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Assessment of Solidification / Stabilization as a Remedial Strategy for PFAS Contaminated Transportation Sites

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16. Abstract
Per- and polyfluoroalkyl substances (PFAS) are a group of man-made chemicals that includes PFOA, PFOS, GenX, and many other chemicals. PFAS have been manufactured and used in a variety of industries around the globe, including in the United States, since the 1940s. According to the USEPA, airports, and military installations that use or train with Class B firefighting foams are considerable sources of PFAS to the environment. Strategies to reduce or eliminate the environmental or human health risk are needed to address PFAS contamination in the environment. Solidification and Stabilization (S/S) is a remedial strategy that has been employed at many hazardous waste sites to treat soils, sediments, and liquid waste containing a variety of chemical pollutants. While this strategy does not destroy or eliminate the pollutant it effectively sequesters the material within a solid matrix and eliminates its pathway to environmental or human exposure. This project conducted research to determine the potential applicability of S/S for remediation of PFAS contamination in a soil matrix. S/S utilizes a pozzolanic binder which, when mixed with water and the subject soil, will cure into a solid matrix. Specific binder mixes were developed and tested using PFAS contaminated soils collected from a former aviation site in NJ. The results indicate that S/S of PFAS contaminated soils can effectively sequester the chemical within a stabilized soil matrix and there is no significant difference between the two leaching protocols that were used to assess the effectiveness of the process.

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Introduction:

Per- and polyfluoroalkyl substances (PFAS) are a group of man-made chemicals that includes PFOA, PFOS, GenX, and many other chemicals. PFAS have been manufactured and used in a variety of industries around the globe, including in the United States, since the 1940s. According to the USEPA, airports, and military installations that use or train with Class B firefighting foams are considerable sources of PFAS to the environment. Even at relatively low concentrations, PFAS that are released to the environment have the potential to represent a environmental and human health risk. The USEPA issued a lifetime Health Advisory for PFOA of 4 ng/L and PFOS of 20 ng/L in drinking water, either individually or when combined. The New Jersey Department of Environmental Protection (NJDEP) adopted the first enforceable Maximum Contaminant Levels (MCLs) for any PFAS in the U.S. when it adopted an MCL for PFNA of 13 ng/L in 2018, and has more recently adopted MCLs for PFOA at 14 and PFOS at 13 ng/L.

Class B aqueous film-forming foams (AFFF) are a complex mixture containing known and unknown PFAS. AFFF is a product which is used to fight petroleum-based fires, particularly at aviation facilities including U.S. Department of Defense and U.S. Department of Transportation sites. AFFF systems spray the chemical fire suppressor onto the fire to form a thick blanket of foam which effectively smothers the fire. PFAS are used in the AFFF for their surfactant qualities, which allows the AFFF to spread across the surface of a hydrocarbon fuel. Many airports all over the world have been utilizing PFAS containing AFFF as their primary fire suppression strategy for years. The U.S. Federal Aviation Administration (FAA) required commercial airports to use AFFF fire suppression systems, including use in practice drills and the calibration of the fire suppression systems.

Historically, the impacts of PFAS containing AFFF were not well investigated or known. As a result, management of the waste was not as controlled as it is today. Often the AFFF was discharged to the environment and allowed to seep into the soil or conveyed to the stormwater system. In this manner, PFAS were released to the environment and contaminated site soils, sediments, surface water, and groundwater. Only recently are the potential impacts of these AFFFs becoming known in the scientific community. Strategies for addressing this contamination are not very well established due to the extremely low concentrations that may represent an environmental and human health risk.

