. Although the regulations and guidance for managing PFAS solid waste are in the early development stages, stringent environmental standards will likely evolve due to the chemicals' ubiquitous presence and extreme persistence. Therefore, determining effective adsorbents and the dosage as well as knowing the corresponding PFAS leachability reduction help us to optimal the PFAS source zone treatment in order to meet the upcoming regulations and guidance.

Soil heterogeneity can complicate the immobilization processes. For example, PFAS sorption is strongly influenced by hydrophobic interactions governed by chemical hydrophobicity and soil organic matter. Soil organic matter, usually measured as total organic carbon (TOC) in soil, can vary significantly in heterogeneous soils and can compete with sorption-enhancing additives, reducing PFAS immobilization efficiency. Hence, this study aimed to test the efficiency of different adsorbents as stabilization agents for PFAS contaminated source zones, the effect of dose on PFAS immobilization, and the impact of soil organic carbon on PFAS sorption.

This study is informed by published research comparing 44 inorganic and organic sorbents to remove PFAS from the aqueous phase showing that activated carbon (AC)-based adsorbents outperformed other materials. [Reference 2](#) Accordingly, several AC-based adsorbents were used for the experiment. The AC-based adsorbents were applied and mixed with AFFF-impacted soils at two doses and the PFAS leachability reductions were compared.

SECTION 3.0

Proof of Concept Experiment:

Reducing PFAS leachability by mixing AC-based adsorbents in PFAS source zones

Table 1

Extractable PFAS Concentrations in Tested Site 1 Soil

Compound	Concentration (µg/kg)
PFOA	200
PFBS	1,100
PFOS	17,000
Sum of other PFAS	6,784

Table 2

Extractable PFAS Concentrations in Tested Site 2 Soil

Compound	Concentration (µg/kg)
PFOA	2,100
PFBS	54
PFOS	3,700
Sum of other PFAS	2,593

Soil samples were obtained from two different AFFF-impacted sites: an airport site in Sweden (Site 1) and a former firefighting training site in Italy (Site 2). The most abundant PFAS compounds in Site 1 soil (after spiking as described below) are PFBS, PFHxS, and PFOS, while in Site 2 soil are PFOA, PFDA, and PFOS. The sample collected from Site 2 contained more than twice the TOC concentration than the Site 1 sample, 23.5 g/kg and 10.4 g/kg, respectively. Thus, the competition from soil organic matter for PFAS sorption sites on the AC-based materials was also assessed.

The extractable PFAS concentrations from these two tested soils are shown in [Table 1](#) and [Table 2](#). Due to the relatively low PFAS concentration in the original Site 1 soil (total extracted PFAS was 25.2 µg/kg), legacy C8-based AFFF was spiked to mimic the highly AFFF-impacted source soil [Table 1](#). Soils tested in the leachability experiments were passed through a 2-mm sieve before use.

Batch-scale experiments were conducted to evaluate PFAS immobilization efficiency after mixing AC-based adsorbents with PFAS-impacted soils. Four AC-based adsorbents were applied to the soil samples at 1% and 5% doses by weight. PFAS immobilization was determined by examining the difference in PFAS leachability between treated and untreated soils.

For each batch condition, 100 grams of soil were mixed with either 1 gram or 5 grams of AC-based adsorbent and 15 milliliters of deionized water. After mixing, the treated soil samples were sent for leachability tests and PFAS analysis by Eurofins Laboratory (Lancaster, PA). The leachability test was done by Synthetic Precipitation Leaching Procedure (SPLP, per EPA method 1312), and PFAS concentrations in the leachate were analyzed by EPA 537 LC/MS/MS method. Due to a limited soil sample volume, Site 1 soil was tested with three chosen AC-based adsorbents, while Site 2 soil was tested with four adsorbents. Leachability testing was also performed on one hundred grams of untreated soil (no adsorbents added).

