Practical Considerations for Implementing ISCO-ISS: Bench Testing, Design & Field Implementation

Soil & Groundwater Remediation Webinar | May 1, 2024

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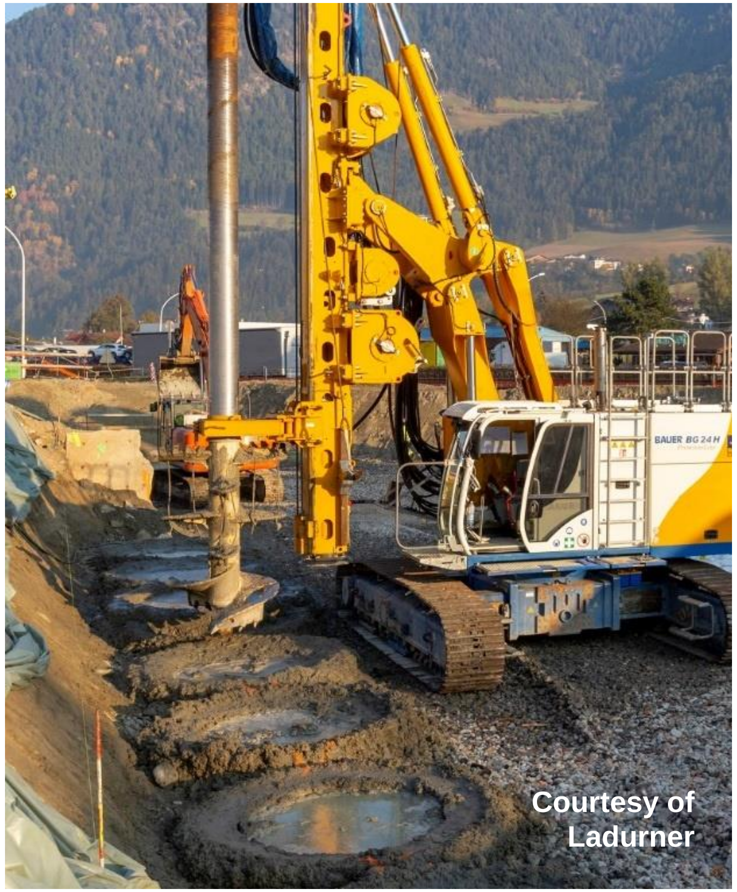
Presentation Outline

- Technology Overview
  - Combining ISCO with ISS
  - Benefits & Synergies
  - Common Remedial Goals
- Bench Testing & Design Parameters
- Field Implementation
  - Soil Mixing Methods & Limitations
- Application and Performance Monitoring
- Case Examples



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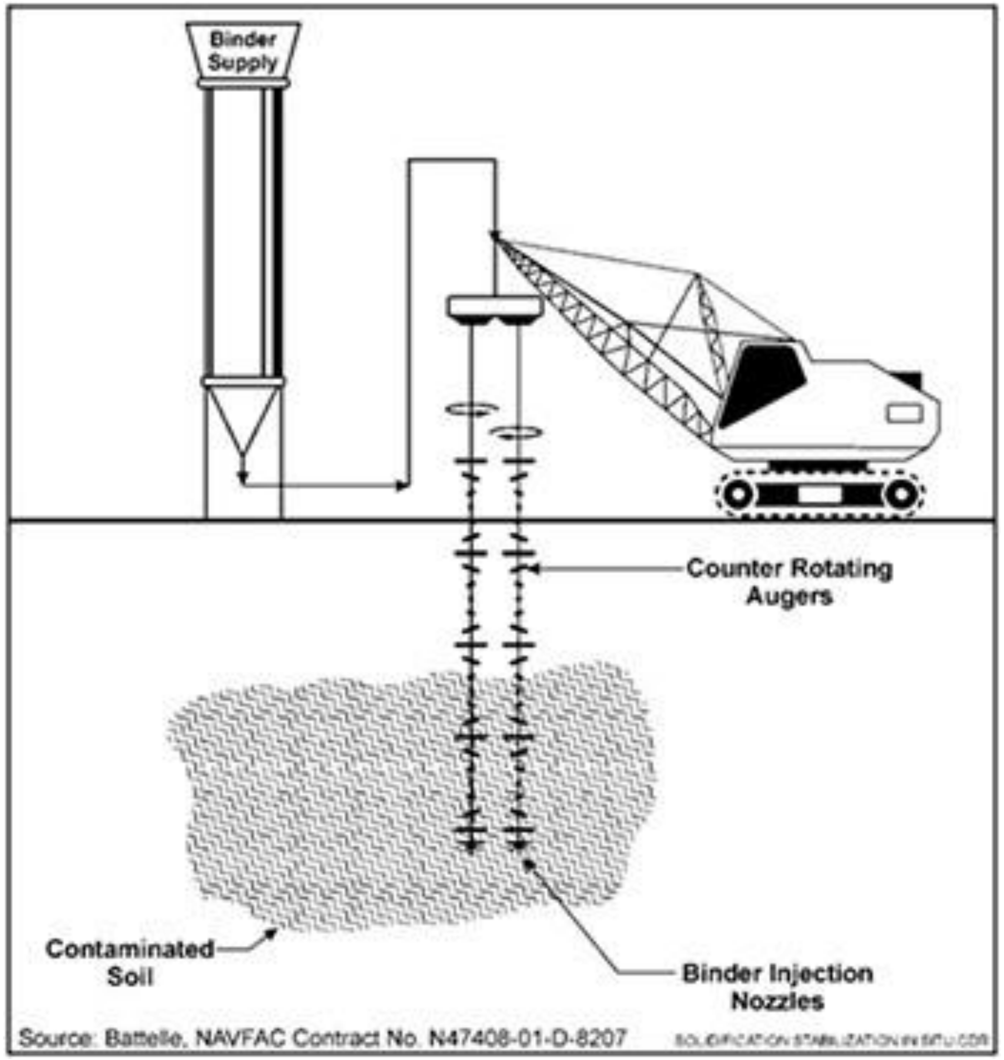
In Situ Solidification and Stabilization

- Use of soil mixing to blend binding agent(s) with contaminated soils:
  - – Portland Cement
  - – Blast Furnace Slag

- Methods:
  - – Stabilization:
    - – Chemical processes that reduce leachability
  - – Solidification:
    - – Decreasing of hydraulic conductivity & effective porosity
    - – Increasing compressive strength

- Immobilize contamination in place



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Common Objectives of ISS

1. Reduced hydraulic conductivity
   - 2-3 orders of magnitude below native soils
   - 1 x 10^{-6} cm/sec

2. Unconfined Compressive Strength (UCS)
   - "Workable" ~20-60 psi
   - Hardened
     - ISS often targets 50 psi

3. Lower contaminant flux and leachate concentrations

General Relationship between Soil Consistency and Unconfined Compressive Strength

Consistency	Unconfined Compressive Strength (UCS) Ranges			
	psi		kPa (KN/m^2)	
	Low	High	Low	High
Very soft	0	3	0	24
Soft	3	7	24	48
Medium	7	14	48	96
Stiff	14	28	96	192
Very Stiff	28	56	192	383
Hard	>56		>383	

Typical target range for "workable" soils ~20-60 psi

In Situ Chemical Oxidation

- What it is:
  - Oxidants are reagents that <u>accept/take</u> electrons from, or oxidize, contaminants of concern → CO_2
  - Typically applied via injection or soil mixing
- Objectives:
  - Contaminant destruction / mass reduction
  - Reduced concentrations in soil, groundwater, leachate and vapors