Strategy: Solidification and Stabilization

Strategies to reduce or eliminate the environmental or human health risk are needed to address PFAS contamination in the environment. Solidification and Stabilization (S/S) is a remedial strategy that has been employed at many hazardous waste sites to treat soils, sediments, and liquid waste containing a variety of chemical pollutants. While this strategy does not destroy or eliminate the pollutant it effectively sequesters the material within a solid matrix and eliminates its pathway to environmental or human exposure. The scope of this project was to conduct research to determine the potential applicability of S/S for remediation of PFAS contamination in a soil matrix. S/S utilizes a pozzalonic binder which when mixed with water and the subject soil will cure into a solid matrix. The processes that occur in this strategy are: 1) Solidification, or the physical encapsulation of the contaminant with the soil matrix. During the curing process, the soil matrix gains geotechnical strength and the hydraulic conductivity is reduced, and 2) Stabilization, the chemical alteration of the soil matrix to encourage chemical / soil particle surface reactions and decrease the solubility of chemical pollutants. There are several potential benefits associated with this type of remedial strategy. These benefits include a lower cost than more energy intensive treatment, results that can be seen on a relatively short timescale, and a beneficial use product that can provide an offset for the cost of the remedial project. In addition, S/S may be conducted in-situ which can eliminate transportation and disposal costs which can often be the main driver in soil remediation projects.

Mix Design

The binder mix-design for S/S projects is extremely important. The two variables that should be used to determine the proper mix design are 1) leaching potential of contaminants of concern, and 2) geophysical strength which is required to determine the final, end use of the mitigated soil. During the presently reported study, only the impact of S/S upon leaching was investigated. Although toxicity for many PFAS compounds are limited, 175 individual PFAS compounds have been added to the USEPA Toxics Release Inventory and they are considered a potentially hazardous chemicals at even very low concentrations. As a result, the stabilization of PFAS contaminated soils must limit the leaching potential to extremely low values. Although stabilization can be completed with standard Portland cement alone, additional admixtures that can increase the affinity of the soil for PFAS represent a significant increase in the performance of the S/S process. For example, activated carbon (AC) has been employed effectively to adsorb many chemicals in both air and water treatment technologies as well as in in-situ sediment capping projects. The high affinity of these chemicals for AC suggests that pretreatment of the contaminated sediments paired with subsequent stabilization has the potential to eliminate an exposure pathway. In addition, the use of ground blast furnace slag can be used to increase the density of the stabilized sediment and effectively reduce the hydraulic conductivity which can enhance sequestration of the chemicals within the solidified matrix.

Methodology:

Assessment of the effectiveness of S/S for the sequestration of PFAS compounds in soils required the collection and treatment of soil samples that contained significant concentration of the target compounds. A soil sample was collected at an historic aviation fire training facility located at a US Department of Defense facility (five, 3 gallon plastic buckets of material). This sample was transported to the Weeks sediment Laboratory at Rutgers University for stabilization and subsequent shipping to an external analytical laboratory for chemical analysis.

The collected soil was composited in a 30 gallon steel container then placed into clean 3 gallon plastic buckets for storage. The composited soil was sampled to determine if the total PFAS constituents were large enough to justify a S/S treatability study. The sample was sent (duplicate, 1A and 1B) to RTI Laboratories (Livornia, MI) for analysis for Perfluorinated Compounds Solid

Matrix LC/MS/MS - DOD QSM5.3 B15. The results shown in Tables 1. indicate significantly elevated concentrations of many compounds. As a result, it was decided to complete the treatability study using this soil sample.

Table 1. Raw Soil PFAS Laboratory Analytical Results (Method DOD QSM5.3 B15)