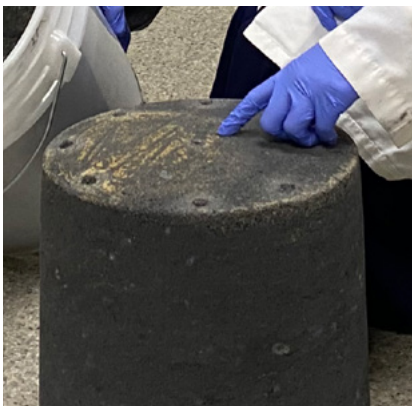
SECTION 4.0

Results and Discussion

Mobility of PFAS in the treated test soils was evaluated by SPLP, which simulates soils exposed to 100 years of acid rain. PFAS concentration reductions in the SPLP leachate were evaluated and compared to understand the PFAS immobilization performance of the tested AC-based adsorbents. Due to their relative abundance in the tested soils and target for regulation, the PFAS compounds PFOA, PFBS, and PFOS are highlighted to discuss the results.

SECTION 4.1

Site 1 Soil Results



The leaching reduction of total PFAS after mixing 1% and 5% different AC-based adsorbents with spiked Site 1 soil is demonstrated in [Figure 1](#). The results show that more than 95% PFAS leachability reduction could be attained for all treatment conditions in this study, including using a 1% dose. Furthermore, by using a 5% dose, all three tested adsorbents achieved 99% PFAS immobilization efficiency.

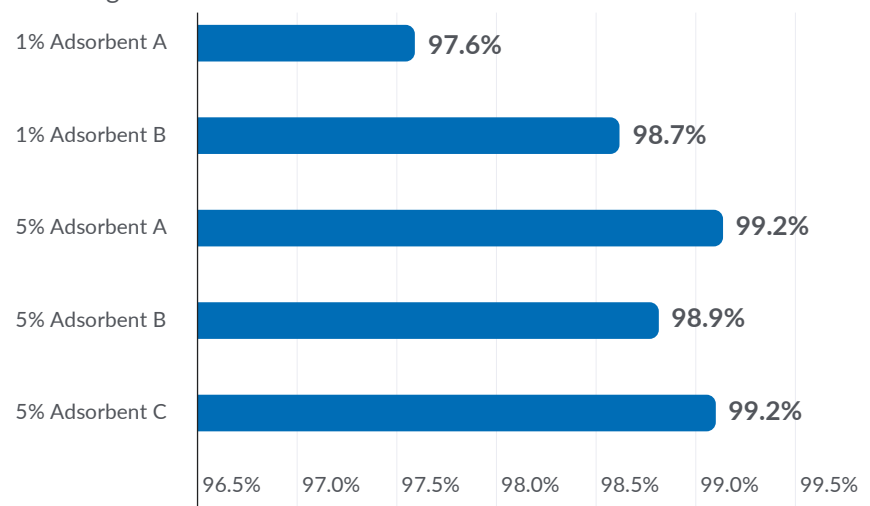
For the untreated soil, the dominant PFAS leached out during SPLP was PFOS with 430,000 ng/L, mainly due to its very high concentration in the legacy C8-based AFFF. The leaching concentrations of PFOA, PFBS, and the rest of PFAS from the untreated are 6,000, 35,000, and 201,102 ng/L, respectively.

Figure 1

Leaching reduction of total PFAS from spiked Site 1 soil after mixing with 1% or 5% AC-based adsorbent A, B, or C. The number on each bar represents the leaching reduction percentage under each condition.

Leaching Reduction Total of PFAS - Site 1

Leaching Reduction



With over 95% leachability reduction, the leaching total PFAS concentration after applying 1% AC-based adsorbents ranged in 8,944-15,851 ng/L. By using a 5% dose, a 99% leachability reduction for total PFAS, compared to the untreated soil was seen. Across the 3 different AC-based adsorbents, the total PFAS leaching concentrations ranged from 5,455 to 7,615 ng/L. The dominant PFAS compound was PFOS as its concentration during SPLP was 4,200-5,600 ng/L when using a 5% dose, significantly lower than in the 1% PAC dose.

Our results from Site 1 soil demonstrate that:

- Leaching from untreated AFFF-impacted soil can be one of the major sources of PFAS contamination to ground and surface waters.
- With 1-5% AC-based adsorbents, PFAS leaching from the source zone can reduce by more than 95%.
- By using a 5% dose, all 3 tested adsorbents were able to provide 99% PFAS leachability reduction.

