Evaluating Colloidal Silica Barriers and PFAS Leaching Behavior in the Vadose Zone

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Per- and polyfluoroalkyl substances (PFAS) are a large class of persistent synthetic contaminants that pose significant environmental and public health concerns due to their mobility, chemical stability, and resistance to degradation. PFAS contamination is commonly associated with sites where aqueous film-forming foams (AFFF) were historically used, including airports, military installations, and firefighter training facilities. At many of these sites, PFAS remains stored within vadose zone soils decades after release and continues to leach slowly into groundwater. The unsaturated zone plays a critical role in PFAS transport because water infiltration can mobilize contaminants downward through preferential flow paths, while sorption at soil surfaces and air-water interfaces can delay migration. Because of the complexity of these processes, predicting long-term PFAS leaching from contaminated soils remains difficult, and effective remediation strategies are limited.

This research proposes evaluating the use of colloidal silica (CS) gel barriers to reduce PFAS transport in the vadose zone, while also investigating the extent to which PFAS may leach through or around such barriers (Figure 1).

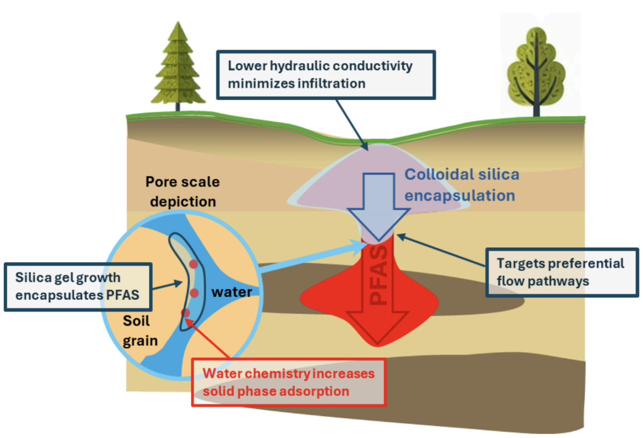

Figure 1. Schematic of an applied CS barrier preventing infiltration to a PFAS plume.

CS consists of nanoscale silica particles suspended in an aqueous solution that can be transported through porous media prior to gelation. Once gelation occurs, the particles form a three-dimensional network that fills pore spaces and reduces permeability. Previous laboratory and field studies have demonstrated that CS can be transported through granular porous media primarily by advection and can subsequently form low-permeability barriers that alter groundwater flow behavior. These characteristics suggest that CS infiltration could intercept preferential flow pathways in the vadose zone and form a passive barrier that limits contaminant transport to underlying groundwater.

The main idea of this study is that CS infiltration within unsaturated soils can create a gel barrier that significantly reduces PFAS migration through the vadose zone, while partially retaining PFAS and limiting continued leaching into groundwater. This hypothesis addresses two key knowledge gaps: (1) whether CS can effectively infiltrate heterogeneous unsaturated soils before gelation and (2) whether the resulting gel barrier can reduce PFAS leaching rates rather than redirecting contaminant transport around the treated zone. Although CS has been studied extensively for geotechnical stabilization and permeability reduction, its role as a contaminant immobilizer remains largely unexplored.

The scientific value of this research lies in improving the understanding of both colloid transport and contaminant leaching in unsaturated porous media. PFAS migration in the vadose zone is influenced by complex interactions among infiltration processes, preferential flow pathways, and retention at soil surfaces and air-water interfaces. Identifying cost-effective and passive remediation methods for PFAS-impacted soils is crucial for environmental cleanups around the world. Many existing remediation technologies are expensive or disruptive to infrastructure, and passive stabilization approaches may provide a practical alternative for sites where excavation or intensive treatment is not feasible.

To test the hypothesis, a series of laboratory soil column experiments will be conducted to examine both the transport of CS and the subsequent leaching behavior of PFAS under unsaturated conditions. Soil columns representing common vadose zone materials, including sand, silty sand, and mixed sediments, will be prepared at controlled densities and saturation levels. Initial tracer experiments will be conducted using a conservative dye or salt tracer to characterize baseline infiltration patterns and flow paths. A CS solution will then be applied at the soil surface, allowing it to infiltrate vertically and laterally through the porous media before undergoing gelation. Following gel formation, synthetic PFAS solutions will be introduced at the surface to simulate contaminated infiltration events. Effluent samples collected from the base of the column will be analyzed to quantify PFAS breakthrough concentrations and determine the extent of contaminant leaching through the treated zone.

These experiments will evaluate the effectiveness of the gel barrier by comparing PFAS breakthrough curves and mass recovery between untreated and treated soil columns. A reduction in PFAS breakthrough concentration or delayed contaminant arrival would indicate that the CS barrier effectively reduces contaminant leaching. Conversely, if PFAS transport bypasses the barrier through preferential pathways or if leaching continues at rates similar to untreated conditions, the results could suggest that the barrier provides limited containment. In addition, the experiments will examine whether PFAS interacts with or sorbs to the silica gel matrix itself, which could further influence contaminant retention. Experimental results can be used to develop a simplified numerical model describing fluid and contaminant transport through porous media containing a gelled CS barrier; however, this component may not be fully explored due to time constraints.

The proposed research will be conducted over approximately five months (March to July 2026). During month one, the first phase will involve a literature review, experimental design, and preparation of the soil column apparatus. Months two and three will focus on baseline tracer and infiltration experiments to characterize unsaturated flow behavior. During months four and five, CS injection experiments will be performed to establish gel barrier formation under different soil conditions. PFAS leaching experiments will then be conducted to measure contaminant breakthrough through treated and untreated soils. The final month will involve data analysis, conceptual and numerical model development, and a final synthesis of results.