Analyte (unit ng/kg dry soil)	1A	1B
11-Chloroeicosfluoro-3-oxaundecane-1-sulfonate (11Cl-PF3OYUdS)	200	310
1H,1H,2H,2H-Perfluorodecanesulfonate (8:2 FTS)	180,000	170,000
1H,1H,2H,2H-Perfluorohexanesulfonate (4:2 FTS)	470	540
1H,1H,2H,2H-Perfluorooctanesulfonate (6:2 FTS)	4,200	3,800
9-Chlorohexadecafluoro-3-oxanonane-1-sulfonate (9Cl-PF3ONS)	28	21
Dodecafluoro-3H-4,8-dioxanonanoate (ADONA)	ND	ND
HFPO-DA (GEN X)	20	24
N-ethyl perfluorooctanesulfonamidoacetic acid (N-EtFOSAA)	320	250
N-methyl perfluorooctanesulfonamidoacetic acid (N-MeFOSAA)	390	470
Perfluorobutanesulfonic acid (PFBS)	60	46
Perfluorobutanoic acid (PFBA)	330	250
Perfluorodecanesulfonate (PFDS)	300,000	250,000
Perfluorodecanoic acid (PFDA)	31,000	30,000
Perfluorododecanoic acid (PFDoA)	4,900	4,500
Perfluoroheptanesulfonate (PFHpS)	1,200	970
Perfluoroheptanoic acid (PFHpA)	3,200	3,200
Perfluorohexanesulfonic acid (PFHxS)	7,900	7,700
Perfluorohexanoic acid (PFHxA)	3,900	4,100
Perfluorononanesulfonate (PFNS)	120,000	110,000
Perfluorononanoic acid (PFNA)	3,800	3,200
Perfluorooctanesulfonic acid (PFOS)	1,800,000	1,600,000
Perfluorooctanoic acid (PFOA)	33,000	29,000
Perfluorooctansulfonamide (FOSA)	580,000	650,000
Perfluoropentanesulfonate (PFPeS)	210	65
Perfluoropentanoic acid (PFPeA)	800	780
Perfluorotetradecanoic acid (PFTeDA)	ND	ND
Perfluorotridecanoic acid (PFTrDA)	1,500	2,000
Perfluoroundecanoic acid (PFUdA)	6,000	6,500

The treatability study was completed by creating several Portland cement-based binder mixes to determine the most effective mix. This was completed in two phases. The first mixes were created on June 22, 2021 and a second set was created on November 15, 2021. Samples were created in the Weeks Sediment Laboratory though a standardized procedure. The procedure involved mixing of the soils with a 1:1 water/binder slurry in a laboratory mixer for a period of ten minutes. Five minutes into the mixing, the process was stopped and the walls of the mixing bowl were scraped with a spatula to ensure mixing of the entire sample with the added binder. After mixing, the mix is placed into molds for curing. The molds were 33 mm in diameter and 71 mm in height. These mold are specifically required for EPA 1310b (Extraction Procedure, Toxicity Test Method and Structural Integrity Test). Samples were allowed to cure for a period of 30 days prior to subjecting them to the structural integrity test outlined in EPA 1310b. Subsequently the cores were submitted to RTI Laboratories for both SPLP and TCLP extraction and leachate analysis for Perflorinated Compounds.

Table 2. SPLP PFAS Laboratory Analytical Results

Analyte (ng/L)	SPLP Extract
11-Chloroeicosfluoro-3-oxaundecane-1-sulfonate (11Cl-PF3OYUdS)	ND
1H,1H,2H,2H-Perfluorodecanesulfonate (8:2 FTS)	5,400
1H,1H,2H,2H-Perfluorohexanesulfonate (4:2 FTS)	ND
1H,1H,2H,2H-Perfluorooctanesulfonate (6:2 FTS)	140
9-Chlorohexadecafluoro-3-oxanonane-1-sulfonate (9Cl-PF3ONS)	ND
Dodecafluoro-3H-4,8-dioxanonanoate (ADONA)	ND
HFPO-DA (GEN X)	ND
N-ethyl perfluorooctanesulfonamidoacetic acid (N-EtFOSAA)	ND
N-methyl perfluorooctanesulfonamidoacetic acid (N-MeFOSAA)	ND
Perfluorobutanesulfonic acid (PFBS)	ND
Perfluorobutanoic acid (PFBA)	28
Perfluorodecanesulfonate (PFDS)	88
Perfluorodecanoic acid (PFDA)	430
Perfluorododecanoic acid (PFDoA)	ND
Perfluoroheptanesulfonate (PFHpS)	27
Perfluoroheptanoic acid (PFHpA)	210
Perfluorohexanesulfonic acid (PFHxS)	370
Perfluorohexanoic acid (PFHxA)	240
Perfluorononanesulfonate (PFNS)	210
Perfluorononanoic acid (PFNA)	100
Perfluorooctanesulfonic acid (PFOS)	55,000
Perfluorooctanoic acid (PFOA)	1,300
Perfluorooctansulfonamide (FOSA)	1,600
Perfluoropentanesulfonate (PFPeS)	ND
Perfluoropentanoic acid (PFPeA)	66
Perfluorotetradecanoic acid (PFTeDA)	ND
Perfluorotridecanoic acid (PFTrDA)	ND
Perfluoroundecanoic acid (PFUdA)	43

