Don Mouth Naturalization and Port Lands Flood Protection Project

Treatment Technology Evaluation Program

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Executive Summary

The Don Mouth Naturalization Project and Port Lands Flood Protection Project is one of the most significant active brownfield redevelopment projects in Canada. This project was merged with the Lower Don Lands Transportation and Servicing Master Plan Class EA (LDL) during a Due Diligence Study (2016) to form the Port Lands Flood Protection Project (PLFP). PLFP is one of the most significant active brownfield redevelopment projects in Canada. The overall goal is to transform 356 hectares of flood-prone, under-utilized commercial/industrial land into a vibrant mixed-use community. The overall scope of the project involves the construction of a new, naturalized mouth for the Don River, along with associated flood-protection infrastructure to allow for redevelopment of the study area. Current (2019) estimates include 1,494,000 m^3 of excavation, and 1,068,000 m^3 of fill placement. Three key challenges for this transformative project are:

1. Contaminated soil and groundwater from over 150 years of fill placement and industrial activity within the project area.
2. Excavating the new river valley through the relatively low strength native soils and fill.
3. Treatment of large volumes of groundwater extracted from the excavated area.

To minimize the environmental and social impacts of the PLFP, innovative technologies were considered to minimize the volumes of soil exported from the site because of chemical contamination and/or geotechnical properties. In addition, potential technologies for the treatment of dewatering effluent were also considered. The first part of the project included bench scale tests of eleven technologies with limited quantities of soil, groundwater, and hydrocarbon products from the site:

1. Biological Soil Stabilization
2. Block and Adsorb
3. Surfactant and Oxidant Treatment
4. STAR® (in-situ thermal treatment)
5. STARx® (ex-situ thermal treatment)
6. Biodegradation
7. In-situ Soil Stabilization via Cutter Soil Mixing
8. In-Situ Soil Stabilization (2nd Stage)
9. Phys-Chem Bio Treatment
10. Electro-Thermal Dynamic Stripping (ET-DSP™)
11. Segregation and Soil Washing

Each of the project teams was required to produce documentation of the methodology for their technology along with verification of the results through laboratory testing of soil and water chemistry and/or geotechnical properties of the final products. Following the bench-scale testing program, Waterfront Toronto considered the bench scale test results along with an evaluation of the probability of success within the site-specific technical, schedule, and budgetary constraints of the PLFP. The following six technologies were selected for pilot scale testing, and in-situ soil stabilization was selected for further bench-scale testing.

1. Biological Soil Stabilization
2. Block and Adsorb
3. Surfactant and Oxidant Treatment
4. STAR® (in-situ thermal treatment)
5. STARx® (ex-situ thermal treatment)
6. Biodegradation

The pilot scale testing was done at the Port Lands site, with each team assigned a specific test area. Results of previous soil and groundwater chemistry testing were used to identify the candidate sites, although not all the project area was available because of access constraints. As with the bench-scale testing, each project team produced a report detailing the methodology and results from their pilot test program, along with estimated costs (Class V) and feasibility assessment for application of the technology at the site scale. Documentation included laboratory tests for soil and groundwater quality and/or the geotechnical properties of the final product. At the conclusion of the program, all the equipment, monitoring wells, and excess soil and water were removed from the site.

All the treatment technologies assessed as part of this study provided some degree of soil strength improvement, permeability reduction, and/or contaminant mitigation. However, as expected with emerging remedial technologies and a large, complex site like the PLFP, no one technology provides a perfect solution, especially under field conditions.

Of the field scale studies, the thermal remediation methods (STAR/STARx) provided the most significant contaminant reductions, particularly for highly impacted soils. The in-situ approach (STAR), however, would be limited to areas where the impacts are focussed and where the soil strata is more homogeneous. These conditions are not generally found in the PLFP, so the ex-situ approach has a greater chance of successful implementation.

For a project such as the PLFP, time is a critical factor, given the high volumes of contaminated soil being excavated, and limited storage space available. This requires high volume throughput to keep the project moving forward on schedule. Technologies that are scalable, with short reaction times, have the greatest probability of success on the PLFP. Therefore, thermal-based strategies such as STAR and STARx and physical stabilization via Portland Cement or other additives may be appropriate for this project, especially for some of the more highly contaminated soils, or areas where native soil strength must be increased. Slower processes such as bioremediation may be utilized as part of the overall solution, provided treatment area is available.

The PLFP has a significant overall budget ($1.25 billion), but is subject to a firm price ceiling, with a multitude of other cost items such as building bridges and installing or moving key infrastructure components. Therefore, the funds available for soil remediation are fixed, with a low tolerance for overruns. This means that the remedial strategy must consider economic realities.

The ex-situ approach (STARx) will have predictable and controllable results. Therefore, it would be best utilized to treat the most impacted soils. Bioremediation strategies are cost effective, but would be limited to less impacted soils, or soils subject to higher criteria limits.

This project evaluated the use of eleven different soil stabilization and contaminant mitigation technologies. Each of these approaches has the potential to be part of a remedial action plan to achieve the overall site remediation goals and minimize the volume of contaminated soil shipped offsite to one or more landfills. However, based on the results of the testing, and the site-specific constraints for the PLFP, the following technologies represent the most favourable options for consideration as part of the full-scale remedial action plan:

- STAR and STARx for highly impacted soils,
- Physical soil stabilization with Portland Cement and/or other additives, especially for the base of the river excavation, or areas that require an increase in in-situ soil strength,
- Enhanced bioremediation for treatment of lightly impacted soils, and/or soils subject to higher criteria thresholds, and
- Use of activated carbon as a pervious reactive layer. Although this was not specifically tested, activated carbon was shown to be effective as part of the Block and Absorb testing process.

Table of Contents

Figures

Tables

GLOSSARY/ACRONYMS

Activated Carbon: A form of charcoal usually from source such as coal, coconut husks, or bamboo that is processed to have many small volume pores that attract and retain chemical contaminants such as hydrocarbons and metals.

Bench Scale Test: An evaluation of a remedial technology completed in a laboratory on a sample size at a scale of kilograms or litres.

Bioslurry: A mixture of contaminated soil, water, nutrients, and bacteria that is utilized in bioremediation processes.

BTS: Brazilian Tensile Strength. This laboratory test indirectly measures the tensile strength of rock or concrete and is typically about an order of magnitude less than the compressive strength.

California DTSC: California Department of Toxic Substances

CBRA: Community Based Risk Assessment

CNP: Carbon:nitrogen:phosphorous ratio; an important factor in bioremediation.

CPT: Cone Penetration Test. A field test to determine the in-situ strength of subsurface soils and sediments. The test involves the measurement of the amount of resistance to pushing a tool with a conical tip into the subsurface.

C.V.: Combustible Vapours; organic compounds that can ignite in the presence of oxygen (i.e., methane).

DI: Deionized water; water that has been treated to remove anions/cations to trace levels.

DMNP: Don Mouth Naturalization and Port Lands Flood Protection Project

DNAPL: Dense, Non-Aqueous Phase Liquid. These liquids have low solubility in water, and have densities greater than 1 g/ml, which causes them to sink when added to water. They include a wide variety of chlorinated solvents and heavier petroleum hydrocarbons such as coal tar.

ET-DSP™: Electro-Thermal Dynamic Stripping Process

GAC: Granular Activated Carbon. A coarse-grained carbon with particles 0.2-1.0 mm in diameter.

GREM: Green Remediation Evaluation Matrix

GU: General Use cement

GUL: Portland-Limestone cement

HC: Hydraulic Conductivity; the inherent ability of a porous medium to transmit water. Also known as “k”.

HPLF: High Pressure, Low Flow; a soil washing technique that can help minimize water use, especially for soil mixtures subject to clumping (i.e., well graded silty sands with some clay).

HUB: Hydrocarbon Utilizing Bacteria

ISS: In-situ Soil Stabilization

kPa: kilopascals, a measure of pressure; 1 kPa equals 0.145 pounds per square inch.

LNAPL: Light, Non-Aqueous Phase Liquid. These liquids have low solubility in water, and have densities less than 1 g/ml, which causes them to float on water. They include a wide variety of petroleum hydrocarbons.

LPHF: Low Pressure, High Flow; a soil washing technique that works best with mobile contaminants from soil mixtures not subject to clumping (i.e., uniform sands).

MECP: Ministry of the Environment, Conservation, and Parks (formerly MOECC, the Ministry of the Environment and Climate Change).

MW: Multiple Wash cycles; a soil wash process that involves both moderate pressure and flow, with repeated cycles to facilitate the breakup of cohesive soil clumps.

NC: NewCem; cement mixture containing slag.

O.V.: Organic Vapours; includes both combustible (i.e., methane) and non-combustible compounds (i.e., trichloroethylene).

PAC: Powdered Activated Carbon. A fine-grained type of activated carbon (<0.2 mm) that can be injected into the subsurface to adsorb contaminants.

PAHs: Polynuclear Aromatic Hydrocarbons. These heavier organic compounds are sometimes referred to as semi-volatile organics, since they are less volatile than VOCs. They include such compounds as anthracene and naphthalene (found in mothballs).

PC: Portland Cement

PHCs: Petroleum hydrocarbons. These comprise a wide range of organic compounds ranging from lightest fraction (F1) to the heaviest fraction (F4). They are typically associated with gasoline, diesel fuel, and lubricants.

Phi: internal friction angle, a measure of geotechnical strength

Pilot Scale Test: An evaluation of a remedial technology conducted at the project site on a limited volume of soil or water at a scale of tonnes or cubic metres.

PLFP: otherwise known as the Port Lands Flood Protection and Enabling Infrastructure Project (PLFPEI or PLFP for short), refers to the project that resulted from the merging of the Don Mouth Naturalization and Port Lands Flood Protection Project (DMNP) with the Lower Don Lands Transportation and Servicing Master Plan (LDL) to coordinate the integration of the river creation works with the supporting municipal infrastructure and servicing works.

ppm: parts per million. Equivalent to milligrams per litre (mg/L), micrograms per gram (μg/g), and milligrams/kilogram (mg/kg).

Resistivity: The inverse of conductivity; a measure of how resistive a soil mass is to pass an electrical current.

SCPT: Seismic Cone Penetration Test. This technology combines geophysics with cone penetration equipment. A geophone-equipped cone is advanced to a specific depth, and an automatic hammer is used as the seismic source. The test is repeated at various depth intervals to obtain a subsurface seismic velocity profile.

SEPR™: Surfactant Enhanced Product Recovery. A remediation strategy that utilizes one or more surfactants to make contaminant molecules more soluble, and therefore easier to recover from the subsurface.

S-ISCO®: Surfactant enhanced In-Situ Chemical Oxidation. A remediation strategy that combines surfactant(s) to increase organic contaminant mobility and oxidation to convert toxic contaminants into non-toxic forms.

Smouldering: A flameless form of combustion where the contaminants in the soil are the fuel for chemical reactions that occur in an oxidizing environment.

Spiked: An analytical technique that involves adding a specific quantity of a chemical or chemical mixture to a sample of soil or water. In the case of this study,

SPLP: Synthetic Precipitation Leachate Procedure. Methodology to simulate the potential for leaching of contaminants from soil by precipitation, which has a pH of about 4.2 in the Greater Toronto Area. This low pH increases the mobility of metals and some other contaminants compared to a distilled water leach test.

STAR: Self-sustaining smouldering combustion Treatment for Active Remediation, in-situ.

STARx: Self-sustaining smouldering combustion Treatment for Active Remediation, ex-situ.

SVOCs: Semi-Volatile Organic Compounds, which includes polynuclear aromatic hydrocarbons.

TCLP: Toxicity Characteristic Leachate Procedure; an analytical method that assesses the potential mobility of contaminants in a soil sample.

TPH: Total Petroleum Hydrocarbons; a measure of the concentration of petroleum hydrocarbons in soil or water.

UCS: Unconfined Compressive Strength

VOCs: Volatile Organic Compounds (includes chlorinated solvents)

PORT LANDS FLOOD PROTECTION PROJECT

The PLFP is one of the most significant brownfield redevelopment projects in Canada. It represents a unique opportunity to transform 356 hectares of under-utilized commercial/industrial land into a vibrant live-work-play community with affordable housing, job opportunities, and renewed connections to the Don River and the natural environment (Waterfront Toronto, 2019). The overall scope of the PLFP involves the construction of a new, naturalized mouth for the Don River, along with associated flood-protection infrastructure to allow for redevelopment of the study area.

Key ecosystem enhancements of the project include the creation of:

- Over 1 km of new river channel for the Don River,
- 13 hectares of new coastal wetlands,
- 5 hectares of terrestrial habitat both inside and outside the new river valley system,
- 14 hectares of new aquatic habitat.

In addition to the above ecosystem enhancements, the flood protection component of the project includes the removal of flood risk to 240 hectares of land that will be unlocked for future redevelopment. The majority of the remaining 50 hectares of flood-vulnerable lands will be located within a robust natural heritage system that can be enjoyed by both future residents and visitors to this exciting new community, though some of that area includes ~8 hectares of urban land remaining at flood risk north of the Metrolinx railway embankment on the east side of the Don River, and portions of the lower Don Valley Parkway (DVP).