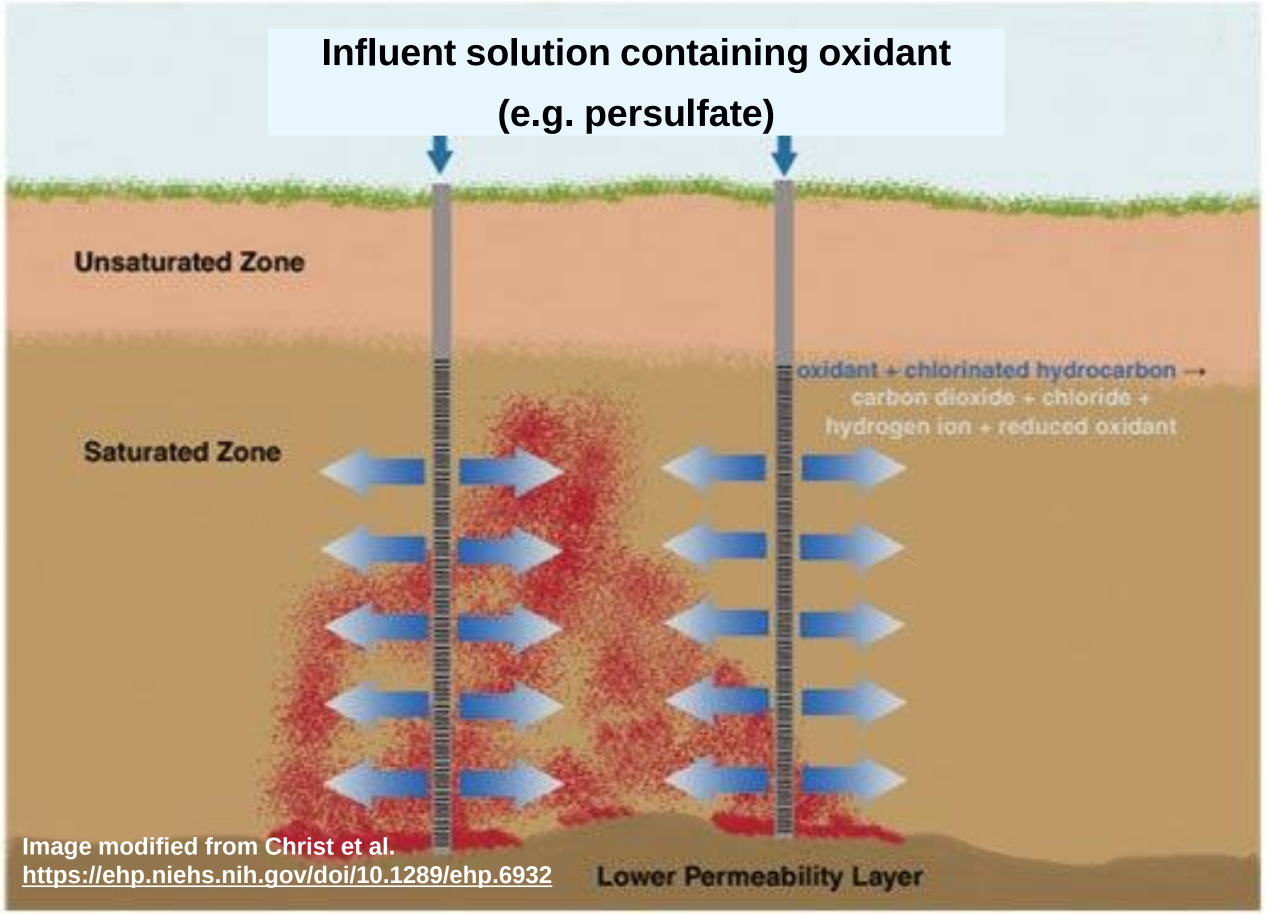

Image modified from Christ et al. https://ehp.niehs.nih.gov/doi/10.1289/ehp.6932

Examples (persulfate reactions):

Benzene: $15\ S_2O_8^{-2} + C_6H_6 + 12\ H_2O \rightarrow 6\ CO_2 + 30\ HSO_4^{-1}$

PCE: $2\ S_2O_8^{-2} + C_2Cl_4 + 4\ H_2O \rightarrow 2\ CO_2 + 4\ Cl^- + 4\ H^+ + 4\ HSO_4^{-1}$

Klozur® Persulfate Degradation Pathways / Contaminants Treated

Oxidative ← **Either** → **Reductive**

Oxidative

- Petroleum Hydrocarbons
- Gasworks Residuals
- BTEX
- PAHs
- Oxygenates
- 1,4-Dioxane

Either

- PCE, TCE, DCE and VC
- Chlorobenzenes
- Phenols
- Select Pesticides
- Select Fluorinated Compounds
- PCBs
- Select Energetics

Reductive

- Carbon Tetrachloride
- 1,1,1-Trichloroethane
- Dichloroethanes
- Select Pesticides
- Select Energetics

Activation Methods: Alkaline, Hydrogen Peroxide, and Heat

Activation Method: Iron Chelate

Single Technology Limitations

- **ISCO:**
  - Multiple applications may be needed for heavily contaminated sites → cost prohibitive
  - Contaminants that sorb strongly to the soil (low partitioning in water / high K_{oc} value) more challenging to treat, sometimes requiring multiple applications
- **ISS:**
  - Contamination is left in place maintaining environmental liability
  - Addition of binders can cause soils to swell (increase in volume), which then requires treatment or disposal
  - More mobile contaminants (low K_{oc}) more difficult to stabilize / requires higher dose binder

Combining the Technologies: ISCO/ISS

ISCO (sodium persulfate) and ISS reagents applied together in single application:

- More soluble (mobile) fraction preferentially treated via oxidation
- Remaining heavier contaminant fractions stabilized