A total of eight binder mixes were investigated during Phase I (June 22, 2021). The binder mixes included combinations of Type I/II Portland cement, Green cement, cement kiln dust and blast furnace slag (Table 3).

Table 3. Phase I Binder Mixes

		A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8
Soil	(g)	100	100	100	100	100	100	100	100
Ravena (Type I/II Portland cement	(g)	10	0	11.3	7.5	11.3	0	0	0
Holly Hill 1L (Green Cement)	(g)	0	10	0	0	0	11.3	7.5	11.3
Blast Furnace Slag	(g)	0	0	3.7	7.5	0	3.7	7.5	0
Alpena Cement Kiln Dust	(g)	0	0	0	0	3.7	0	0	3.7
Water in Soil (in-situ)	(g)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Water added	(g)	6.8	6.8	11.8	11.8	11.8	11.8	11.8	11.8
Binder Dose	(%)	10	10	15	15	15	15	15	15

Although the results from Phase I of this investigation were promising and there were significant reductions in the leaching potential from the stabilized matrix, it was decided that additional mixes should be considered. In addition, the use of Powdered Activated Carbon was investigated due to its demonstrated success as an absorbent for Perflorinated Compounds in water treatment (ref). The results from Phase I were used to inform the binder mixes to be investigated in Phase II (Table 4). Those results that showed the worst results were eliminated and those that showed greatest promise were incorporated into Phase II. A total of nine binder mixes were investigated during Phase II.

Table 4. Phase II Binder Mixes

		B-1	B-1	B-3	B-4	B-5	B-6	B-7	B-8	B-9
Soil	(g)	200	200	200	200	200	200	200	200	200
Alpena (Type I/II Portland cement	(g)	0	15	0	0	0	40	0	0	0
Holly Hill 1L (Green Cement)	(g)	15	0	15	15	40	0	6	6	6
Blast Furnace Slag	(g)	15	15	15	15.2	0	0	24	24	24
Powdered Activated Carbon	(g)	0	0	2	6.1	0	0	0	2	6
Water in Soil (in-situ)	(g)	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Water added	(g)	23.6	23.9	24.4	24.1	33.8	33.8	23.6	23.8	23.4
Binder Dose	(%)	15	15	15	15	20	20	15	15	15

Results and Discussion:

The SPLP leachate concentrations for each of the mixes in Phases I and II of this study are presented in Tables 5 and 6.