One of the main challenges for the PLFP is the presence of fill, soils, and sediment that have been impacted by the former filling of the wetland and the subsequent commercial and industrial activities. Extensive environmental investigations along with the associated testing of soil and groundwater has delineated areas that are impacted above the relevant generic provincial standards for the anticipated future land use (MOE, 2011).

A Community-based Risk Assessment was started by Waterfront Toronto (CH2MHill, 2016a), and risk management measures have been developed to manage some of the impacted soil and groundwater in place. However, because of the required excavation of large quantities of fill and sediment to create the new river valley, combined with the high concentrations of certain parameters above the site-specific criteria, a large volume of soil would either have to be remediated on site prior to re-use, or transported to a secure landfill for disposal.

In recognition of the carbon cost, societal impacts, and overall economics of off-site disposal of both soil and groundwater, Waterfront Toronto embarked on a project to test the effectiveness and economic viability of innovative, on-site soil and groundwater treatment technologies.

In addition to the multiple community benefits of parkland, water access and new natural habitat, the project has the potential to deliver wide economic benefits. A third-party economic impact study estimates that spending on construction alone will generate approximately:

- $1.1 billion in value to the Canadian economy,
- 10,829 person years of employment; and,
- $373 million in tax revenues to all orders of government.

The study also indicates that there are economic benefits related to future development unlocked by the project, including approximately:

- $4.0 billion in value added to the Canadian economy,
- 41,100 person years of employment; and,
- $1.5 billion in revenues to the three orders of government.

Location

The overall PLFP (**Figure 1**) is being undertaken in the area east to Saulter Street, west to the Inner Harbour, south of the Keating Channel and north of the Ship Channel (**Figure 1**). The project area also includes:

- The Sediment Management Area (SDMA) and access road on west bank of the Don River, north of Lakeshore Boulevard;
- The Cadillac-Fairview lands north of Lakeshore Boulevard and east of the Don River, including a potential grading solution at the Eastern Avenue underpass.

This project area represents man-made land that was created by historic infilling of the Ashbridges Bay wetland in the 1800s. The bench and pilot scale remediation programs were undertaken in the central part of the study area, in the general location of the former oil refinery.

History

The project area has a long history of commercial and industrial land uses, including a former oil refinery, and a munitions factory during World War II.

Challenges

Preliminary estimates of the cut/fill balance for the PLFP developed in 2016 include 1,494,000 m^3 of excavation, and 1,068,000 m^3 of fill (CH2M Hill, 2016b). The key challenges with respect to the re-use of the excavated on-site soils are geotechnical stability and the presence of contaminants above the site-specific restoration criteria. The study area was once a delta with an associated wetland complex. The filling of the wetland in the 1800s did not consider either the geotechnical or environmental suitability of the imported materials. In addition, the PLFP area is surrounded by Lake Ontario on three sides, with the water table being close to ground surface. Therefore, excavation of the river valley without some form of soil stabilization or barrier wall will result in in significant sloughing of the unstable soils. resulting in at least a three-fold increase in excess soil generation.

In terms of soil quality, the conventional “dig and dump” approach, if applied to the entire project, would result in about 215,000 one-way truck movements through a very busy urban area. The combined economical, societal, and carbon impacts of this approach are simply not acceptable. Therefore, innovative on-site solutions are needed to mitigate both the volumes of material to be excavated and filled.

Figure 1: Location Map and Site Plan

Opportunities

A wide range of innovative remedial technologies have been developed to stabilize soils in-situ and reduce the concentrations of contaminants or the bioavailability of those contaminants. However, given the tight timeframes for the PLFP, combined with the physical and chemical nature of the on-site soils and the overall scope and scale of the project, thorough testing and evaluation of potential remedial solutions was considered essential. Given these requirements, bench and pilot scale testing was recommended to identify the most effective technologies that could be implemented at the site scale.

Selection of any of these technologies under this evaluation program should not be considered as an endorsement of the technology or the providers with respect to future applications. Similarly, non-selection of a bench scale remedial approach for pilot scale testing is not intended as a rejection of the technology or the providers for potential future applications.

Pilot and Bench Scale Remediation Project

The main objective of this project was to identify innovative on-site remedial technologies to reduce the volumes of contaminated sediments hauled from the PLFP area to secure landfills for disposal and the overall carbon footprint of the project. A secondary objective was the identification of such remedial technologies that could be employed at other sites along the Lake Ontario waterfront to optimize remedial costs, minimize the import/export of soils, and protect human health and the environment.

Waterfront Toronto undertook a competitive bidding process to identify proponents for the bench scale tests, which resulted in the following technology selections for bench scale assessments:

1. Biological Soil Stabilization (Consortium Leader: Groundwater Technology BV)
2. Block and Adsorb Technology (Consortium Leader: WSP Canada Inc. and Vertex Environmental)
3. Surfactant and Oxidant Treatment (Consortium Leader: EthicalChem)
4. STAR (Consortium Leader: Geosyntec Limited)
5. STARx (Consortium Leader: Geosyntec Limited)
6. Enhanced Aerobic Biodegradation (Consortium Leader: WSP Canada Inc.)
7. In-situ Soil Stabilization via Cutter Soil Mixing (Consortium Leader: Golder Associates)
8. PhysChemBio (Consortium Leader: Law Environmental)
9. ET-DSP™ (Consortium Leader: McMillan-McGee)
10. Segregation and Soil Washing (Consortium Leader: WSP Canada Inc.)

Following the completion of the 10 bench-scale tests, Golder's in-situ soil stabilization technology was selected for further bench-scale testing in collaboration with Jacobs.

The selection process for the Remedial Technology Evaluation Program included a variety of criteria, including compatibility with the complex scheduling needs of the PLFP, budget, degree of innovation, and expected feasibility of implementation. Therefore, selection of any of these technologies under this evaluation program should not be considered as an endorsement of the technology or the providers with respect to future applications. Similarly, non-selection of a bench scale remedial approach for pilot scale testing does not imply rejection of the technology or the providers for future remedial projects.

Based on the review of the bench scale test results, the proposals for pilot scale remediation, and the available budget remaining in the project, six technologies were carried forward to the pilot test scale. Each team was provided with a portion of the study area to undertake their tests. The actual size of the pilot scale projects was dependent on the technology used and the equipment required. The pilot scale testing portion of the Remedial Technology Evaluation Program included:

1. Biological Soil Stabilization (Consortium Leader: Groundwater Technology BV)
2. Block and Adsorb Technology (Consortium Leader: WSP Canada Inc. and Vertex Environmental)
3. Surfactant and Oxidant Treatment (Consortium Leader: EthicalChem)
4. STAR (Consortium Leader: Geosyntec Limited)
5. STARx (Consortium Leader: Geosyntec Limited)
6. Enhanced Aerobic Biodegradation (Consortium Leader: WSP Canada Inc.)

This document is intended as a succinct summary of the eleven bench scale projects and six pilot scale tests. Therefore, the information presented is limited to key findings from the work. The reader is directed to the individual reports for a detailed account of the methodologies and the assessment of the chemical testing. The author would like to thank the team of fourth year students from the University of Guelph, who provided their insights into the remedial strategy evaluation (Armstrong et al, 2019).

TECHNOLOGICAL SOLUTIONS

Project Goals

Goal 1: Soil Stabilization

Soil stabilization will be a key aspect of the overall PLFP implementation. Geotechnical studies to date CH2M Hill, 2016b) have confirmed that the on-site soils are saturated, non-cohesive materials containing varying amounts of compressible organic soils that will require significant over-excavation without some form of barrier or soil stabilization. In addition, soils that remain after the river valley has been excavated will be subject to varying loads from new construction. Therefore, soil stabilization can mitigate both the volume of material excavated as well as the volume of material that can be re-used on-site.

Goal 2: Contaminant Treatment

Any excavated soils that are re-used on-site will have to meet the site-specific standards developed as part of the CBRA. Therefore, remedial technologies that either destroy contaminants or limit their bioavailability have the potential to significantly reduce the volume of soil removed from the site.

Project Phasing

Following the release of CH2M Hill's Stage 2 Environmental Assessment and Geotechnical and Earthworks Report in May 2016 (CH2M Hill, 2016b), Waterfront Toronto began a project to assess innovative technologies to:

1. Minimize the volume of soil excavated during the project, and
2. Minimize the volume of soil and/or groundwater trucked off-site for disposal.

Bench Scale Testing

The first phase of the project began in September 2016 with ten technologies selected for bench scale testing. The intent of this first phase was to identify technologies and specific methodologies that might be effective with respect to one or both goals. The contractors were provided with representative samples of soil or groundwater, and NAPL, if required. Note that the methodologies and results presented in this report are only summaries of the approximately 3000 pages of documentation prepared by the individual project teams. For detailed accounts of the procedures and test results, readers are referred to the individual bench-scale reports.

Pilot Scale Testing

The second phase of the project involved additional testing of specific solutions at a larger scale, either in-situ, or ex-situ. The key objectives of the second phase of testing were to assess effectiveness at a larger scale under site-specific conditions and develop scaled-up cost estimates for each technology. As with the bench-scale testing, note that this document is intended as a summary of the methodologies used and the key findings. As with the Bench Scale project, detailed accounts of the procedures and test results are provided in the individual pilot study reports.

BENCH SCALE EVALUATION OF REMEDIAL TECHNOLOGIES

Biological Soil Stabilization (Groundwater Technology BV)

Technology Summary

This bench scale testing program was undertaken by a consortium headed by Groundwater Technology BV (Netherlands). The other principal partners were:

- Accuworx (technology provider),
- Provectus (technology provider),
- Deltares (technology development),
- Delft University of Technology (scientific advisors), and
- Arizona State University (scientific advisors).

This technology involves the use of natural soil biological processes to generate calcium carbonate ($CaCO_3$), which acts as a cementing agent for soil particles. This process relies on naturally occurring bacteria that transform urea and calcium chloride into calcium carbonate and ammonium chloride. (Groundwater Technology, 2017). These reactions result in creating some degree of cohesive strength in non-cohesive materials (i.e., sand). The final cohesive strength is dependent on the chemical and physical characteristics of the native materials. The initial enrichment testing involved the collection of five soil samples and two water samples from the site. The soil samples were submitted for testing of routine geotechnical properties, including moisture and organic content, grain size, specific gravity, density, and internal friction angle. In addition, the hydrocarbon content of the samples was also quantified, since hydrocarbons can interfere with biological processes.

Bench Scale Treatment Objectives

The key objective of this remedial process is to increase the strength of in-situ soils to either stabilize the edges of excavations or decrease the potential for settlement post-construction.

Summary of Methodology

The bench scale testing was completed in three main stages:

1. Enrichment testing (assessment of the presence of natural urea-utilizing bacteria),
2. Toxicity testing (assessment of urea to calcium carbonate conversion success), and
3. Testing of soil stabilization (assessment of the increase in cohesion).

The enrichment testing involved a single extraction step followed by several enrichment steps. For extraction, demineralized water was added to the soil samples, agitated, then allowed to settle for several hours. The liquid was then removed and processed through a series of enrichment steps. Enrichment was accomplished by adding the extracted liquid to a series of solutions containing a mix of nutrients (sugar, acetate, ammonium chloride, and/or urea) as well as varying levels of calcium chloride, yeast, and nickel chloride. The mixed solutions reacted for 1-3 days, after which 10% of the liquid suspension was extracted for a second enrichment step. The final extract was added to one or more of the soil samples (Groundwater Technology, 2017).

For the toxicity testing, a small amount of the enriched liquid was added to a solution of calcium chloride, urea, and nickel chloride. The ammonium concentration was then measured at 1, 8, and 24 hours to assess the urea reaction rate (Groundwater Technology, 2017).

For the final testing of soil stabilization, a larger volume of soil from the site and consolidated into sand columns in a triaxial test cell. Each sand column was then inoculated with the enriched solution from the first step that exhibited the highest urea conversion rate. After 24 hours, the samples were flushed with a solution of calcium chloride, urea, and nickel chloride. After another 24 hours, the samples were flushed with water, and subjected to shear strength testing.

Effectiveness

The bench scale testing program revealed that natural bacteria are present in the site soils that will hydrolyze urea and that adding urea and ammonium chloride has the potential to transform cohesionless soils to low-strength cohesive soils. However, the presence of petroleum hydrocarbons in the soil inhibits the biological activity. Higher strengthening may be attained with further optimization at the pilot scale.

This technology scored very well with respect to the Green Remediation Evaluation Matrix (GREM), developed by the California Department of Toxic Substances (California DTSC, 2007). The most significant negative effect is the generation of biological by-products that may have to be captured and treated at full scale implementation.

