In Situ Solidification and Stabilization at Former MGP Sites

Technical Report

In Situ Solidification and Stabilization at Former MGP Sites

1000727

Final Report, December 2000

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This report describes research sponsored by EPRI, WEPCO, PP&L and Georgia Power.

The report is a corporate document that should be cited in the literature in the following manner:

In Situ Solidification and Stabilization at Former MGP Sites, EPRI, Palo Alto, CA, WEPCO, Milwaukee, WI, PP+L, Allentown, PA and Georgia Power, Atlanta, GA: 2000. 1000727.

REPORT SUMMARY

In situ solidification and stabilization (S/S) techniques are one potential approach for remediating former manufactured gas plant (MGP) sites. This report discusses S/S techniques and summarizes the work carried out at three former MGP sites where in situ S/S was considered a remedial option.

Background

EPRI has been studying methods for cost-effective characterization and remediation of former MGP sites since the 1980s. As part of this on-going research, a review of in situ S/S case studies was performed.

When used properly, in situ S/S techniques can bind contaminants in a structurally sound, solid mass, thereby allowing the site to be remediated without excavation and ex situ treatment of contaminated materials. The ability to treat contaminated materials in place is particularly important at former MGP sites for several reasons. For example, since MGP tars are denser-than-water non-aqueous phase liquids (DNAPLs), they can sink through groundwater until reaching a confining layer, and some tar constituents can leach into the groundwater. As a result, both saturated and unsaturated material can be impacted and the areal and vertical magnitude of contamination can be extensive. In addition, since contamination at former MGP sites can be a result of different processes and materials used or produced over long periods of time, chemical constituents and concentrations can vary significantly from location to location. Consequently, characterizing a former MGP site in sufficient detail to surgically excavate materials can be a prohibitively costly venture. Thus, having a method to effectively treat a variety of chemical contaminants in situ would benefit former MGP site owners.

Objective

To review and summarize several case studies of in situ S/S use at former MGP sites.

Approach

The project team obtained information from utility companies that had examined the possibility of using in situ S/S at former MGP sites as the remedial method of choice. Once the information was compiled, the team reviewed and summarized it, then prepared the report.

Results

Three utility companies provided information to EPRI on site where in situ S/S was evaluated as a remedial method. In one case study, results of treatability studies, a feasibility study, and a risk assessment indicated that in situ S/S would be an appropriate treatment method. After a conceptual plan was prepared, the in situ S/S was carried out successfully. The site was restored for use as a public park and scenic river front walkway. Eleven rounds of post-remediation groundwater monitoring using 10 monitoring wells showed that none of the chemicals of concern was found above its maximum contaminant level (MCL). In addition, a majority of the samples had no detectable levels of any chemicals of concern.

For the other two case studies, although extensive treatability studies were carried out using a variety of binding agents and proportions of binding agent to soil, in situ S/S was not implemented at either site. At one site, in situ S/S was not used for several reasons, including: cost, potential problems concerning future site uses, and the large amount of soil that would have to be excavated prior to implementation of in situ S/S. As a result, another method of remediation, in situ chemical oxidation, was selected. At the third site, no remedial action has been implemented to date.

Even though in situ S/S was implemented at only one of three sites studied, it is a potentially viable remedial option at former MGP sites, either as a treatment method for the entire site or in selected areas, such as former gas holders.

EPRI Perspective

The EPRI review of case studies concerning potential use of in situ S/S at former MGP sites is valuable to companies, particularly those that plan to evaluate remediation options. The in situ S/S techniques described in this technical report show that solidification is a process that reduces migration of contaminants by decreasing the surface area exposed to leaching or coating the contaminants. S/S techniques were considered from three sites discussed in this report. Of the three sites studied, there were mixed results reported. However, it was determined that S/S process has significant merit where partial treatment is required along with partial removal of source materials at a site. Proper additives must be considered to render S/S treatment a viable, cost-effective treatment along with conventional remediation solutions at a site.

Keywords

MGP sites
Remediation
Solidification
Stabilization
NAPL

ABSTRACT

This report presents the results of a review of three case studies examining the potential use of in situ solidification and stabilization (S/S) as a remedial measure at former manufactured gas plant (MGP) sites. At one of the sites, in situ S/S was implemented successfully and the site was restored for public use. At the other two sites, extensive treatability studies were completed, but remediation of the site using in situ S/S was not implemented. The results presented in the report include the performance test data from a variety of mixtures of binding agents with MGP-contaminated soils.

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INTRODUCTION

Background

There are more than a thousand former manufactured gas plant (MGP) sites located throughout the United States (Moore, 1989). While many of these sites have undergone at least some type site investigation, waste characterization, or remedial option assessment, some sites have not been completely remediated.

The remediation of former MGP sites is particularly difficult for several reasons. For example, historical gas production was carried out at most former MGP sites over a period of time from several decades to a hundred years. Often times, more than one gas production process was employed at a single site, either in different site locations or at the same location during different time periods, resulting in the generation of process-specific and time-dependent wastes. Sites which contained coal carbonization facilities at some point in their past can have residual wastes, including cyanide-containing purifier materials, which are different from those generated from oil gas or carburetted water gas processes. As a result, the wastes generated from gas production can vary at a given site, particularly if more than one gas production process was used.

Additionally, in the 1800s and early 1900s, standard plant practices sometimes included the disposal of by-product tars and other wastes at convenient locations around the site, such as tar wells, open trenches, or other locations, potentially resulting in the distribution of wastes in discontinuous areas of the site. If the wastes were mobile in their pure form or had leachable constituents, contamination could potentially spread. Furthermore, because MGP tars are denser than water nonaqueous phase liquids (DNAPLs), if the MGP tars are mobile, they can potentially migrate downward below the water table and can flow through fractures in bedrock. Since MGP sites were often located near bodies of water, seepage of mobile tar into the water could also occur.

Finally, many former MGP sites were used for various purposes after gas production was halted and, as such, could contain wastes from these uses, in addition to the former MGP process wastes.

Thus, remedial options for former MGP sites often need to consider how to remediate different types and ages of historical wastes, wastes that may be laterally and vertically spread out with varying types and concentrations of chemicals found at multiple locations, wastes that likely are present below the water table, wastes that may have entered into or migrated through bedrock, and wastes that may have or continue to seep into rivers or other bodies of water.

Any remedial action at a former MGP site would involve either ex situ actions (removing the contaminated material and treating it or disposing of it) or in situ actions (removing, altering, or treating the contaminants in place). While the excavation of material followed by subsequent treatment is a common method of remediation, there are many different types of potential in situ remedial technologies that can be used in certain circumstances. For example, in 1998 EPRI performed a literature review and evaluated 17 potential in situ remedial technologies for the treatment or management of soil contaminated with hydrocarbons, including: soil vapor extraction (SVE), vitrification, and enhanced aquifer bioremediation (EPRI, 1998). While some of the methods discussed in that report could be used at former MGP sites, some others might not be appropriate.

One type of potential in situ remedial measure for former MGP sites is in situ solidification and stabilization. This report provides a brief general discussion of that in situ method and summarizes the results of three case studies in which site remediation using in situ solidification and stabilization was evaluated. In the first case study, in situ solidification and stabilization was selected as the remedial measure for the site and was successfully implemented. In the other two case studies, however, only feasibility and/or treatability studies were carried out and in situ remediation using solidification and stabilization was not selected as the remedial method for the site.

In Situ Solidification and Stabilization

Definitions

Solidification/stabilization (S/S) is a general term used to describe a category of techniques used to treat wastes or other materials. The EPA distinguishes and defines solidification and stabilization in the following manner (EPA, 1993; EPA, 1999; EPA, 2000):

Solidification

“processes that encapsulate a waste to form a solid material and to restrict contaminant migration by decreasing the surface area exposed to leaching and/or coating the waste with low-permeability materials.”

Stabilization

“processes that involve chemical reactions that reduce the leachability of a waste.”

Solidification can occur either by a chemical reaction using a binding agent or by mechanical processes. The resulting solidified material can be a small granular particulate, a large monolithic block, or other material considered “solid”. When very fine particles, approximately 2 mm or less, are solidified, microencapsulation is the term that is generally used while macroencapsuslation is the term used for the production of a large monolithic block or a container by solidification.

Stabilization of waste or contaminated material reduces its hazard potential because the contaminants are changed to a less mobile, less soluble, or less toxic form. However, during stabilization, the handling characteristics and physical nature of the material is not necessarily altered as it is in solidification.

When combined, solidification and stabilization result in the mixing of contaminated materials (e.g., soils, sludges, wastes) with agents (e.g., cement, lime, fly ash, organic materials, etc.) to chemically and physically reduce the mobility of chemical contaminants, thereby reducing the potential for human or environmental exposure to them. For example, very high temperatures (typically in excess of 816°C) can be used in S/S processes to vitrify wastes, resulting in the production of glass-like end-products that contain the wastes (EPA, 2000). Thus, while S/S techniques reduce or eliminate the mobility of the chemical contaminants, they do not destroy them.

S/S Techniques

S/S techniques were developed in the mid-1900s and have been used in the last several decades for the treatment of a wide variety of municipal, hazardous, industrial, and radioactive materials (Grasso, 1993; EPA, 2000). S/S techniques can be used on either liquids or solids and can be done as an ex situ or in situ action, although it is most often employed ex situ.

S/S Binding Agents

In general, the binding agents can be grouped into the following four categories (Wolfe, 1996;

- cement-based binders (e.g., Portland Type I Cement, cement kiln dust) used for inorganic wastes,
- pozzolanic binders (e.g., fly ash and bottom ash) used for inorganic wastes,
- thermoplastic binders (bitumen and polyethylene) used for organic wastes, and
- polymer binders (organic polymers) used for organic wastes.

According to the EPA (2000), the binding agents and reagents most frequently used for S/S at Superfund sites were cement (47%) and proprietary agents (22%), followed by phosphates (14%), pH controls (12%), fly ash (10%), lime (10%), sulfur (4%), and asphalt (1%).

Ex Situ S/S Applications

For ex situ S/S treatment of soils, water (or other liquid additives) and binder agents (and other reagents, if needed) are mixed with excavated and pre-treated (size screened, dewatered, neutralized, etc.) soils. The mixing can be carried out continuously in a reaction mechanism (e.g., a pug mill, Mueller mixer, ribbon blender, screw conveyer, extruder, or other device) or by a batch process, such as “area mixing” using a backhoe or other equipment. (EPA, 1990; EPA, 1993; Grasso, 1993; Wolfe, 1996)

According to the EPA (1993), the resulting S/S mixtures can be placed in molds or other containers to cure prior to on-site or off-site disposal, injected into the subsurface, placed in on-site waste management trenches or cells for disposal, or used as construction material after curing if regulatory approvals are given.

In Situ S/S Applications

In situ S/S treatment can be carried out in relatively shallow soils, to depths of about 10 meters, using an open-bottom cylinder in which a crane-mounted mixer is enclosed. Typically, the blending agent slurry with or without additives is pumped into the area to be solidified and stabilized while the mixer moves throughout the vertical treatment zone. After completion of one vertical area, the mixing mechanism is moved to an adjacent location and the process is repeated until the entire zone has been treated using an overlapping pattern of mixing. Deeper soils, down to depths of about 50 meters, are treated in a similar manner, typically using hollow stem augers with the augerflights breaking up the soil and moving it to affect mixing. Overlapping auger holes are also used to ensure complete mixing of the subsurface materials. (EPA, 1993; Wolf, 1996)

Limitations of In Situ S/S

Although the use of in situ S/S can immobilize contaminants in place, can result in a structurally sound treatment zone, and can be a cost-effective means of remediating a former MGP site, its use it does have some limitations and potential problems.

For example, by injecting a slurry of binding agents, the volume of material is increased. As a result, some excavation and materials handling prior to mixing is typically needed. In addition, because the process is carried out in place, maintaining quality control is difficult. There also is the potential for incomplete mixing or inappropriate mixing ratios and, therefore, inadequate treatment of the contaminated material. Furthermore, there are many physical and chemical characteristics of the media to be treated that can interfere with the effectiveness of the treatment. For example, clay matrices can clump making mixing difficult, chemical reactions can occur that impact the mixing or curing, and some constituents in the matrix (including oil and grease, some metals and sodium salts, sulfate, phenols, and surfactants) can interfere with the S/S treatment. In addition, high moisture content and high organic compound content can also reduce the effectiveness of the S/S treatment. After treatment, the solidified material can deteriorate over time, potentially releasing contaminants by leaching and, as a result, long-term monitoring may be required. (Grasso, 1993; EPA, 1993; Wolf, 1996)

S/S Performance

Typically, when S/S is employed its performance is determined after the treated material has cured. Several tests typically are commonly used to evaluate the performance of the treatment. One test is the Toxicity Characteristic Leachate Procedure (TCLP) which is used to determine the efficacy of the S/S treatment (i.e., how well the end material has reduced the leachability of the chemical contaminants) as well as to determine if the solidified material would be deemed hazardous as a result of a toxic characteristic (TC). A second type of test, the unconfined compressive strength (UCS) test, is used to evaluate the load bearing strength of the resulting solidified material. Permeability testing is also typically done to evaluate the effectiveness of the solidified material to retard groundwater flow. Other performance testing can include total waste analysis for organic compounds, freeze/thaw and wet/dry weathering cycle (durability) testing, density and specific gravity, and microstructural analysis. (EPA, 1993; Wolfe, 1996)

S/S Applications

According to the EPA (2000), the application of S/S techniques is one of the top five source control methods employed at Superfund sites in the United States, with more than 160 Superfund sites using them between 1982 and 1998. However, of these sites, the vast majority of S/S techniques have employed ex situ, such as the treatment of process sludges or waste materials. Most of the S/S projects summarized by the EPA (2000) concerned treatment of metal wastes, either alone or in combination with other contaminants. While some of the sites did treat wastes containing organic compounds, only two of the 160 sites discussed by the EPA using S/S techniques were coal gasification sites.

Although S/S has most often been used for inorganic wastes, particularly nonvolatile heavy metals, studies have been conducted on the solidification and stabilization of soils contaminated with organic contaminants. For example Bates and others (1992 and 2000) did studies on wood treatment facility wastes which included pentachlorophenol (PCP), polycyclic aromatic hydrocarbons (PAHs), and polychlorinated dibenzo-p-dioxins (PCDDs). The results from these studies have shown that the mobilities of the chemical contaminants (as determined by the TCLP and synthetic precipitation leachate procedure (SPLP)) were effectively reduced, the permeability values of the resulting solidified materials were low (below 10^{-6} cm/sec), and the UCS values were up to seven times greater than the recommended level for placement in a hazardous waste landfill (3.5 kg/cm^2 or 50 psi). Based on the work reported by Bates and others (1992 and 2000), not only were organic contaminants effectively treated using S/S, but also the treatment would be cost-effective. The estimated treatment costs for ex situ treatment would range from $11 to $110/metric ton or $78 to $157/cubic meter.

Thus, S/S treatment is a potential remedial alternative for contaminated materials at MGP sites and can be carried out in either an in situ or ex situ manner. The use of in situ S/S at former MGP sites could be for a specific area, such as a gas holder (as discussed in the EPRI (1999) report “Remediation of Gas Holders at MGP Sites: A Manual of Practice”) or for the entire site.

Report Organization

This report contains four additional technical sections followed by Section 6, containing a list of references. Section 2 covers a discussion of an in situ containment and stabilization remediation that was carried out at a former MGP site. Included in that section are background information about the site, treatability and feasibility study results, the selection of in situ containment and S/S, and the implementation of the remedial method. Sections 3 and 4 discuss treatability studies carried out at two former MGP sites and a discussion of why in situ S/S was not selected as the remedial measure at either of these sites. Finally, Section 5 provides conclusions from the work discussed.

2

CASE STUDY 1

In the early 1990s, the remediation of a former MGP site in Georgia was carried out using in situ solidification and stabilization. The work began with a series of investigations to characterize the MGP residues. Two phases of site investigations were performed, followed by both a treatability study and a focused feasibility assessment evaluating the potential for in situ S/S. Following completion of the feasibility study, a risk assessment was carried out to determine the risk-reduction efficacy of using in situ S/S. Based on the results of both the feasibility study and the risk assessment, in situ S/S was selected as the remedial method.

Prior to implementing the remediation, additional site characterization and treatability testing were carried out at the request of the state environmental agency. After completion of this additional work, the remediation was initiated. Following the successful remediation of the site using in situ S/S, a public park and a riverfront walkway were constructed as part of the site restoration.

This section provides a summary of the background of the site, the site investigation results, the selection and implementation of in situ stabilization, and the site restoration.

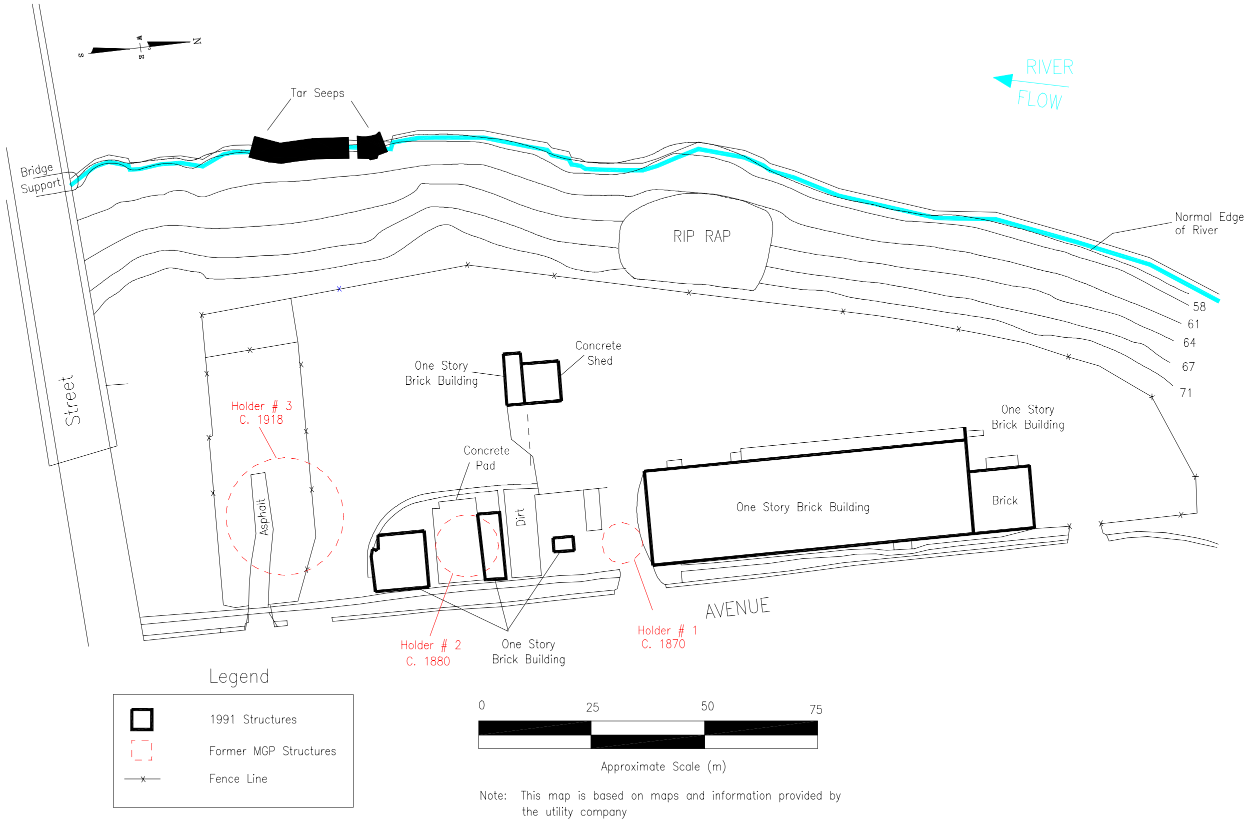
Background

Site Description Prior to Remediation

The former MGP site was located along the eastern bank of a river in a central business district of a Georgia city. Prior to remediation, the key features of the site included extensive fill material and a steep river embankment. The river embankment extended approximately north and south more than 230 meters along the border of the river, as shown in Figure 2-1. As indicated in this figure, the river embankment was about 12 meters high and contained riprap. A bridge crossing the river was located along the southern edge of the site. In addition, there was a tar seep zone observed near the south end of the embankment, about 40 to 50 meters north of the bridge.