Table 5. Phase I SPLP Leachate Concentrations

Analyte (ng/L)	A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8
11-Chloroeicosfluoro-3-oxaundecane-1-sulfonate (11Cl-PF3OYUdS)	ND	ND	ND	ND	1.3	ND	ND	ND
1H,1H,2H,2H-Perfluorodecanesulfonate (8:2 FTS)	510	1,000	1,200	1,200	840	1,000	1,000	1,100
1H,1H,2H,2H-Perfluorohexanesulfonate (4:2 FTS)	17	18	10	6	20	11	6	20
1H,1H,2H,2H-Perfluorooctanesulfonate (6:2 FTS)	1,400	1,500	1,000	590	1,600	940	570	2,000
9-Chlorohexadecafluoro-3-oxanonane-1-sulfonate (9Cl-PF3ONS)	ND	ND	ND	1	2	ND	ND	ND
Dodecafluoro-3H-4,8-dioxanonanoate (ADONA)	ND	ND	ND	ND	ND	ND	ND	ND
HFPO-DA (GEN X)	ND	ND	2	ND	ND	ND	ND	ND
N-ethyl perfluorooctanesulfonamidoacetic acid (N-EtFOSAA)	ND	ND	ND	2	2	2	ND	ND
N-methyl perfluorooctanesulfonamidoacetic acid (N-MeFOSAA)	40	120	160	130	100	110	150	160
Perfluorobutanesulfonic acid (PFBS)	18	18	14	9	23	11	6	23
Perfluorobutanoic acid (PFBA)	210	240	170	150	230	190	110	280
Perfluorodecanesulfonate (PFDS)	7	49	84	83	33	53	73	26
Perfluorodecanoic acid (PFDA)	74	180	200	200	110	170	160	110
Perfluorododecanoic acid (PFDoA)	ND	1	2	3	2	1	4	0
Perfluoroheptanesulfonate (PFHpS)	34	64	60	42	81	50	32	81
Perfluoroheptanoic acid (PFHpA)	360	400	250	190	410	260	170	440
Perfluorohexanesulfonic acid (PFHxS)	1,300	ND	1,000	560	0	770	380	0
Perfluorohexanoic acid (PFHxA)	1,300	1,400	1,000	790	1,300	1,100	650	1,700
Perfluorononanesulfonate (PFNS)	32	150	230	210	95	140	160	94
Perfluorononanoic acid (PFNA)	67	98	76	55	76	62	45	75
Perfluorooctanesulfonic acid (PFOS)	16,000	27,000	24,000	20,000	18,000	19,000	15,000	19,000
Perfluorooctanoic acid (PFOA)	5,000	5,400	3,600	2,600	5,600	3,800	2,400	5,600
Perfluorooctansulfonamide (FOSA)	3,400	7,300	5,300	4,600	6,300	5,900	4,700	9,000
Perfluoropentanesulfonate (PFPeS)	76	110	97	58	140	82	33	160
Perfluoropentanoic acid (PFPeA)	300	340	230	180	320	250	140	350
Perfluorotetradecanoic acid (PFTeDA)	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorotridecanoic acid (PFTrDA)	ND	ND	ND	ND	ND	ND	ND	ND
Perfluoroundecanoic acid (PFUdA)	ND	7	11	14	7	9	13	3
% moisture	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
UCS	308	383	457	567	407	592	642	365