Potential Constraints

In terms of strength improvement, this innovative solution provides enhancement of cohesion of sandy site soils from 0 to about 5 kPa, with an increased internal friction angle (phi) from 33 to 35 degrees (Groundwater Technology, 2017). The treated sample values would typically support a slope angle of 1:2, but do not provide the same level of physical stabilization as Portland Cement or alternatives (200-1000 kPa, Jacobs, 2019). Although the test results suggest that petroleum hydrocarbons are not toxic to the bacteria involved, the presence of petroleum hydrocarbons appears to inhibit the biological reactions needed to drive the conversion of urea to calcium carbonate (Groundwater Technology, 2017). Given the existence of the former petroleum refinery within the subject lands, the successful application of this technology in the PLFP study area is expected to be limited to less impacted soils.

The reaction is expected to produce about 28 kg of ammonium chloride per cubic metre of soil. Flushing and recovery of this by-product will increase the overall remediation cost and could also require additional time in the project schedule, which is already highly constrained. If the ammonium chloride is not flushed, it has the potential to be a significant source of excess nitrogen, which could result in algal growth in the aquatic ecosystem of the new river valley. In other site settings, this constraint may not be a significant issue, and could be a benefit, if it enhances natural biological degradation of contaminants.

Block & Adsorb (WSP Canada Inc., Vertex Environmental)

Technology Summary

This technology was advanced by WSP Canada and Vertex Environmental (WSP, 2017a). It involves the addition of Portland Cement (PC) and Granular Activated Carbon (GAC) to soils from the site with the goal of improving the geotechnical properties (compressibility, cohesive strength) of the soil and immobilizing any contaminants present. Soil stabilization with Portland Cement is a proven remedial approach, but the innovation of adding GAC provides has the potential of enhanced protection, particularly for metals and hydrocarbons, with reduced requirements for PC.

Bench Scale Treatment Objectives

The objectives of the bench scale testing were to test different mixtures of PC and GAC to identify the optimal blend(s) of PC and GAC to effectively stabilize the soil, reduce the hydraulic conductivity of the blended mixture, and prevent leaching of contaminants.

Methodology

The bench scale testing of this technology was accomplished in two stages. In the first stage, samples were mixed with selected concentrations of PC (0.5%, 1%, 2%, 5%, and 10%) or GAC (1%, 5%, 10%, 15%, and 20%). The mixed samples were stabilized for about a week, and then were subjected to a series of tests, including:

- Saturated liberation (dosed with oil-soluble, hydrophobic dye and submerged in water),
- Relative penetration,
- Qualitative workability (measure of soil-like properties vs “concrete”),
- Hydraulic conductivity,
- Leachate pH, and
- Sheet inspection of leachate.

In addition, soil cylinders from each batch were cured for 21 days for subsequent compressive strength testing. Some of the site soil samples were spiked with a 50:50 mixture of diesel fuel and motor oil to simulate a concentration of F2 and F3 hydrocarbons of 15,000 or 30,000 ppm. This was done to ensure that the bench tests were completed on samples representative of known site conditions (WSP, 2017a).

These samples were then mixed with PC and GAC, at concentrations based on the Stage 1 testing. Ten mixtures were selected as shown in **Table 1**. The GAC was added first and stored for a week before the PC was added. The Stage 1 testing was then repeated on these samples after one week and two weeks of stabilization. Similarly, cylinders of each mixture were cured for 21 days for compressive strength testing. In addition, the treated samples were sampled and tested for bulk and leachable hydrocarbons (ranges F1 to F3) after one and two weeks of stabilization.

Table 1: Stage 2 Testing Program, Block and Adsorb

Test No.	Hydrocarbons (mg/kg)	PC (%)	GAC (%)
1	30,000	5.0	20
2	30,000	3.5	15
3	30,000	3.5	7.5
4	30,000	1.0	5
5	30,000	0.5	5
6	30,000	1.0	2
7	30,000	0.5	2
8	15,000	1.0	2
9	15,000	0.5	2
10	0	3.5	15

Effectiveness

Stage 1

In terms of strength and workability, the results showed the expected increase in strength from higher PC concentrations, and as expected, no strength increase from higher concentrations of GAC. The hydraulic conductivity of the mixed samples decreased by up to 95% at a concentration of 10% PC. However, the pH of the soil increased dramatically from 6.5 to 13 with only 0.5% PC. The leachate sheen tests showed an improvement with higher PC and GAC concentrations, but a sheen was still visible at a concentration of 10% GAC and 2% PC.

Stage 2

The Stage 2 results indicated that the free-phase hydrocarbons were immobilized with either a PC concentration of 1% and a GAC concentration of 2% OR a lower PC concentration (0.5%) and a higher concentration of GAC (2-5%). In terms of geotechnical properties, at a PC concentration of 1%, the samples were comparable to very weak ("soft") soil. Higher concentrations (about 5% PC) were required to attain soil strength comparable to a glacial till.

Potential Constraints

The significant increase in pH from the addition of PC may increase the mobility of some contaminants (i.e., metals), at least over the short term (Caporale, A.G. & Violante, 2016). The pH is expected to gradually return to baseline conditions through reactions with acidic precipitation, which has an average pH value of 4.4 in the Toronto area (Environment and Climate Change Canada, 2019). Both PC and GAC are expensive soil amendments, and if used, should be studied at a large scale before implementation to allow for optimization of dosages. At the higher GAC/PC concentrations, significant bulking will occur, which is counter productive to the PLFP, given the significant net excavation volume required to create the river valley. This constraint may not apply to other projects in the GTA with either a net zero or positive fill requirement.

Surfactant and Oxidant Treatment (EthicalChem)

Bench Scale Treatment Objectives

The EthicalChem proprietary processes known as SEPR™ (Surfactant Enhanced Product Recovery), and S-ISCO® (Surfactant enhanced In-Situ Chemical Oxidation) are innovative green chemistry solutions for the remediation of NAPL, creosote, and heavy-end hydrocarbon contamination (ibid). The key objective of these combined treatment technologies is the permanent chemical treatment for soil and non-aqueous phase liquid (NAPL) contamination. The surfactant enables desorption, which increases NAPL mobility, and facilitates contaminant mass removal by the oxidant (EthicalChem, 2017).

Methodology

The bench scale testing process for these technologies included the following steps:

1. Untreated samples were homogenized and submitted to a laboratory for analysis of hydrocarbons, VOCs, SVOCs, and PAHs. In-house analysis with a Sitelab fluorescence spectrophotometer was also conducted because the surfactants used in the SEPR™ process can interfere with the laboratory testing of hydrocarbons.

2. Surfactant screening tests were completed on NAPL collected from the study area to determine the most effective blend for the SEPR™ process to solubilize the NAPL. Four blends were considered based on previous work by EthicalChem.

3. Surfactant screening tests were completed on soil samples from the site to determine the most effective surfactant blend to desorb NAPL from the soil.

4. Column leaching tests on spiked (30 grams of site NAPL added) and non-spiked sets of samples of site soils with the following treatments:

    a. Deionized (DI) water flush control column
    b. SEPR™ column
    c. Sequenced SEPR™ and S-ISCO® column

    All the columns were set up vertically, with a flow rate of about 0.5 ml/min. The SEPR™ columns were treated with 25 g/l of VeruSOL-3 surfactant supplemented with 1% hydrogen peroxide for seven days. The sequenced SEPR™ and S-ISCO® columns were treated in the same manner as the SEPR™ columns, followed by a 21-day treatment with 100 g/L sodium persulfate.

5. The soil from each of the columns was homogenized and submitted for laboratory analysis for comparison to the untreated samples.

Effectiveness

The untreated samples had concentrations of 7,000-10,000 mg/kg TPH, and 16,000 to 18,000 mg/kg PAHs. VOCs and SVOCs (excluding PAHs) were below the laboratory detection limits. The on-site TPH testing revealed similar results, confirming that the Sitelab fluorescence spectrophotometer is adequate for field verification.

Two of the surfactants (AFX-74 and MSX-6) produced unstable emulsions when mixed with NAPL samples from the subject site. In addition, the AFX-74 surfactant did not fully emulsify the NAPL. Therefore, these two options were not tested further. The VeruSOL-3 and VersSOL-10 surfactants, however, created stable emulsions, with no residual NAPL. The subsequent surfactant screening tests on soil revealed that the VeruSOL-3 surfactant was more effective at desorbing and emulsifying NAPL and was therefore selected as the surfactant for the column tests.

The column tests are summarized in **Table 2**. The most favourable results were recognized when SEPR™ and S-ISCO® were performed sequentially, especially for the spiked samples, where greater than 99% contaminant reduction was achieved.

Table 2: Summary of Column Test Results, SEPR™ and S-ISCO®

Spiked/ Non-Spiked	Sample	Total PAHs (mg/kg)	PAH Reduction	Total VOCs (mg/kg)	VOC Reduction	TPH (Sitelab) (mg/kg)	% TPH Reduction
Non-Spiked	Untreated	17,152	n/a			9,057	n/a
Non-Spiked	DI Flush	15,453	10%			8,736	4%
Non-Spiked	Post SEPR	1799	90%			2,443	73%
Non-Spiked	Post SEPR/SISCO	923	95%			675	93%
Spiked	Untreated	1,299,700	n/a	99,400	n/a	17,581	n/a
Spiked	DI Flush	1,102,920	15%	100,000	-1%	13,997	20%
Spiked	Post SEPR	529,100	59%	58,400	41%	5,231	70%
Spiked	Post SEPR/SISCO	4,287	>99%	1917	98%	186	99%

Potential Constraints

On its own, SEPR™ achieved only 73-90% contaminant reduction, and produced a significant volume of leachate that would then require further treatment. Combining SEPR™ and S-ISCO® achieved higher levels of contaminant reduction (93% to greater than 99%), with oxidative destruction of contaminants, which would reduce further treatment requirements of the leachate. These technologies have significant promise for the in-situ treatment of soil highly impacted with PAHs, VOCs, and TPH. Overall costs may be prohibitive for less impacted soils, given the requirements for leachate treatment.

STAR (Geosyntec Consultants International, Inc.)

Technology Summary

Geosyntec Consultants International Inc. completed the bench scale testing for this technology. STAR (Self-sustaining smouldering combustion Treatment for Active Remediation in-situ) has been completed at bench, pilot and full-scale at sites with similar contaminant profiles as found at the Toronto Portlands (Geosyntec, 2017a).

Smouldering is a flameless form of combustion where the contaminants in the soil are the fuel for chemical reactions that occur in an oxidizing environment (Geosyntec, 2017a). STAR is initiated by electrical energy applied for a short period of time in wells installed into the impacted soil horizon(s). It requires the input of air into the soil to provide the required oxidizing environment. Once smouldering combustion has been initiated, it is self-sustaining, if there are sufficient fuel and oxygen in the subsurface. The smouldering front propagates at a rate of 1-2 m per day, under ideal conditions (ibid). This in-situ technology is used where source destruction is required, and excavation is neither feasible nor desired.

Bench Scale Treatment Objectives

The key objectives of the bench scale testing program were to confirm that the site soils can support self-sustaining smouldering combustion and identify off-gases that may require treatment during pilot-scale testing.

Methodology

At the bench scale, three samples were selected to representing shallow, intermediate, and deep soils at the site. A portion of each sample was submitted to an off-site laboratory to confirm pre-treatment contaminant concentrations, A portion of each remaining sample was placed in a 16 cm diameter steel tube and ignited with a convection ignition source that injected air at a rate of 5 cm/s (ibid). For the shallow soil, combustion was initiated at an air injection temperature of 450°C, and self-sustaining combustion was detected via thermocouples in the sample tube. A peak temperature of 597°C was observed, with a propagation velocity of 0.28 cm/min.

For the intermediate depth soil sample, combustion occurred at an air inlet temperature of 400°C, with self-sustaining smouldering behavior. However, likely because of heterogeneities in the sample, ignition happened in multiple places in the tube simultaneously. A peak temperature of 1260°C was attained but propagation velocity could not be determined because of multiple ignition points.

No combustion happened in the sample representative of deep soil conditions at the site, since it did not contain sufficient concentrations of contaminants to ignite. This was confirmed by the off-site analytical testing, which found non-detectable concentrations of TPH, PAHs, and VOCs.

Effectiveness

The STAR process was very effective, reducing the TPH (C6-C50) from 1500 mg/kg in the shallow soil sample to non-detectable levels. Similarly, for VOCs and PAHs, non-detectable levels were attained, except for 0.01 mg/kg of benzene. Metal concentrations were not affected, since they are not combustible. Similar results were attained for the intermediate depth soil sample, with initial TPH (C6-C50) of 11,500 mg/kg and post-treatment concentrations below the detection limits. VOCs and PAHs were low initially, and non-detectable after treatment. As mentioned above, the deep soil sample did not undergo combustion, and therefore was not tested post-treatment.

Concentrations of volatile organic compounds in the effluent stream were negligible, with low detections of acetone (<9 ppm), methyl ethyl ketone (<2 ppm), propylene (< 25 ppm), and 1,3 butadiene (< 3 ppm). Therefore, off-gas treatment at the pilot stage should not be an issue.

Potential Constraints

The main constraint for this treatment technology is in-situ soil heterogeneity, which can hamper the combustion reactions either through channelizing air flow, or the creation of isolated pockets of impacts, which may or may not be ignited during treatment. For the PLFP a second constraint is the requirement for a soil cap to contain the thermal reaction and the air flow. Usually, this technology is employed at depth, and lack of cover is not a concern. However, because of scheduling constraints for the Portlands remediation, early removal of the shallow soils precludes implementation of this technology for this project.