Site History

The former MGP began producing gas in the 1850s by distilling wood in iron retorts. The gas production process changed in the 1860s to coal carbonization. Later, in 1918, a carburetted water gas process was added at the site. MGP operations ceased in 1931 when the site was converted to a natural gas storage and metering facility. During the gas production history, three gas holders were constructed and used to store gas at the site. The locations of the three gas holders (containing gas capacities from 340 to 5,700 cubic meters) are shown by the dotted lines in Figure 2-1. By 1920, the smallest holder (Holder #1) had been converted to a tar well to hold by-product tar residues from the gas production process.



Note: This map is based on maps and information provided by the utility company

Figure 2-1

By 1951, the three former gas holders were demolished, oil tanks were removed, and the water gas plant was dismantled. A propane-air plant was installed where the water gas plant was previously located and brick buildings, shown by the thick solid lines in Figure 2-1, were constructed over former MGP structures. By 1973, an old retort building had been demolished and a service center facility was constructed consisting of offices, a workshop, and a concrete storage shed with a carport for vehicle maintenance. All remaining structures were demolished in 1991 in preparation for site remediation and restoration.

Thus, gas was manufactured at the site from the 1850s through 1931 using several methods of gas production. During this time, MGP process wastes and residues, including: pure product tars, oils, and a limited amount of purifier wastes, were generated. Some of the by-product tars were placed in Holder #1 after it was taken out of service in 1920. After 1931, the property was used as a natural gas storage and metering facility until site remediation activities were initiated in 1991.

Site Characteristics

Much of the site contained a variety of fill materials (consisting of imported river sands, coal and cinder fragments, and construction and metal debris) to depths of about 1.4 to 11 meters. Underlying these fill materials were unconsolidated sediments varying in thickness from 1.2 to 8.5 meters and beneath the unconsolidated sediments was a layer of coarse to medium fine sand and gravel.

As a result of the lock and dam operations on the adjacent river, the water table fluctuations at the site were significant, although the typical depth to the water table was about 6.1 meters. The saturated zone thickness was about 3 meters and was underlain by saprolite (weathered bedrock) which was underlain by competent bedrock, located at a depth of about 20 meters below ground surface (bgs).

Site Investigations

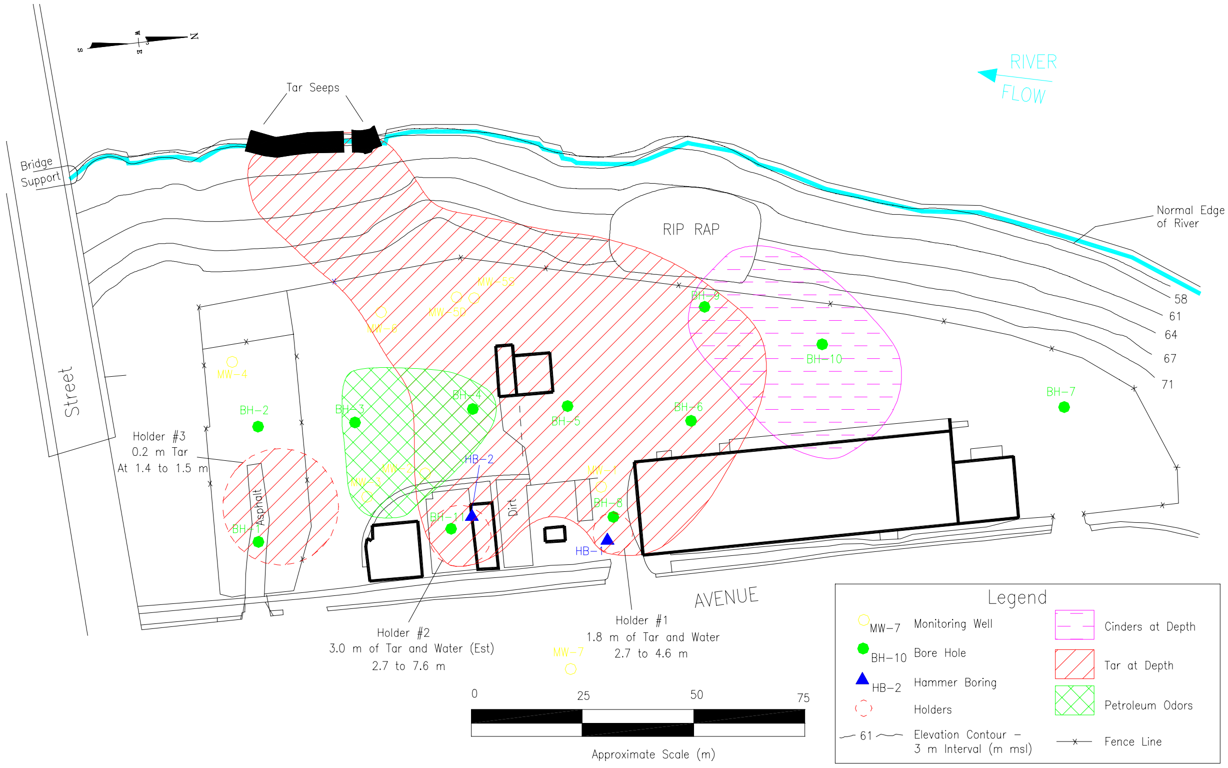
Two phases of site investigations were carried out at the site prior to selection of the remedial measures. The following paragraphs briefly summarize the work carried out and results found during each of these investigations.

Phase I Results

During the first phase of investigation, carried out in 1990 and 1991, 11 soil borings were advanced to a maximum depth of approximately 12 meters bgs and soil samples were collected for analysis about every 1.5 meters. In addition, two hammer borings were advanced in the vicinity of the two smaller holders and eight monitoring wells were installed (seven were placed on-site and one was placed in an upgradient off-site location). Of these eight wells, three were installed using 3-meter screens in a layer of fine to medium sand, three were installed using 1.5-meter screens placed just above the saprolite, one was installed using a 3-meter screen just above the saprolite, and one was installed with a 4.6-meter screen just above the competent bedrock (about 20 meters deep) through the saprolitic layer.

The results of the Phase I investigation showed the presence of PAHs in several of the soil borings, hammer borings, and groundwater samples. In soil, the highest total PAH concentrations were found in one soil boring (26,400 mg/kg) and one hammer boring (17,800 mg/kg). Detectable levels of total PAHs in groundwater ranged from 2.3 to 76 mg/L and were found in five of the eight monitoring wells. The highest level of oil and grease was 27,000 mg/kg. None of the four samples tested using the TCLP test exceeded any of the TC regulatory limits and, as such, none of the materials were deemed hazardous as a result of a toxic characteristic.

Figure 2-2 shows the locations of the Phase I soil borings, hammer borings and monitoring wells, along with the estimated extent of MGP residues in the subsurface, petroleum odors identified, and the locations of cinders at depth. As indicated in this figure, the area most impacted by MGP tarry residues extended from the former carburetted water gas plant and the two smaller holders westward toward the riverbank where tar seeps had been observed. Tarry materials were also found in shallow soils (about 1.4 to 1.5 meters) where the largest gas holder (Holder #3) had been located. Cinders were observed in the northern portion of the site and extended from the large brick building westerly to the rip rap. Petroleum odors were observed in the eastern portion of the site, approximately between Holders #2 and #3 and slightly west.



Note: This map is based on maps and information provided by the utility company

Figure 2-2

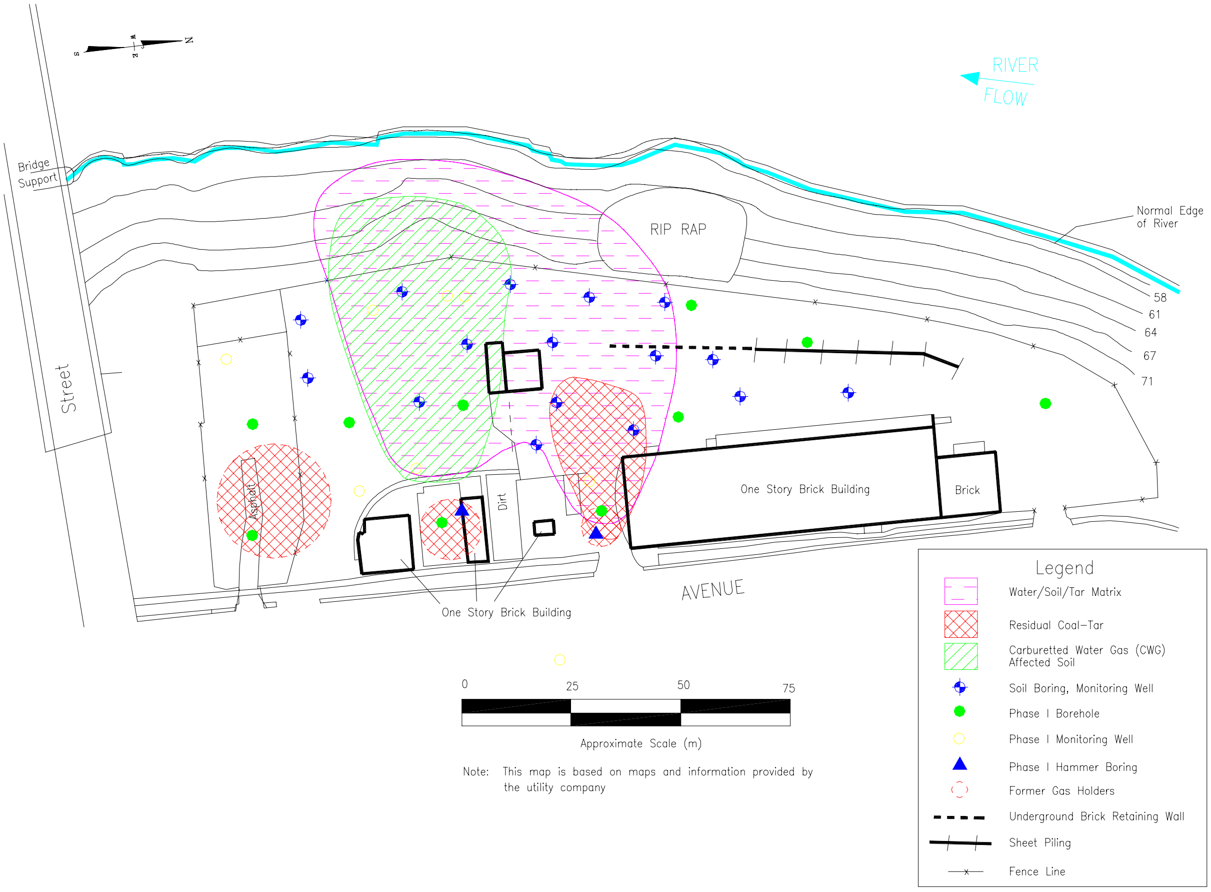
Slug injection, constant head, and falling head permeability tests were conducted in three of the wells that were screened directly above the saprolite. The resulting hydraulic conductivity values varied from about 2.78 x 10^{-3} to 5.32 x 10^{-2} cm/sec and reflected the variation in the sediment material proximate to each of the wells tested. The average permeability of the saturated zone based on the middle five values (6.02 x 10^{-3} to 1.62 x 10^{-2} cm/sec) was 9.49 x 10^{-3} cm/sec.

Phase II Results

The second phase of work took place during the summer of 1991 and consisted of the advancement of 15 soil borings and the installation of one additional monitoring well. A total of 11 soil samples were collected for analysis from seven of the borings with no samples collected from the remaining eight borings. In general, tarry residues were most apparent in the soils collected near the top of the saprolitic layer, approximately 12 meters bgs.

The highest total PAH concentration in a soil sample was 2,400 mg/kg and the highest oil and grease concentration was 5,500 mg/kg, both of which were lower than the maximum concentrations observed for soils in the Phase I work. In addition, PAHs were detected in seven of the monitoring wells at concentrations ranging from 0.6 to 14 mg/L for total PAHs.

Based on the results from the second phase of work and the previously completed work, the extent of three types of MGP residues were estimated and are shown in Figure 2-3, along with the locations of the soil borings from each of the phases of work. Also shown in this figure are an underground brick retaining wall and sheet piling (installed in 1959) located about 20 to 25 meters west of the large brick building. As indicated in Figure 2-3, viscous tar residue was found in the vicinity of each of the three gas holders and extended westward from Holder # 1, the smallest holder that was converted to a tar well in 1920. Unsaturated soils with contamination indicative of former carburreted water gas residues were observed west of Holder #2 toward the river. Finally, in the saturated zone, a third area was identified west of Holders #s 1 and 2 which contained water, soil, and tar. The tarry material in that area was less viscous than the tar observed in Holder #1 (the tar well) and appeared similar to the tar observed in the river seeps. The tarry material in the saturated zone was typically encountered within about 1.5 meters of the saprolite.

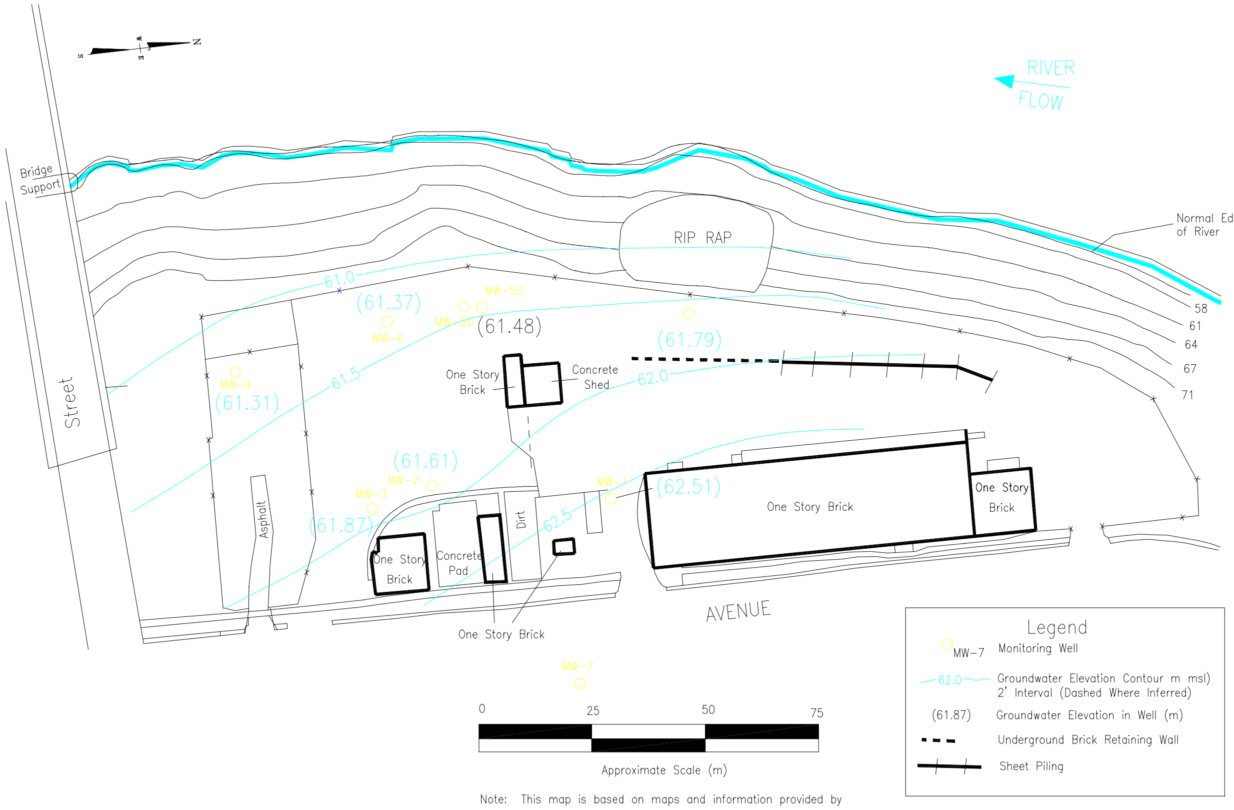


Note: This map is based on maps and information provided by the utility company

Figure 2-3

The saturated zone contained the highest concentrations of MGP residues and, as such, was the area of most concern. In addition, the tarry material in this layer was mobile, as evidenced by the observation of the tar seeps along the riverbank. Thus, the primary objectives of any remedial action needed to address both the treatment and immobilization of the MGP materials in the saturated zone and the elimination of tar seeping into the river.

Figure 2-4 shows the groundwater elevation contours based on the results from the second phase of work. As shown in this figure, the groundwater flow direction was approximately westerly in the middle portion of the site and southwesterly in the southern portion of the site. This difference in groundwater flow direction between the southern and middle portions of the site likely was caused by steel sheet pilings that were driven down to the saprolite in 1959, as shown in Figures 2-3 and 2-4. No information was available on the groundwater flow direction in the northern-most portion of the site.



Note: This map is based on maps and information provided by the utility company

Figure 2-4

Differing water table elevations measured in shallow and deep wells at the same location (aquifer well MW-5S and bedrock well MW-5D) indicated that either there was no hydraulic connection between the water table aquifer and the bedrock aquifer, or there was a vertical component to groundwater flow direction between these two zones. Additionally, the presence of tar constituents in the shallow well and the absence of these chemicals in the deep well indicated that any vertical component to groundwater flow in that area would be upward from the deeper bedrock to the shallower water table aquifer.

During the second phase of work, four undisturbed soil samples were collected using Shelby tubes and subjected to geotechnical testing. The results of the testing indicated that at least 90%

of the natural sand contained particles less than No. 4 sieve size (4.75 mm) and the material was deemed suitable for deep soil mixings, although larger materials present in the fill could pose a hindrance. The cohesion of the saprolite ranged from (84 to 170 kg/m^2) and the permeability of the saprolite was found to be very low (less than 10^{-6} cm/sec) which would provide mitigation against seepage.

Selection of In Situ S/S for Remediation

Initially, three remedial strategies were evaluated for the site to select an option that would: 1) minimize exposure to MGP residues, 2) immobilize the residues to prevent off-site migration of contaminants, and 3) protect human health and the environment. The three initial remedial options evaluated are briefly described in the following paragraphs.

Strategy 1

The first remedial strategy examined consisted of the removal of the soil and MGP residues from the gas holder foundations, the demolition of the upper portion of the foundations, and the excavation of overtly contaminated soil to about 1.8 meters bgs. The excavated material would be segregated and disposed of off-site and the excavated areas would be backfilled. In addition, a barrier wall with a tar collection system would be installed along the riverbank to prohibit any tar from seeping into the river. The limitations of this strategy were that site usage restrictions would be necessary and contaminated groundwater would continue to migrate toward the river. The estimated cost for this remedial option ranged from 0.7 to 3 million (M) dollars.

Strategy 2

The second remedial strategy was similar to the first strategy except that the excavation would be carried out to a depth of about 3 meters bgs. Furthermore, in addition to the tar collection system, a slurry wall would be constructed around the entire contaminated area. The groundwater contained within the slurry wall would be pumped to the surface, treated, and reintroduced within the containment area to accelerate contaminant removal from both the saturated and unsaturated zones. The advantage of this strategy over the initial one was that land use options would increase and the release of contaminants to the river would be minimized. The cost for this remedial option was estimated to be between \$4 M and \$7.5 M.

Strategy 3

The third remedial strategy consisted of dewatering the site by installing a cofferdam of sheetpiling around the contaminated area and pumping the contained groundwater to the surface for treatment and discharge to a publicly owned treatment works (POTW). In addition, all of the overburden soils would be excavated above the saprolite layer. The excavated soils would be treated either on-site or off-site. The estimated cost of this remedial strategy would be from \$13 M to \$31 M.