Table 6. Phase II SPLP Leachate Concentrations

Analyte (ng/L)	B-1	B-1	B-3	B-4	B-5	B-6	B-7	B-8	B-9
11-Chloroeicosfluoro-3-oxaundecane-1-sulfonate (11Cl-PF3OYUdS)	ND	ND	ND	ND	ND	ND	ND	ND	ND
1H,1H,2H,2H-Perfluorodecanesulfonate (8:2 FTS)	1,200	940	ND	ND	630	770	1,400	ND	ND
1H,1H,2H,2H-Perfluorohexanesulfonate (4:2 FTS)	ND	ND	ND	ND	21	17	ND	ND	ND
1H,1H,2H,2H-Perfluorooctanesulfonate (6:2 FTS)	910	510	ND	410	1,100	5,900	3,200	490	1200
9-Chlorohexadecafluoro-3-oxanonane-1-sulfonate (9Cl-PF3ONS)	ND	ND	ND	ND	ND	ND	ND	ND	9.9
Dodecafluoro-3H-4,8-dioxanonanoate (ADONA)	ND	ND	ND	ND	ND	ND	ND	ND	ND
HFPO-DA (GEN X)	ND	ND	ND	ND	ND	25	ND	ND	ND
N-ethyl perfluorooctanesulfonamidoacetic acid (N-EtFOSAA)	ND	ND	ND	ND	ND	ND	ND	ND	ND
N-methyl perfluorooctanesulfonamidoacetic acid (N-MeFOSAA)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorobutanesulfonic acid (PFBS)	5	6.7	ND	ND	13	7.4	8.1	ND	ND
Perfluorobutanoic acid (PFBA)	87	110	70	90	140	100	88	56	90
Perfluorodecanesulfonate (PFDS)	45	31	ND	ND	11	8.7	86	ND	ND
Perfluorodecanoic acid (PFDA)	140	130	ND	ND	75	110	240	ND	7.7
Perfluorododecanoic acid (PFDoA)	14	15	ND	ND	15	13	19	ND	14
Perfluoroheptanesulfonate (PFHpS)	12	9.5	ND	ND	17	11	21	17	10
Perfluoroheptanoic acid (PFHpA)	97	110	ND	ND	200	150	160	ND	ND
Perfluorohexanesulfonic acid (PFHxS)	250	310	ND	ND	540	480	380	ND	ND
Perfluorohexanoic acid (PFHxA)	410	510	110	26	740	520	620	100	20
Perfluorononanesulfonate (PFNS)	83	75	ND	ND	40	41	130	ND	ND
Perfluorononanoic acid (PFNA)	34	33	ND	ND	50	42	40	ND	ND
Perfluorooctanesulfonic acid (PFOS)	16,000	16,000	110	170	16,000	15,000	27,000	3200	69
Perfluorooctanoic acid (PFOA)	3,000	1,800	170	29	2,800	2,400	2,800	26	24
Perfluorooctansulfonamide (FOSA)	3,900	3,600	ND	24	4,200	4,200	5,800	13	9.3
Perfluoropentanesulfonate (PFPeS)	ND	ND	ND	ND	18	17	ND	ND	ND
Perfluoropentanoic acid (PFPeA)	110	130	72	72	170	140	140	65	64
Perfluorotetradecanoic acid (PFTeDA)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorotridecanoic acid (PFTrDA)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluoroundecanoic acid (PFUdA)	17	18	ND	ND	ND	ND	26	ND	ND

In order to quantify this impact, the concentrations were normalized by the raw sample results.