STARx (Geosyntec Consultants International, Inc.)

Technology Summary

This technology is essentially identical to the STAR technology described above, with the exception that the soil is excavated and placed in a treatment vessel. The excavation and repacking processes can help overcome issues with respect to heterogeneity, and address issues with respect to removal of the soil cap.

Bench Scale Treatment Objectives

The key objectives of the bench scale testing program were to confirm that the site soils can support self-sustaining smouldering combustion and identify off-gases what may require treatment during pilot-scale testing.

Methodology

The bench scale testing for this technology is described above with respect to the STAR Technology, since the technologies are identical at the bench scale.

Effectiveness

The STAR process was very effective, reducing the TPH (C6-C50) from 1500 mg/kg in the shallow soil sample to non-detectable levels (Geosyntec, 2017b). Similarly, for VOCs and PAHs, non-detectable levels were attained, except for 0.01 mg/kg of benzene. Metal concentrations were not affected, since they are not combustible. Similar results were attained for the intermediate depth soil sample, with initial TPH (C6-C50) of 11,500 mg/kg and post-treatment concentrations below the detection limits. VOCs and PAHs were low initially, and non-detectable after treatment. As mentioned above, the deep soil sample did not undergo combustion, and therefore was not tested post-treatment. Energy inputs are modest, since most of the energy is utilized to initiate combustion, with lesser amounts required for the blowers to maintain air flow.

Concentrations of volatile organic compounds in the effluent stream were negligible, with low detections of acetone (<9 ppm), methyl ethyl ketone (<2 ppm), propylene (< 25 ppm), and 1,3 butadiene (< 3 ppm). Therefore, off-gas treatment at the pilot stage should not be an issue.

Potential Constraints

The primary constraint for this technology is the limited throughput during full-scale implementation, which could affect the construction schedule for the overall PLFP.

Biodegradation (WSP Inc.)

Technology Summary

This remedial technology involves the stimulation of naturally occurring bacteria to accelerate biodegradation of organic contaminants such as petroleum hydrocarbons (WSP, 2017b). Bench scale testing is critical to ensure that the necessary bacteria are present, and there are correct substrates and nutrient and oxygen levels for optimal performance. The bench scale testing can also inform timelines for larger scale remediation.

Bench Scale Treatment Objectives

The bench scale testing program had four key objectives:

1. Evaluate the effects of bulking agents (inert sand or straw)
2. Assess the effects of supplying oxygen via mechanical soil mixing or from anthropogenic fertilizers.
3. Compare hydrocarbon degradation rates between nutrients sourced from natural materials and inorganic chemical sources.
4. Assess hydrocarbon degradation rates with different commercial amendments (i.e., Matsphere, MAT 540, Micro-Blaze, and Emergency Spill Control, BOS 200).

Methodology

Baseline chemical testing was conducted through an off-site laboratory to assess contaminant levels as well as calculate the carbon:nitrogen:phosphorous (CNP) ratio to inform nutrient supplementation requirements (WSP. 2-17b). Supplemental sampling was conducted to assess the presence of hydrocarbon-utilizing bacteria (HUB).

Eleven batch reactors were established in metal pans with foil covers, each containing about 5 kg of site soil. The CNP ratios were adjusted to CNP ratio of 100:10:1 (a typical value for efficient biodegration), a moisture content in the range of 45-80% and neutral pH. The temperatures were kept at about 20°C during the testing. The reactors included an inert control reactor with no soil amendments, a standard treatment reactor, and a series of reactors amended with a variety of nutrient sources, microbial growth substrates, and microbial cultures.

The reactors were operated for four weeks, and then samples of the soil were collected and submitted for off-site laboratory analysis.

Effectiveness

The test results are summarized in **Table 3**. The HUB concentrations decreased substantially for some of the reactors. This suggests that longer term remediation might be less successful under those conditions. In particular, the addition of natural nutrients (blood meal) and BOS-200 amendment resulted in not only significant reduction of hydrocarbons during the test, but also much higher HUB levels, which suggests that hydrocarbon concentrations will decline further over time (WSP, 2017b).

Over the four-week bench scale testing period, the degree of hydrocarbon degradation was similar for many of the reactors. In general, significant reduction in the BTEX, F1, and F2 fractions occurred in all reactors, except for the BOS-200. It is possible that this one anomalous result was due to the presence of NAPL in the sample. The changes in the

F3 and F4 hydrocarbon fractions were much more inconsistent, which could have been the result of the heterogeneity of the samples and/or the presence of NAPL in one or more of the samples.

The lack of complete reactions is likely due, in part, to the short timeframe for the bench scale testing. However, the natural nutrient and total enhancement reactors showed improvement over the other technologies. Both reactors were treated with blood meal, which supplies not only major nutrients such as nitrogen and phosphorous, but also potentially limiting micronutrients. It should also be noted that some of the advanced technologies provided significantly better performance than routine aerobic bioremediation for specific hydrocarbon fractions. For full details regarding the chemical results, the reader is directed to the complete report issued by WSP Canada Inc.

Table 3: Summary of Bioreactor Test Results

Reactor	Change in TPH F1 (%)	Change in TPH F1 (BTEX- %)	Change in TPH F2 (%)	Change in TPH F3 (%)	Change in TPH F4 (%)	Change in TPH (F1-F4) (%)	Change in HUB (%)
Inert Control	-69	-69	-38	+28	+61	-17	-15
Oxygen/ Moisture Control	-98	-98	-40	+6	+27	-30	+50
Standard Treatment	-89	-89	-40	-7	+17	-33	-99
No bulking	-83	-83	-36	-18	+1	-34	-99
Inert bulking	-90	-90	-33	-18	-24	-35	-98
Straw bulking	-92	-92	-42	-15	+2	-38	-99
Natural Nutrients	-92	-92	-47	-13	+15	-39	+1873
Matsphere	-87	-87	-27	-12	+12	-28	-84
Microblaze	-85	-85	-20	-5	+21	-21	-98
BOS-200	+159	+158	-2	-45	-100	-1	+468
Total Enhancement	-93	-93	-68	-21	+16	-53	+80

Potential Constraints

The increase in hydrocarbon fractions for some samples suggests that the distribution of hydrocarbons was not consistent across all the reactors. Although this hampers a thorough assessment of the results, some of the technologies performed better than others. The most significant constraints for this technology are time and temperature. Bacterial processes proceed much faster at temperatures greater than 20°C, and the PLFP project must proceed through all four seasons. Even with innovative enhancements, remediation of site soils to the MECP generic criteria is estimated take about 78-134 days. These timelines represent a significant challenge for implementation of this technology on the PLFP, but this timing issue may not be as much of a concern on other remedial projects with more flexible timelines.

In-situ Soil Stabilization via Cutter Soil Mixing (Golder Associates)

Technology Summary

In-situ Soil Stabilization (ISS) is a well-documented technology that utilizes Portland Cement (PC), or to other cementitious materials (i.e., fly-ash, kiln dust, slag) to increase the cohesive strength of native soils and decrease the leachability of contaminants from the stabilized material (Golder, 2017).

The bench scale testing was limited to investigating potential soil amendments and obtaining data to support possible pilot scale testing.

Bench Scale Treatment Objectives

The key objectives of the bench scale testing were to:

1. Identify potential soil amendments
2. Assess selected amended soil mixes with respect to increasing the compressive strength of the site soils and decreasing the hydraulic conductivity, and vapour release from the same soils.
3. Provide supporting data to develop an on-site pilot scale testing program.

Methodology

The first step in the bench scale test involved the screening of potential soil amendments. Key elements that were considered were demonstrated effectiveness on other soil stabilization projects, the ability to reduce the native soil's hydraulic conductivity, use of existing waste products (i.e., flyash, kiln dust, slag), and cost and availability of materials.

Pre-treatment analytical testing was conducted by an independent laboratory on a bulk sample (880 kg) of soil from the site. This testing included PHCs, PAHs, metals, and leachate analysis using the standard TCLP (Toxicity Characteristic Leachate Procedure) as well as leachate tests with simulated rainwater (diluted sulphuric and nitric acids with pH of 4.2, typical of rainwater in the Toronto area) and groundwater (bottled spring water from Feversham, Ontario with pH of 7.7).

Once the preferred amendments were identified, six mix designs were selected for testing, as follows:

- Mix Design 1: 12% Portland-Limestone cement (GUL);
- Mix Design 2: 8% General Use cement (GU);
- Mix Design 3: 6% GUL cement and 3% bentonite;
- Mix Design 4: 5% GUL cement and 3% bentonite;
- Mix Design 5: 4% GU cement, 4% flyash, and 1% calcium peroxide;
- Mix Design 6: 2% GU cement and 4% furnace slag.

Note that all mixes were based on dry weights of both soil and amendments. The soils and amendments were mixed in a concrete mixer along with enough tap water to saturate the sample. Separate amended soil cylinders of various sizes were cast using the amended mixtures and cured for specific times in temperature-controlled curing tank. These cylinders were then tested for hydraulic conductivity, compressive strength, and bulk and leachate chemistry. The chemistry results were compared to the soil, groundwater and sediment standards for use under Part XV.1 of the Environmental Protection Act (MOECC, 2011), as well as the leachate quality criteria under O.Reg. 347 (Golder, 2017).

Effectiveness

The groundwater leachate tests for metals, inorganics, PAHs, and VOCs met both the O. Reg. 153/04 Table 3 standards (shallow soils, non-potable groundwater condition) as well as most of the Table 9 standards (within 30 m of a waterbody, non-potable groundwater condition) for all parameters tested for all six mix designs.

The chemical testing indicated that mixes SS-1, SS-2, and SS-6 provided effective chemical stabilization for the bulk soil samples obtained from the site (Golder, 2017). The vapour test results, as summarized in **Table 4**, confirm that all six mixes significantly reduced organic vapour releases and eliminated combustible gas releases. This suggests that this technology would be very effective in reducing vapour intrusion risks for both utility workers and residents living in the future Villiers Island community.

The geotechnical test results, as summarized in **Table 4**, confirm that the soil amendments reduced the hydraulic conductivity of the site soils by a factor of 1-2 orders of magnitude to 10^{-8} m/s or less. Significant strength improvements were noted as well, particularly for mixes SS-1, SS-2, and SS-6. Furnace slag appears to enhance strength, since mix SS-6 contained only 6% total amendments and yet met the strength target of 1000 kPa. This would be considered a “greener” product in that only 2% GU cement was required, with 4% furnace slag (a by-product that otherwise would be a waste). Overall, these results suggest that in-situ soil stabilization could facilitate excavation of the river valley through cohesionless soils and the resulting soil mass will be a barrier to both vapour transmission as well as groundwater flow.

Table 4: Summary of Geotechnical Assessments of Six Mix Designs

	Vapours				Compressive Strength				Hydraulic Conductivity	
	Initial		Amended							
Mix ID	C.V. (ppm)	O.V. (ppm)	C.V. (ppm)	O.V. (ppm)	Cure Time 1 (days)	UCS (kPa)	Cure Time 2 (days)	UCS (kPa)	Initial (m/s)	Amended (m/s)
SS-1	70	70	0	7	27	2750	41	3070	3.1 E-7	2.0 E-10
SS-2	10	10	0	11	24	760	38	1000	2.8 E-7	1.1 E-9
SS-3	45	45	0	7	23	180	37	260	7.4 E-7	3.1 E-9
SS-4	70	70	0	8	21	160	35	230	2.3 E-7	6.0 E-9
SS-5	5	5	0	15	16	160	30	250	4.7 E-7	1.2 E-8
SS-6	195	195	0	9	15	140	29	1010	1.4 E-7	7.3 E-9

Notes:
C.V. - Combustible Vapours (initial/amended)
O.V. - Organic Vapours (as isobutylene, initial/amended)
UCS - Unconfined Compressive Strength
ppm - parts per million
kPa - kilopascals

Potential Constraints

Although the leachate testing of the stabilized soils generally met the criteria in O. Reg. 153/04 Table 3, some of the PAH and VOC parameters exceeded the criteria or had higher detection limits that the respective criteria. Therefore, further testing would be required to confirm that the stabilized soils will function as a form of long-term physical fixation.

Phys/Chem/Bio (Law Environmental Ltd., CleanEarth Technologies Ltd.)

Technology Summary

PhysChemBio is a proprietary technology developed by Law Environmental Ltd. (LAW) that involves a combination of physical, chemical, and biological treatment processes. For the bench scale test, three processes were evaluated: particle size separation, density separation, and chemical separation.

The LAW treatment process can also be utilized to dewater sediments, which could be beneficial for excavations below the water table, a significant issue for the PLFP (LAW, 2017).

Bench Scale Treatment Objectives

The primary objectives of the bench scale tests were to confirm the overall effectiveness of this treatment technology and to optimize the treatment sequence.