Soil mixing using excavator with mixing attachment

Soil mixing using large diameter augers

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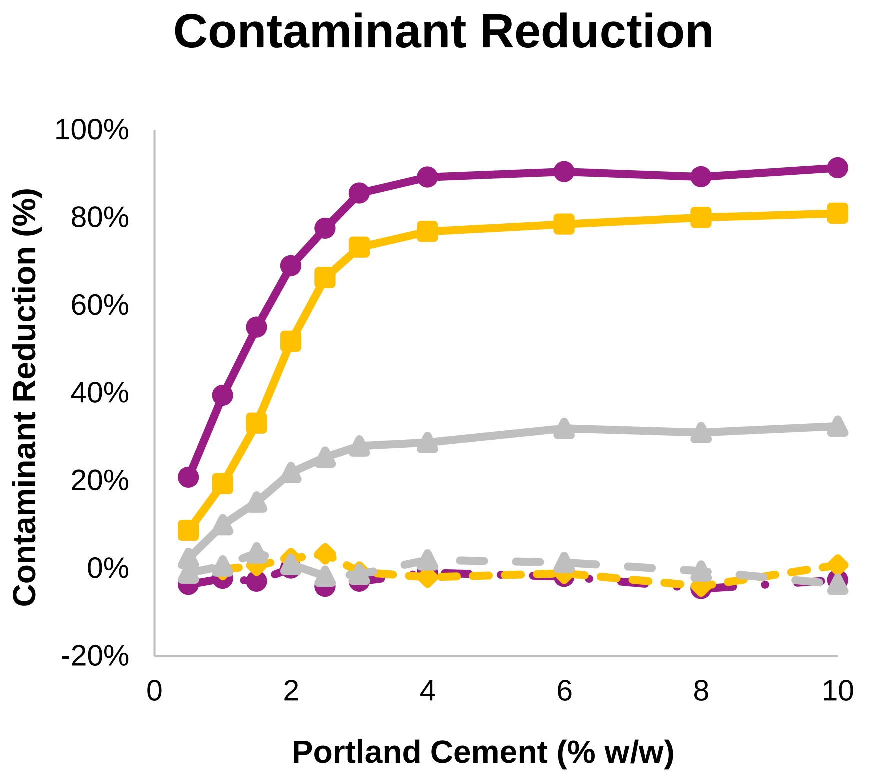
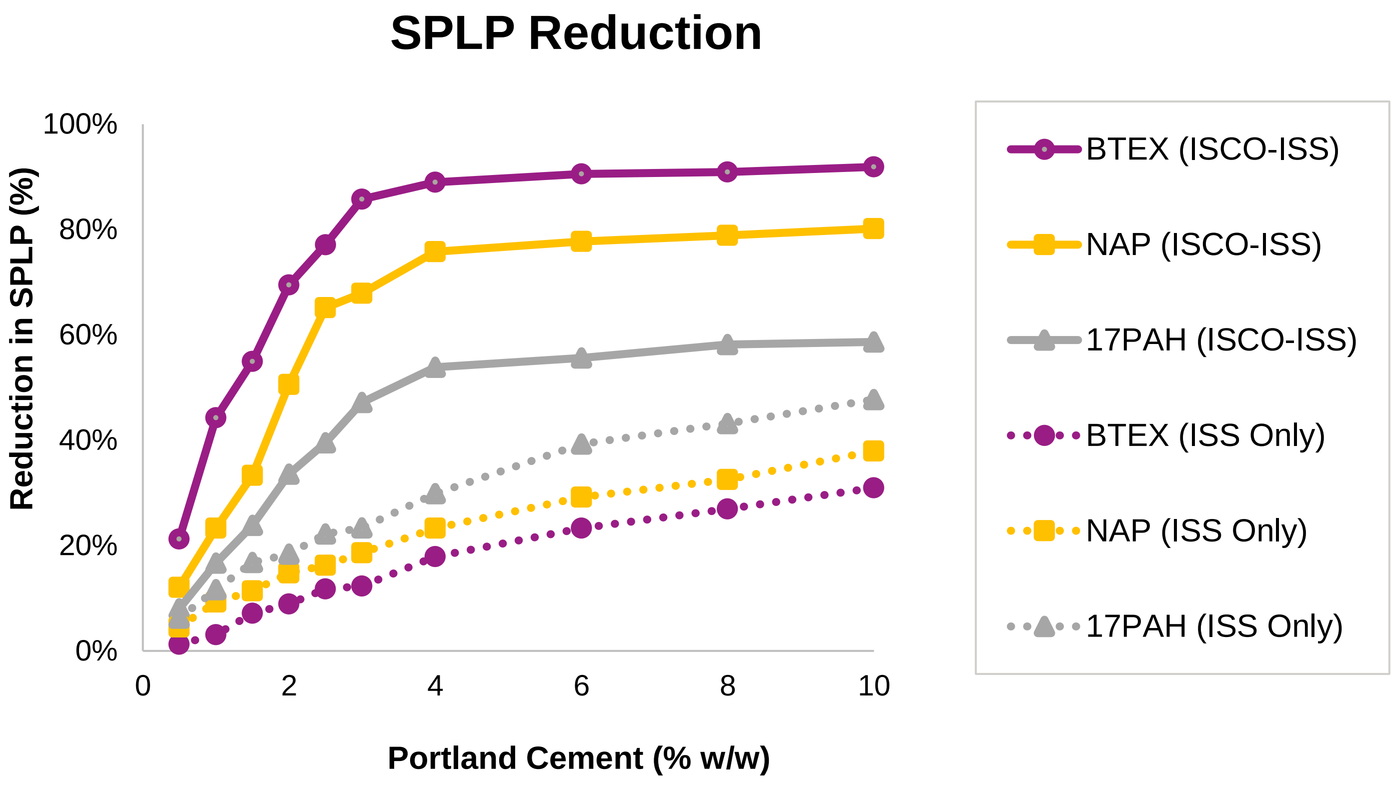
Synergistic benefits with combined approach

Contaminant destruction can result in lower leachate concentration compared to ISS Only





2:1 Ratio of PC:SP

>37,000 mg/Kg MGP Residuals

Reference: Srivastava, V.J., Hudson, J.M., and Cassidy, D.P., (2016b) "Achieving Synergy between Chemical Oxidation and Stabilization in a Contaminated Soil," Chemosphere, 154, 590-598

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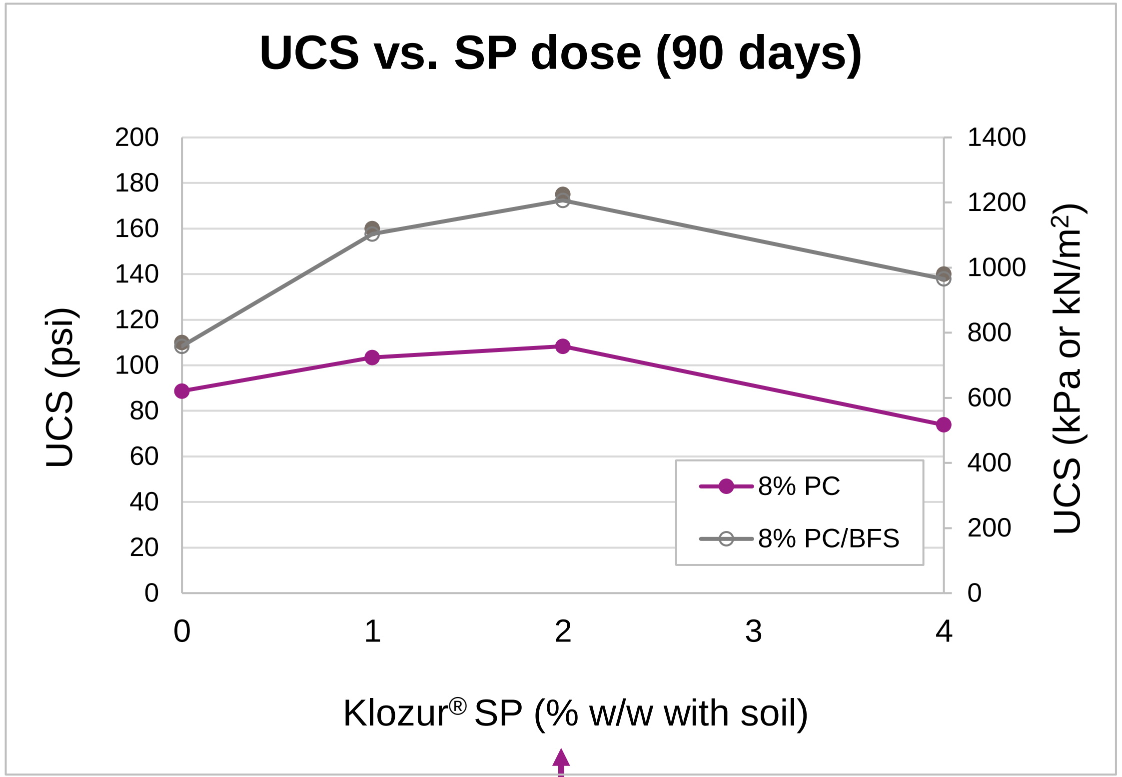
Synergies: Improved UCS