Table 7. Phase I Normalized Leachate Concentrations

Analyte	A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8	**Raw Sediment SPLP (ng/L)**
11-Chloroeicosfluoro-3-oxaundecane-1-sulfonate (11Cl-PF3OYUdS)	ND	ND	ND	ND	ND	ND	ND	ND	ND
1H,1H,2H,2H-Perfluorodecanesulfonate (8:2 FTS)	0.09	0.19	0.22	0.22	0.16	0.19	0.19	0.20	5,400
1H,1H,2H,2H-Perfluorohexanesulfonate (4:2 FTS)	ND	ND	ND	ND	ND	ND	ND	ND	ND
1H,1H,2H,2H-Perfluorooctanesulfonate (6:2 FTS)	10.00	10.71	7.14	4.21	11.43	6.71	4.07	14.29	140
9-Chlorohexadecafluoro-3-oxanonane-1-sulfonate (9Cl-PF3ONS)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dodecafluoro-3H-4,8-dioxanonanoate (ADONA)	ND	ND	ND	ND	ND	ND	ND	ND	ND
HFPO-DA (GEN X)	ND	ND	ND	ND	ND	ND	ND	ND	ND
N-ethyl perfluorooctanesulfonamidoacetic acid (N-EtFOSAA)	ND	ND	ND	ND	ND	ND	ND	ND	ND
N-methyl perfluorooctanesulfonamidoacetic acid (N-MeFOSAA)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorobutanesulfonic acid (PFBS)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorobutanoic acid (PFBA)	7.50	8.57	6.07	5.36	8.21	6.79	3.93	10.00	28
Perfluorodecanesulfonate (PFDS)	0.08	0.56	0.95	0.94	0.38	0.60	0.83	0.30	88
Perfluorodecanoic acid (PFDA)	0.17	0.42	0.47	0.47	0.26	0.40	0.37	0.26	430
Perfluorododecanoic acid (PFDoA)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluoroheptanesulfonate (PFHpS)	1.26	2.37	2.22	1.56	3.00	1.85	1.19	3.00	27
Perfluoroheptanoic acid (PFHpA)	1.71	1.90	1.19	0.90	1.95	1.24	0.81	2.10	210
Perfluorohexanesulfonic acid (PFHxS)	3.51	ND	2.70	1.51	0.00	2.08	1.03	0.00	370
Perfluorohexanoic acid (PFHxA)	5.42	5.83	4.17	3.29	5.42	4.58	2.71	7.08	240
Perfluorononanesulfonate (PFNS)	0.15	0.71	1.10	1.00	0.45	0.67	0.76	0.45	210
Perfluorononanoic acid (PFNA)	0.67	0.98	0.76	0.55	0.76	0.62	0.45	0.75	100
Perfluorooctanesulfonic acid (PFOS)	0.29	0.49	0.44	0.36	0.33	0.35	0.27	0.35	55,000
Perfluorooctanoic acid (PFOA)	3.85	4.15	2.77	2.00	4.31	2.92	1.85	4.31	1,300
Perfluorooctansulfonamide (FOSA)	2.13	4.56	3.31	2.88	3.94	3.69	2.94	5.63	1,600
Perfluoropentanesulfonate (PFPeS)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluoropentanoic acid (PFPeA)	4.55	5.15	3.48	2.73	4.85	3.79	2.12	5.30	66
Perfluorotetradecanoic acid (PFTeDA)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorotridecanoic acid (PFTrDA)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluoroundecanoic acid (PFUdA)	ND	0.16	0.26	0.33	0.16	0.21	0.30	0.07	43
Green indicates a reduction									
Red indicates and increase									

The measured concentrations observed in the SPLP leachate from the various binder mixes indicate that stabilization had a considerable impact upon the leachate concentration of certain compounds when compared with the leachate from the raw sample. The largest observed decreases were seen in the concentration of PFOS. The concentration was reduced by a factor of approximately 3 from 55,000 ng/L to a range of 15,000 to 20,000 ng/L. Increased leaching was observed for several other PFAS compounds. The mixed results obtained through this phase of the project led to the second phase which included the use of PAC as an admixture due to it adsorptive capacity for PFAS compounds.