Methodology

The first step in the bench scale testing program was the completion of grain size testing of the nine soil/sediment samples from the site that were supplied to LAW by Waterfront Toronto. Independent laboratory testing of PHCs, PAHs, and selected metals was conducted on the samples to establish the pre-treatment baseline.

The first soil/sediment treatment simulation involved wet sieving of the samples as a form of physical particle size separation. The second simulation utilized a density separation technology, while the third simulation involved variations in wash time, wash water/soil ratios, rinse water/wash water ratios, and wash water chemical additives. Because of the proprietary nature of the processes, specifics for the additives are not available. Note that the final step in the PhysChemBio treatment (Bioslurry) was not completed as part of the bench scale assessment.

For the sediment dewatering tests, pre-treatment testing for PHCs and PAHs was conducted on five groundwater samples from the site by an independent laboratory. These five samples were then processed by a combination of chemical precipitation, flocculation, and filtration (multi-media zeolite/activated carbon).

Effectiveness

Based on the grain size testing, about 50% of the impacted soil provided for this project is fine grained. The dewatering testing confirmed that LAW's process can treat dewatering effluent from the site at a rate of up to 5670 litres per minute (L/min), with non-detectable concentrations of PHCs and PAHs in the final effluent.

Potential Constraints

The high concentration of fine-grained soil suggests that the process will generate a significant volume of impacted fine sediments (about 50%). Further testing would be required to confirm the efficacy of the hydrocarbon remediation process for these excess materials (i.e., bioslurry).

ET-DSP™ (McMillan-McGee)

Technology Summary

The Electro-Thermal Dynamic Stripping Process (ET-DSP™) utilizes electrical energy to heat soil in-situ and thereby liberate organic contaminants (McMillan-McGee, 2017). These volatilized contaminants are then removed via vapour extraction. The extraction rate is dependent on the volatility of the contaminants as well as the electrical properties of the in-situ soils.

Bench Scale Treatment Objectives

The objectives of the bench scale testing were to:

1. Quantify the soil resistivity to determine the site-specific equipment and voltage requirements, and
2. Assess the recovery of the technology on a representative soil sample from the site.

Methodology

Two, 25-L pails of soil were obtained from the site. The soil was homogenized, and baseline chemistry samples were prepared and submitted to an external laboratory for testing of PHCs. Metals were not tested, since this technology does not address inorganic contaminants.

The ideal soil resistivity for this technology is between 5 and 400 Ω·m under ambient conditions (ibid). Therefore, the first component of the bench scale test was a Static Resistivity Test. This process involved placement of a soil sample in a test container. Two copper electrodes with the same cross-sectional area as the soil sample were then placed on opposite sides of the container and connected to a power supply in series with an ammeter. A voltmeter was connected across the electrodes in parallel.

A second step, a Dynamic Resistivity Test, was then undertaken to assess the changes in resistivity under increasing temperatures, since the process heats the soil, and resistivity drops as the soil temperature increases. For this test, a second soil sample was placed in the test container with the same electrodes. Water was then added until the sample was saturated. A temperature sensor was then inserted in the centre of the container to record temperature once a minute during the test. The test was terminated once the heating rate began to decrease.

Once the resistivity testing was complete, a miniature version of a field-scale system was created, including the electrodes, temperature sensor, water injector, and an extraction well. The electrodes were powered at a voltage that attained the target temperature determined through the resistivity testing. Once that temperature was achieved, the water injection and vacuum systems were activated, and the rates adjusted to maintain the target soil temperature. The test cell was monitored via a photoionization detector, and the test was terminated once the results indicated that the reactions were complete (36 days). During the test, the following parameters were continuously monitored:

1. Applied Voltage/current/power usage and density;
2. Soil temperature;
3. Vapour discharge flow rate and pressure;
4. Vapour carbon inlet pressure;
5. Vacuum on vapour extraction "well"; and
6. Water injection flow rate.

Effectiveness

The static resistivity of the soil was 20.3 Ω·m, which is within the ideal range for this technology. During the dynamic test, the soil resistivity dropped to about 9 Ω·m, which is at the low end of the ideal range of 5 to 400 Ω·m.

The bench scale test experienced an interruption of about 1% of the total test period when the injection pump lost prime, but this disruption is not believed to have affected the test outcome. The chemical results are summarized in **Table 6**, and overall demonstrated a reduction in extractable PHCs of 47-60% and a reduction in volatiles of 54-98%. The concentrations of ethylbenzene, xylenes, and the F1 PHC fraction were reduced to values below the laboratory detection limits, and the lowest removal rates (47%) were associated with the F3 and F4 PHC fractions. Overall, the bench scale test confirmed that the technology can be very effective at remediating lighter hydrocarbons (F1 and F2) but will be less effective with the heavier hydrocarbon fractions (F3 and F4).

Table 6: Summary of ET-DSP™ Test Results

Parameter	MECP Table 3[1]	Initial Concentration	Final Concentration	% Reduction
Benzene	0.32	0.078	0.016	80%
Toluene	9.5	0.120	0.055	54%
Ethylbenzene	68	0.038	<0.01	>74%
M&P -Xylenes	nc	0.220	<0.04	>82%
O-Xylene	nc	0.078	<0.02	>74%
Xylenes (total)	26	0.298	<0.04	>87%
PHC F1 (BTEX)	55	**520**	<10	>98%
PHC F1	55	**520**	<10	>98%
PHC F2	230	**4,800**	**1,900**	60%
PHC F3	1,700	**6,800**	**3,600**	47%
PHC F4	3,300	1400	740	47%

Notes:
All values in mg/kg (ppm)
[1]Table 3 = Soil, ground water and sediment standards for use under Part XV.1 of the Environmental Protection Act, Generic Site Condition Standards for Use within 30 m of a Water Body in a Non-Potable Ground Water Condition. Bolded values exceed criterion.
nc - no criterion

Potential Constraints

The low dynamic resistivity results indicate that an in-situ pilot test will require full electrical and hydraulic control for the duration of the process. The water circulation system must be capable of continuous water injection at every electrode to maintain the resistivity within the optimal range. The bench scale test did not include any water extraction. A field scale pilot test should include active liquid recovery, which is expected to enhance the overall remedial success, particularly for the heavier hydrocarbons. Overall, the bench scale test achieved significant reductions of PHCs, particularly for the lighter fractions. Remediation of other organic contaminants (i.e., PAHs, VOCs) was not assessed, but given the lower extraction of heavier hydrocarbons, the degree of PAH remediation with this technology is expected to be low. Overall, the bench scale test confirm that this technology is better suited to areas impacted with PHCs in the F1 to F2 range.

Implementation of this technology requires continuous monitoring of the input parameters (i.e., power, water, vacuum), and the process will generate both liquid and vapour that will require treatment. These treatments will increase the overall cost of implementing this technology.

Segregation and Soil Washing (WSP Inc. and Vertex Environmental Inc.)

Technology Summary

Segregation involves the dry separation of soil fractions by screening, while washing enhances the separation process utilizing water (WSP, 2017c). Even though PHCs have low solubility, washing can be effective at removing them from soil, particularly with the use of surfactants to enhance recovery (although not tested as part of this program). Water usage can be minimized through recycling of the process water.

Bench Scale Treatment Objectives

The bench scale testing focused on:

1. Determination of the effectiveness of soil segregation and soil washing to remove PHCs from soil;
2. Assessment of the potential for treated soil to produce LNAPL or sheen in the future; and
3. Confirmation of the chemical quality of the treated soil products.

Methodology

Two bulk soil samples were obtained from the site and a fraction was submitted for independent laboratory analysis of moisture content, PHCs, and SPLP (Synthetic Precipitation Leachate Procedure) tests for PHCs.

The first bench scale testing involved physical dry screening of the bulk soil samples from the site into four fractions: > 12.7 mm, 6.4-12.7 mm, 2 mm-6.4 mm, and < 2mm. Each fraction was assessed with respect to chemical quality, quantity, and ease of separation.

The second stage of testing involved both physical and hydraulic separation of the bulk soil samples to assess the treatment efficacy. The tests included low pressure/high flow (LPHF), high pressure/low flow (HPLF), and multiple washes at moderate pressure/moderate flow (MW).

After each test, the various soil fractions were subjected to saturated liberation testing and laboratory analysis to assess the potential for the treated soil to release PHCs, NAPL, or sheen.

Effectiveness

The results are qualitatively summarized in **Table 7**. The dry screening did not result in effective partitioning because of the presence of soil clumps. Overall, the best concentration of contaminants in the fines was achieved by two cycles of washing with moderate pressure and moderate flow. The use of high pressure washing resulted in better breakdown of the soil clumps, but a single wash still resulted in PHCs present in the sediments.

Table 7: Qualitative Summary of Segregation/Soil Washing Bench Scale Test Results

Methodology	BTEX/PHC Fractionation	Comment
Dry Screening	70-80% on the coarse screen (>12.7 mm)	PHCs associated with soil clumps, not effective partitioning.
LPHF	More than 75% in the fines (<2 mm)	Some partitioning, but incomplete breakup of soil clumps.
HPLF	About 95% in the fines and sediments (<6.4mm)	Significant partitioning to the fine grained soil fraction.
MW, 1 cycle	60% in the fines (< 2mm)	Some partitioning, but incomplete
MW, 2 cycles	93% in the fines (<2 mm)	Excellent partitioning into the fine grained soil fraction

Notes:
LPHF: Low Pressure/High Flow: Washing of soil with high volumes of water at low pressure.
HPLF: High Pressure/Low Flow: Washing of soil with low volumes of water at high pressure.
MW: Multiple wash cycles at moderate pressure with moderate flow.

Potential Constraints

The presence of clumps of cohesive silt/clay prevented effective dry segregation. High pressure washing broke up some of the clumps but was less effective than multiple washes at lower pressure. Multiple wash cycles will produce more wastewater. This could be mitigated by recycling the wash water. Because fines (<2 mm) comprised 60-70% of the site soils tested, a significant quantity of these sediments would be left over, either requiring additional treatment or adding to the waste stream. This same challenge was noted in previous soil washing tests in the Port Lands area (pers. comm, Waterfront Toronto). Enhancements of the washing process may be recognized using surfactants and flocculants.

Technology Review

Proceeding to Pilot Phase

The bench scale test results for all the technologies were reviewed by a group of stakeholders from the PLFP including Waterfront Toronto, the City of Toronto, and Toronto and Region Conservation Authority. The review process included considerations of the bench scale treatment effectiveness, cost of pilot scale testing, potential remedial timelines, and overall likelihood of implementation at the site scale. As mentioned previously, a decision to not proceed with pilot testing of a particular technology does not indicate failure of the bench scale testing, or the review committee’s lack of confidence in the process(es). Technologies that did not proceed to the pilot phase may be appropriate for other brownfield redevelopment projects not subject to the site-specific constraints of the PLFP.

In-situ Soil Stabilization (Golder Associates/Jacobs Engineering Group)

Technology Summary

As discussed above, in-situ Soil Stabilization (ISS) is a well-documented technology that utilizes Portland Cement (PC), or to other cementitious materials (i.e., fly-ash, kiln dust, slag) to increase the cohesive strength of native soils and decrease the leachability of contaminants from the stabilized material (Jacobs, 2019).

Following the completion of the 10 bench-scale tests, Golder's in-situ soil stabilization technology was selected for further bench-scale testing in collaboration with Jacobs.

ISS was a remedial option considered for a 5-6 hectare portion of the Port Lands Flood Protection project for both structural improvement and environmental protection. The first phase of this treatability study focused on geotechnical assessments of various mix designs. The second phase was intended to examine long-term leachability from selected mixes that met the geotechnical requirements but was not conducted because of a change in the overall remedial action program for the site (ibid). This testing was required to refine the soil stabilization amendments that were originally considered by Golder in the bench scale testing described above.

Bench Scale Treatment Objectives

The key objectives of the bench scale testing were to:

1. Identify potential soil amendments and mix ratios to increase soil cohesiveness and prevent leaching of organic and inorganic contaminants.
2. Provide supporting data to develop an on-site pilot scale testing program.

Methodology

The first step in the bench scale test involved the screening of potential soil amendments. Key elements that were considered were demonstrated effectiveness on other soil stabilization projects, the ability to reduce the native soil's hydraulic conductivity, use of existing waste products (i.e., flyash, kiln dust, slag), and cost and availability of materials.

While the amendment screening was being completed, baseline testing of water, NAPL, and soil from the site was performed for both geotechnical properties (i.e., strength, durability, permeability) as well as chemistry (PHCs, PAHs, VOCs, and inorganics). Based on the chemical test results, two types of site soils were selected for testing – one representative of the fine sand, and the other representing a mixture of peat and fine sand. These samples were then spiked with NAPL from the site to attain a target baseline PHC concentration of 8,000 mg/kg.

Fifteen mix designs were tested, with varying concentrations of Portland Cement (PC) and NewCem (NC) slag cement and 0.5 % bentonite. At least 22, 5 cm by 10 cm cylinders were created for each mix design to allow for geotechnical and environmental testing after curing for 7 and 28 days. Additional 10 cm by 20 cm cylinders were created for some of the mixes to allow for strength testing of 56-day cures. Mix water for the sample preparation was obtained from a test pit on the subject property to ensure that the bench scale testing would be representative of site conditions. Curing was completed in a 23^{o}C constant temperature water bath.