Selected Strategy

After reviewing the initial three remedial options, the selected remedial approach sought to achieve the same goals as Strategy 2, but avoid the need for long-term pumping and treatment of groundwater. In order to prevent tar migration to and seepage into the river and to restrict groundwater flow, in situ solidification/stabilization of the saturated zone soils was proposed. The S/S would be accomplished by mixing a Portland Type I Cement (cement) additive with the overburden soils. The mixing process would be carried out by drilling or digging through the soil and 0.3 to 0.6 meters into the saprolite, and injecting cement additives from a depth of approximately 1.5 meters above the water table. The resulting mixed material was expected to have a permeability of about 10^{-6} cm/sec or less. In addition, to further reduce contaminant migration, a cement wall keyed into the saprolite would be constructed as a barrier parallel to the river. Using this remedial strategy, the construction of a public park area on the restored site and a riverwalk along the river could be achieved, thereby achieving an aesthetically pleasing, community-oriented end use of the site. The cost for the selected remedial strategy was estimated to be between $8 M and $10 M.

A summary of the costs and characteristics for each of the initial three remedial strategies and the final in situ S/S strategy selected is provided in Table 2-1.

Table 2-1
Summary of Remedial Options

Strategy	Characteristics and Estimated Costs
1	Excavate (1.8 meters bgs), segregate, and off-site disposal with a tar containment wall along the river ($0.7 M to $3 M)
2	Excavate (3 meters bgs), segregate, and off-site disposal with a tar containment wall along the river and slurry wall around all contaminated area with groundwater pump and treat ($4 M to $7.5 M)
3	Dewatering site, pumping and treating groundwater, excavating all soil above saprolite with on-site or off-site treatment ($13 M to $31 M)
S/S	Excavation with S/S in contaminated area with cement barrier wall along the river ($8 M to $10 M)

Preliminary Activities Prior to In Situ Remediation

Before the selected remedial strategy could be implemented, several preliminary activities or studies had to be completed. First, a treatability study needed to be completed, then a feasibility study was required, and, finally, a risk assessment was needed.

Treatability Study

The major focus of the treatability study was to test the stability of the contaminated soils that were expected to undergo in situ S/S with different amounts and types of cement additives. Thus, a series of bench-scale screening tests were carried out using soil samples collected from the site with various amounts of cement and mixtures of both cement and fly ash.

The two main parameters of interest in the treatability testing were the unconfined compressive strength (UCS) and the final permeability of the final mixed materials. The UCS measurements were done to assess the ability of the treated soil to withstand overburden loads. The UCS was determined using a standard pocket penetrometer instead of the standard ASTM method since neither the curing time and sample volume needed for the ASTM method could be met. Based on previous work, the results from the standard penetrometer tests were expected to be equivalent to about twice the value expected using the ASTM method. For the permeability testing, samples were prepared and tested according to ASTM D-2434.

UCS results indicated that all of the soil samples contained PC at 10% by weight achieved a value of about 4.4 kg/cm^2 (63 psi) after five days of curing. Samples that contained both cement and fly ash achieved similar UCS values at comparable weight percentages, but after longer curing times. These results indicated that both tar-containing and uncontaminated soils were effectively solidified using either cement or a combination of cement and fly ash. For example, the EPA considers a solidified material with a UCM of at least 3.5 kg/cm^2 (50 psi) to be satisfactory in order to provide a stable foundation for loads such as impermeable caps, cover fill, and construction equipment (USEPA OWSER Directive No. 9437.00-2A).

Using weight percentages of 10% for cement or a combination of cement and fly ash resulted in permeability values of about 10^{-6} cm/sec or less, with lower permeability values obtained at the longer curing times.

Feasibility Study

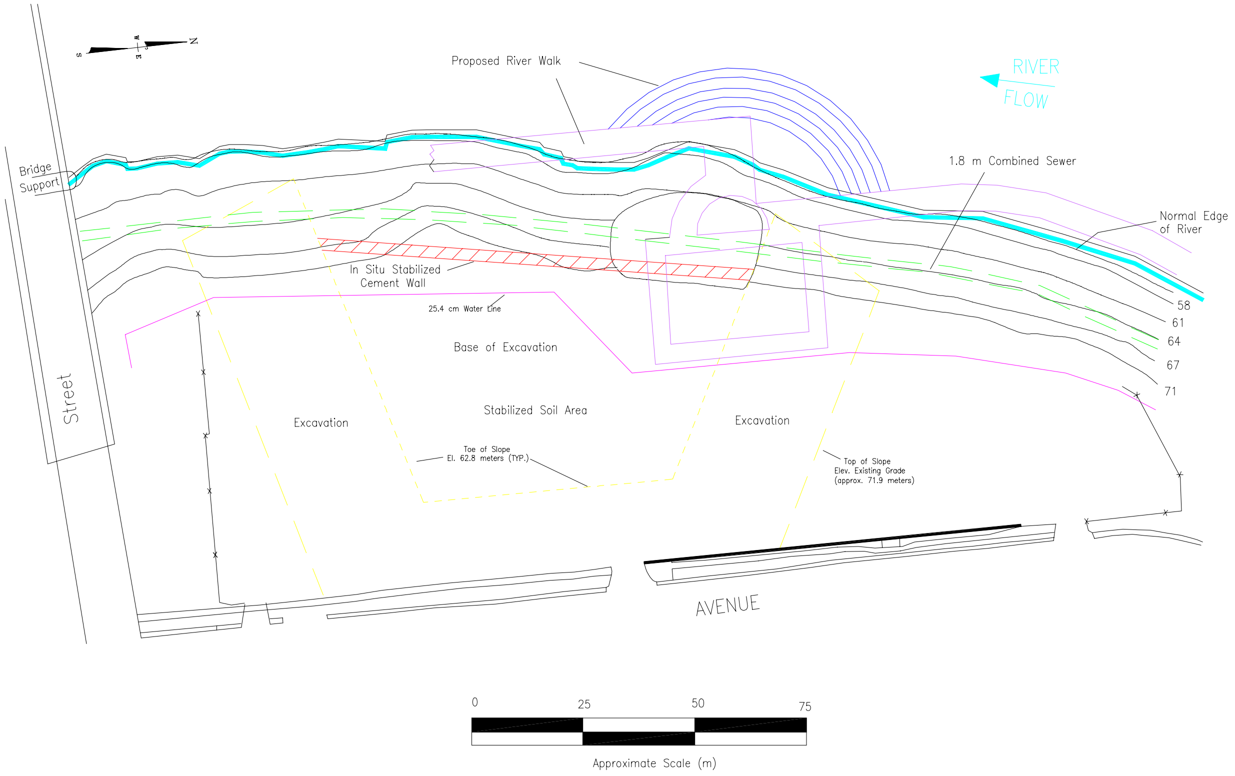
A focused feasibility study was carried out after the treatability study. The feasibility study concluded that the auger-type drilling method appeared to be the most appropriate for application at the site and the costs would range from about $58 to $106 per cubic meter, not including the costs for groundwater treatment. In addition, the feasibility study recommended that the following actions be taken:

- conduct a risk assessment to determine site-specific cleanup goals,
- quantify the soil volume in excess of the cleanup goals,
- perform a comprehensive site-specific treatability study to verify remedial effectiveness and optimize the use of additives,
- prepare a conceptual and preliminary engineering design,
- prepare project plans and specification for contractor bid selections,
- provide construction period oversight services,

- photodocument and record or video construction activities,
- prepare construction as-built drawings and a closure inspection, and
- conduct post-construction monitoring to verify remedial effectiveness.

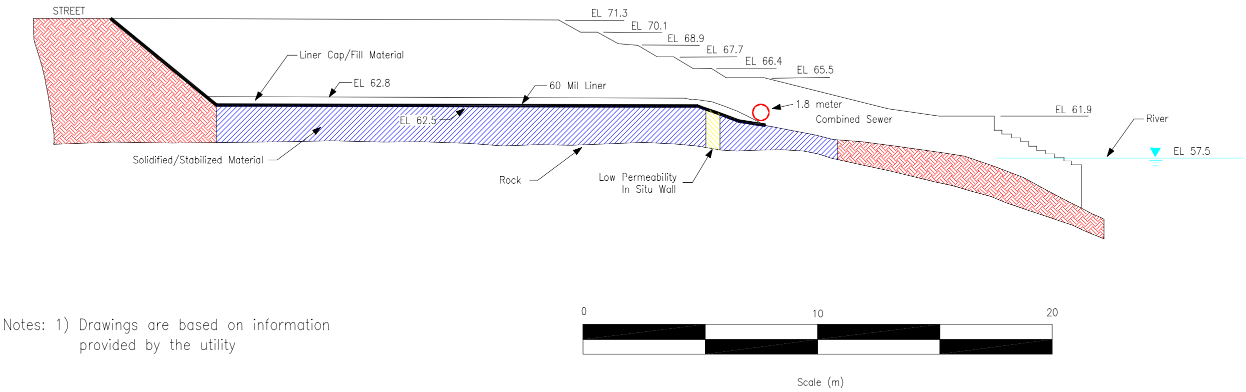
Conceptual Plans

The conceptual drawings of the remedial strategy selected are shown in Figures 2-5 and 2-6. Figure 2-5 shows in an areal view the anticipated locations of soil excavation, the major area undergoing in situ S/S, the solidified cement barrier wall, combined sewer system, and proposed riverwalk area. As indicated in this figure, the excavated and solidified area accounted for a significant portion of the site and encompassed essentially all of the contaminated zones identified in the two phases of site characterization. Figure 2-6 illustrates the cross-sectional view of the proposed remediation, including the elevations for the solidified area, the cement barrier wall, and the combined sewer system.



Note: This map is based on maps and information provided by the utility company

Figure 2-5



Notes: 1) Drawings are based on information provided by the utility

Figure 2-6

According to the conceptual plan, the material excavated during the remediation would be segregated for disposal and clean fill would be brought in as necessary. After in situ S/S was completed, a synthetic liner (shown in Figure 2-6) would be installed over that area and clean fill would be placed over it. The final grading and restoration of the site would depend on the specific construction plans for the proposed public park and riverwalk.

Risk Assessment

A preliminary health-based risk assessment was prepared to determine the risk-reduction effectiveness of the in situ method selected for the site. The resulting report identified the chemicals of concern, described their possible off-site routes of migration, identified the possible human receptor populations, estimated the potential chemical exposure levels, evaluated the possible adverse effects of chemical exposure, and determined how effectively the in situ stabilization would reduce potential health risks following redevelopment of the site into a public park area and riverwalk.

Estimated risk levels were calculated for exposure models and toxicity values for the chemicals of concern and compared for park use with and without in situ remediation. The results showed that even without remediation the risks from exposure pathways were relatively low. However, without any remediation, the estimated potential cancer risk to young children from contact with contaminated soils and ingestion of fish from the river exceeded the upper-bound of the range deemed reasonable and appropriate for the site (a 10^{-6} excess risk). For example, without remediation, the summed cancer risks for all chemicals of concern, primarily the PAHs, indicated that there unacceptable cancer risks to young children as a result of anticipated contact with contaminated soils, as shown in Table 2-2.

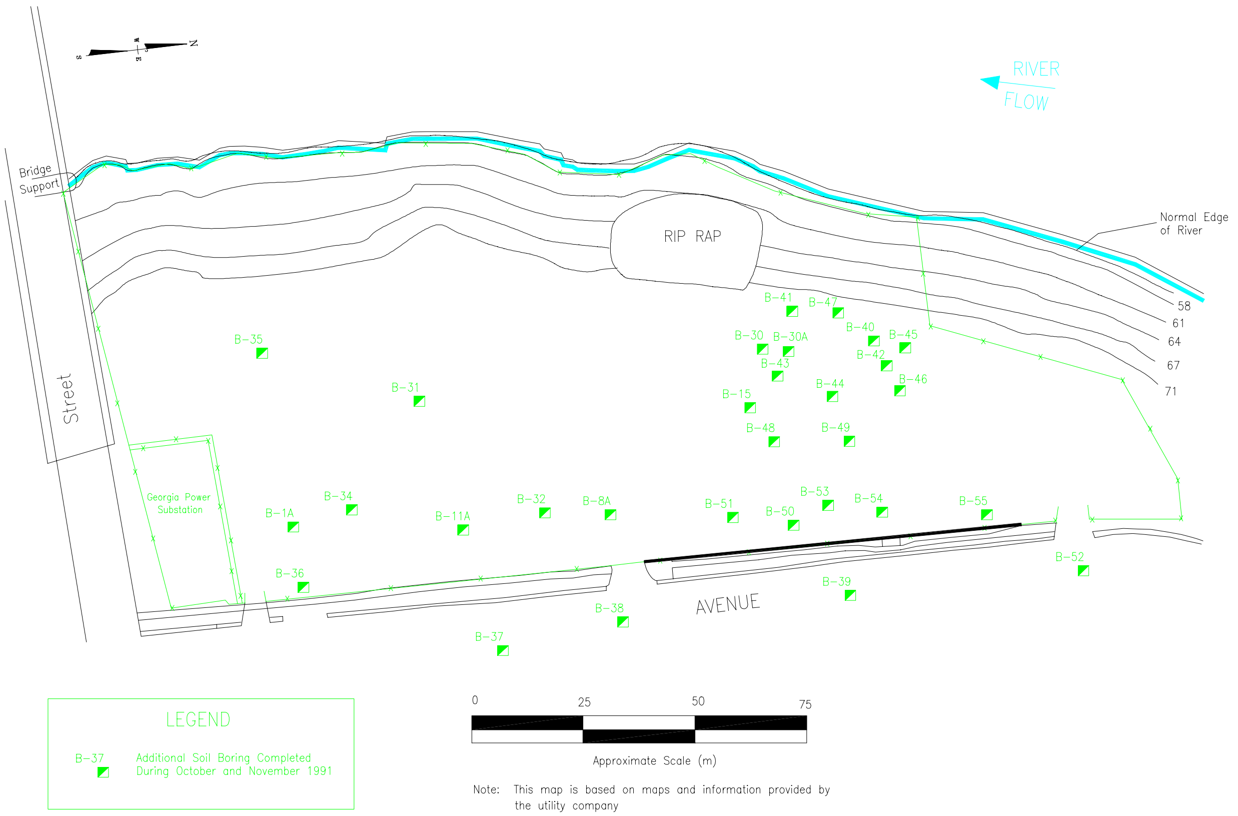
Table 2-2
Comparison of Overall Hazard Indices and Cancer Risks

	Sum of Hazard Indices		**Sum of Increased Long Term Cancer Risks**	
Pathway	**Without Remediation**	**With S/S Remediation**	**Without Remediation**	**With S/S Remediation**
Inhalation of vapor-phased compounds	2.1×10^{-4}	negligible	7.8×10^{-9}	negligible
Incidental ingestion of soil - child	1.8×10^{-1}	negligible	1.5×10^{-4}	negligible
Dermal contact with soil - child	2.9×10^{-1}	negligible	3.2×10^{-4}	negligible
Incidental ingestion of water while swimming	2.5×10^{-7}	1.4×10^{-11}	1.7×10^{-10}	9.5×10^{-15}
Dermal exposure while swimming	3.1×10^{-5}	1.7×10^{-9}	2.0×10^{-9}	1.1×10^{-13}
Ingestion of fish	2.2×10^{-3}	1.3×10^{-7}	9.4×10^{-5}	5.3×10^{-9}

Using in situ S/S, the cancer risks from the exposure to the chemicals of concern could be dramatically reduced or essentially eliminated. For example, all of the risks associated with contact with the river water would be reduced to well below 10^{-6}. Additionally, the calculated hazard indices were less than one for all of the exposure scenarios examined, including both short-term and long-term exposures, meaning that the risk after in situ remediation were not significant, as shown in Table 2-2.

Final Site Characterization and Treatability Study

Additional site characterization was carried out prior to the remediation at the request of the Georgia Department of Natural Resources (DNR). This work consisted of the completion of 14 soil borings (BH-27 through BH-40) located primarily at the borders of the proposed excavation to better define the extent of contamination, as shown in Figure 2-7 and the collection and analysis of soil samples. The results of this investigation showed that elevated PAH and TPH concentrations (greater than 500 mg/kg of TPH or 200 mg/kg of PAHs) were found in the northwestern portion of the site, typically at depths of 7 to 15 meters bgs.



Note: This map is based on maps and information provided by the utility company

Figure 2-7

In addition, three samples of subsurface media were collected for a comprehensive treatability study. The results from this study showed that the treated material using 10% by weight of cement would easily achieve a UCS of 7.0 kg/cm^2 or greater with permeability values as low as 10^{-7} cm/sec. Furthermore, TCLP tests on the treated material showed that neither the volatile nor the semivolatile organic compounds (VOCs and SVOCs) would leach in excess of the TC regulatory levels. Using the results from this study, a design mix with 10% by weight of cement was specified for the treatment of contaminated soils and a richer mixture using 25% by weight was specified for the containment wall along the river portion of the site.

Finally, fifteen borings (B-41 through B-55) were advanced with no collection of soil samples for analysis. These borings were primarily located in the northern portion of the site and were advanced to note changes in the subsurface in intervals of about 1.5 meters. Using the results from these and the previous borings, the extent of the subsurface contamination was determined at various depths. The MGP-impacted materials were separated into two categories: 1) soils containing tar and 2) soils containing coal, ash, and cinders. In the shallower soils (1.5 meters below grade) tar-containing soils predominated in the southern portion of the site while soils in the northern part of the site contained coal, ash, and cinders. From 3 to 11 meters below grade, the contamination pattern was somewhat different since coal, ash, and cinders were observed in the soil along the western edge of the site while the tar-containing soils were found in both the southern portion of the site and in discontinuous pockets in the northwestern portion. At the 12 to 14 meters deep, tar- contaminated soils were observed only in the southern to central portion of the site and by about 15 meters, only a small pocket of tar-contaminated soils in the northwest corner of the site was found.

Based on the extent of MGP-impacted materials observed in the various subsurface layers examined, the estimated volume of MGP-impacted soils was calculated to be approximately 39,100 cubic meters. Additionally, a saprolite contour map was generated to aid in the remediation effort.

In Situ Solidification/Stabilization

Pre-excavation Actions

First, a detailed work plan was prepared to serve as the guidance document covering all aspects of the in situ S/S, including specifications for personal protection during all portions of the work.

Second, site control activities were carried out. These activities included mobilizing material, equipment, and personnel to the site and enclosing the entire work area using a 1.8-meter high security fence and altering traffic flow patterns along the avenue located parallel to the eastern edge of the site in order to ease traffic congestion during the remediation. Following these initial steps, a floating boom and adsorbents were installed along the riverbank to protect the river from potential tar seepage during remedial activities, as per the Army Corps of Engineers permit. Each day the boom and adsorbent material were inspected and the adsorbent was replaced when needed. Next, erosion control measures were taken, including the construction of storm water diversion structures and siltation containment barriers. For example, storm water was either diverted around the site using a system of ditches and berms or allowed to percolate into the ground within the zone of construction. If any water ponded, it was sampled and analyzed for TPH, PAHs, and BTEX and discharged to the local POTW in accordance with a temporary wastewater discharge permit issued for that purpose. To reduce siltation of the river by erosion, hay bales and silt curtains were placed about 1 meter inside the security fence along the riverbank.

Third, after the site control measures were completed, the existing facilities and structures on the site were demolished and the resulting debris was taken off-site for disposal as a solid waste at the local municipal landfill. Initially, the asphalt was removed along with rails and cross ties from an obsolete railroad spur. Then, clearing and grubbing of trees and other vegetation along the riverbank were carried out. Next, Holder # 3, the largest gas holder, and other concrete structures encountered during excavation were removed and tested before being disposed of in the municipal landfill. Other structures removed during the demolition phase of the work included four on-site buildings, an abandoned steel gas line, two underground storage tanks, and a propane gas tank farm.