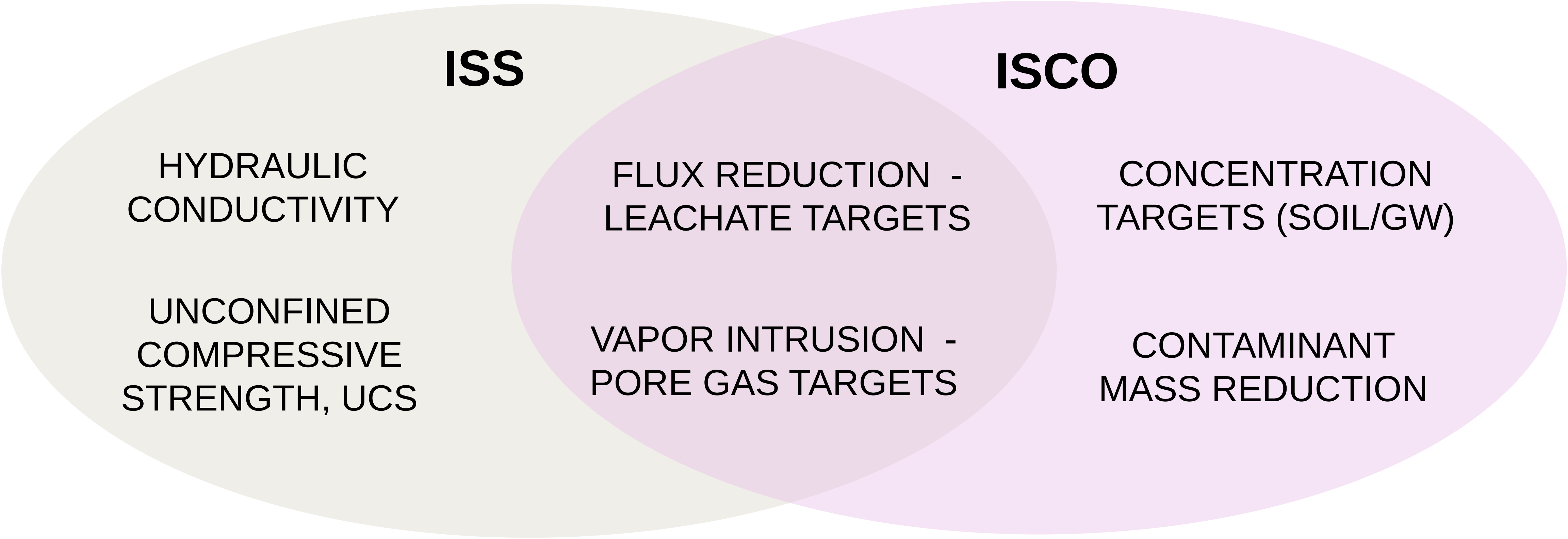
- Persulfate addition can improve UCS to a certain point
  - Lowering binder requirements to achieve remedial goals
  - Less soil bulking → Cost savings

Klozur® SP (% w/w soil)	8% PC		8% PC/BFS	
	Day 90 UCS (psi)	% of ISS only	Day 90 UCS (psi)	% of ISS only
0	90	100%	110	100%
1	105	117%	160	145%
2	110	122%	175	159%



Bench Testing can help determine the sweet spot

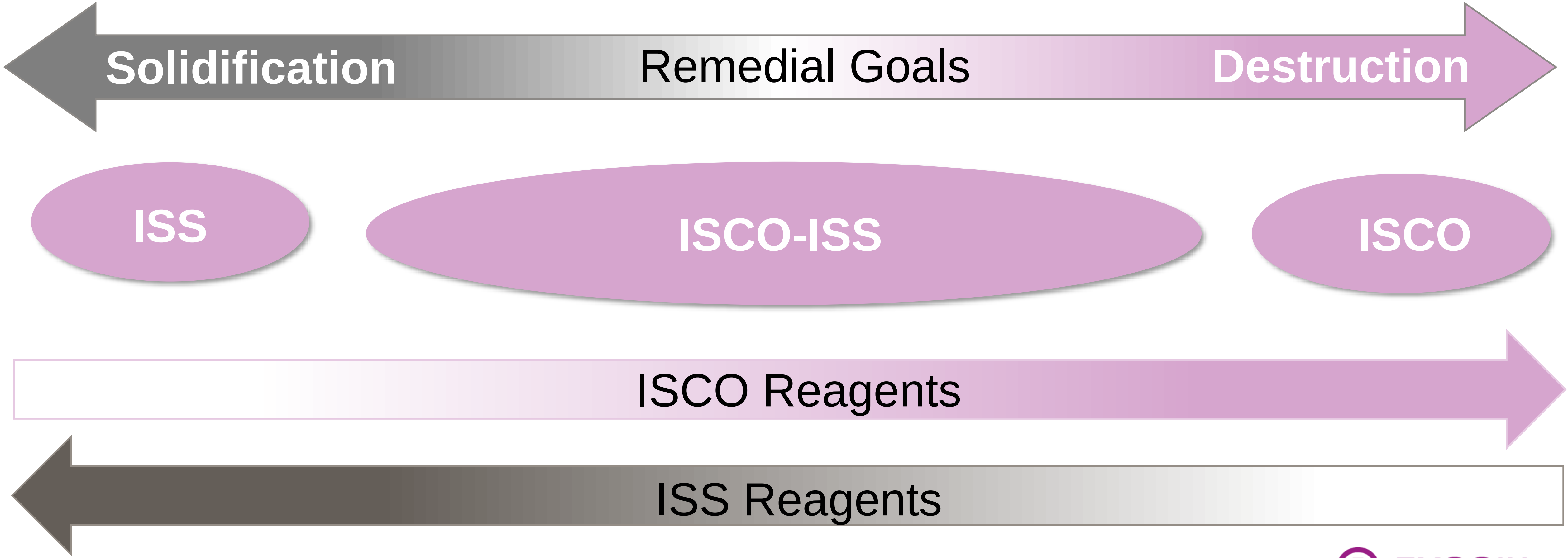
Common Remedial Goals



ISCO Can Help

Remedial Goals and Reagent Ranges

ISCO and ISS reagent doses can be varied to achieve a variety of remedial goals



Benefits of Combined Approach

Benefits of adding ISS to ISCO applications:

- Improved soil stability allowing for site activities and redevelopment soon after the application.
- Low-cost alkaline activators for Klozur® persulfate.

Benefits of adding ISCO to ISS applications:

- Small additions of ISCO reagents can lower the amount of ISS reagents needed to reach UCS and K targets, resulting in less soil bulking and disposal costs.
- Lower long-term risk due to contaminant mass reduction.
- Faster plume reduction due to reduced flux.

ISCO-ISS Bench Testing & Design Parameters

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What Data is Needed to Screen Sites