An additional test was conducted on the NAPL from the site to assess potential porewater chemistry at 20% NAPL saturation. For this test, 400 g of NAPL were added to 1600 g of de-ionized water and rotated in a zero-headspace reactor for 16 hours at 50 rotations per hour. The sample was then left undisturbed for 7 days, and the aqueous phase was then analyzed for PHCs, PAHs, and VOCs (Golder, 2017).

Effectiveness

The geotechnical test results are summarized in **Table 5**. The results confirm the conclusions from the previous bench scale testing by Golder that the cementitious amendments reduce the hydraulic conductivity of the site soils to 10^{-8} m/s, or lower, and significantly enhance the compressive strength. The reduced hydraulic conductivity will effectively retard contaminant transport, and will also impede NAPL migration, since the solidification process reduces the pore throat diameter to an estimated 0.002 mm. Golder's calculations predict a NAPL head of 10 m would be required to mobilize diesel-range hydrocarbons through the stabilized soil.

Table 5: Summary of Geotechnical Assessments of Various Mix Designs

Mix ID	Ratio Sand:Peat	PC/NC Dosage (wt %)	28-Day BTS (kPa)	7-Day UCS (kPa)	28-Day UCS (kPa)	56-Day UCS (kPa)	28-Day Durability (% Loss)	28-Day HC (m/s)
H1	100:0	6	42.6	193	433	715	DNF (4)	6.0 E-9
H2	100:0	8	118	294	717	1182	DNF (9)	4.0 E-9
H3	100:0	10	205	555	1477	2416	7.0	3.2 E-10
H4	100:0	12	220	568	1548	2684	8.9	1.0 E-9
H5	100:0	14	338	1053	2466	4306	0.2	5.8 E-11
H6	75:25	8	17.8	115	143	175	DNF (2)	1.1 E-8
H7	75:25	10	33.8	131	219	310	DNF (2)	5.2 E-9
H8	75:25	12	52.5	174	360	577	DNF (4)	6.9 E-9
H9	75:25	14	64.1	190	440	714	DNF (5)	7.7 E-9
H10	75:25	16	94.5	256	571	957	DNF (6)	7.4 E-9
H11	75:25	15	99.8	281	702	1142	DNF (8)	2.2 E-9
H12	75:25	17.5	116	300	794	1398	DNF (8)	2.1 E-9
H13	75:25	20	196	535	1304	2285	DNF (9)	6.7 E-10
H14	75:25	22.5	216	598	1559	2729	DNF (10)	4.3 E-8
H15	75:25	25	287	769	1726	3397	3.8	3.74 E-10

Notes:

Sand:Peat is the ratio of sandy soil to peat in the mix. Both materials were obtained from the site.
All mixes were amended with 0.5 wt% dry bentonite powder
PC/NC Blend is 60% Portland Cement and 40% NewCem added dry to wet weight of soil
BTS – Brazilian Tensile Strength
UCS – Unconfined Compressive Strength
DNF – Did not finish targeted 12 cycles (cycles completed in brackets)

HC – Hydraulic Conductivity

Potential Constraints

Soil stabilization is a proven technology for physical fixation, strength improvement, and reduction of hydraulic conductivity. The potential issue for the PLFP is that the solidified mass may crack with changes in either the confining pressure or the upward groundwater pressure, especially given the size of the area involved and the presence of a dynamic river above. If cracks should develop in the stabilized soil mass, the preferential flow paths created could result in release of NAPL or dissolved phase contaminants into the river valley. The presence of peat and organic silts across the study area will also reduce the effectiveness of this soil stabilization process.

PILOT SCALE PROJECTS

Based on the evaluation process described above, Waterfront Toronto and its partners selected six technologies for further testing at the pilot scale. The overall purpose of this phase of the project was to identify the most innovative technologies with the greatest probability of success within the site-specific technical, schedule, and budget limitations of the PLFP.

Biological Soil Stabilization (Groundwater Technology BV)

Pilot Scale Objectives

The consortium led by Groundwater Technology undertook two pilot projects (Groundwater Technology, 2019). The first considered the urea-based soil improvement process (Microbially Induced Carbonate Precipitation via ureolysis, or MICP) assessed at the bench scale. The second tested a nitrate reduction technology (Microbially-Induced Desaturation and Precipitation via denitrification or MIDP). The objectives of both projects were to assess the feasibility of increasing soil strength via biological action.

Methodology

As with the bench scale testing, the first step in the process involved growing the bacterial cultures for injection. About 11.6 m^3 of the culture medium was generated and distributed amongst 16 storage containers for use in the pilot testing program.

Each of the two field studies involved the installation of three extraction wells in a line about 5 m apart. Six, 40 mm diameter injection wells were then installed around each of the extraction wells. For the MICP test, the soil amendments, including a ureolytic bacteria culture grown by Accuworx, urea, and calcium chloride were mixed on-site and then pumped into the injection wells. Groundwater was then withdrawn from the extraction wells and pumped into the injection wells over a period of five days. Each extraction well was considered as one “plot” with different concentrations of the urea/calcium chloride mixture added to each. The first plot received the full-strength mixture, with a targeted calcium carbonate concentration of 2.3%. The second was dosed with a 50% strength solution and a targeted calcium carbonate concentration 1.15%. For the third plot, a 25% solution was injected, with a targeted calcium carbonate concentration of 0.56%.

Over the injection period, the bacterial solution was injected first, followed by 14 m^3 of the urea/calcium chloride solution over the remaining four days; 4.1 m^3 into Plots 1 and 2, and 2.7 m^3 into Plot 3. Concentrations of calcium, ammonium, pH, and conductivity were measured in the three extraction wells and six monitoring wells during the pilot test to ensure target concentrations were reached and to allow for field adjustments.

For the MIDP pilot test, 12 batches of a 1:2 mixture of calcium acetate and calcium nitrate were injected into the subsurface. Partway through the injection process, micronutrients were added (magnesium sulphate, dipotassium phosphate, ferrous sulfate, and yeast extract) to ensure that microbial activity continued.

Changes in soil geotechnical properties were measured using cone penetrometer testing as well as seismic velocity measurements.

Effectiveness

The effectiveness of the MICP soil stabilization process was evaluated by nine seismic cone penetration tests to depths up to 10 m. Six of these tests were completed before the pilot test, while three were done four months after the stabilization was completed. The analysis of corrected cone resistance (q_t), and shear wave velocity (V_s) from the post-MICP stabilization did not identify any significant change in the geotechnical properties of the soil strata.

The effectiveness of the MIDP soil stabilization process was evaluated by nine seismic cone penetration tests (SCPT) to depths up to 10 m. Six of these tests were completed before the pilot test, while three were done four months after the stabilization was completed. The analysis of corrected cone resistance (q_t), and shear wave velocity (V_s) from the post-MIDP stabilization did not identify any significant change in the geotechnical properties of the soil strata. The lack of quantifiable geotechnical strength improvement is supported by the groundwater monitoring data, which confirmed that urea ureolysis did occur, but the reaction was not complete. Soil sampling confirmed that the site soils have naturally high calcium content; higher than that which would be created by the MIDP process.

Spatial seismic data were collected inside and outside the MICP and MIDP stabilization pilot test cells using a T-Rex mobile “shaker truck”. This included twelve direct push cross-hole seismic profiles and one non-linear shaking test. The shear wave results from this work were comparable to the SCPT data. The primary wave (V_p) velocity profiles showed an increase in seismic velocities (i.e., higher density) for the 100% treated MECP cell, and decreased velocities for the MIDP treated cell, likely from the presence of gas bubbles from the biological activity.

Overall, the soils present at the pilot sites contained generally higher clay content than would be preferred for these soil stabilization processes. The result was that the amendments were dispersed further in the permeable zones and dispersed unequally through the low permeability zones. This resulted in a larger treatment zone than anticipated, but with lower than expected strength improvement. There was some qualitative improvement observed in treated vs untreated test excavations, but definitive conclusions cannot be made from the excavations. This technology would likely be more effective in areas with more homogeneous soils with higher permeability (i.e., uniform sands).

Implementation Costs

No implementation costs were provided for this technology.

Block & Adsorb (WSP Canada Inc.)

Treatment Objectives

The primary objectives of the Block and Adsorb pilot test were to assess the effectiveness of granular activated carbon (GAC) and Portland Cement (PC) in the field-scale mitigation of hydrocarbon contamination (WSP, 2018b). Two different delivery methods were assessed - soil mixing and injection.

Methodology

Baseline soil and groundwater quality data were collected prior to implementing the Block and Adsorb pilot program. Three boreholes were advanced in the pilot test area, and field-screened for hydrocarbons. The most heavily impacted samples were submitted to an external laboratory for analysis of inorganics, petroleum hydrocarbons, PAHs, and leachate toxicity.

The bench scale test results were used in combination with the pre-remediation hydrocarbon concentrations to optimize the amounts of activated carbon and Portland Cement required. However, the injection technology is limited to a carbon concentration of about 3%, or about half the dose suggested from the bench scale testing program.

The pilot test utilized three plots – one control site, one for soil mixing, and one for injection. A monitoring well was installed in each plot to allow for the collection of groundwater data.

For the 3 m x 3 m soil mixing plot, 3750 kg of GAC was applied (target concentration of 8.3% by weight) to the soil surface, mixed with an excavator to a depth of 4 m. The following day, 1560 kg of PC was mixed in (target dosage of 3.5% by weight). The staged mixing approach allowed the GAC to adsorb some of the hydrocarbons and prevented the PC from blocking the pores of the GAC. During the mixing process, LNAPL was observed in the test plot.

For the 2.5 m x 2.5 m injection plot, powdered activated carbon (PAC) was used in place of GAC, because the coarser GAC material would not produce an injectable suspension. As with the soil mixing plot, the PAC was injected first, followed by the PC. Eight injection points were used to deliver 3900 L of PAC suspension (1255 kg) and 2400 L of PC slurry (1280 kg) to a depth of about 4.3 m. A thick PC slurry was used to ensure adequate stabilization of the saturated soils.

The groundwater conditions were monitored in the two amendment plots at intervals of 2, 4, and 8 weeks after treatment, including water levels, pH, and presence of LNAPL and/or hydrocarbon sheen. In addition, water quality samples were collected from the monitoring wells and single-well response tests were completed to assess changes in hydraulic conductivity. At the end of the evaluation period, each of the test plots was excavated to assess the soil structure and identify residual LNAPL, if present.

Effectiveness

The soil mixing test plot contained LNAPL prior to treatment, but no LNAPL or sheen was observed in the monitoring well following treatment for the duration of the testing (94 days post-mixing). For the injection test plot, LNAPL was present prior to treatment, but was not observed from the end of the injection process to 4 weeks after treatment. The LNAPL reappeared about 4 weeks and was still present at 8 weeks post-treatment. This suggests that the hydrocarbon concentration was too high for a single injection process, because of the maximum PAC concentration possible in an injectable suspension.

The groundwater chemistry results indicated that dissolved phase hydrocarbon reductions of 50-96% are possible for soil mixing and 90-94% for injection. However, neither approach had any significant effect on the dissolved phase PAH concentrations.

For both treated plots, the post-remediation excavations confirmed that the treated soil could be easily excavated with traditional equipment. As would be expected, the injection plot soils were much more heterogeneous, and less cohesive than in the soil mixing plot. In addition, some evidence of preferential pathways (i.e., discrete layers of PC) were observed in the injection test excavation. However, the soil in both plots exhibited much more cohesiveness than the untreated soils in the control plot.

The single well response tests suggest that the soil mixing reduced the hydraulic conductivity by about 53%, while the injection process reduced it by about 95%. The contractors suggest that the injection approach preferentially seals off the more permeable zones, while the soil mixing process produces a more consistent, but conductive soil mass.

Implementation Costs

The estimated full-scale treatment costs are estimated to be in the range of $90 to $250 per cubic metre of soil for soil mixing, and $120 to $375 per cubic metre of soil for the injection process. These cost estimates are inclusive of engineering fees, fieldwork, and disbursements, including confirmatory testing.

Surfactant and Oxidant Treatment (EthicalChem)

Treatment Objectives

The primary treatment objectives were to assess the effectiveness of sequential SEPR (Surfactant Enhanced Product Recovery) and S-ISCO (Surfactant enhanced In-Situ Chemical Oxidation) treatments to remediate petroleum hydrocarbons associated with the Portlands site and to establish the parameters (i.e., flow rates, injection pressures and well spacings, etc.) to execute this remedial strategy at full scale (EthicalChem, 2018).

Methodology

The SEPR and S-ISCO methodologies are described in more detail in the bench scale testing portion of this report. The pilot test location was chosen based on evidence of petroleum hydrocarbon contamination and the presence of LNAPL.