Excavation

Before the in situ remediation could begin, about 4.6 to 6.1 meters of overburden had to be excavated and segregated into “affected” and “non-affected” materials. The “affected” materials were defined as those having chemical concentrations at or above the following levels: 200

mg/kg of total PAHs, 100 mg/kg of carcinogenic PAHs, 100 mg/kg of BTEX, and 500 mg/kg of TPH. The segregation of material was first accomplished by inspecting each lift for the presence of odors or discoloration indicative of tar. Composite grab samples of excavated material were collected for analysis and any material that exceeded the above limits was temporarily stored until it could be added during subsequent in situ mixing. However, because the volume of affected material was higher than anticipated, some of the affected material was disposed of off-site in a double-lined special waste landfill. Material that was found to be unaffected was stored off-site until it could be used either as clean backfill material after the solidification/stabilization was completed or as clean backfill for the local municipal landfill.

During the excavation process, several procedures were followed to reduce the release of fugitive dust and odors from contaminated materials. For example, water was applied to the adjacent streets and the excavation areas to suppress dust during the site activities and areas that contained odiferous material were covered until the materials were removed. In addition, when the material from Holder # 1 were being removed, an aqueous film-forming foam was sprayed on the exposed material to reduce odors.

The excavation was carried out in strips moving from east to west using lifts of about 0.76 meters until a depth of approximately 0.61 meters above the water table was achieved. During this phase of work, about 66,000 cubic meters of soil were excavated and segregated. Additional excavation occurred near the river during a later phase of the remediation in order to prepare for the construction of the riverwalk and the combined storm water/sewer system.

In Situ S/S

Bulk storage for the cement binding agent and a batch plant were set up in the southeastern corner of the site to prepare the design mix slurry materials. In general, the slurry was pumped to a drill rig fitted with 2.4-meter diameter hollow-stem augers and was introduced into the subsurface through three exit ports at the bottom of the auger. The depth of advancement for each auger hole was specified based on the results of the site characterization work. Both the depth and location were used to calculate the amount of slurry needed to achieve either the 10% or 25% by weight mixture. The ratio of water to cement varied across the site, but typically was approximately 1.5 to 1. Figure 2-8 generally illustrates the process of in situ S/S.

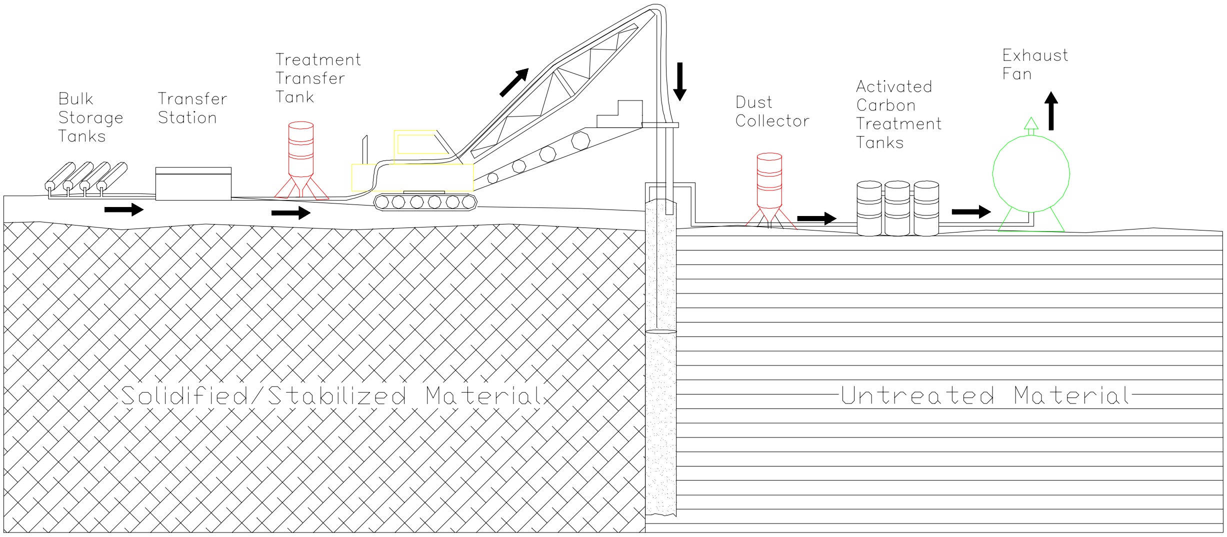


Figure 2-8

Containment Wall and Riverwalk

The containment wall along the river side of the site was completed first. During this portion of the work, the water level in the river was maintained below an elevation of 58 meters by controlling the upstream lock and dam operations.

As specified in the final treatability study, a mixture containing 25% by weight of cement was used during the advancement of the overlapping auger holes that constituted the containment barrier. The auger holes were keyed about 1 meter into the saprolite and resulted in a barrier wall that was about 2.4 meters wide and 137 meters long.

After the wall was completed and cured for five days, excavation of the river side of the wall was carried out in a strip 9 to 15 meters wide down to the saprolite (about 9 meters below the original grade) at an elevation of about 59 meters. Tar-impacted soils were temporarily stored on the other side of the wall for subsequent in situ S/S with the in-place soils. The exposed saprolite was sprayed with a sealing agent to reduce potential migration of materials from this layer to the underlying bedrock.

After completion of the in situ containment wall along the west site of the site, a portion of the area was between the wall and the river was converted to a scenic riverwalk for the public.

In Situ S/S of On-site Soils

The area of the site west of the containment wall underwent in situ stabilization by simultaneously mixing and drilling a slurry of cement with the soils. The slurry was mixed and drilled to a depth of about 11 meters bgs using an 2.4-meter diameter auger and keying the mix about 0.3 meters into the saprolite. Figure 2-9 shows the pattern of overlapping borings that was used to accomplish a thorough mixing and stabilization of the impacted soils. In all, approximately 1823 borings were required to complete the treatment process.

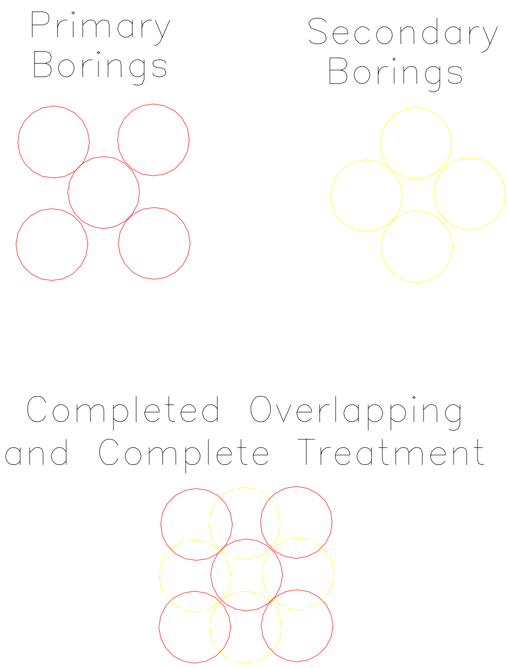
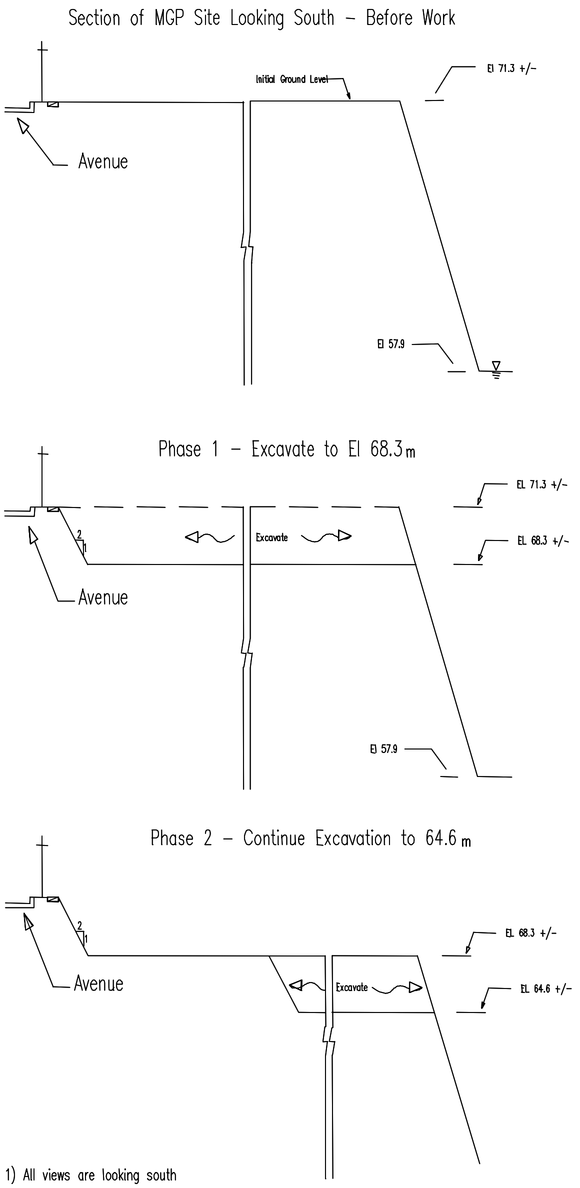


Figure 2-9

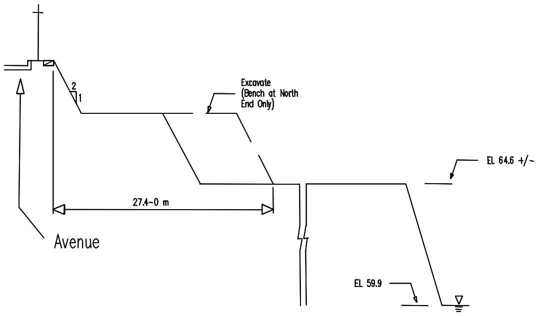
Figures 2-10 through 2-11 illustrate the sequence of actions carried out for the in situ treatment in a series of cross sections, including the construction of the containment wall along the west side of the site. As shown in these figures, there were several phases of construction, beginning with excavation and segregation of on-site soils and ending with in situ S/S of the MGP-impacted soils. Approximately 72,000 cubic meters of MGP-affected soils were treated in situ at this site and 65,000 cubic meters of soil were excavated. Some of the excavated soils were treated and returned to the site.



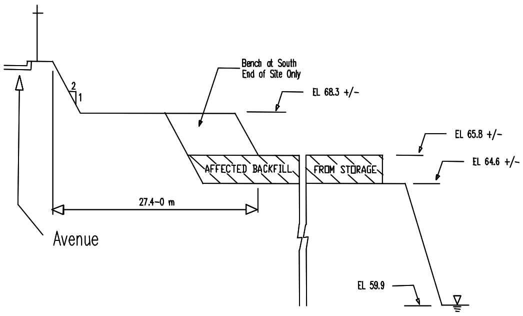
Notes: 1) All views are looking south
2) Drawings are based on information provided by Engineering Company
3) Drawings are not to scale

Figure 2-10

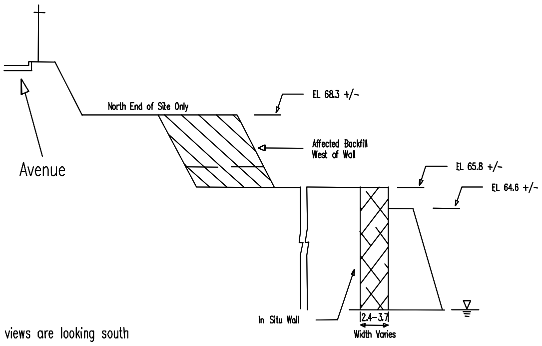
Phase 3 – Complete Excavation to El 64.6 m



Phase 4 – Return Portion of Affected Material to Site



Phase 5 – In Situ Wall, Return Additional Affected Material



Notes: 1) All views are looking south
2) Drawings are based on information provided by Engineering Company
3) Drawings are not to scale

Figure 2-11

After all of the stabilization was completed, the area was covered with 0.3 meters of unaffected soil and a 60-mil high density polyethylene (HDPE) synthetic liner. Backfill, consisting of unaffected soils previously excavated from the site and temporarily stored off-site, was placed over the liner in lifts and compacted to 90% Standard Proctor Density. The backfilled material restored the elevation to approximately the pre-excavation elevation of about 71 meters. Additional topsoil was added to the planned grade for the public park area.

In Situ S/S Performance

The performance criteria for the treated materials were:

- a UCS of 4.2 kg/cm^2 or more within 28 days,
- a minimum permeability value of 10^{-6} cm/sec for the containment wall,
- a minimum permeability value of 10^{-5} cm/sec for the solidified soils in the rest of the site, and
- a PAH content in TCLP leachate below 10 mg/L.

UCS testing was done on approximately 300 randomly selected shafts of freshly treated soils and permeability and TCLP leachate testing was carried out on about 10% of those samples. If any shafts were found to exceed the performance criteria, they had to be reprocessed.

Post-Remediation Monitoring

Starting in 1993, post-remediation monitoring was conducted semiannually on ten monitoring wells to determine if any of the tar constituents were leaching from the solidified material. Results from 11 rounds of groundwater sampling and analysis showed that all of the constituents tested (including: PAHs, total BTEX, benzene, and total and amenable cyanides) consistently were below their respective Maximum Contaminant Levels (MCLs) under the Safe Drinking Water Act (SDWA).

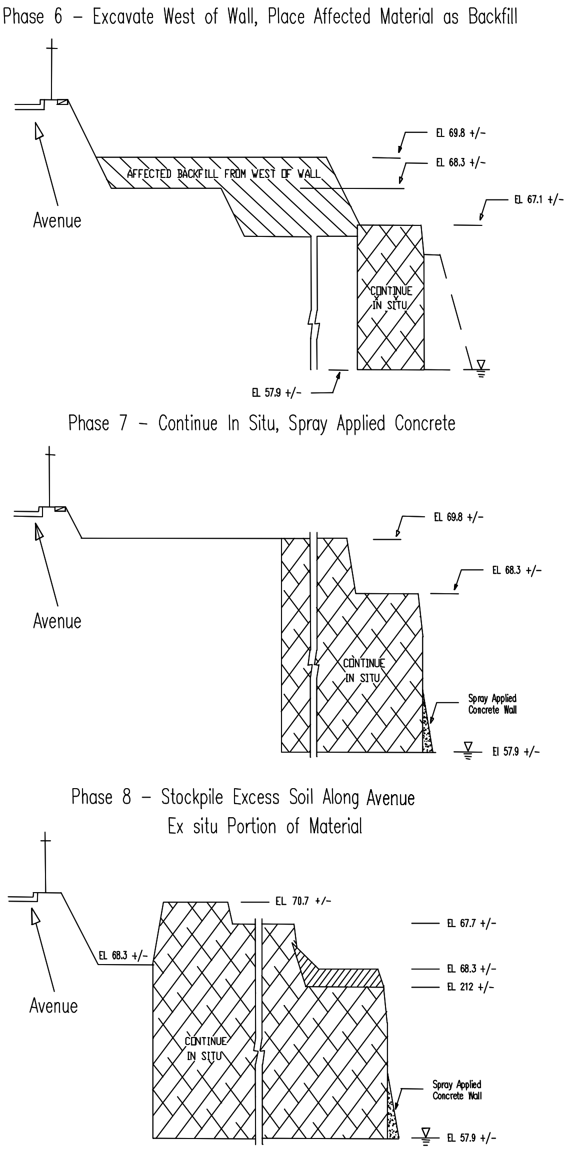
For example, total PAH concentrations ranged from non-detect to 6.5 mg/L prior to the completion of remediation, with six of the 10 wells showing detectable levels. Post-remediation sample results from all 10 wells were non-detect for PAHs during all 11 sampling rounds. Similarly, total BTEX concentrations ranged from non-detect to 0.6 mg/L before remediation with 5 of the 10 wells showing detectable levels. Post-remediation BTEX results showed one detectable value for benzene (0.002 mg/L) below the MCL (0.005 mg/L) in one well during only one of the 11 sampling rounds. None of the other BTEX compounds were detected in groundwater samples collected during post-remediation monitoring from any of the wells.

Total and amenable cyanide concentrations were detected in all of the groundwater samples from the 10 wells prior to remediation. After remediation most of the sample results were non-detect. However, some of the wells had detectable levels of cyanide during a few rounds of sampling and all of the wells had low levels of cyanide during one round of sampling in early 1997. All of the cyanide concentrations observed during post-remediation monitoring were below the MCL of 0.2 mg/L. In addition, an analysis was carried out on the cyanide data from the three wells that had detectable levels more than once during post-remediation monitoring. The results from the analysis showed that the trend in each of the wells was a pattern of decreasing cyanide concentrations over time.

Based on the results of the post-remediation monitoring during 11 rounds of sampling, the utility proposed to Georgia EPD that further groundwater sampling be discontinued and that the monitoring wells be appropriately abandoned. Furthermore, the utility proposed that a deed restriction be made that would prohibit any future on-site development that could negatively impact the efficacy of the solidified material.

Current Site Status

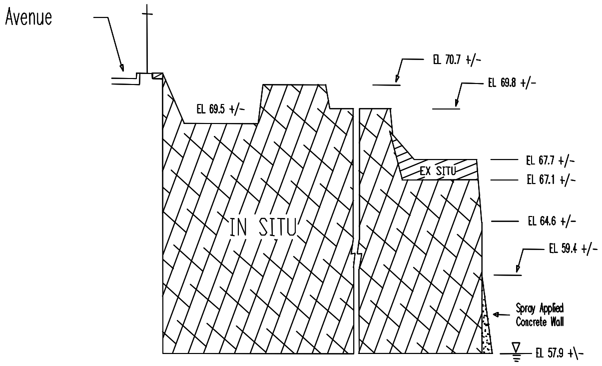
All data collected to date indicate that the remediation using in situ S/S was a complete success at this site. Not only were the site remediation goals satisfied and the post-remediation monitoring successful, but also a public park and scenic riverfront walkway were completed.



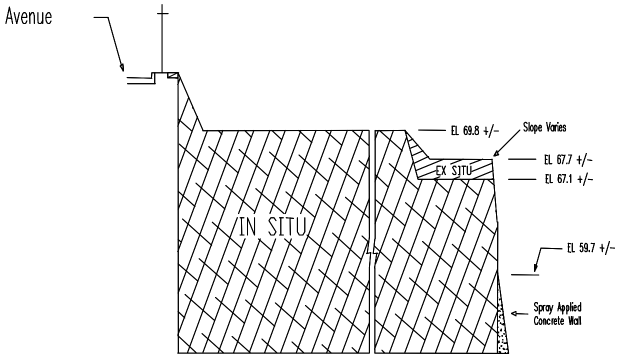
Notes: 1) All views are looking south
2) Drawings are based on information provided by Engineering Company
3) Drawings are not to scale

Figure 2-12

Phase 9 – Complete In Situ



Phase 10 – Level In Situ to EL 68.9 m



Notes: 1) All views are looking south
2) Drawings are based on information provided by Engineering Company
3) Drawings are not to scale

Figure 2-13

3

CASE STUDY 2: A TREATABILITY STUDY ON SOILS FROM A FORMER MGP SITE IN WISCONSIN

Site Description

The treatability study described in this case study was performed for a former MGP site located on a river in Wisconsin. The former MGP used the Lowe carburetted water gas process to produce gas from 1907 to 1948. Three separate environmental site investigations were performed at the site during the 1990s. These investigations showed that most of the soils at the site consist of silty sand and gravel, except for a 1.8-meter layer of silt that covers approximately one third of the site. In addition, VOC and PAH contamination was present above regulatory standards in soil and groundwater over much of the site.

Remedial Approach

Based on the site characteristics that were known for the former MGP site, a review of remedial options was performed. It was decided that the in situ S/S remedial approach would be pursued. As a result, a treatability study was performed, as recommended by EPA guidelines (EPA, 1993), since it is the only method to document the applicability and performance of S/S mixtures for a particular site.