SECTION 4.2

Site 2 Soil Results

PFAS leaching reductions from Site 2 soils varied for the 1% AC-based adsorbents, while more consistent reductions were observed between the amendments applied at the 5% dose (Figure 2). At the 1% dose, PFAS immobilization performance from best to least is adsorbent B, adsorbent A, and adsorbent D, as their PFAS leaching reductions are 98%, 85%, and 49%, respectively. However, at a 5% dose, the influence of adsorbent source/properties on PFAS sorption appears to be less critical. With a 5% dose, adsorbents A, B, and D attained more than 99% PFAS leaching reduction, while adsorbent C nearly reached this metric (98.7%).

Compared to Site 1 soil, the PFAS leachability reduction shows more impact on Site 2 soil from adsorbent properties when using a 1% dose. The leaching reduction for Site 1 soil is 97.6-98.7% when using different AC-based adsorbents, while its range increased to 48.9%-98.0% for Site 2 soil. Since Site 2 soil contained more than twice higher TOC than Site 1 soil, this variation could be due to the competition from soil organic matters. Nevertheless, the consistent PFAS leaching reduction when using a 5% dose implies that enough adsorbent can overcome the sorption competition from soil organic matters.

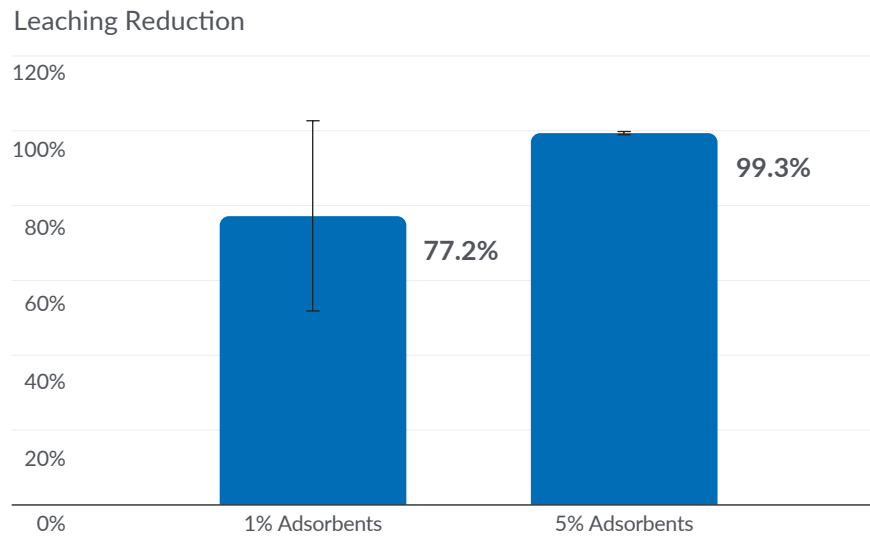
The leaching total PFAS concentration from the untreated soil 2 is 168,322 ng/L. Since both PFOA and PFOS are dominant PFAS in Site 2 soil, their leaching concentrations from the untreated soil account for 41% and 34%, respectively, of total leaching PFAS.

When applying 1% AC-based adsorbents, the leaching total PFAS concentration dropped to 3,355-86,022 ng/L. With >99% PFAS leaching reduction, the total PFAS concentration in SPLP leachate was 570-2,141 ng/L after mixing with 5% AC-based adsorbents.

Figure 2

Leaching reduction of total PFAS from Site 2 soil after mixing with 1% or 5% AC-based adsorbents. The number on each bar represents the average leaching reduction percentage under each condition and the error bars represent the standard deviation of leaching reduction by using different AC-based adsorbents at the same dosage.