Once the pilot site was selected, five extraction/monitoring wells, one dedicated monitoring well and one injection well were installed at the site. Baseline soil and groundwater chemistry samples were collected and submitted to an independent laboratory for analysis of PHCs, VOCs, and PAHs. In addition, baseline measurements of water levels and field groundwater chemistry (pH, temperature, dissolved oxygen, conductivity, and oxidation reduction potential) were obtained.

Following mobilization of the required equipment to the site, SEPR injection and extraction were completed along with process and performance monitoring for a week. A mixture of 0.5-1% hydrogen peroxide and 25-30 g/l of proprietary E-Mulse 3 surfactant were injected into five direct push injection sites and gravity fed into the injection well. A total of 22,500 L of SEPR fluid was injected over a period of one week. Injection flow rates were 1.2 -26.7 liters per minute at injection pressures ranging from 15 to 120 psi. Groundwater was extracted from the extraction well network at least 2 hours following each injection, to allow for chemical interactions. The extracted water was removed from the site and taken to a licensed treatment facility. The week-long series of injections/extractions were followed by a second round of soil and groundwater sampling.

The S-ISCO injections followed the SEPR testing and included process and performance monitoring for 10 days. The chemicals used included 170 g/L sodium persulfate, 20-40 g/L sodium hydroxide, and 20g/L of E-Mulse 3 surfactant. In total, 6,900 kg of sodium persulfate, 1,304 kg of sodium hydroxide, and 825 L of E-Mulse 3 were injected into ten direct push injection sites and gravity fed into the injection well during the S-ISCO portion of the testing. The average injection rate 13.6 litres per minute at 30 to 120 psi. Overall, 42, 870 L of S-ISCO fluid was injected over the course of the pilot test.

A third round of soil and groundwater testing was then completed followed by confirmatory testing about 75 days after completion of the S-ISCO injections.

Effectiveness

The chemical test results demonstrated that the SEPR and S-ISCO processes removed NAPL from the site soils. The SEPR/S-ISCO process reduced the PHC concentrations by up to 36% in the subsurface in 10 of 13 sampled locations, while S-ISCO reduced the PHC concentrations by up to 74% in 7 of 11 sampled locations. The concentrations of PHCs in groundwater declined by up to 71% in three out of the five wells sampled. Because the treatment focused on a small soil volume within the pilot test area, some NAPL remained in the subsurface, and likely resulted in some "recontamination" of the groundwater. The laboratory analysis of the soil samples also indicated that a longer SEPR reaction time would have removed more NAPL and resulted in more complete oxidation of the PHCs. Overall, the pilot test indicated that these technologies can reduce PHC concentrations in both soil and water, but further refinement of oxidant dosage rates and volumes, the injection/extraction geometry, and reaction times would be required for full-scale implementation, particularly in areas with the highest PHC concentrations.

Implementation Costs

The potential costs for full-scale implantation were based on the following assumptions:

- Treatment of 10 grid cells, each with dimensions of 60 m x 60 m.
- Average initial PHC concentration of 5,000 µg/g.
- The treatment horizon is at a depth of 5-9 m below grade.
- Each cell would include 15 injection wells and up to 10 monitoring wells.

Based on the above assumptions, treatment costs were estimated to be in the range of $28-32 million (approximately $100/m^3), including both SEPR and S-ISCO processes as well as all costs associated with project planning, permitting, well installations and decommissioning, chemical sampling, site services, and reporting.

STAR (Savron and Geosyntec Consultants International, Inc.)

Treatment Objectives

As discussed in the bench scale section of this document, STAR (Self-sustaining Treatment for Active Remediation) is an in-situ thermal treatment technology for organic contaminants that relies on the principle of smouldering combustion. The specific objectives of the pilot test program were to assess the radius of influence of the smouldering combustion process, confirm the possible rates of contaminant mass destruction and combustion front propagation, and measure the production of hydrocarbon vapours (Savron and Geosyntec, 2018a).

Methodology

The 15 m x 15 m pilot test site was chosen to ensure that NAPL and elevated PHC concentrations were present. The base of the targeted treatment zone was 7.3 m below grade. Two ignition (IP-1 and IP-2) and four vapour extraction points were established in the treatment area. The second ignition point was established in case sustained combustion could not be initiated at the first point. Multi-level thermocouples were installed around the ignition points to monitor the smouldering reaction in three-dimensional space. An air injection system was also established, with a compressor and desiccant air dryer. The vapour collection system included a continuous emission monitoring system, flammability monitor, a condensate holding tank and activated carbon treatment of the vapours.

The pilot test was conducted from January 5 to 16, 2018. The vapour injection and extraction systems were operated for 24 hours prior to ignition at point IP-1. This ignition site was operational for 78 hours, but with limited evidence of self-sustaining combustion. The second ignition point, IP-2 was then operated for 85 hours. Early termination was required because of ice formation in the air injection lines and failure of the heater.

Effectiveness

Ignition was successful at IP-1 with a 9 kwh heater and air injection at 20 cubic feet per minute (cfm). However, the capture of combustion gases was limited because of the presence of a shallow, low permeability silt/clay unit. Effective remediation was limited to a sand layer which exhibited high air permeability. Limited remediation was measured in the overlying lower permeability silts and clays and in the deeper peat layer at the base of the ignition point.

Ignition at IP-2 also utilized a 9 kwh heater with air injection at 20 cfm. Ignition and smouldering combustion were initiated, but as with IP-1, preferential air flow and remediation occurred in the middle sand unit. Lower air flow and remediation occurred in the lower permeability silts and clays. Also, vapour capture was again limited by the overlying low permeability unit. Extreme cold temperatures resulted in ice blockage of the air injection lines, and subsequent overheating and failure of the ignition element. This issue could be addressed at full-scale implementation by ensuring all lines are fully insulated during winter operations.

Table 8: Summary of PHC Reductions around Ignition Point IP-1

Parameter	MECP Table 3[1]	Pre-STAR (IP-1)	Pre-STAR (TC-6)	Post-1	Post-2	Post-4	Post-8	Post-5
Distance from Pre-STAR Core		0	0	0.3	0.75	0.6	0.75	1.4
Depth (m)		5.33	5.33	5.64	5.64	5.64	5.64	5.33
PHC F1 (C6-C10)	55	**499**	**162**	<5.0	<5.0	<5.0	<5.0	<5.0
PHC F2 (C10-C16)	230	**1,410**	**2,810**	12	<10	<10	<10	14
PHC F3 (C16-C34)	1,700	**3,510**	**4,800**	60	63	<50	<50	<50
PHC F4 (C34-C50)	3,300	1,110	610	<50	<50	<50	<50	<50
Total PHCs (C6-C50)	nc	6,530	8,390	<72	<72	<72	<72	<72

Notes:
All values in mg/kg (ppm)
[1]Table 3 = Soil, ground water and sediment standards for use under Part XV.1 of the Environmental Protection Act, Generic Site Condition Standards for Use within 30 m of a Water Body in a Non-Potable Ground Water Condition. Bolded values exceed criterion.

Table 9: Summary of STAR Pilot Test Results

Parameter	STAR Treatment Result	Comment
Observed Radial Treatment Extent	1.4 m	Within the sand layer
Estimated Radius of Influence (ROI)	3.0 m	Within the sand layer
Treatment Zone Thickness	~1.0	Thickness of higher permeability sand layer
Smouldering Front Propagation Rate	0.4 m/day	Within the sand layer
Estimated Mass Removed via Volatilization	6.7 kg	Based on volume of extracted air and on-site air quality monitoring
Estimated Total Mass Removal	76-152 kg	Based on ROI, treatment zone thickness and pre/post chemical analysis

Implementation Costs

Implementation costs (Class V estimate) at the site scale were estimated based on the following key assumptions:

1. 31,000 m^2 treatment area
2. Average treatment depth of 10 m
3. 1,060 Ignition points arranged in cell clusters each with 10 ignition points.
4. Up to 15 multi-level thermocouples per cell.
5. STAR propagation velocity of 0.43 m/day
6. ROI of 3 m
7. Entire impacted zone can be treated from a single depth (1-2 m)
8. A surface vapour cap will not be required
9. Site security and waste disposal by others

Based on the complete list of assumptions documented in Pilot Test Report (Geosyntec, 2018), the Class V cost estimated is $21.5 million if remediation in one year is required, and $14.5 million if remediation can be extended over a 3-year time horizon. The significant additional costs for the shorter remedial time scale recognize the increased capital expenditures for multiple treatment systems.

STARx (Savron and Geosyntec Consultants International, Inc.)

Treatment Objectives

The key objective of the pilot scale testing was to evaluate the key design parameters and confirm treatment performance and treatment time to support full scale implementation of this technology.

Methodology

The Hottpad™ module used for STARx is essentially a steel box with a plenum at the base to contain the air handling and mechanical equipment. The plenum is protected by steel grating to allow for soil loading through a swing door on one side. Six, 8.5 kW heaters are used to initiate combustion, and the air handling system draws air from below the plenum to the top of the pile to propagate the combustion front upwards through the soil pile. A 30 cm thickness of clean soil is added to the top of the pile to help contain the heat of combustion in the pile.

Two separate tests were conducted for this technology between January 23 and February 13, 2018. Both tests utilized approximately 10 m^3 of soil and a single Hottpad™. Five multi-level thermocouples were installed in the soil pile to measure the progress of the smouldering combustion reaction, while others were installed to ensure that the heaters did not overheat. Pre-treatment soil samples were collected at depths of 30, 60, and 100 cm above the plenum and analyzed for PHCs, VOCs, PAHs, and metals (although the technology is not intended for remediation of heavy metal contamination).

As with the in-situ STAR method, the air handling system was activated prior to ignition. For Test 1 (silty sand), the heaters were turned on for 27.2 hours and were turned off when thermocouples and combustion gas monitoring indicated that ignition had occurred. However, monitoring indicated that self-sustaining combustion only occurred in part of the chamber. Another heating cycle of 37.9 hours was completed, and evidence of a strong combustion reaction was detected. Therefore, a total heating time of 65.1 hours was required with an air injection rate of 119 m^3/hr. After the heaters were turned off, the air flow rate was adjusted to 229 m^3/hr to increase the mass destruction rate, and ensure the self-sustaining reaction proceeded to completion. Once combustion was complete, the air injection rate was increased to 382 m^3/hr to cool the soil pile until the test was terminated after a total of 236.5 hours.

Test 2 was conducted on a sample of sand with some silt (i.e., coarser than the soil in Test 1), with a pre-treatment PHC concentration of about 18,767 ppm. The heaters were turned on for 98 hours, with an air flow rate that ranged from 34 to 255 m^3/hr. Ignition temperatures were achieved within all five thermocouple bundles, but self-sustaining combustion did not propagate to the top of the pile. Air injection was continued for 64 hours to allow for cooling of the soil pile.

Effectiveness

The soil pile in Test 1 reached a maximum temperature of 1082 °C, with a propagation velocity between 0.2 and 0.5 m/day. The lowest propagation rate was in the centre of the pile, where the soil density was likely highest because of the centre-loading procedure for the soil. The analytical data confirm a destruction efficiency of 94.8% to more than 99.7%, depending on the parameter. A summary of the results is provided in **Table 10**. Monitoring of the extracted air confirmed elevated concentrations of CO (1,141 ppm), CO_2 (1.3%), and VOCs (435 ppm).

Table 10: Summary of PHC Reductions from Test 1 of STARx (silty sand)

Parameter	MECP Table 3[1]	Pre-STARx			Post-STARx			
		30 cm	60 cm	100 cm	30 cm	60 cm	100 cm	100 cm
PHC F1 (C6-C10)	55	**266**	**106**	**146**	<5.0	<5.0	<5.0	<5.0
PHC F2 (C10-C16)	230	**2,510**	**891**	**912**	52	<10	<10	21
PHC F3 (C16-C34)	1,700	**25,200**	**17,900**	**18,100**	1,660	135	<50	782
PHC F4 (C34-C50)	3,300	**7,250**	**4790**	**4,970**	124	<50	<50	<50
Total PHCs (C6-C50)	-	35,200	23,700	24,100	1,840	135	<72	803

Notes:

All values in mg/kg (ppm)

[1]Table 3 = Soil, ground water and sediment standards for use under Part XV.1 of the Environmental Protection Act, Generic Site Condition Standards for Use within 30 m of a Water Body in a Non-Potable Ground Water Condition. Bolded values exceed criterion.

nc - no criterion

The soil pile in Test 2 reached a maximum temperature of 599 °C, but a propagation velocity could not be calculated because self-sustaining combustion was not attained. The consultant's assessment was that external air leakage into the Hottpad™ chamber caused the reaction to cease. The analytical data confirm that thermal destruction occurred at the base of the pile, but not at the top. A summary of the results is provided in **Table 11**. Monitoring of the extracted air confirmed elevated concentrations of CO (388 ppm), CO_2 (0.3%), and VOCs (392 ppm).