Treatability Study

Introduction

A treatability study was performed to determine the feasibility of treating the site soils from the former MGP site in Wisconsin using the S/S process. As part of the study, the chemical and physical properties of the site soils were determined. This information was used to select additives for mixing with the site soils that would improve the physical characteristics of the soils and reduce leaching of contaminants.

The treatment goals for the treated soils were based on the federal guidelines for S/S treatment of soils (EPA, 1989) and prior experience of the contractors. Evaluation performed during the study included leaching tests (SPLP and sequential batch leaching), UCS, permeability testing, durability testing (freeze/thaw and wet/dry), and cost determinations of the mixtures used. In addition, it was decided that recycled materials, such as fly ash, would be preferable additives.

The treatability study was performed using a phased approach so that the best additive mixtures for implementing the S/S process could be determined during the course of the study. These phases were as follows:

1. untreated soils characterization
2. preliminary testing to evaluate a variety of additives at different proportions
3. intermediate testing to further evaluate additives at different proportions
4. confirmation testing to determine the performance of a few candidate mixtures of additives
5. additional testing for the final mixtures, using the worst case soils from the site

Untreated Soil Characterization

Two bulk samples were received from the site for testing. The first sample was considered representative of the soils at the site and was called the "original untreated material". Later, a sample was collected that was believed to be representative of the most highly contaminated soils at the site. This second sample was called the "worst case" sample and was used in the last phase of the treatability study.

After each sample was received, it was gently homogenized to reduce the volatilization of organic compounds. In addition, particles measuring more than 1.25 cm in diameter were removed to ensure that the material was appropriate for bench-scale testing. The worst case sample was a black, gravelly, sandy soil that did not contain any oversized particles.

The purpose of characterizing untreated soils was to establish a baseline for monitoring the ability of the S/S mixtures to improve the soil characteristics. For this reason, the untreated soils were subjected to a variety of chemical and physical analyses. Total constituent analyses for the soils included measurements for BTEX compounds, PAHs, and total cyanide. In addition, two leaching tests, SPLP and sequential batch leaching, were performed, with analysis of the leachates for BTEX, PAHs, and total cyanide. Physical testing performed on the soils included moisture content, bulk density, and grain size determinations. Table 3-1 shows the results of the total constituent analyses for the untreated soils.

Table 3-1
Untreated Soil Characterization

Analyte	Original Untreated Material	Worst Case
Total BTEX (mg/kg or ppm)	100 ppm	324 ppm
Total PAHs (mg/kg or ppm)	1970 pmm	422 ppm[1]
Total Cyanide (mg/kg or ppm)	1.9 ppm	20 pmm

[1] Sample considered worst case due to higher BTEX and CN concentrations

The other results for the untreated soils are discussed with results from the treated soils testing, where appropriate, and were one of the key factors for evaluating the efficacy of different mixtures.

Preliminary Solidification Testing

Preliminary screening was used as an initial assessment of the ability of various mixtures to improve the characteristics of the site soils. A broad range of additives at various concentrations was selected based on the past experiences of the contractor in working with MGP-impacted soils. The mixtures selected are presented in Table 3-2.

Table 3-2
Preliminary Solidification Testing Mixtures

Mixture	Additives	Quantity (% of Soil Weight)
1	Portland Type I Cement (Cement)	10
2	Cement	20
3	Cement	25
4	Pleasant Prairie Fly Ash	20
5	Holnam Fly Ash	20
6	Blast Furnace Slag	20
7	Cement / Pleasant Prairie Fly Ash	10 / 10
8	Cement / Pleasant Prairie Fly Ash	3.3 / 16.7
9	Cement / Pleasant Prairie Fly Ash	1.8 / 18.2
10	Cement / Pleasant Prairie Fly Ash	0.5 / 19.5
11	Cement / Holnam Fly Ash	10 / 10
12	Cement / Blast Furnace Slag	1.8 / 18.2
13	Cement / Lime Kiln Dust	10 / 10
14	Cement / Hydrated Lime	10 / 10
15	Cement / Powdered Activated Carbon / Organophillic Clay	15 / 4 / 1

The mixtures shown in Table 3-2 were created by mixing the additives with water and then adding the resulting grout to the soils. A bench top mixer was used to mix the samples until they appeared homogeneous. During the process, the temperature and organic vapor emissions were monitored for later use in designing the field-scale operation. After mixing, the samples were packed into cylindrical molds with a diameter of approximately 5 cm and a height of 10 cm and allowed to cure in a humid room at approximately 21°C for 7 days.

Strength Testing

The strength of the treated soils was determined using a cone penetrometer after 1, 3, and 7 days of curing. These measurements are presented in Table 3-3. As shown in the table, five of the mixtures achieved the maximum measurable strength (4.4 kg/cm^2) in the treated soil in just 1 day of curing. Each of these five samples contained a mixture with at least 10% cement by weight of the untreated soils. After 7 days of curing, three more samples achieved the maximum penetrometer strength. In general, there was a positive correlation between the cement content and the strength of the material.

Table 3-3
Penetrometer Testing of Preliminary Mixtures (kg/cm^2)

Mixture	1 Day	2 Days	7 Days
10% Cement	1.0	1.0	2.9
20% Cement	> 4.4	> 4.4	> 4.4
25% Cement	> 4.4	> 4.4	> 4.4
20% Pleasant Prairie Fly Ash	1.0	2.4	1.5
20% Holnam Fly Ash	< 0.5	0.5	0.5
20% Blast Furnace Slag	< 0.5	< 0.5	< 0.5
10% Cement / 10% Pleasant Prairie Fly Ash	2.9	> 4.4	> 4.4
3.3% Cement / 16.7% Pleasant Prairie Fly Ash	0.5	1.0	2.4
1.8% Cement / 18.2% Pleasant Prairie Fly Ash	< 0.5	< 0.5	< 0.5
0.5% Cement / 19.5% Pleasant Prairie Fly Ash	0.5	0.5	1.0
10% Cement / 10% Holnam Fly Ash	> 4.4	> 4.4	> 4.4
1.8% Cement / 18.2% Blast Furnace Slag	< 0.5	1.0	> 4.4
10% Cement / 10% Lime Kiln Dust	> 4.4	> 4.4	> 4.4
10% Cement / 10% Hydrated Lime	1.5	4.4	> 4.4
15% Cement / 4% PAC / 1% Organophillic Clay	> 4.4	> 4.4	> 4.4

Volumetric Expansion

The volumetric expansion of the samples was measured during curing to determine how much soil had to be excavated from the site in order to maintain the same ground level after remediation. The volume of the soil was measured before mixing and after the addition of the stabilization mixtures and subsequent curing for 1, 3, and 7 days. The volumetric expansion was expressed as a percentage of the initial volume and was not affected by curing time. Expansion varied from 25 to 42% for all of the mixtures, except for the 15% cement with 4% powdered activated carbon (PAC) and 1% organophillic clay mixture, which had a volumetric expansion of 64%. These volume increases reflected bulking of the soil from the addition of the mixtures as well as changes in density.

Slake (Submergence) Testing

Slake or submergence testing was performed to qualitatively evaluate the leachability and physical integrity of the treated soil. This procedure was performed after 7 days of curing and involved submergence of the cylinder-shaped monoliths of treated soil into deionized water for 3 days. After this time, visual observations were recorded, such as the presence of a sheen or film on the surface of the water, the presence of tar residuals, and the structural integrity of the monolith.

The results of the slake testing suggested that there was a strong correlation between the penetrometer strength and the deterioration observed in the monolith. In general, all of the mixtures containing cement showed little deterioration of the monolith and minimal discoloration of the deionized water. The water for these samples was typically slightly cloudy with a thin film present on the water surface. In particular, the 20% cement-only and 25% cement-only mixtures performed well, with clear water and minimal surface films being observed after 3 days of testing.

Intermediate Solidification Testing

Based on the results of the preliminary solidification testing, several additives and rates of addition were determined to be effective at improving the physical characteristics of the soil. Using this information, 10 mixtures were developed for the intermediate solidification testing. These mixtures included some of the mixtures used previously, along with some new mixtures based on different combinations and percentages of additives. As shown in Table 3-4, all of these mixtures incorporated cement, based on the positive results for cement in the preliminary testing. As before, the mixtures were added to the soils as a grout and mixed thoroughly in a bench top mixer.

Table 3-4
Intermediate Solidification Testing Mixtures

Mixture	Additives	Quantity (% of Soil Weight)
1	Cement	15
2	Cement	20
3	Cement / Pleasant Prairie Fly Ash	10 / 10
4	Cement / Pleasant Prairie Fly Ash	7.5 / 12.5
5	Cement / Holnam Fly Ash	5 / 15
6	Cement / Blast Furnace Slag / Bentonite	12 / 5 / 3
7	Cement / Blast Furnace Slag	1.8 / 18.2
8	Cement / Lime Kiln Dust	10 / 10
9	Cement / Hydrated Lime	10 / 10
10	Cement / PAC / Organophillic Clay	15 / 4 / 1

Viscosity

During the preparation of the mixtures indicated above, the viscosity of each grout was measured using a viscometer. The viscosity of the grout is an important consideration, as the field application of the S/S technology requires that the mixtures be pumpable. Eight of the ten mixtures had viscosities ranging from 5 to 11 centipoises (cP), calculated by dividing the reading of the viscometer at 600 rotations per minute (rpm) by 2. Two other mixtures had significantly higher viscosity values. Specifically, the 15% cement with 4% PAC and 1% organophillic clay mixture had a viscosity of 23 cP and the 10% cement with 10% hydrated lime had a viscosity of 112 cP. Typically, a grout viscosity of less than 50 cP is required to keep the grout workable during field-scale operations.

Strength Testing

The same procedure for strength testing was used during the intermediate solidification testing, as for the preliminary testing. The results of the cone penetrometer testing after 1, 3, and 7 days of sample curing are presented in Table 3-5. As shown in the table, eight of the ten mixtures achieved the maximum measurable strength (4.4 kg/cm^2) in the treated soils after curing for 7 days. The other two mixtures, consisting of mostly fly ash with some cement, had results of 2.9 and 2.4 kg/cm^2 after curing for 7 days. These results confirmed that cement was the key additive for providing strength in the treated soils.

Table 3-5
Penetrometer Testing of Intermediate Mixtures

Mixture	1 Day	2 Days	7 Days
15% Cement	3.9	> 4.4	> 4.4
20% Cement	> 4.4	> 4.4	> 4.4
10% Cement / 10% Pleasant Prairie Fly Ash	< 0.5	4.4	> 4.4
7.5% Cement / 12.5% Pleasant Prairie Fly Ash	< 0.5	2.9	2.9
5% Cement / 15% Holnam Fly Ash	< 0.5	1.0	2.4
12% Cement / 5% Blast Furnace Slag / 3% Bentonite	3.4	> 4.4	> 4.4
1.8% Cement / 18.2% Blast Furnace Slag	< 0.5	3.9	> 4.4
10% Cement / 10% Lime Kiln Dust	2.9	> 4.4	> 4.4
10% Cement / 10% Hydrated Lime	1.5	> 4.4	> 4.4
15% Cement / 4% PAC / 1% Organophillic Clay	2.4	> 4.4	> 4.4

Volumetric Expansions

The volumetric expansion of the treated soils resulting from the S/S process was measured in the same fashion as for the preliminary testing. As before, curing time did not have a significant effect on the expansion measured for the different mixtures. The volume increases after 7 days of curing ranged from 46 to 64%, with lower percentages measured for the cement-only and cement and lime kiln dust mixtures.

Sequential Batch Leaching Tests

Sequential batch leaching tests were performed according the method of the American Nuclear Society (ANS 16.1). During testing, the samples were submerged in deionized water and allowed to leach for three testing intervals, 7 hours, 48 hours, and 14 days. Treated soils from five of the ten mixtures were selected for the test based on the results of the penetrometer testing and visual observations. The selected mixtures were the 15% cement; 10% cement with 10% fly ash; 12% cement with 5% blast furnace slag and 3% bentonite; 10% cement with 10% hydrated lime; and 15% cement with 4% PAC and 1% organophillic clay mixtures.

The results of the sequential batch leaching tests indicated that the selected mixtures had the potential to reduce leaching of MGP constituents from the site soils after stabilization. In particular, the cement with PAC and organophillic clay mixture was very effective, resulting in no detectable concentrations of individual PAHs or total cyanide for each leaching interval.

Although the other four mixtures did not perform as well as the cement with PAC and organophillic clay mixture, three mixtures did produce leachate concentrations that were generally lower than the untreated soil. One sample, the cement-only mixture did not immobilize MGP constituents as illustrated by the fact that the leaching results for the solidified soil were not significantly less than those for the untreated soil. The results for all of the treated soils did suggest that the leaching of contaminants was slowed somewhat by the solidification of the soils into a monolith.

Optimization Testing and Evaluations

Based on the results of the intermediate testing, four mixtures were developed for the optimization phase of the testing, which was designed to further test the best candidate mixtures for application at the former MGP site. Table 3-6 presents the four mixtures that were developed for the optimization testing. Mixture 1 was very similar to a previously tested mixture, with some of the cement replaced by more fly ash to save cost. Similarly, the third mixture was based on the cement with PAC and clay mixture, with fly ash substituted for some of the cement to save cost. The second mixture was based on the 10% cement with 10% hydrated lime mixture previously tested, with the addition of Spersene, a drilling fluid, to decrease the viscosity to within appropriate limits. Finally, in the last mixture, petroleum coke was substituted for PAC to save cost.

Table 3-6
Optimization Testing Mixtures

Mixture	Additives	Quantity (% of Soil Weight)
1	Cement / Pleasant Prairie Fly Ash	8.5 / 11.5
2	Cement / Hydrated Lime / Spersene	10 / 10 / 0.5
3	Cement / Pleasant Prairie Fly Ash / PAC / Organophillic Clay	10 / 5 / 1 / 1
4	Cement / Petroleum Coke / 1% Organophillic Clay	15 / 4 / 1

As was done previously, the viscosity of the grout mixtures was checked prior to mixing with the soil and the temperature changes were monitored. The addition of Spersene lowered the viscosity of the cement and hydrated lime mixture to 23.5 cP, which is suitable for pumping. Similar to the previous work, the temperature changes and the viscosities for the other mixtures were all suitable for application in the S/S process.

After the samples were mixed in the bench top mixer, they were packed into the cylindrical molds and allowed to cure for 28 days. Similar to before, cone penetrometer measurements were performed during the curing process. Based on the initial strength testing, the cement with hydrated lime and Spersene sample was eliminated from further consideration because of poor sample integrity. In addition, a decision to eliminate the cement with fly ash and PAC and organophillic clay was made because of the prohibitive cost of the mixture. As a result, only the two remaining mixtures were subjected to further testing during the optimization phase.

The calculated volumetric expansions for the treated soils from the two remaining mixtures were 54% for the cement with fly ash and 54% for the cement with pet coke and organophillic clay. These values were very comparable to the previous value obtained during the intermediate testing.

In addition to the testing already discussed, the treated soils from the two mixtures were also subjected to the following list of tests, after both 7 and 28 days of curing:

- UCS (ASTM D 2166)
- Permeability (ASTM D 5084)
- Durability
  - Wet/Dry (ASTM D 4843)
  - Freeze/Thaw (ASTM D 4842)
- Sequential batch leaching (ANS 16.1) for BTEX, PAHs, and total cyanide
- SPLP (EPA Method 1312) for BTEX, PAHs, and total cyanide

The results of the optimization testing indicated that the soils treated with the two final candidate mixtures both performed well relative to the treatment objectives. The following subsections briefly discuss the test results.

Unconfined Compressive Strength

The UCS of the treated soils was determined to assess their ability to withstand overburden loads. The EPA considers a soil that has been treated with S/S to be a stable foundation for construction equipment, impermeable caps, and soil cover material if the UCS is 3.5 kg/cm^2 or greater (USEPA OSWER Directive, No. 9437.00-2A).

Both of the treated soils tested met this criterion after 28 days of curing. The UCS result for the cement with fly ash mixture was 7.7 kg/cm^2, while the result for the cement with pet coke and organophillic clay mixture was 7.5 kg/cm^2.

Permeability Testing

Permeability testing was performed to determine the ability of the treated soil to retard the flow of groundwater. Although EPA guidelines (EPA, 1989) recommend a maximum permeability of 10^{-5} cm/sec for treated soil, a treatment goal of 10^{-6} was set for this treatability study.

The treated soils for both mixtures exhibited lower permeability values after 28 days than after 7 days, suggesting the permeability of the treated soils decreased with longer curing times. The 28-day permeability values were 1.3×10^{-6} for the soil treated with cement and fly ash and 7.1×10^{-7}

cm/sec for the soil treated with cement, pet coke and organophillic clay. These values are satisfactory compared to permeability criterion set for this study.

Durability Testing

Durability testing was performed to evaluate the ability of the treated soils to withstand weathering and maintain their physical integrity. The durability tests performed were the freeze/thaw and wet/dry tests. EPA guidelines for S/S recommend a maximum weight loss of 15%, when performing durability tests (EPA, 1989).

Both durability tests involved 12 cycles of 24 hours at each extreme. For example, the freeze/thaw test was performed by alternately freezing and thawing the samples for 24 hours at a time. Similarly, the wet/dry test was performed by alternately soaking and drying the samples for 24 hours at a time. At the end of each cycle, a wire brush scratched the samples at a constant pressure. After 12 cycles, the weight of the sample was compared to the initial weight of the sample, and a percent material loss was calculated.

The treated soils for both mixtures passed the wet/dry durability test after only 7 days of curing, with mass losses of less than 1% for each sample. However, the freeze/thaw results were not as consistent. While the results for the cement with pet coke and organophillic clay were 3% or less for the 7- and 28-day curing times, the cement with fly ash sample failed the test with greater than 30% mass loss for both curing times. As a result, the test was repeated for a sample that had cured for 81 days, and the result was 2%, which is well within the limits for S/S soils.

Sequential Batch Leaching Tests

Sequential batch leaching tests were performed for the two mixtures to assess the leachability of BTEX, PAHs, and total cyanide from the treated soil monoliths into deionized water. During the testing, which was performed according to the method described previously for intermediate solidification testing (ANS 16.1), leaching periods of 7 hours, 48 hours, and 14 days were used.

The results indicated that both mixtures slowed the dissolution of contaminants from the soil. For instance, the 14-day leachates for the untreated soils did not have detectable concentrations of PAHs, since the leaching occurred within the first 48 hours of submergence. Conversely, the treated soils both had detectable concentrations of PAHs in the 14-day leachate, although the concentrations in the 7- and 48-hour leachates were less than those of the untreated soils. The delayed release of contaminants was caused by the slower diffusion rate through the treated soils, demonstrating that there would be reduced leachate concentrations of contaminants would leach from a monolith created at the site.

In comparison to each other, the cement with fly ash mixture had lower concentrations in the 14-day leachates and comparable results in the 7- and 48-hour leachates. As a result, the data suggested that the organic content of the fly ash in the cement with fly ash mixture resulted in reduced leaching of the contaminants.

SPLP Testing

To further evaluate the success of the mixtures at immobilizing contaminants in the treated soils, SPLP testing was performed after the treated soils were broken into small pieces. The SPLP results indicated that both mixtures decreased the leaching of BTEX compounds from the stabilize soils. However, this reduction was likely from volatilization of these compounds into the air during the mixing process, as is common during S/S processes. The PAH results, which showed higher SPLP concentrations for the treated soils than the untreated soils, suggested that organic compounds were not immobilized. The contractor believed the increased concentrations of PAHs in the treated soils were the result of greater PAH solubility at elevated pH, caused by the alkalinity of the cement. Similarly, the total cyanide results were comparable for treated and untreated soils, suggesting that the mobility of the cyanide was not affected.

Final Solidification Testing of the Worst Case Soils

Based on the results of the optimization testing, two final mixtures were developed to stabilize the worst case soils collected from the site. One of the mixtures was the 8.5% cement with 11.5% fly ash mixture tested in the optimization testing. As shown in Table3-7, the other mixture was similar, with the percentage of cement increased to evaluate the benefits adding more cement.