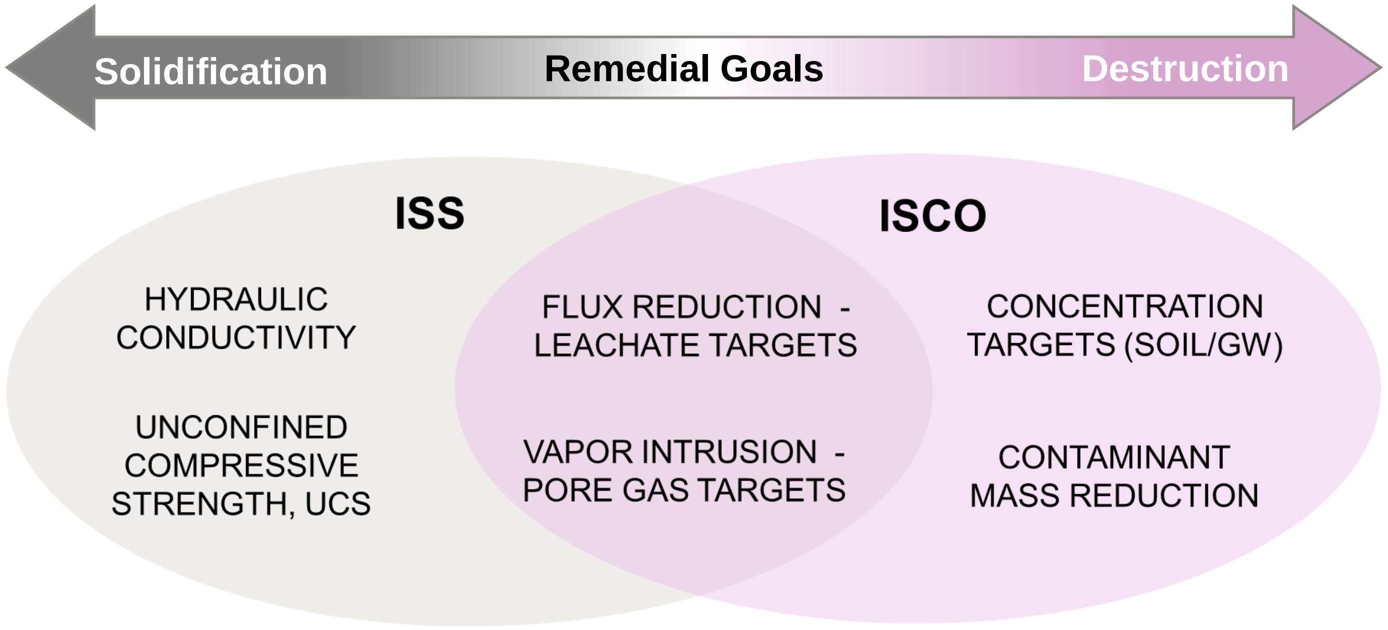
- Site Access
  - ISCO-ISS applied via soil mixing or potentially jet grouting → need physical access
- Can soils be mixed?
  - Overburden soil / no boulders
- Can contaminants be treated?
  - Limits to ISCO (~10,000 mg/Kg)
- Remedial Goals
  - Can goals be achieved with ISCO-ISS
- Bench scale testing highly recommended to optimize dosages to meet project goals

Baseline Parameters
Contaminants (Soil & GW)
Soil Type
Moisture Content
Dry Bulk Density
Boulders (size)
Native UCS
Fraction Organic Carbon on Soil
Sodium/Potassium/Sulfate Ions
Soil Oxidant Demand (SOD)
Electric Conductivity
Oxidation-Reduction Potential
pH
Dissolved Organic Carbon

Additional resource: Section 3 & 4, Interstate Technology & Regulatory Council (ITRC), 2011, “Development of Performance Specifications for Solidification/Stabilization”

Bench Study Scope Varied Based on Site-Specific Goals

- Bench studies are designed to confirm site goals and generate design parameters
- Scope varied based on site specific goals



Common Analysis

- Soil Oxidant Demand, SOD
- Base Buffering Capacity, BBC
- Soil stability, UCS
- Hydraulic Conductivity, K
- Soil Analysis
- Leach Testing
- Soil Volumetric Expansion

ISCO-ISS Bench Testing – Typical Outline

- **Baseline Analysis:**
  - Soil Analysis (contaminants)
  - Design Parameters: SOD and BBC

Helps estimate Klozur® SP dosing requirements based on destruction targets

- **Phase I**
  - Screen larger set of test conditions for UCS using pocket penetrometer

Helps determine appropriate dose binder for select persulfate dosages based on stability targets

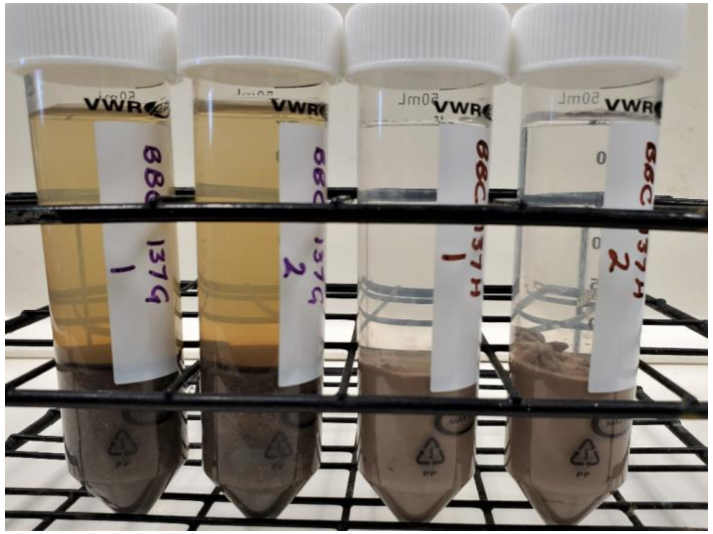
- **Phase II**
  - A more limited number of test conditions selected for the full treatability study based on Phase I results
  - Analysis varied depending on project goals and needs

Baseline Analysis and Preliminary Dosing Estimations

- **Contaminant Concentrations:**
  - Soil analysis (duplicate)
  - Leachate concentration (optional)

- **Base Buffer Capacity (BBC) Test**
  - Amount NaOH needed to raise pH of soil to 10.5

- **Soil Oxidant Demand (SOD) Test / Klozur Demand Test (KDT)**
  - Batch reactors set up with soil + persulfate solution + NaOH activator
  - Uncontaminated soil preferred for background SOD
  - SOD estimated based on persulfate consumption after 7 days



SOD Test Set-Up and Example Results

Sample ID	Trial Activator	Soil Wt. (g)	Water Vol. (mL)	Klozur Dosage (g/Kg Soil) t=0 hrs.	Klozur SP Consumption (g persulfate / kg dry soil)	
					t=48hr	t=168 hr
1	High pH	10	30	15	0.63	1.02

SOD will in part be a function of dose and time assessed – following the same procedure allows us to compare different soils & flag anomalies

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Example Preliminary Dosing Estimations

- Example Baseline Results:

– COC: 1,000 mg/kg

– SOD: 1 g persulfate per kg soil

- Degradation ratio (example):

-- 15 g SP per g COC*

*Varies by COC and concentration

Klozur® SP dosing estimation (g/kg soil) = COC Conc x Deg. Ratio + SOD

Example: 1,000 mg/kg COC x 15 g/g ratio + 1 g/kg SOD = 16 g/kg = 1.6% SP by soil mass

- Adding Safety Factors (SF):

– Low Dose (~1x) → 1.5% by soil mass

– Medium Dose (~2x) → 3% by soil mass

– High Dose (~3x) → 5% by soil mass

Adjust SF to consider destruction goals – could be less than 1x

Phase I – Screening Level UCS

- Identify blends that will solidify within the target range

- Test Conditions (10-15 blends):
  - 2-3 concentrations of Klozur® SP, each with 3-4 binder dosages
  - May also include binder only controls

Phase I sample set-up

- Sample evaluation:
  - Samples analyzed using in house pocket penetrometer + visual inspection
  - Two sampling time points, usually Day 7 and Day 14 or 28 (if time allows)
    - If solidification is going well: Day 7 is typically ~30% of long term UCS and Day 28 is typically ~50-75% of long term UCS

Sample evaluation using penetrometer

Phase II – Treatability Testing

- Typically, 5 to 6 test conditions are selected for the full treatability testing based on their performance in Phase I

- Phase II tests are varied depending on site remedial goals, client wishes, and client budget, but it can include:
  - UCS (28 / 56 / 90 days) – external analysis
  - Hydraulic conductivity (28 / 56 days)
  - Contaminant concentrations on soil (28 days)
  - Leach Testing
  - Vapor Intrusion (similar to leach test but analyzing gas phase)
  - Volumetric Expansion

Tedlar bags set up for shipment to accredited lab for soil analysis and cylinders for leach testing and UCS analysis