Table 8. Phase II Normalized Leachate Concentrations

Analyte	B-1	B-1	B-3	B-4	B-5	B-6	B-7	B-8	B-9	**Raw Sediment SPLP (ng/L)**
11-Chloroeicosfluoro-3-oxaundecane-1-sulfonate (11Cl-PF3OYUdS)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1H,1H,2H,2H-Perfluorodecanesulfonate (8:2 FTS)	0.22	0.17	ND	ND	0.12	0.14	0.26	ND	ND	5,400
1H,1H,2H,2H-Perfluorohexanesulfonate (4:2 FTS)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1H,1H,2H,2H-Perfluorooctanesulfonate (6:2 FTS)	6.50	3.64	ND	2.93	7.86	42.14	22.86	3.50	8.57	140
9-Chlorohexadecafluoro-3-oxanonane-1-sulfonate (9Cl-PF3ONS)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dodecafluoro-3H-4,8-dioxanonanoate (ADONA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
HFPO-DA (GEN X)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
N-ethyl perfluorooctanesulfonamidoacetic acid (N-EtFOSAA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
N-methyl perfluorooctanesulfonamidoacetic acid (N-MeFOSAA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorobutanesulfonic acid (PFBS)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorobutanoic acid (PFBA)	3.11	3.93	2.50	3.21	5.00	3.57	3.14	2.00	3.21	28
Perfluorodecanesulfonate (PFDS)	0.51	0.35	ND	ND	0.13	0.10	0.98	ND	ND	88
Perfluorodecanoic acid (PFDA)	0.33	0.30	ND	ND	0.17	0.26	0.56	ND	ND	430
Perfluorododecanoic acid (PFDoA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluoroheptanesulfonate (PFHpS)	0.44	0.35	ND	ND	0.63	0.41	0.78	0.63	0.37	27
Perfluoroheptanoic acid (PFHpA)	0.46	0.52	ND	ND	0.95	0.71	0.76	ND	ND	210
Perfluorohexanesulfonic acid (PFHxS)	0.68	0.84	ND	ND	1.46	1.30	1.03	ND	ND	370
Perfluorohexanoic acid (PFHxA)	1.71	2.13	0.46	0.11	3.08	2.17	2.58	0.42	0.08	240
Perfluorononanesulfonate (PFNS)	0.40	0.36	ND	ND	0.19	0.20	0.62	ND	ND	210
Perfluorononanoic acid (PFNA)	0.34	0.33	ND	ND	0.50	0.42	0.40	ND	ND	100
Perfluorooctanesulfonic acid (PFOS)	0.29	0.29	0.00	0.00	0.29	0.27	0.49	0.06	0.00	55,000
Perfluorooctanoic acid (PFOA)	2.31	1.38	0.13	0.02	2.15	1.85	2.15	0.02	0.02	1,300
Perfluorooctansulfonamide (FOSA)	2.44	2.25	ND	0.02	2.63	2.63	3.63	0.01	0.01	1,600
Perfluoropentanesulfonate (PFPeS)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluoropentanoic acid (PFPeA)	1.67	1.97	1.09	1.09	2.58	2.12	2.12	0.98	0.97	66
Perfluorotetradecanoic acid (PFTeDA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorotridecanoic acid (PFTrDA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluoroundecanoic acid (PFUdA)	0.40	0.42	ND	ND	ND	ND	0.60	ND	ND	43
Green indicates a reduction										
Red indicates and increase										

The concentrations of almost all of the compounds were reduced in the binder mixes that contained PAC (B-3, B-4, B-8, and B-9). Three compounds were found that exhibited an increase or essentially no change after stabilization. These were 1H,1H,2H,2H-Perfluorooctanesulfonate (6:2 FTS), Perfluorobutanoic acid (PFBA), and Perfluoropentanoic acid (PFPeA). The leachate concentration of PFPeA is relatively unchanged after stabilization (<10%). The other two compound leachate concentrations were observed to increase after stabilization. These compounds were present at low concentrations relative to several of the other PFAS compounds. The four compounds with the highest concentration in the raw leachate were 1H,1H,2H,2H-Perfluorodecanesulfonate (8:2 FTS), Perfluorooctanesulfonic acid (PFOS), and Perfluorooctanoic acid (PFOA), and Perfluorooctansulfonamide (FOSA). The leachate concentrations for each of these compounds were reduced to Non-Detect or by orders of magnitude.

Conclusions:

The ability to stabilize contaminated soil in-place represents a low-cost alternative to more expensive ex-situ treatment strategies. This is especially the case for persistent, hard to treat compounds. These compounds a particularly challenging to deal with when they are present at low concentrations. Stabilization with a pozzalonic binder reduces the mobility of the compound as well as the movement of water through the matrix. The binders that were tested were seen to be moderately successful at reducing the concentration of PFAS compounds, however several compound exhibited an increase in leachate concentration. During the second phase of this treatability project, PAC was introduced as an additive to the binders. The results indicate significant reductions in the leachate concentrations for each of these binder types. Thus, it is apparent from the findings of this treatability project that addition of PAC to a stabilization binder mix will enhance the PFAS sequestration potential.