Leaching Reduction Total of PFAS - Site 2



SECTION 5.0

Conclusions & Implications

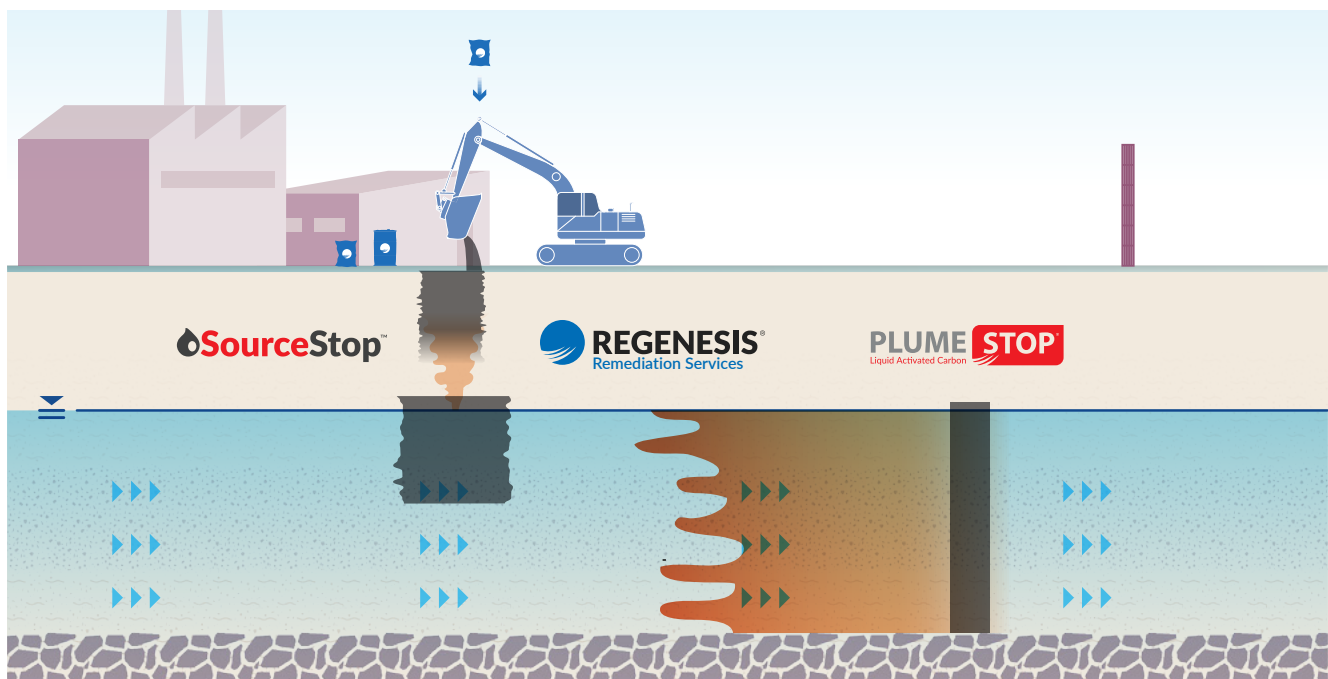
AFFF-impacted soils were obtained from two sites with different PFAS distributions and TOC levels. Multiple AC-based adsorbents were applied at two doses and the reduction of PFAS leachability was assessed. The results of the study suggest:

- There is a similar performance after applying different AC-based adsorbents at a 5% dose. More than 99% PFAS leaching reduction was achieved at this dose, regardless of the adsorbent source/properties.
- Performance is variable for the AC-based adsorbents applied at a 1% dose, suggesting that the carbon source/properties may be important to treat PFAS-impacted soils at lower doses.
- The presence of TOC in the soil appears to have a limited impact on immobilizing PFAS when using the 5% AC-based adsorbents.

After directly mixing 1-5% AC-based adsorbents, significant PFAS leaching reduction can be achieved up to 99%. PFAS immobilization can be further improved by a comprehensive source zone treatment approach. It includes amending the soil to reduce the hydraulic conductivity, emplacing SourceStop™ (a colloidal AC-based amendment) to the base of a source zone treatment to prevent further vertical migration, placement of permeable reactive barriers (PlumeStop®) downgradient of the source to prevent further plume development, or a combination of these approaches (see [Figure 3](#) below).

Figure 3

Combined Soil and Groundwater Source Treatment



SECTION 6.0

References

1. Interstate Technology Regulatory Council. Treatment Technologies and Methods for Per- and Polyfluoroalkyl Substances (PFAS). Published online August 2020.
2. Söregård M, Gago-Ferrero P, B. Kleja D, Ahrens L. Laboratory-scale and pilot-scale stabilization and solidification (S/S) remediation of soil contaminated with per- and polyfluoroalkyl substances (PFAS). *Journal of Hazardous Materials*. 2021;402:123453. doi:10.1016/j.jhazmat.2020.123453