Table 11: Summary of PHC Reductions from Test 2 of STARx (sand with some silt)

Parameter	Table 3[1]	Pre-STARx			Post-STARx		
		30 cm	60 cm	100 cm	30 cm	60 cm	100 cm
PHC F1 (C6-C10)	55	**715**	**525**	**440**	<5.0	<5.0	8.5
PHC F2 (C10-C16)	230	**13,400**	**9,350**	**9,720**	<10	<10	**17,600**
PHC F3 (C16-C34)	1,700	**7,440**	**5,670**	**5,730**	69	<50	**8,170**
PHC F4 (C34-C50)	3,300	1,230	975	1,080	<50	<50	680
Total PHCs (C6-C50)	-	22,800	16,500	17,000	<72	<72	26,400

Notes:
All values in mg/kg (ppm)
[1]Table 3 = Soil, ground water and sediment standards for use under Part XV.1 of the Environmental Protection Act, Generic Site Condition Standards for Use within 30 m of a Water Body in a Non-Potable Ground Water Condition. Bolded values exceed criterion.
nc - no criterion

Implementation Costs

The cost of implementing this technology is dependent of two key variables: processing rate, and volume of soil requiring treatment. Therefore, three different scenarios were considered in the generation of Class V cost estimates for this technology:

1. 70,000 m^3 of PHC-impacted soil treated over a period of two years – total cost of $11.5 million.
2. 105,000 m^3 of PHC-impacted soil treated over a period of three years – total cost of $12.7 million.
3. 140,000 m^3 of PHC-impacted soil treated over a period of four years – total cost of $13.9 million.

For the scale of remediation required for the Portlands site, staggered batch operations would be required, with four assemblies each comprising 12 individual Hottpads™ manufactured into a single unit. A total flow rate of about 2,300 cfm (3,900 m^3/hr) would be required, along with thermal oxidation of the off gases. The complete list of assumptions for the cost estimate are included in Savron and Geosyntec, 2018b. The longer remedial periods allow for more efficient use of the capital expenditures, which results in a lower cost per cubic metre of contaminated soil. It should be noted that degradation of peat through implementation of this technology would be an added benefit, since treatment of the peat is being considered separately from a budgeting standpoint.

Biodegradation (WSP Canada Inc.)

Treatment Objectives

The key objectives of the pilot scale testing of enhanced biodegradation were to assess the feasibility of constructing and maintaining both aerobic and anaerobic biopiles, determine the relative effectiveness of both approaches, and develop Class V cost estimates and remedial timelines for full scale implementation of bioremediation for the Portlands area (WSP, 2018b).

Methodology

Before the test biopiles were constructed, the consultant completed a site characterization of the pilot-scale testing area to identify pre-treatment soil conditions and ensure that the tested soils had adequate PHC levels for bioremediation. Once the test soils were identified, four biopiles of about 20 m^3 each were constructed to allow for testing of various soil amendments and pile operation parameters. The biopiles were built on an HDPE membrane to prevent leaching from the piles during the testing. One biopile was used as a control, while the others were designed to be as follows: aerobic; enhanced aerobic; and anaerobic. Unfortunately, it was not possible to maintain anaerobic conditions during this pilot test because it was performed above grade, on excavated soils. Therefore, it is not possible to evaluate the effectiveness of anaerobic degradation.

For each pile, a temperature and oxygen testing control system were built to allow for monitoring of the biopiles over time. The control biopile was equipped with a non-contact heating system only. The aerobic pile was dosed with 430 kg of sawdust as a bulking agent as well as 200 kg of blood meal as a nutrient source. This pile was thoroughly mixed to ensure oxygen entrainment throughout the pile and was equipped with perforated piping to allow for the addition of heated air to maintain temperature and aerobic conditions in the pile as well as allow for monitoring of temperature, and air chemistry (CO_2) in the pile. They also allowed for the collection and treatment of off-gases with activated carbon prior to discharge into the atmosphere.

The enhanced bioremediation biopile had the same base amendments and construction as the aerobic biopile. However, for this pile, 10 kg of Matsphere, 2 kg of bacteria (microbium), and 4.2 litres of Microblaze were also mixed into the soil matrix to provide optimized soil conditions for bioremediation.

The piles were then covered with an impermeable liner to prevent infiltration or runoff from the piles. Soil samples were taken from each of the piles over the length of the biopile testing operation. The testing was done from December 2018 to January 2019 and is therefore considered representative of worst-case temperature conditions. The biopiles and the heating/ventilation systems were inspected weekly, and two soil samples were collected from each pile were analysed for pH and moisture content. At the conclusion of the testing, the treated soil was removed off-site for disposal.

Effectiveness

The effectiveness of each of the treatment biopiles was assessed via soil samples collected at four and eight weeks after pile construction was completed and the heating/ventilation systems were activated. The temperature and CO_2 readings from both manual measurements and automated sensors were also reviewed to assess the progress of biological activity.

Table 12: Summary of Baseline Testing for Bioremedation

Biopile	MECP Table 3[3]	Baseline		Control	
		Sample A	Sample B	4 weeks	8 weeks
Average Temp (°C)				12.7	19.6
Average CO_2[1] (ppm)				9,600	23,600
Benzene	0.32	<0.0068	<0.0068	<0.0068	0.0204
Toluene	68	<0.08	<0.08	<0.08	<0.08
Ethylbenzene	9.5	<0.018	<0.018	<0.018	0.02
Xylenes (total)	26	<0.05	<0.05	<0.05	0.102
PHC – F1	55	7.5	8.2	<5.0	15.9
PHC – F2	230	**632**	143	**247**	**478**

Biopile	MECP Table 3[3]	Baseline		Control	
		Sample A	Sample B	4 weeks	8 weeks
PHC – F3	1,700	**1,820**	523	1,490	**1,860**
PHC – F4	3,300	720	237	691	779
PHC – Total		3,180	911	2,430	3,140

Notes:
[1] Manual Weekly readings
[2] Maximum of analyses of control pile
All chemical test results in µg/g
[3]Table 3 = Soil, ground water and sediment standards for use under Part XV.1 of the Environmental Protection Act, Generic Site Condition Standards for Use within 30 m of a Water Body in a Non-Potable Ground Water Condition. Bolded values exceed criterion.

Table 13: Summary of Biopile Testing

Biopile	MECP Table 3[3]	Control		Aerobic		Enhanced Aerobic		Anaerobic	
		4 wks	8 wks	4 wks	8 wks	4 wks	8 wks	4 wks	8 wks
Average Temp (°C)[1]		7.5/5.9		12.7/8.9		19.6/8.2		8.4/7.3	
Average CO_2[2]		3200/119		9600/461		23600/906		5400/208	
Benzene	0.32	<0.0068	0.0341	0.0157	0.0155	0.0102	0.0161	0.0156	0.0072
Toluene	68	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080	<0.080
Ethylbenzene	9.5	<0.018	0.019	<0.018	<0.018	<0.018	<0.018	0.027	<0.018
Xylenes (total)	26	<0.050	0.089	0.080	<0.050	0.081	0.086	0.136	<0.050
PHC – F1	55	<5.0	10.4	<5.0	<5.0	<5.0	10.0	13.1	14.6
PHC – F2	230	**247**	**375**	**270**	162	**233**	188	**356**	**414**
PHC – F3	1,700	1490	**1780**	1590	1130	1370	893	**1940**	1570
PHC – F4	3,300	691	771	737	496	599	416	823	644
PHC – Total	nc	2430	2960	2600	1780	2200	1510	3130	2640

Notes:
All hydrocarbon concentrations in µg/g (ppm)
[1] Temperatures from weekly manual monitoring/continuous soil sensors
[2] CO_2 from weekly manual monitoring/continuous soil sensors
[3] Table 3 = Soil, ground water and sediment standards for use under Part XV.1 of the Environmental Protection Act, Generic Site Condition Standards for Use in a Non-Potable Ground Water Condition. Bolded values exceed criterion.
nc - no criterion

Of the piles, the enhanced aerobic pile had the greatest reduction in total PHCs, although the limited number of samples and high degree of soil heterogeneity makes it impossible to accurately state specific contaminant reduction estimates. The enhanced aerobic pile also had the highest temperature and average CO_2 concentrations, both strong indicators of biological activity, although the injected air heating of the aerobic piles was likely more efficient than the radiant heating used in the control and anaerobic piles. The oxygen levels in all the piles ranged from about 19-21%.

These values are acceptable for aerobic processes, but not for anaerobic biodegradation. Maintaining anaerobic conditions in small biopiles can be challenging, as can raising temperatures during winter operations. Overall, the pilot testing suggests that bioremediation of the soils in the study area is possible but will require warmer ambient conditions and residence times greater than 8 weeks. The potential schedule risks from utilizing this technology for the PLFP remediation cannot be understated. Prior to full scale implementation, testing during summer conditions would be required.

Implementation Costs

Implementation costs (Class V Estimate) are based on the following key assumptions:

1. 300,000 m^3 of soil requiring remediation for PHCs
2. Soil excavation and transport to the treatment area provided by others
3. Four-year timeframe for remediation assuming three treatment cycles per year
4. Average biopile volume of 100 m^3
5. Up to five hectares of land available for soil treatment.

The estimated remedial costs, including fees, expenses, laboratory expenses, and all mobilization/demobilization costs to be in the range of $45 to $65 per cubic metre of treated soil, or $13.5 million to $19.5 million if implemented at full scale for the entire project.

CONCLUSIONS

Treatment Effectiveness

All the treatment technologies assessed as part of this study provided some degree of soil strength improvement, permeability reduction, and/or contaminant mitigation. However, as expected with emerging remedial technologies and a large, complex site like the PLFP, no one technology provides a perfect solution, especially under field conditions.

At the bench scale, temperatures, reaction rates, and fluid movements through the samples can be more tightly controlled. As the scale of assessment increases to the pilot scale, sample and in-situ heterogeneities also increase, resulting in less effective remediation overall and longer time scales.

Of the field scale studies, the thermal mitigation methods (STAR/STARx) provided the most significant contaminant reductions, particularly for highly impacted soils. The in-situ approach (STAR), however, would be limited to where the soil strata is more homogeneous. These conditions are not generally found in the PLFP, so the ex-situ approach has a greater chance of successful implementation.

The use of surfactants and oxidants (SEPR/S-ISCO) reduced the contaminant concentrations by up to 96%, but not to the extent of the thermal technologies of STAR and STARx, which brought the hydrocarbon concentrations from over 8,000 ppm to near non-detectable levels, at a similar cost of implementation. This technology is also hampered by the same issues as STAR, where the chemical solutions follow preferential pathways through the subsurface, bypassing contaminants retained in lower permeability sediments. This is especially challenging in the Port Lands area, where soil heterogeneity is consistently very high.

Solutions that mitigate the contaminant impacts and enhance soil strength (i.e., in-situ or ex-situ soil stabilization) are particularly favourable for the PLFP. It is the author's understanding that soil stabilization was seriously considered for full-scale implementation, except that the risk of poor compressive strength due to organic soils was considered too high for this technology to move forward.

The innovative methods of chemical soil stabilization developed by the Groundwater Technology team provided some strength improvement, but the results were much lower than for physical treatment with Portland Cement. The Block and Absorb technology is of interest, but the benefits are not worth the high and uncertain cost of implementation (\$90-\$375/m^3). The use of activated carbon as a pervious reactive layer, without the addition of cement is being carried forward as a part of the overall remedial strategy for the PLFP.

Schedule Viability

For a project such as the PLFP, time is a critical factor, given the high volumes of contaminated soil being excavated, and limited storage space available. This requires high volume throughput to keep the project moving forward on schedule.

Technologies that are scalable, with short reaction times, have the greatest probability of success on the PLFP. Therefore, thermal-based strategies such as STAR and STARx and physical stabilization via Portland Cement or other additives may be appropriate for this project, especially for some of the more highly contaminated soils, or areas where native soil strength must be increased.

Slower processes such as bioremediation may be utilized as part of the overall solution, provided treatment area is available.

Economic Viability

The PLFP has a significant overall budget ($1.25 billion), but is subject to a firm price ceiling, with a multitude of other cost items such as building bridges and installing or moving key infrastructure components. Therefore, the funds available for soil remediation are fixed, with a low tolerance for overruns. This means that the remedial strategy must consider economic realities.

The ex-situ approach (STARx) will have predictable and controllable results. Therefore, it would be best utilized to treat the most impacted soils. Bioremediation strategies are cost effective, but would be limited to less impacted soils, or soils subject to higher criteria limits.

RECOMMENDATIONS

This project evaluated the use of eleven different soil stabilization and contaminant mitigation technologies. Each of these approaches has the potential to be part of a remedial action plan to achieve the overall site remediation goals and minimize the volume of contaminated soil shipped offsite to one or more landfills. However, based on the results of the testing, and the site-specific constraints for the PLFP, the following technologies represent the most favourable options for consideration as part of the full-scale remedial action plan:

- STAR and STARx for highly impacted soils,

- Physical soil stabilization with Portland Cement and/or other additives, especially for the base of the river excavation, or areas that require an increase in in-situ soil strength,
- Enhanced bioremediation for treatment of lightly impacted soils, and/or soils subject to higher criteria thresholds, and
- Use of activated carbon as a pervious reactive layer. Although this was not specifically tested, activated carbon was shown to be effective as part of the Block and Absorb testing process.

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