Table 3-7
Final Solidification Testing Mixtures

Mixture	Additives	Quantity (% of Soil Weight)
1	Cement / Pleasant Prairie Fly Ash	8.5 / 11.5
2	Cement / Pleasant Prairie Fly Ash	11.5 / 8.5

As before, the temperature and organic vapor emissions were monitored during the mixing process. The results for the temperature increases were consistent with the previous phases of testing and within acceptable limits. As expected, the organic vapor emissions for the worst case soils were higher than those measured previously, which was consistent with the higher BTEX concentrations measured in the worst case soils.

After mixing, the soils were packed into the cylindrical molds and allowed to cure for 28 days under controlled conditions. Cone penetrometer testing was performed and volumetric expansions were determined after 1, 3, 7, 14, and 28 days of curing. The penetrometer results indicated that the maximum measurable strength was achieved for the mostly cement mixture after 3 days of curing and for the mostly fly ash mixture after 7 days. The volume increases were significantly lower than those for the original untreated soils. Specifically, the mostly cement mixture had a volume increase of 28%, while the mostly fly ash mixture increased by 30%.

In addition to the testing previously discussed, the soils treated with the two final candidate mixtures were subjected to the following list of tests:

- UCS (ASTM D 2166)
- Permeability (ASTM D 5084)
- SPLP (EPA Method 1312) for BTEX, PAHs, and total cyanide

The results of the final solidification testing using the worst case soils from the site were similar to the results obtained previously during the optimization testing for the cement with fly ash mixture. The following subsections summarize the results of this testing.

Unconfined Compressive Strength Testing

The results of the UCS testing are presented in Table 3-8. As shown in the table, both mixtures essentially met the strength criterion of 3.5 kg/cm^2 after 7 days of curing. In addition, the strength of both soils improved by more than a factor of 2 when allowed to cure for 28 days. These results clearly demonstrated that both of the cement and fly ash mixtures were successful at achieving the required strength recommended for S/S in the worst case soils from the site.

Table 3-8
UCS Testing Results for Final Mixtures

	Curing Time		**Strength Criterion (Min)**
Mixture	**7 Days**	**28 Days**	
8.5% Cement / 11.5% Pleasant Prairie Fly Ash	4.5	8.6	3.5 kg/cm^2
11.5% Cement / 8.5% Pleasant Prairie Fly Ash	3.4	8.0	

Permeability Testing

Permeability testing was performed on the treated soils for the two final mixtures after curing for 28 days. The results of the permeability testing are presented in Table 3-9. As shown in the table, neither treated soil achieved the project-specific criterion for permeability of less than 10^{-6} cm/sec after 28 days of curing. However, the permeability data gathered at different curing times during the optimization testing suggest that the permeability may decrease further with additional curing.

Table 3-9
Permeability Testing Results for Final Mixtures

Mixture	Permeability (28 days of curing)	Project Criterion (Max)
8.5% Cement / 11.5% Pleasant Prairie Fly Ash	6.4×10^{-6}	1×10^{-6} cm/sec
11.5% Cement / 8.5% Pleasant Prairie Fly Ash	3.2×10^{-6}	

SPLP Testing

The SPLP testing results (BTEX, PAHs and total cyanide) for detected analytes are presented in Table 3-10 for the soils treated using the two final mixtures. In addition, the untreated soil results and SPLP criteria are presented for comparison. As shown in the table, benzene, toluene, and naphthalene concentrations exceeded the SPLP criteria for both of the treated soils. Also, the concentration of total xylenes was above its criterion for the mostly fly ash mixture. All of the other analytes were below the groundwater standards in the SPLP leachates. In general, both of the final mixtures significantly reduced the SPLP concentrations of all BTEX compounds and naphthalene.

Table 3-10
SPLP Testing Results for Final Mixtures

Analyte	SPLP Criteria (mg/L)	Untreated Soils (Worst Case)	8.5% Cement / 11.5% Fly Ash	11.5% Cement / 8.5% Fly Ash
SPLP BTEX				
Benzene	0.005	**7.9**	**0.71**	**0.024**
Ethylbenzene	0.7	**1.9**	0.65	0.20
Toluene	0.343	**15**	**2.3**	**0.71**
Total Xylenes	0.62	**3.6**	1.5	0.44
SPLP PAHs				
Acenaphthene	NS	0.050	0.063	0.067
Acenaphthylene	NS	0.082	0.057	0.054
Fluorene	0.40	0.045	0.051	0.051
2-Methylnaphthalene	NS	0.19	0.16	0.16
Naphthalene	0.04	**0.78**	**0.34**	**0.34**
Phenanthrene	NS	0.072	0.084	0.082
SPLP Cyanide				
Total Cyanide	0.2	0.09	< 0.02	< 0.02

Bold results exceed the SPLP leachate criteria (state groundwater water standards)
NS = No standard exists

Treatability Study Conclusions

In general, the final two mixtures improved both the physical characteristics and the appearance of the site soils after the stabilization process. Previously tarry soils were transformed into a strong, monolithic, and durable treated material, as illustrated by the results of the UCS testing (more than twice the minimum criterion of 3.5 kg/cm^2). In addition, the permeability of the treated soils was reduced to near the project specific maximum criterion of 1 x 10^{-6} cm/sec. Also, the testing data suggested that the permeability might decrease further with longer curing time.

Some of the results were not as favorable, however. For instance, the freeze/thaw durability test required a curing time of 81 days to meet the criterion of less than 15% mass loss. In addition, the SPLP results suggested that the cement and fly ash mixtures were not able to immobilize organic compounds. When applied to a site, however, the large monolith that is created will reduce the leaching of organic compounds, as shown by the sequential batch leaching tests. The binding of organic compounds could be improved by using other additives, such as PAC or clay. However, one of the goals of this study was to use recycled additives, which is why fly ash was used.

Overall, the recommended S/S mixture for the site was 11.5% cement with 8.5% Pleasant Prairie fly ash. The cement and fly ash combined for this mixture were priced at $30 per cubic meter. Based on the site soil volume and density estimates, approximately $2.1 M in additives would be required. The total cost to perform the remediation was estimated at $4.84 M.

Selection of Remedial Measure

The S/S process was not chosen for remediation of the site for a variety of reasons. One major reason was that the costs appeared high. In addition, there were concerns about the future uses of the site. Initially, a housing development and then a large structural project were proposed for the site. Both of these future site uses would require very stable soils. The leaching characteristics, durability, and strength of the treated soils from the treatability study did not seem sufficient for either of these future uses of the site. Also, a large volume of soil would have to be removed from the site prior to implementing the S/S process.

During the screening of alternative remedial measures, in situ chemical oxidation using hydrogen peroxide to produce Fenton's reagent was chosen for further study. As a result, laboratory scale and field pilot tests were performed. Based on the results of the pilot test, the owner of the site is currently pursuing remediation involving full-scale chemical oxidation of the 1.0-hectare site.

4

CASE STUDY 3: A FORMER MGP SITE IN PENNSYLVANIA

During the late 1980s and early 1990s, multiple site investigations and an Interim Remedial Measure (IRM) to address a tar spill were performed at a former MGP site in Pennsylvania. This work was followed by an evaluation of remedial alternatives. After other remedial options were dismissed, in situ S/S was selected as the likely remedial method. As a result, a treatability study was performed, as recommended by EPA guidelines (EPA, 1993). This section provides details on the background of the site, site investigation results, and the results of the treatability study. As of this writing, no remedial activities have been initiated at the site.

Site Background

Description

The former MGP site is located on a 0.24-hectare site, just east of the confluence of river and a creek. As shown on Figure 4-1, the site is bounded to the north by the creek, to the west by the river, to the east by town street and to the south by an automobile salvage operation. The locations of former MGP structures are shown on Figure 4-1, along with the existing structure at the site, an old substation building, currently used by the local water department. The former MGP site is located in the floodplain of the river and in close proximity to residences and commercial businesses. The topography of the site is relatively flat, except for an approximately 3-meter embankment down to the river.

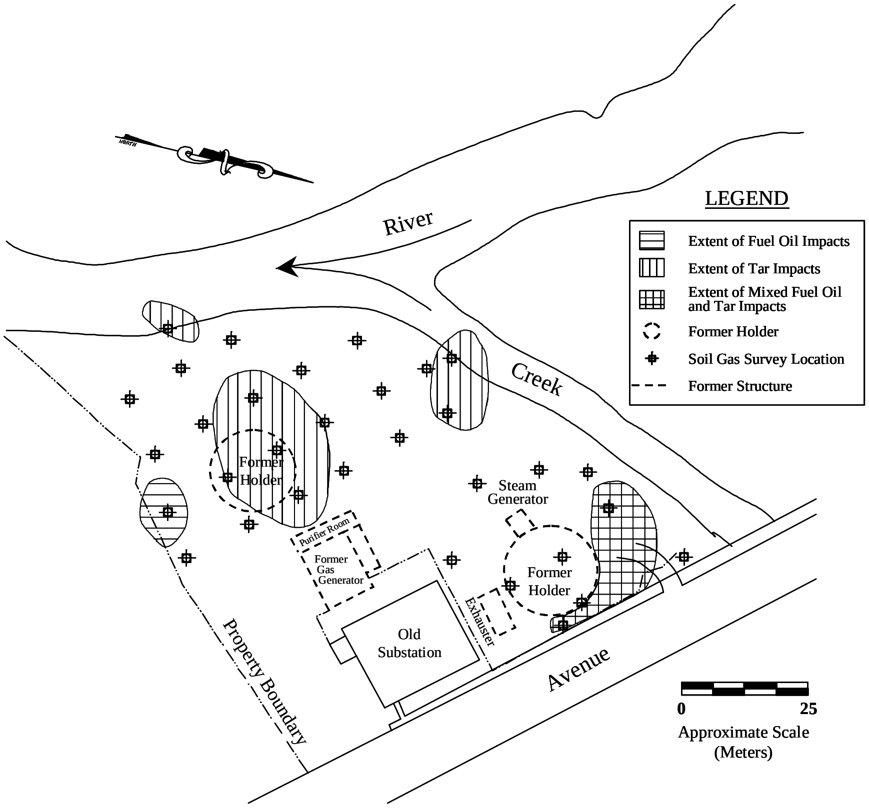


Figure 4-1

Geology and Hydrogeology

The stratigraphy of the site consists primarily of three lithologic units, which can be described as fill, alluvium, and bedrock. The fill unit includes ash, coal, slag, other MGP by-products, and demolition debris from the former MGP structures, along with clean fill brought to the site during an IRM in 1988. The clean fill was used to cap an area in the center of the site where tarry soils were excavated following a release from the former gas relief holder. The combined fill at the site ranges from 2.4 to 3.0 meters thick and is underlain by a sand and gravel alluvium. The alluvium has an average thickness of 1.2 meters and overlays weathered sandstone bedrock, which slopes toward the river. The weathered portion of the bedrock has an average thickness of 1.8 meters and is underlain by competent bedrock. The depth to groundwater at the site ranges from 1.5 to 2.4 meters below grade. Groundwater flow at the site is generally toward the river. Hydraulic conductivities at the site range from 5.6×10^{-4} to 3.2×10^{-2} cm/sec, based on pump test results.

History

The former MGP site operated between approximately 1889 and the late 1950s, using the carburetted water gas process to provide gas to the local community for lighting and heating. After the site was abandoned in the late 1950s, the former MGP structures, such as a gas relief holder, tar tank, oil tank, tar/water separator, and a small purifier unit, remained mostly intact until 1987, when they were dismantled.

Sometime between 1984 and 1985, an inadvertent release of tar occurred at the site when a drain line for an old relief tank was opened. As a result of this significant release of tar, an IRM was performed during 1987 and 1988, including the removal of over 1000 metric tons of tar-contaminated soils. After the site was regraded with clean fill, surface soil contamination was no longer visible on the site or along the river and creek banks, until a tar seep was discovered along the bank of the river in 1988. As a result, a site investigation and preliminary risk assessment were performed. Based on the results of this work, which indicated that tar was present in the alluvium at the interface with the weathered bedrock, an evaluation of remedial alternatives was later performed.

In October 1988, a local conservation commission funded a project that resulted in modifications to the river. Boulders were placed in the river as artificial stream flow diverters to create an environment more conducive to trout, which were stocked periodically in the river.

The remedial options for the site were evaluated in 1990. Based on an informal cost/benefit analysis performed on the remedial options, the Contained Recovery of Oily Wastes (CROW™) process was evaluated, through a cofunding agreement with EPRI. Testing of the shallow aquifer, which was performed at the site to determine the feasibility of applying the CROW™ process, did not suggest that it would be applicable to the site. Remedial alternatives were reevaluated by EPRI in 1994 to select an appropriate remedial technology for the site. During the 1994 EPRI study, the viable remedial option with the lowest cost was determined to be in situ solidification/stabilization. As a result of this study, the S/S option was considered for the former MGP site, and a treatability study was performed to determine the optimal mixing agents for the tar-impacted soils at the site.

Site Investigations

As part of the IRM to address the tar release, four test pits were excavated between the relief holder and the river in 1987. However, the primary site investigation performed at the former MGP site was performed in 1988, after the discovery of a tar seep on the bank of river. The primary purpose of the investigation was to determine the extent of coal tar contamination at the site and then to investigate and quantify the nature of contaminant movement off the property. In addition, a preliminary risk assessment was performed using the information gathered from the subsurface investigation.

Field Work and Analytical Data Summary

A subsurface hydrogeologic investigation was performed to determine the nature and extent of the tar contamination at the site. The field work included a soil gas survey, installation of 14 soil borings, completion of 13 of the soil borings as monitoring wells, and a riverbank and streambed survey.

Soil Gas Survey

A soil gas survey was performed at the former MGP site in October 1988 using a portable field gas chromatograph. A total of 38 sampling locations were screened for volatile organic compounds in the soil gas, including three along the banks of the river and creek (Figure 4-1). A grid approach was used to place the sampling points, with approximately 10 meters between sampling locations. The results of the survey indicated that there were five zones with the highest levels of soil gas contamination, as shown on Figure 4-1. However, low and trace levels of volatile organic compounds were present on all areas of the site. It appeared from the soil gas chromatograms that both tar and fuel oil were present in the subsurface soils.

Soil Borings

The placement of soil borings was based upon the results from the soil gas survey, the site topography, and knowledge of waste handling practices. Fourteen soil borings were advanced at the locations shown on Figure 4-2. All of the overburden borings were advanced until refusal. In addition, two bedrock borings were completed to a total depth of 15.3 meters to assess contaminant migration beneath the bedrock surface.

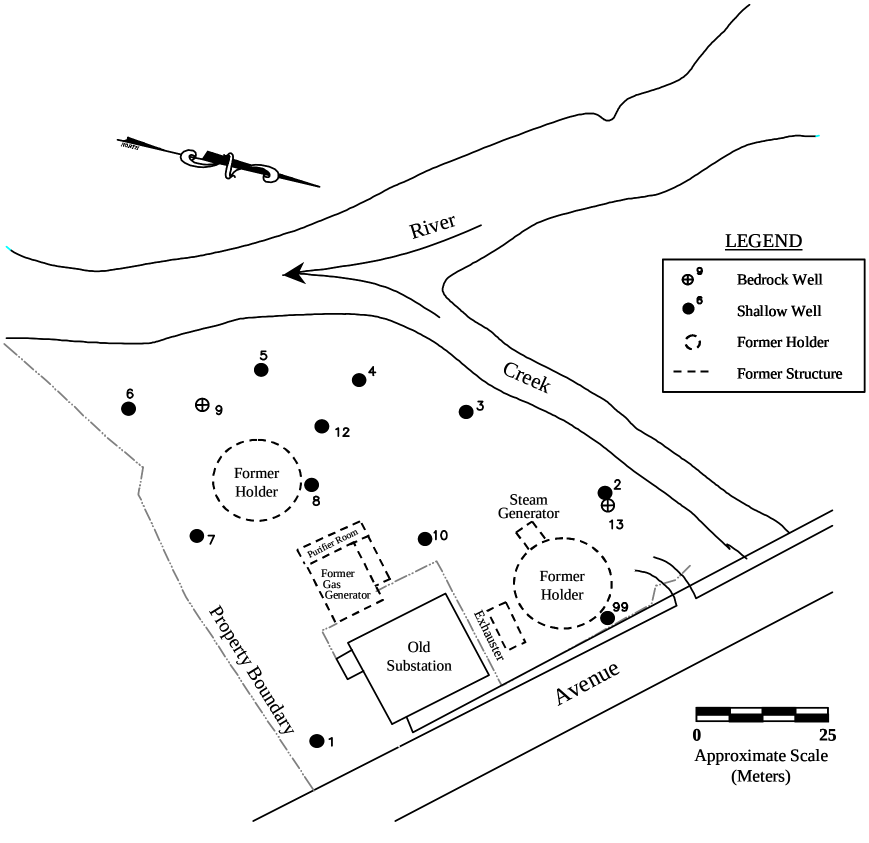


Figure 4-2

During the advancement of soil borings, visual observations were recorded and soil samples were collected for chemical analysis. All of the borings had soil impacted by tar or fuel oil constituents. In general, visual and olfactory evidence of contamination was limited to soils greater than 1.8 meters bgs. Chemical analysis for the soils collected between 1.8 meters bgs and the bedrock verified the presence of MAHs and PAHs. In fact, PAHs were detected in every sample that was analyzed. However, cyanide was not detected in any of the soil samples analyzed from the soil borings.

Monitoring Wells

Thirteen of the fourteen soil borings were completed as monitoring wells. Two of the thirteen were completed as bedrock wells. MAHs, PAHs, and cyanide were widely detected in groundwater samples collected from the monitoring wells, indicating that groundwater quality across the site was impacted by former MGP operations. In addition to dissolved-phase constituents, approximately 15 cm of DNAPL was measured in one overburden well, located between the former relief holder and the river. The tar in this well was fluid enough to be easily pumped from the well separately from groundwater.

Groundwater levels in each monitoring well were measured on several occasions and used to generate groundwater potentiometric maps, such as the one for November 29, 1988 (Figure 4-3). As shown on the figure, groundwater flows toward the river and creek from a central high point located near the former purifier room. The groundwater flow correlated fairly well to the slope of the bedrock on the site, which is also high in this area. Hydraulic conductivities were measured in three of the overburden wells by performing rising head pump tests. The calculated hydraulic conductivity values ranged from 5.6×10^{-4} to 3.2×10^{-2} cm/sec, which were consistent with values for silty sands to well-sorted clean sands, according to Freeze and Cherry (1979).

Riverbank and Streambed Survey

As part of the investigation, a riverbank and streambed survey was performed on October 12, 1989. The main objectives of the survey were to determine impacts to the sediments from tar seeps, evaluate the stability of the riverbank, and evaluate the effects of the river meander construction project on the plant property and contaminate migration. The survey included visual examination and probing for indications of tar impacts, photodocumentation, and the collection of sediment samples for chemical analysis.

During the survey, it was determined that there were apparently two narrow bands of tar-impacted sediments that extended approximately 1.5 meters into the riverbeds. One band measured approximately 6.5 meters along the bank of creek, just upstream from the confluence with the river. The other band was located approximately 15 meters downstream, along the bank of the river, and measured 35 meters in length.

The banks of the river were determined to be quite stable and resistant to erosion. However, the banks of creek adjacent to the site were being undercut by the flow of water downstream. In addition, the meander construction and bank modification performed in 1988 appeared to increase the likelihood of contaminants entering the waterway by directing the river flow against the southwest corner of the site. Also, the water level of the river near the site was raised as a result of narrowing the river, increasing the portion of the bank exposed to the water.