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Leaching Tests

- **TCLP (Toxicity Characteristic Leaching Procedure; SW-846 Method 1311)**
  - Meant to emulate municipal landfill leachate
  - Single point leach test. Uses acetic acid
- **SPLP (Synthetic Precipitation Leaching Procedure; SW-846 Method 1312)**
  - Meant to emulate acid rain (west and east of Mississippi)
  - Single point leach test. Uses nitric and sulfuric acid
- **LEAF (Leaching Environmental Assessment Framework; SW-846 Method 1313-1316)**
  - Multiple point leach test (multiple pore volume flushes and contact times)
  - Multiple methods with varied test conditions
  - Does not grind sample

TCLP and SPLP

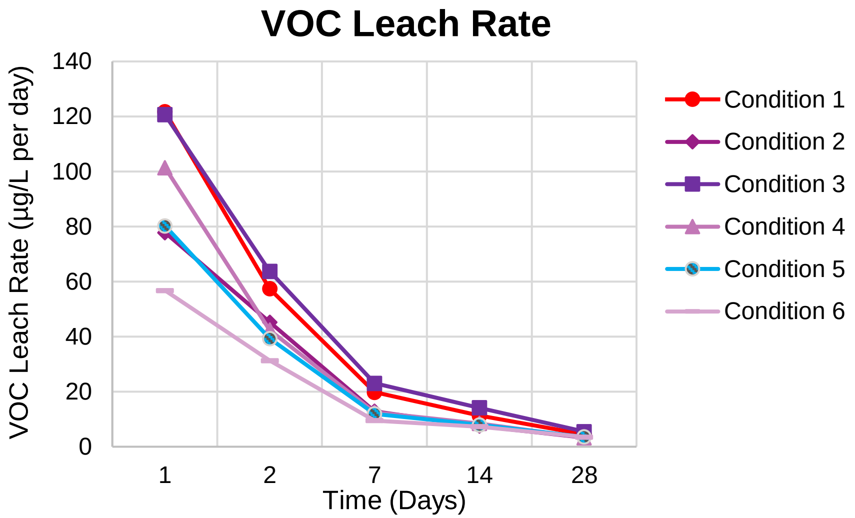
- **Both method grind samples to less 1 cm in size, negating benefit of solidification**
- **Acid addition may not be typical of site groundwater**

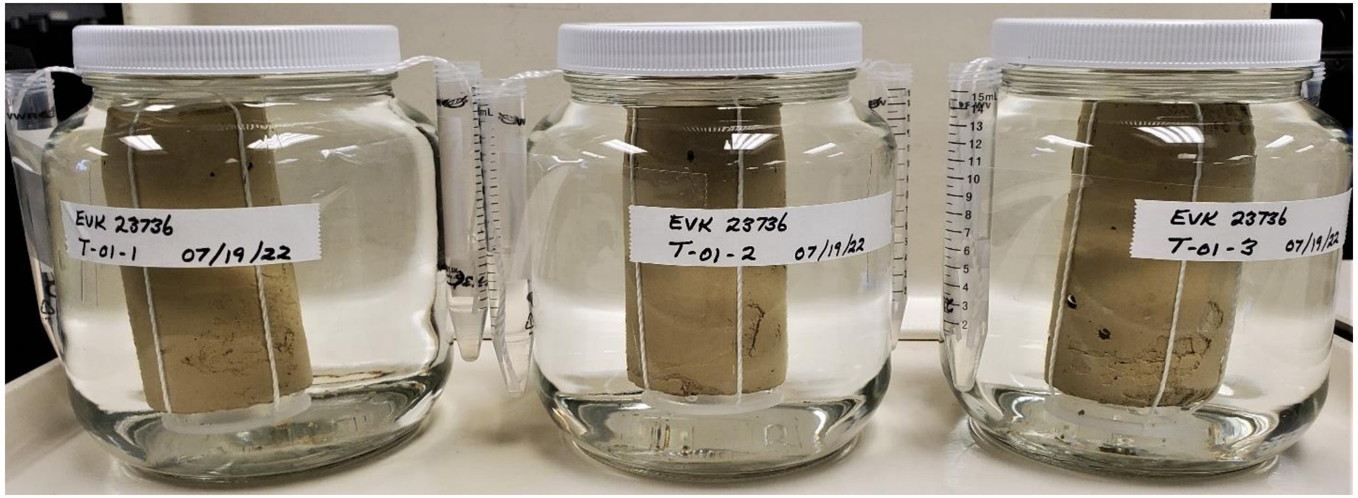
LEAF

- **Can be expensive and often requires significant time**

Leaching Tests

- **Evonik Tank Method developed reviewing various other methods**
  - Solidified matrix is suspended in tank
  - GW is exchanged at different time intervals (1, 3, 7, 14, and 28 days)
  - GW sampled for dissolved COCs at each exchange
  - Leachate concentrations presented on ug/L-day
  - Rate of diffusion from matrix based on surface area can be modeled