Conclusions

The results of the investigation showed that free product tar was present in the central and western portion of the site, from the purifier room to the river. The tar was located in the overburden, just above the bedrock and varied in thickness from 0.3 to 1.2 meters. The bedrock at the site slopes towards the river, which explained the tar observed flowing into the streambed. One of the main conclusions of the work was that the tar was migrating into the river, and sufficient volumes were present to continue the seepage for some time. In addition, on-site areas impacted by fuel oil were noted. Specifically, the northern corner of the site near the town street and a smaller area along the southern property boundary were impacted by fuel oil.

The collection and analysis of samples from the monitoring wells showed that groundwater contained dissolved-phase MAHs and PAHs across the site. The majority of the groundwater impacts were associated with the observed tarry soils in the 3 meters of overburden overlaying the bedrock at most soil boring locations. In general, the upper 1.8 meters of soil did not appear to be heavily contaminated based on visual and olfactory observations.

Based on the hydraulic conductivity testing and the measured hydraulic gradients at the site, the groundwater discharge to the river was calculated to be approximately 49,000 liters per day. Using measured and 10 year-7 day low flow stream volume estimates, the dilution factor for compounds entering the river in groundwater was estimated to be between 240 and 3300. The results of this investigation were used to perform a preliminary risk assessment.

Preliminary Risk Assessment

Using the results of the site investigation, a preliminary risk assessment was performed. The groundwater data from the investigation showed that the concentrations of benzene, other VOCs, and PAHs were well above the levels allowable for drinking water. However, the site did not pose a drinking water exposure threat, as the public water supply system received its water from a reservoir north of town.

Although contaminated groundwater was discharging into the river, the primary risk to human health and the environment was determined to be the tar migrating into the river. This tar seepage was potentially damaging the environment and creating contact exposure to people who used the river and river wildlife. It was determined that additional work should be performed to assess the feasibility of mitigating or stopping the discharge of tar into the river.

Remedial Approach

Additional Characterization

In November 1989, additional field data were collected at the former MGP site to perform a feasibility study of remedial options. During this work, 13 test pits were excavated to provide a visual characterization of the tar and better define the extent of tar in the subsurface. A test trench was also installed near the river to serve as a test for an interceptor trench remedial option to prevent tar migration to the river. In addition, the amount of tar present in each well was recorded and groundwater samples were collected and analyzed. Both free tar and tarry soil samples were collected for hazardous waste characterizations and determination of fuel parameters to assess coburning and use as a fuel source options for disposal. Also, grain size and chemical analyses were performed to better characterize the site soils.

The trenching results confirmed that most of the site was contaminated with tar and/or fuel oil or their constituents. The thickness of the tarry soils varied from 1.4 to 2.9 meters. Also, it was observed that the tar in the subsurface was not continuous, but present as fingers in the more permeable soils. No significant pockets or sources of tar were discovered during the trenching. Based on the trenching observations, the volume of tarry soils was estimated to be 11,500 cubic meters or 20,400 metric tons, including a 25% contingency. The areal extent of the impacted soil was estimated as 3700 square meters.

The results of the soil analyses for TCLP, flash point, corrosivity, and reactivity indicated that the site soils were not characteristically hazardous. Although the soils were determined to be too low in BTU content to use as a supplemental fuel, tests showed that the soils should be amenable to thermal desorption. Some soils were separated through a #40 mesh sieve and then tested for PAH content, CEC, TOC, and % solids. These data indicated that 24% of the PAHs were present in the fine fractions of the soil, and that in situ bioremediation could be used to reduce the total PAHs to less than 50 mg/kg in the soil.

Groundwater samples were analyzed for pH, ammonia, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total cyanide, metals, and sulfur. These analyses were used to evaluate the bioremediation potential for the groundwater. The only negative results were high levels of iron in a couple of the monitoring wells. High iron levels can result in clogging of the soil media from precipitation of iron hydroxide, if hydrogen peroxide injections are used to stimulate bioremediation.

Tests performed on the samples of free tar, including flash point, corrosivity, reactivity, metals content, and the paint filter test, indicated that the tar from the site was characteristically hazardous. The flash point of 54.4°C was below the limit of 60°C. In addition, the paint filter test, which determines the amount of free liquid in the tar, yielded a result of 94%, indicating that the tar cannot be disposed of without prior treatment. The thermal properties of the tar were also tested to assess its use as a supplemental fuel, including ash content, chloride, heat content, and kinematic viscosity. The low heat value for the tar (12,330 J/g) was less than the 18,600 J/g usually required for supplemental fuels.

Assessment of Remedial Options (1990)

Based on the trenching work, an evaluation of remedial alternatives to address the tar at the site was performed in 1990. The following remedial strategies were considered at the time:

- stream bank excavation,
- slurry wall,
- interceptor trench,
- excavation with on- and off-site treatments,

- in situ chemical stabilization,
- in situ bioremediation,
- in situ vapor extraction,
- groundwater treatment,
- the CROW™ process, and
- no action.

Each alternative was evaluated using an informal cost versus benefit analysis. As a result of this work, the CROW™ process was pursued, through a cofunded EPRI project. In 1994, additional work was performed at the site to evaluate the characteristics of the shallow aquifer and determine the feasibility of using the CROW™ technology at the site. The results of this work indicated that the CROW™ process would not be successful in recovering tar at the site.

As a result of the elimination of the CROW™ process from consideration as a remedial option, a reevaluation of remedial strategies for the site was performed by EPRI in 1994. The remedial strategies were developed into five alternatives:

- source removal with on-site thermal treatment and reuse of soils as backfill;
- source removal with off-site thermal treatment and clean soils as backfill;
- source removal with burning in off-site utility boiler and clean soils as backfill;
- source removal with off-site treatment in cement or brick kiln, or asphalt plant and clean soils as backfill; and
- in situ solidification/stabilization (S/S).

Unlike the 1990 remedial alternatives evaluation, S/S was now determined to be the lowest cost alternative for the site. As a result of this 1994 study, it was decided that a treatability study would be performed to evaluate the application of the S/S technology to the former MGP site.

S/S Treatability Study Design

Introduction

The primary objective of the S/S treatability study was to determine the most cost-effective mixture of site soils with Portland Type I Cement (cement), and possibly other additives, that could be blended in situ to prevent leaching of tar and tar constituents into groundwater and the river. As a result, the following design questions were developed for the treatability study:

- What are potential additives to cement to stabilize MAHs and PAHs in the resulting soil?
- Should different layers at the site be treated separately, based on their specific characteristics?
- Is there a critical mass of NAPL (tar or fuel oil) in the subsurface that will not stabilize?

- Should different mixtures be used for different areas of the site?
- What is the role of volatilization during mixing, and what measures need to be taken during mixing to control fugitive emissions?
- How much volumetric expansion will occur from the stabilization process?

Selection of Additives

Based on previous work using S/S technology, it was known that cement would be used as the primary ingredient added to soils. Cement has been shown to successfully increase the strength of the soil and reduce the permeability. However, cement has not demonstrated an ability to completely immobilize organic compounds through either a chemical or adsorptive bond. As a result, additives were considered for the cement and soil mixture to increase the binding of organic compounds within the treated soil. For this work, the following additives were considered:

- organically modified clay (OMC),
- powdered activated carbon (PAC),
- petroleum coke (pet coke),
- KAX-100, which is a proprietary additive based on ground tire rubber,
- polymer beads,
- hydrophobized lime,
- fly ash, and
- anthracite coal fines, which were readily available in the area of the site.

Each of these additives was evaluated during a preliminary screening process. This evaluation considered specific site conditions and was based on previous applications, cost-effectiveness, and the inherent safety of the additive.

During the evaluation, polymer beads, hydrophobized lime, fly ash, and anthracite coal fines were eliminated from the treatability study. Polymer beads were expensive and could not be recovered during in site applications. Hydrophobized lime presented serious safety concerns regarding the strong exothermic reaction. Even though water repellent can be used to control this reaction, hydrophobized lime was eliminated from consideration. Fly ash had demonstrated poor ability to adsorb organic compounds and would result in very large increases in volume at the quantities required. Lastly, anthracite coal fines were demonstrated to be ineffective at adsorbing organic compounds during another study.

The four additives that were selected for inclusion in the treatability study were OMC, PAC, pet coke and KAX-100. The rationale for selecting each additive is briefly discussed in the following paragraphs.

OMC has demonstrated ability to adsorb organic compounds because of its high surface area to weight ratio. In addition, the small particle size of OMC makes it easy to mix, as is required for stabilization. The addition of OMC at a rate of 1.5% by weight was proposed, based on previous experience of the contractor. At a price of $1.32 per kilogram, the OMC was determined to cost $19.80 per metric ton of soil.

Similar to OMC, PAC has a proven ability to adsorb organic compounds. In addition, PAC has a higher surface area and is easier to mix than granular activated carbon. Using the 1.5% by weight addition determined from other work and the price of $1.76 per kilogram, the addition of PAC was calculated to cost $26.40 per metric ton of soil.

Pet coke was selected for further investigation during this treatability study based on the results of solid-liquid partitioning work with coal tar, pet coke, and activated carbon. Although the application rate of 4.5% is three times higher than that for PAC, the price was only $.88 per kilogram, making it cost-effective. The cost for pet coke addition was calculated as $39.60 per metric ton of soil.

The last additive selected, KAX-100, was a proprietary product manufactured by Environmental Technologies Alternative, Inc. The additive, based on ground rubber from tires, had been shown to be somewhat less effective than activated carbon at adsorbing organic chemicals. As a result, addition rates of 5% and 10% were used in this study. With a price of $1.10 per kilogram, the cost for KAX-100 was determined to be $55 or $110 per metric ton of soil.

Sample Collection

It was important to collect a “worst case” bulk sample to be used in the treatability study to ensure that the results would be representative of the most contaminated site-specific conditions. As a result, a test pit was installed adjacent to monitoring well TQ-14, located between the former relief holder and the river, in May 1995 (Figure 4-3). Both free tar and fuel oil were observed in the test pit, and bulk samples were collected of the most visibly contaminated fill and alluvium. To mimic the mixing that occurs during the S/S process, part of the fill and the alluvium were composited to represent the soils near the interface of the stratigraphic units. A total of 29 buckets of soil were collected, including 9 buckets of fill, 9 buckets of alluvium, and 11 buckets of composite soils. In addition, groundwater from an upgradient location was collected for groundwater leaching studies.

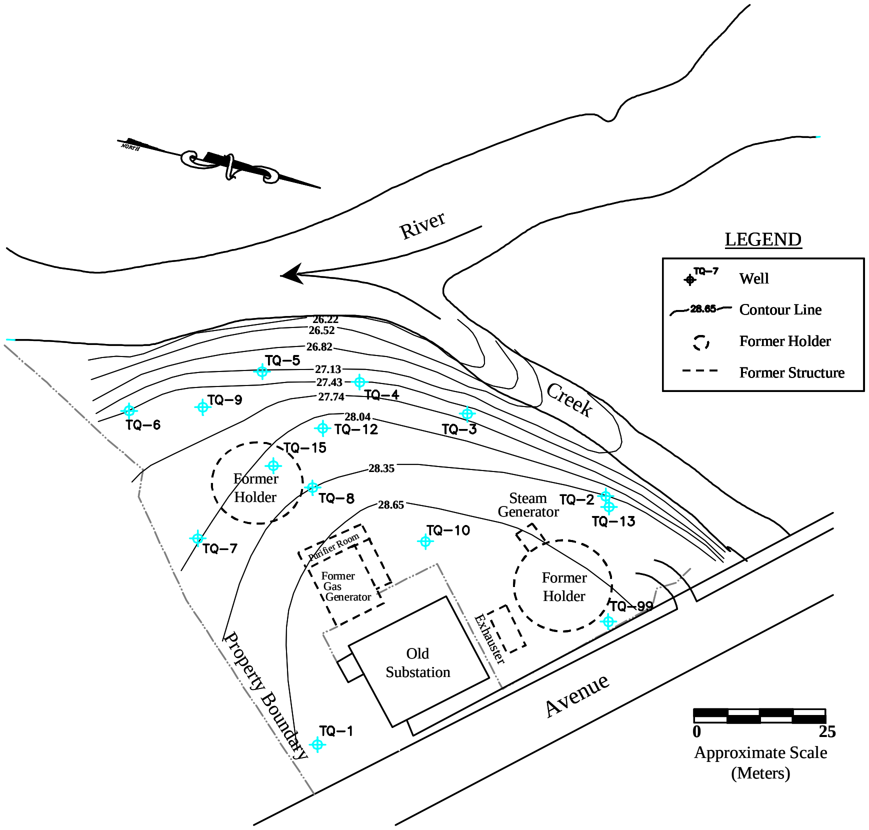


Figure 4-3

Treatability Testing Results

After the samples were collected, the treatability testing sequence was implemented to narrow down the alternative mixtures for stabilization at the former MGP site. The sequence consisted of three phases, as illustrated in Figure 4-4. The first phase was designed to screen the mixtures based on UCS testing of all soil types, TCLP results for the composite samples, and a preliminary cost/benefit analysis. The second phase consisted of performing TCLP analysis on fill and alluvium samples, permeability analysis, and testing the samples for durability. Finally, the third phase was performed to determine the ability of the mixtures to not leach constituents and to assess the total constituents present in the mixtures after the leaching test.

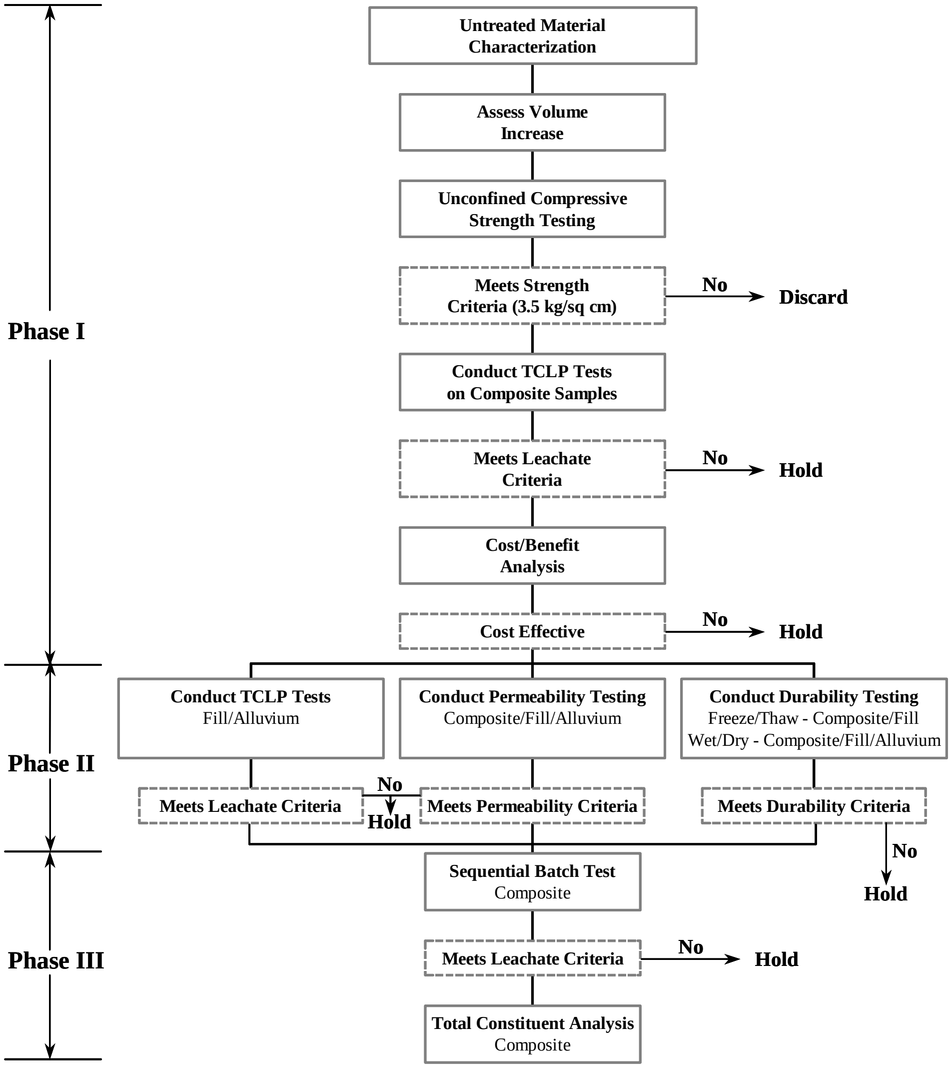


Figure 4-4

Phase I

Untreated Material Characterization

The first step in the treatability study was to characterize the untreated soils. The three types of soil samples were analyzed for grain size and moisture content to physically characterize the different soil types. In addition, samples were collected in duplicate and analyzed for TCLP and total constituent analysis. The grain size of each of the samples was similar and did not suggest that the strength of the treated soil would not be sufficient, as would be the case if the percentage of fines was too high. The moisture content for the soils ranged from 11 to 28%. The TCLP and total constituent analyses were performed to compare with the treated soils later in the study. In addition, as shown in Table 4-1, the soil data collected compared well data from previous investigations at the site, suggesting that the samples were representative of the “worst case”.

Table 4-1
Untreated Soil Characterization

Sample	Total MAHs (mg/kg)	Total PAHs (mg/kg)
Composite	153	2020
Fill	126	2300
Alluvium	40.1	692
Maximum from Previous Work	61.8	1010

The next step was to determine the volume of each soil type, so that it could be compared to the volume of the treated soils to determine the volumetric expansion from treatment. First, each type of soil was passed through a 0.95-centimeter sieve to remove large gravel and debris. Then, each set of untreated soils was packed into the UCS cylinders and the number and weight of the cylinders was recorded. After the volume of soil was documented, the sample mixtures were ready to be created.

Sample Preparation

The mixtures for the soils were all based on the addition of cement at rates of 10, 15 and 20% by weight of the soil to be treated. Cement only, and cement with additions of OMC, PAC, pet coke, and KAX-100 were created for each of the soil types, as illustrated in Table 4-2.

Table 4-2
Solidification/Stabilization Sample Mixtures for the Treatability Study

Soil Type	Sample Number	Mixtures				
		Portland Cement % weight	Organically Modified Clay % weight	Powdered Activated Carbon % weight	Petroleum Coke % weight	KAX-100 % weight
Composite	1	10				
	2	20				
	3	10	1.5			
	4	10		1.5		
	5	10			4.5	
	6	10				5.0
	7	15		1.5		
	8	20	1.5			
	9	20		1.5		
	10	20			4.5	
	10 (Dup)	20			4.5	
	11	20				10
Fill	1	15				
	2	10	1.5			
	3	10		1.5		
	4	10			4.5	
	5	10				5.0
	6	20	1.5			
	7	20		1.5		
	8	20			4.5	
	8 (Dup)	20			4.5	
	9	20				10
Alluvium	1	15				
	2	10	1.5			
	3	10		1.5		
	4	10			4.5	
	5	10				5.0
	6	20	1.5			
	7	20		1.5		
	8	20			4.5	
	8 (Dup)	20			4.5	
	9	20				10

A bench top mixer was used to homogenize the soils during treatment. The cement and additives were added as a grout to the soils to mimic how the mixing would be performed in the field. After mixing, each set of samples was placed into the UCS cylinders in 2.5-centimeter layers and tamped. The weight and number of cylinders was recorded for each sample mixture to allow the volumetric expansion to be calculated. Then, all of the samples were placed in a room at 95% humidity and 21°C to cure for 28 days.

Volume Changes

The volume changes experienced by each set of samples included bulking from the addition of the S/S grout mixture and shrinking during the curing process. Volume changes were not measured for the cement-only mixtures. The cumulative volume changes were indicative of the amount of overlying soil that would have to be removed from the site prior to the S/S process.

The expansion from mixing was determined by filling the UCS cylinders with the treated soil mixtures and comparing the volume of the treated soil to the untreated soil, which was determined during the untreated soil characterization process. Volume decreases during curing were determined by measuring the change in height of the UCS cylinders before and after curing. Table 4-3 shows the cumulative volume increases as a percentage of the initial volume. The low and negative increases for some of the fill soils were caused by poorly packed untreated soils creating a falsely inflated initial volume.