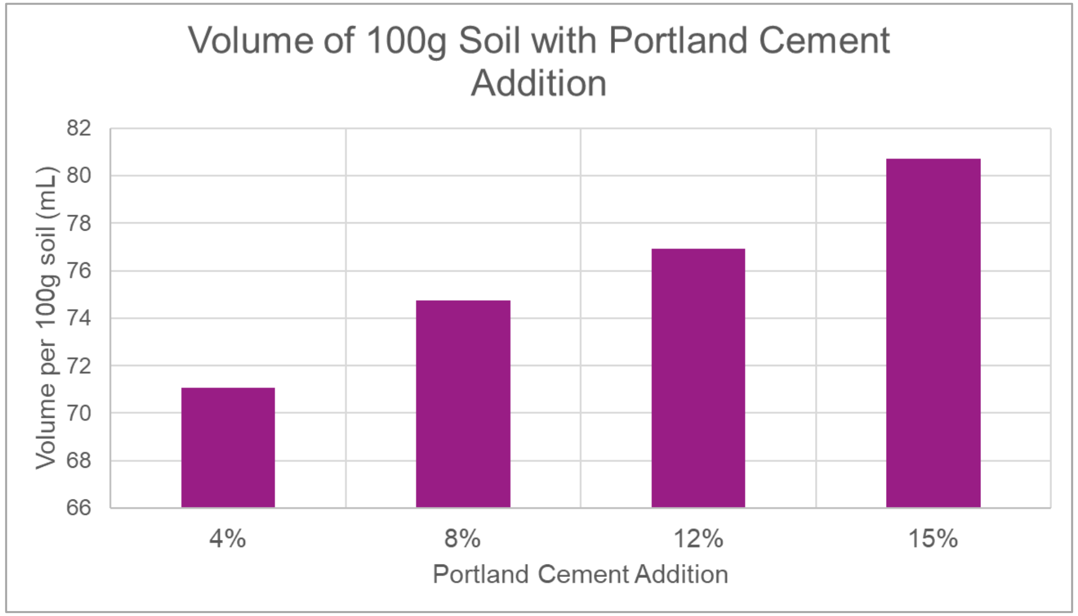


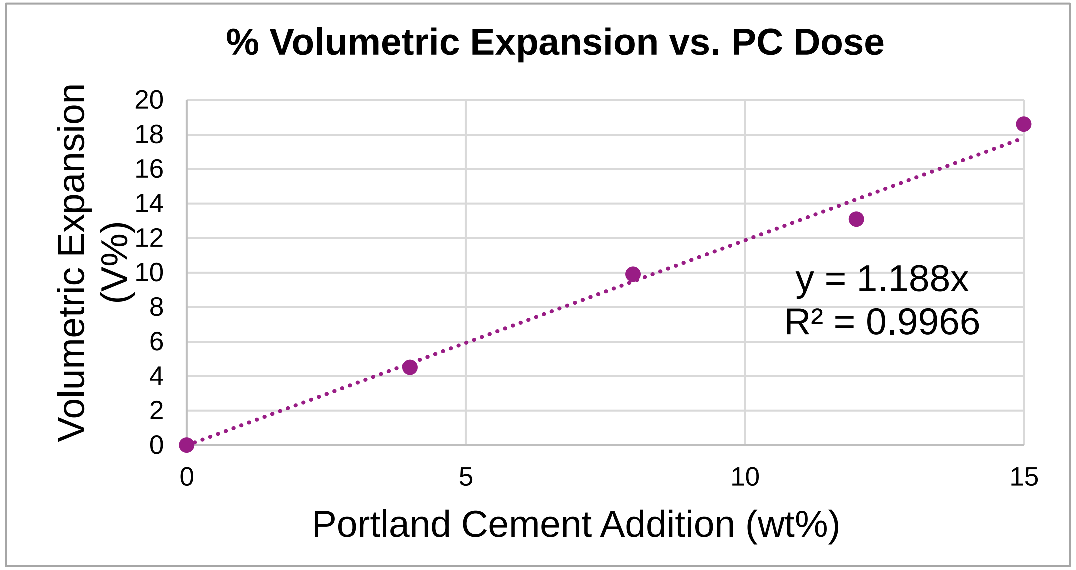
Condition	Reagent Dosing		VOC Leaching Interval Sampling				
	SP	PC	T-01	T-02	T-03	T-04	T-05
	%	%	ug/L per day				
0 (Control)	0%	0%	**141,408**	--	--	--	--
1	1.0%	4.0%	122	57	20	11	4.5
2	1.0%	6.0%	78	45	13	7.5	3.4
3	2.0%	4.0%	121	64	23	14	5.5
4	2.0%	6.0%	101	42	13	8.4	3.3
5	3.0%	6.0%	80	39	12	8.0	3.6
6	4.0%	7.0%	57	31	9.5	7.3	3.5

Volumetric Expansion Test

- The addition of binder will cause the monolith to increase in volume
- Depending on site, excess swell may need to be removed from site
  – Can be significant cost factor
- For soils tested
  – Rate increased at ~1.2x V% monolith per W% PC added
- If ISCO-ISS can be used to achieve project goals with less binder than swell should be decreased

~1.2x V% monolith per W% PC added

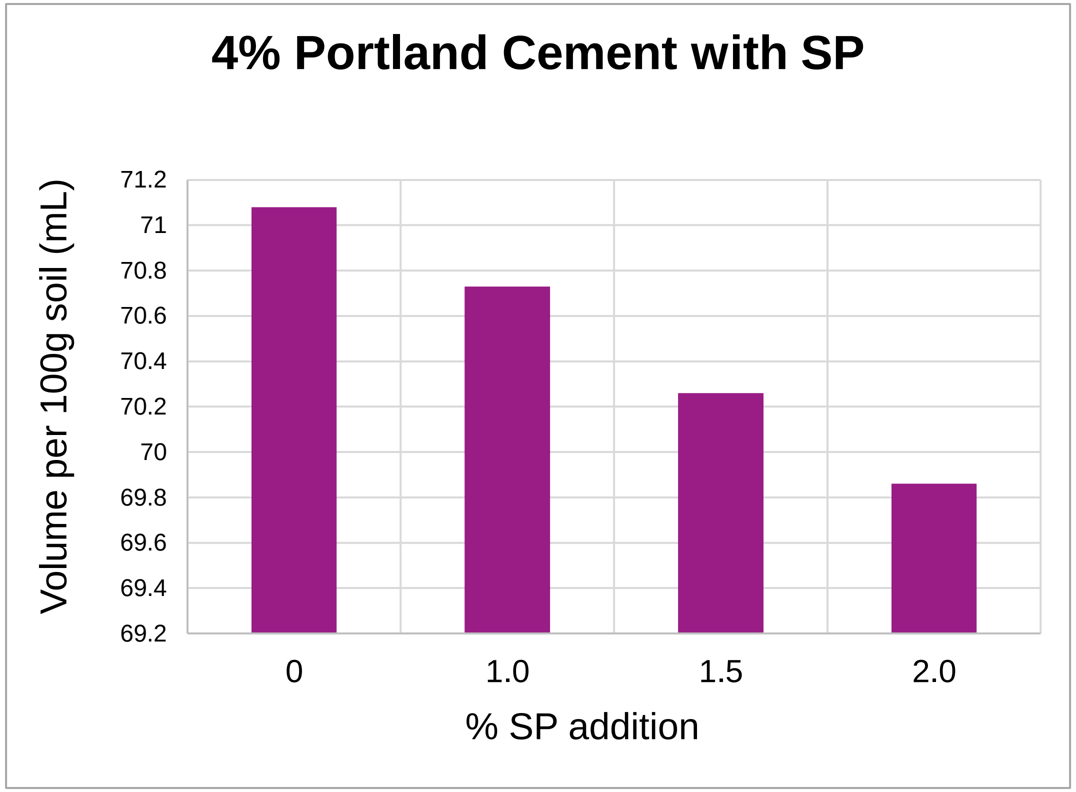




Synergies: Reduction in Swell/Fluff

- Second mechanism:
  - Soils tested had decreasing volumes with increasing SP addition for same amount mass of binder
  - Up to ~40% reduction in swell observed with 2% Klozur SP addition

Example: If you had 20% swell without SP, you may have 12% swell with 2% SP for the same PC addition



Soil Mixing Implementation Methods

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Common Soil Mixing Methods

- **Bucket Mixing using Excavator**
- **Rotary Tools / Mixing Attachments**
- **Large Diameter Augers**

Bucket Mixing

Rotary Mixing Attachment

Large Diameter Augers

Acknowledgements:

- Tony Moran, Entact
- Bill Lang, Lang Tools
- Kim Jensen, Arkil
- Stefan Dahlin, SMG
- Nathan Coughenour, Geosolutions
- Vito Schifano, Formerly of Ladurner

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Bucket Mixing

- Can reach up to 6 m / 20 ft below work pad (limit to length of excavator arm)
- Reagents applied dry at the surface → Best suited for depths up to 2.5 m / 8 ft for homogeneous mixing
- May need a rotary tool as a “polishing” step to improve blending

Adding Dry Reagents.

Blending & addition of water.

Wet mixing completed.

Area after backfill.

Photo Documentation Courtesy of Trident

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Rotary Mixing Attachments

- Various tools in the market (Lang Tool, Allu, Alpine, etc.) with varying penetration depths (up to ~26 ft / 8 m)
- Can apply in lifts to reach greater depths
- Reagents injected via mixing head – more homogeneous placement
- Hard soil may require pre-loosening with excavator

Lang Tool's Dual Axis Blender

Lang Tool's Deep Digger Blender

Allu Mixer attachment

Large Diameter Augers

- Can extend to depths of 60+ feet (20+ m) below the work pad
    - >60 ft / >20 m is possible but increasingly specialized, consult contractors
- Auger diameter may range from 3 to 11+ feet in diameter
    - Varied based on soil density, strength, depth, etc.
- Increasingly cost-effective, especially for larger sites

ISCO-ISS Applied using Large Diameter Augers in Bolzano, Italy

Video courtesy of Ladurner Bonifiche S.r.l.

Sufficient Moisture is important!

- Typically target approximately ~1.5x times full saturation
- Visually want the soil to look soupy with some standing water upon application
- Both Portland cement and Klozur® SP consume water as they react

Video courtesy of Lang Tool

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Application & Performance Monitoring

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Application Monitoring

- Goal is to confirm uniform reagent distribution:
  - Persulfate field test kits
  - Conductivity, pH and ORP should provide distinctive indicator of reagents
  - Analysis: sodium, calcium, sulfate
  - Ensure soil is adequately homogenized (avoid large clumps)
  - Moisture content

Klozur® Field Test Kits

Post Application Performance Monitoring: Parameters

- Key Parameters to monitor:

Parameter	Recommended Method	Benefits	Recommended Interval	Option Intervals
Unconfined Compressive Strength (UCS)	ASTM D1633	Quantifies solidification Can be done in laboratory or field. Field tests very rapid and inexpensive	28 and 90 days	7, 28, 56, and 90 days
Hydraulic Conductivity	ASTM D5084	Key flux objective	>28 days	
Contaminant Concentration on Soil	Contaminant dependent		>14 days	1, 3, 7, 14, 28, 56 days

- Optional Parameters to monitor (depending on site goals):
  - Porosity
  - Leachate
  - Vapor impacts

Post-Application Performance Monitoring: Sample Collection

- Two primary methods of Post-Application Sample Collection:

1. Collect samples using tool attached to excavator arm
   - Collect a slurry at depth
   - Slurry poured into molds and allowed to cure
   - Samples analyzed at times taken from molds

2. Conventional soil sampling methods after solidification:
   - Target solidification is typical of stiff clay
   - After successful solidification, drive sampling equipment onto target area to collect samples

Step 1:

Collect samples through telehandler

Step 2:

Sieve material to remove rock and then add to molds

Step 3:

Allow molds to cure for selected duration in cooler

Interstate Technology & Regulatory Council (ITRC), 2011, “Development of Performance Specifications for Solidification/Stabilization”, Section 6.2

Case Studies

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Former MGP Site in Stockholm being Redeveloped into Residential Area

Client: City of Stockholm

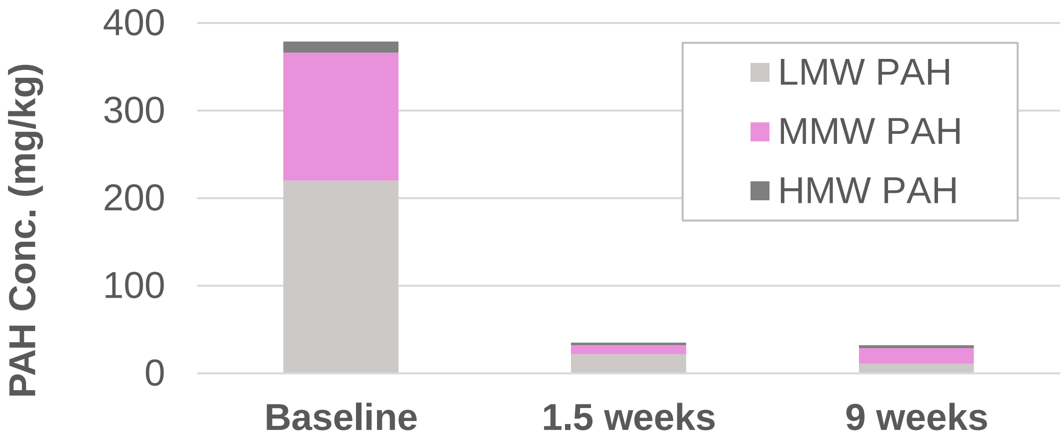
Contractor: PEAB / ARKIL

Treatment Volume: 50,000 m^3 clay layer

Remedial Goals: Prevent vapor intrusion to planned buildings via combination of stabilization and contaminant reduction

Reagent dose:
•1.8wt% Klozur® SP
•4-8 wt% Slag cement

Klozur® SP, cement and water applied using large diameter auger



- ~95% reduction in PAH-L
- ~90% reduction in PAH-M
- ~80% reduction in PAH-H
- Higher % reduction in lower molecular weight fractions.
- All samples below remedial goal of 250 mg/kg

Reference: Uppföljning av föroreningshalter i pelare efter stabilisering och kemisk oxidation av lera (ISS-ISCO), Golder, Jan 2022

ISCO-ISS Successfully Remediates PCE DNAPL at Former Dry Cleaner in Residential Neighborhood

Location: Former Kent Cleaners, Lansing, Michigan

Lead Consultant: Hamp Mathews & Associates

Contractor: Lang Tool

Regulator: EGLE

Contaminants: PCE (up to >1,000 mg/kg)

Goal: Reduce vapor intrusion risk

Treatment volume: 12,354 cy soil

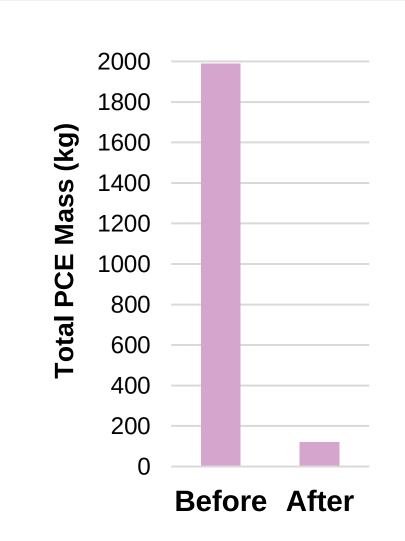
Reagent Dose (w/w soil):

- Klozur® SP: 1-2% (440K lbs)
- Portland Cement: 4% (1.6M lbs)

Results

- 94% reduction in PCE mass
- UCS of 25-50 psi (Day 60)
- Underlying GW conc. reduced by 90 to 99%

Saved client >$2.5 Million compared to excavation estimate



ISCO-ISS Successfully Remediates TCE Contaminated Soils Achieving Clean-Up Goals in One Week

Site: Former Industrial Site / Redevelopment

Location: Västerås, Sweden

Contaminants: TCE source area (up to >500 mg/kg)

Lead Consultant: Wescon

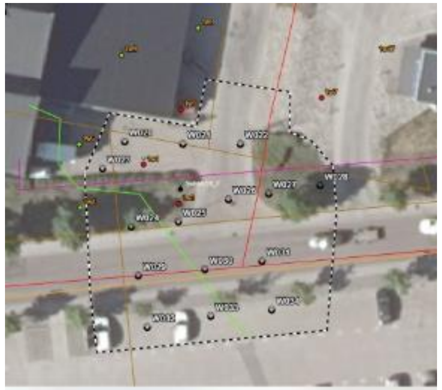
Soil Mixing Contractor: SMG

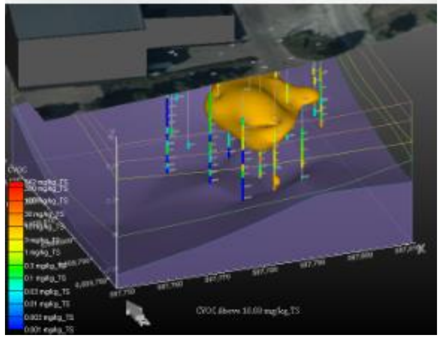
Goal: Reduce TCE mass by 50%

Treatment volume: 600 m^3 soil

Reagent Dose (w/w soil):

- Klozur® SP: 0.8% (8 tons)
- Portland Cement: 7% (70 tons)





Results:

- Goals reached after 1 week and confirmed after 5 weeks
- The stability of the soil was improved
- Infrastructure was minimally affected

Significant cost savings (~70%) relative estimated excavation and disposal costs

	Baseline: CVOCs before treatment	Results: CVOCs 5 weeks post treatment	Reduction
Maximum conc (mg/kg)	542	16.5	97%
Average conc (mg/kg)	45	4.5	90%
Estimated CVOC mass (kg)	35-40	7-9	74 to 83%

Summary

- ISCO-ISS is combined remedy of two established technologies
  - Single application
    - Treat/degrade significant portions of contaminant mass
    - Residual is solidified in a monolith
  - Several synergistic benefits:
    - Higher UCS, lower leachate, lower hydraulic conductivity
    - Less soil bulking can decrease project costs
    - Site ready for redevelopment/access shortly after application

Bench studies can help optimize the dosages of ISCO and ISS reagents

Thank you!

Questions?

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