Table 4-3
Cumulative Sample Volume Percent Increases

Formulation	Composite Soil (% Volume Increase)	Fill (% Volume Increase)	Alluvium (% Volume Increase)
10% Cement			
Cement Only	not measured	no sample	no sample
1.5% OMC	21.1	-2.25	10.1
1.5% PAC	21.0	8.00	19.1
4.5% Pet Coke	28.7	-3.21	29.8
5.0% KAX-100	22.8	2.26	24.0
15% Cement			
Cement Only	no sample	not measured	not measured
1.5% PAC	41.9	no sample	no sample
20% Cement			
Cement Only	not measured	no sample	no sample
1.5% OMC	39.9	21.4	36.1
1.5% PAC	32.3	25.0	44.5
4.5% Pet Coke	47.2	18.7	45.3
10% KAX-100	52.8	-5.53	31.8

As shown in Table 4-3, the maximum volume increase was 53% for the composite soil mixed with 20% cement and 10% KAX-100 additive. If a 3.6-meter vertical column of soils was to be treated at the site using this mixture, approximately 1.8 meters of overlying soil would have to excavated to maintain the current ground elevation. The maximum volume increase for the 20% cement and 1.5% OMC additive was 40% and was found for the composite soil. For this mixture, approximately 1.5 meters of soil would have to be removed prior to implementing the S/S process.

Unconfined Compressive Strength

The UCS of the soil mixtures is determined to assess the ability of the treated waste to withstand overburden loads. The EPA considers a soil that has been treated with S/S to be a stable foundation for construction equipment, impermeable caps, and soil cover material if the UCS is 3.5 kg/cm^2 or greater (USEPA OSWER Directive, No. 9437.00-2A). As a result, 3.5 kg/cm^2 was chosen as the minimum threshold for samples in this study to meet the future potential uses for the site. Any mixtures that did not achieve at least 3.5 kg/cm^2 in the UCS, performed according to ASTM D 1633, were eliminated from further consideration.

The results from the UCS testing are presented in Table 4-4. As shown in the table, the UCS results ranged from 1.6 to 29.8 kg/cm^2, with seven samples having UCS strength less than the minimum threshold of 3.5 kg/cm^2. These four fill samples and three composite samples were eliminated from further testing in the study. In general, the alluvium samples were the strongest, with all of the results for these samples meeting the criterion. In addition, the 20% cement mixtures exhibited higher strength, as was expected.

Table 4-4
Unconfined Compressive Strength Results

Formulation	Composite Strength (kg/cm^2)	Fill Strength (kg/cm^2)	Alluvium Strength (kg/cm^2)
10% Cement			
Cement Only	**1.6**	no sample	no sample
1.5% OMC	4.9	12.4	10.6
1.5% PAC	7.5	**2.5**	8.1
4.5% Pet Coke	4.3	**2.0**	12.0
5.0% KAX-100	7.0	**3.5**	6.9
15% Cement			
Cement Only	no sample	4.0	17.4
1.5% PAC	**3.0**	no sample	no sample
20% Cement			
Cement Only	29.8	no sample	no sample
1.5% OMC	7.4	10.8	17.4
1.5% PAC	29.3	6.0	12.8
4.5% Pet Coke	**3.0 (3.0)**	**3.0 (3.0)**	15.5 (13.7)
10% KAX-100	12.8	6.7	16.2

Notes:( ) indicates results for a duplicate test
Bold results are below the 3.5 kg/cm^2 minimum threshold for the UCS test

TCLP Testing of Composite Samples

The Phase I TCLP testing was planned for all of the composite samples that passed the UCS testing. As a result, eight composite soils were tested for TCLP. TCLP testing was selected as a relatively aggressive leaching test to indicate how well the S/S mixtures immobilized MAHs and PAHs in the treated soils. The leachate results were compared to state and federal drinking water standards (MCLs), as they were the most stringent criteria available.

The TCLP results for the detected organic compounds in the eight composite treated samples are presented in Table 4-5. For comparison, the average TCLP concentrations from the two untreated composite soils analyzed during the untreated soil characterization testing are also presented in this table. All of the S/S samples were ground prior to testing for TCLP. As shown in the table, benzene and naphthalene were the only compounds above the drinking water criteria in the treated soils. Despite some results showing decreased benzene concentrations in the treated soils, all resulting values were at or above the leachate criterion of 0.005 mg/L. In addition, naphthalene levels remained well above the leachate criterion of 0.02 mg/L for all of the treated soils. From the TCLP results, it is evident that the cement-only mixtures did not effectively bind organic compounds.

Table 4-5
TCLP Analytical Results Summary for Composite Soils

			10% Cement				**20% Cement**			
Analyte	**Criteria**	**Soil**	**1.5% OMC**	**1.5% PAC**	**4.5% Pet Coke**	**5% KAX-100**	**Only**	**1.5% OMC**	**1.5% PAC**	**10% KAX-100**
MAHs (mg/L)										
Benzene	0.005	**0.024**	**0.005**	**0.014**	**0.008**	**0.014**	**0.024**	**0.005**	**0.011**	**0.016**
Ethylbenzene	0.7	0.28	0.011	0.039	0.028	0.091	0.58	0.008	0.064	0.008
Toluene	1.0	0.036	0.003	0.008	0.005	0.01	0.047	0.003	0.006	0.008
Total Xylenes	10	0.41	0.059	0.15	0.13	0.16	0.57	0.062	0.14	0.057
PAHs (mg/L)										
Acenaphthene	2.1[1]	0.29	0.29	0.40	0.46	0.20	0.36	0.28	0.44	0.19
Naphthalene	0.02	**7.2**	**1.46**	**6.3**	**8.0**	**4.3**	**9.0**	**1.47**	**6.8**	**1.47**

Bold results exceed the leachate criteria (state and federal drinking water standards)
[1] The acenaphthene criterion was a risk-based concentration calculated from EPA guidelines

Cost/Benefit Analysis

After the Phase I testing, the different mixtures were subjected to a preliminary cost/benefit analysis. During this analysis, the cost per metric ton of the additives (in addition to cement) was compared to the increased performance as demonstrated by increased strength and reduced leaching of organic compounds.

Based on the results of the UCS and TCLP testing, the following mixtures were subjected to the preliminary cost/benefit analysis:

- 20% cement
- 20% cement with 1.5% OMC
- 20% cement with 10% KAX-100

Since all three of the mixtures included 20% cement, the cost of cement was factored out of the analysis. The extra costs for the additives were calculated as $19.80 per metric ton of soil for OMC and $110 per metric ton of soil for KAX-100. Based on the significant increased cost of KAX-100 with no increased performance in strength or leachability over the OMC, the KAX-100 mixture was eliminated from further consideration.

In summary, the 20% cement-only and 20% cement with 1.5% OMC mixtures demonstrated the best performance at reasonable costs. As a result, these two mixtures were carried forward and analyzed further during the Phase II analysis.

Phase II

The second phase of analysis consisted of a further evaluation of the two mixtures that were selected for additional testing based on the Phase I testing results. The second phase of testing consisted of additional TCLP testing, permeability testing, and durability testing.

TCLP Testing of Fill and Alluvium Samples

TCLP testing was previously performed on the composite soil samples. The second phase of TCLP testing was performed to analyze leaching from the fill and alluvium samples for the mixtures screened in Phase I. These results were important because the fill and alluvium soils represented the vertical fringe areas. Specifically, during in situ S/S mixing at the site, fill would be present near the surface, composite soils would be present in the middle, and alluvium would be present near the bottom of the treated soils.

The results for the TCLP testing performed on the fill and alluvium samples for the 20% cement with 1.5% OMC and 20% cement-only mixtures are shown in Table 4-6. As shown in the table, the results for the fill and alluvium samples were similar to the Phase I composite results. Specifically, the addition of OMC to the cement mixture decreased the concentrations of organic compounds in the TCLP leachate, as compared to the cement-only mixture.

Table 4-6
TCLP Analytical Results Summary for Two Selected Mixtures

Analyte	Criteria (mg/L)	Fill (mg/L)	Alluvium (mg/L)	Composite (mg/L)
20% Cement				
Benzene	0.005	**<0.05**	**<0.05**	**0.024**
Ethylbenzene	0.7	<0.05	<0.05	0.58
Toluene	1	<0.05	<0.05	0.047
Total Xylenes	10	<0.15	<0.15	0.57
Acenaphthene	2.1[1]	0.40	0.18	0.036
Naphthalene	0.02	**7.7**	**4.3**	**9.0**
20% Cement with 1.5% OMC				
Benzene	0.005	**<0.05**	**<0.01**	**0.005**
Ethylbenzene	0.7	<0.05	<0.01	0.008
Toluene	1	<0.05	<0.01	0.003
Total Xylenes	10	<0.15	<0.03	0.062
Acenaphthene	2.1[1]	0.44	0.17	0.28
Naphthalene	0.02	**5.1**	**1.2**	**1.47**
Untreated Soils				
Benzene	0.005	**0.05**	**0.005**	**0.024**
Ethylbenzene	0.7	0.36	0.015	0.28
Toluene	1	0.05	0.004	0.036
Total Xylenes	10	0.78	0.14	0.41
Acenaphthene	2.1[1]	0.27	0.30	0.29
Naphthalene	0.02	**8.0**	**4.4**	**7.2**

Bold results or detection limits exceed the leachate criteria (state and federal drinking water standards)

[1] The acenaphthene criterion was a risk-based concentration calculated from EPA guidelines

Permeability Testing

Permeability testing was performed to measure the ability of the treated soil to retard the flow of groundwater. Federal regulatory guidelines (EPA,1989) recommend a maximum permeability of 10^{-5} cm/sec for treated soils. The two mixtures were tested for the composite, fill, and alluvium samples for permeability, according to ASTM D 5084. The test consisted of a falling head of water passed through the sample over a given period of time.

All six of the samples tested had permeabilities less than the 10^{-5} cm/sec threshold. The highest permeability measured (8.07×10^{-6} cm/sec) was for the alluvium sample treated with the 20% cement and 1.5% OMC mixture. The lowest permeability (1.18×10^{-8} cm/sec) was found for the fill sample treated with the 20% cement-only mixture.

Durability Testing

Durability testing was performed to evaluate the ability of the treated soils to withstand weathering and maintain their physical integrity. The durability tests used were freeze/thaw (ASTM D 560) and wet/dry (ASTM D 559). EPA guidelines for S/S recommend a maximum weight loss of 15% for durability tests (EPA, 1989).

Both durability tests involved 12 cycles of 24 hours at each extreme. For example, the freeze/thaw test was performed by alternately freezing and thawing the samples for 24 hours at a time. Similarly, the wet/dry test was performed by alternately soaking and drying the samples for 24 hours at a time. At the end of each cycle, a wire brush scratched the samples at a constant pressure. After 12 cycles, the weight of the sample was compared to the initial weight of the sample, and a percent material loss was calculated.

All of the soil types treated by both mixtures were subjected to each durability test, except for the alluvium samples. The freeze/thaw method was not performed on the alluvium samples since the frost at the site would not penetrate to that depth. All of the samples passed the durability tests. No significant losses were observed during any freeze/thaw tests. The fill samples experienced the maximum weight losses, with 11% for the cement-only mixture and 10% for the cement with OMC mixture.

Phase III

The third phase consisted of additional testing for the two mixtures that were screened out in Phase I and tested further during Phase II. The 20% cement and 20% cement with 1.5% OMC were subjected to sequential batch leaching tests and total constituent analysis during the third phase. These tests were performed to determine the ability of the two mixtures to inhibit the leaching of MAHs and PAHs into site groundwater and to assess the total concentrations present in the samples after the leaching.

Sequential Batch Leaching Test

The sequential batch leaching tests were performed on the composite soil samples for the two S/S mixtures. These tests were conducted to assess the leachability of MAHs and PAHs from the treated material into site groundwater and were less aggressive than TCLP. As a result, sequential batch leaching tests were more indicative of the actual leaching that would occur on-site in the S/S technology was implemented.

During testing, samples were first immersed in site groundwater for 2 hours. Then the samples were removed, rinsed with deionized water, and immersed in fresh groundwater for 7 hours. Then, the process was repeated with a 24-hour immersion. After that, four more immersions of 24 hours were performed. The groundwater leachate was then analyzed individually for each immersion. The detected concentrations of organic compounds from the sequential batch leaching tests are presented in Table 4-7.

Table 4-7
Sequential Batch Leaching Test Results (mg/L)

Analyte	Criteria	2 hours	7 hours	24 hours	2 days	3 days	4 days	5 days
20 % Cement								
Ethylbenzene	0.7	<0.001	0.002	0.004	0.003	0.001	<0.001	<0.001
Total Xylenes	10	<0.003	<0.003	0.005	0.004	<0.003	<0.003	<0.003
Naphthalene	0.02	**0.059**	**0.11**	**0.22**	**0.21**	**0.15**	**0.14**	**0.12**
Acenaphthene	2.1	0.009	0.014	0.04	0.036	0.033	0.029	0.026
20% Cement with 1.5% OMC								
Naphthalene	0.02	**0.045**	**0.10**	**0.25**	**0.24**	**0.14**	**0.12**	**0.02**
Acenaphthene	2.1	0.009	0.017	0.053	0.051	0.023	0.024	0.01

Bold results exceed the leachate criteria (state and federal drinking water standards)
[1] The acenaphthene criterion was a risk-based concentration calculated from EPA guidelines

As shown in Table 4-7, the results for the sequential batch leaching tests indicated that the cement with OMC mixture was more effective in binding organic compounds in the treated soil than the cement-only mixture. This is illustrated by the larger decrease in naphthalene concentrations for the 3rd, 4th and 5th day leachates for the cement with OMC mixture. The results for the cement-only mixture did not decrease over time in a similar fashion. These results are consistent with the TCLP results previously presented.

Total Constituent Analysis

EPA guidelines (EPA, 1993) recommend the use of total constituent analysis (TCA) as means for determining the efficacy of the immobilization of compounds in the treated soil. TCA was performed on the same composite samples that underwent sequential batch leaching tests. These samples were analyzed for MAHs and PAHs and compared to the untreated material characterization results and the batch leaching results. By comparing these results, the effectiveness of the stabilization was evaluated and the potential volatilization of organic compounds during mixing was assessed.

Table 4-8 presents the TCA results for the untreated samples and the samples that were batch leach tested. The percent reduction is equal to the results found in the solidified samples divided by the results from the untreated soils. The results for the percent reduction reflected losses from volatilization during mixing, leaching during batch leach testing, and also adsorption by the mixtures added to the soils.

Table 4-8
Composite Sample TCA Results and Percent Reduction

Sample	Total MAHs (mg/kg)	% Reduction	Total PAHs (mg/kg)	% Reduction
Untreated Soil	153		2020	
20% Cement	0.086	99.9	780	61.4
20% Cement with 1.5% OMC	0.12	99.9	490	75.7

As a result of volatilization, the lower molecular weight compounds had higher percent reductions. In fact, the percent reductions for individual MAHs were all over 99%. In general, the cement-only mixture had lower percent reductions than the cement with OMC mixture, indicating the adsorptive capacity of the OMC. The percent reductions for the cement-only mixture can be attributed mostly to volatilization and leaching, based on the leaching results that suggested low binding of organic compounds.

Treatability Study Results Summary

A summary of the results for the two mixtures that were screened during Phase I of the treatability study is presented in Table 4-9. The two best mixtures were determined to be 20% cement and 20% cement with 1.5% OMC. Based on the volumetric expansion calculations for each mixture, approximately 1.5 meters of overlying fill would have to be removed prior to implementing S/S at the site.

Table 4-9
Summary of Results for Two Mixtures

	20% Cement	20% Cement with 1.5% OMC	Criteria
UCS (kg/cm^2)			
Composite	29.8	7.4	3.5 Min
Fill	4.0	10.8	
Alluvium	17.4	17.4	
TCLP Results (mg/L)			
Benzene			
Composite	0.024	0.005	0.005 Max
Fill	<0.05	<0.05	
Alluvium	<0.05	<0.05	
Naphthalene			
Composite	9.0	1.47	0.02 Max
Fill	7.7	5.1	
Alluvium	4.3	1.2	
Permeability (cm/sec)			
Composite	4.57×10^{-6}	5.02×10^{-6}	1×10^{-5} Max
Fill	1.18×10^{-8}	4.67×10^{-6}	
Alluvium	4.40×10^{-6}	8.07×10^{-6}	
Freeze/Thaw Durability (% weight loss)			
Composite	0.26	0.20	15% Max
Fill	0.21	0.20	
Wet/Dry Durability (% weight loss)			
Composite	7.25	8.22	15% Max
Fill	11.4	10.4	
Alluvium	7.40	7.20	
Batch Leaching Average Leachate Concentration (mg/L)			
Naphthalene	0.14	0.13	0.02 Max
Material Cost (per metric ton soil treated)			
	$16	$34	

The results for the two mixtures were not significantly different for the three soil types, indicating that there would be no advantage to using different mixtures based on soil type. The only major difference between the cement-only mixture and the cement with OMC mixture was that the OMC decreased the leaching of organic compounds from the treated soil. The treatability study determined that there was not a critical mass of free phase organic compounds that would not be retained within the treated mixture. As a result, the S/S technology can be applied effectively at the site.

Although the cement with the OMC was more effective at binding organic compounds, the increased cost did not warrant its use for all of the site soils. The middle of the solidified mass would not be available for leaching because of the impermeable liner placed over the top of the mass during the S/S process. Even the soils around the perimeter may not need to be treated with the OMC additive. A risk assessment would be used to assess post-remediation risks from the leachate. Specifically, naphthalene leaching from the exterior of the treated mass would be most important, as naphthalene was the only compound above the leachate criteria during the sequential batch leaching tests. Depending on the results of the risk assessment, a decision to use the OMC additive around the perimeter of the mass would be made.

The results of the study indicated that significant volatilization of organic compounds would occur during S/S operations at the site using the cement-based mixtures. As a result, a plan would have to be developed for suppressing or capturing these fugitive emissions during the remediation.

The estimated costs for the remediation depended on the results of the risk assessment. The cost for the cement with OMC mixture was approximately twice the cost for the cement-only mixture. As a result, the total project cost was estimated as $1.6 M for stabilizing all of the soils with the cement-only mixture and $1.96 M for using the cement with the OMC for the whole site. If the risk assessment results specified the use of OMC clay around the perimeter of the site, the resulting cost was estimated to be $1.85 M.

Selection of Remedial Measure

To date, no active remediation has been employed at this site. The treatability study was originally commissioned during an interim Pennsylvania program that allowed for in situ treatment. Since then, new state regulations have been issued that allow for risk-based solutions to environmental problems. As a result, addition investigation work and risk assessments are being performed to determine the final disposition of the former MGP site.

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SUMMARY AND CONCLUSIONS

In situ S/S techniques for remediation involve the mixing of contaminated materials with additives that chemically and physically reduce the mobility of the contaminants. As a result, S/S techniques can reduce the potential for environmental damage and human health risks from the contaminants without destroying them and without excavation and ex situ treatment of contaminated subsurface media. The two processes at work, solidification and stabilization, act in different ways to reduce the mobility of the contaminants.

Solidification is a process in which waste is encapsulated in a solid form, which reduces the migrations of contaminants by decreasing the surface area exposed to leaching or coating the contaminants with low permeability materials. In the case studies discussed in this report, the goal of the solidification process was to create a large monolithic block. It was demonstrated that cement was successful at solidifying contaminated MGP soils into a monolithic structure, thereby decreasing the surface area exposed to leaching, as well as reducing the permeability of the treated soils.

The process of stabilizing materials involves chemical reactions, which reduce the hazard potential of the contaminants by changing them to a less mobile, less soluble, or less toxic form. During stabilization, the handling characteristics and physical nature of the material are not necessarily altered, as during solidification. The treatability studies presented in this report suggest that complete stabilization of organic tar constituents is not achieved by the addition of cement, but that other additives that adsorb organic compounds can be added to improve the stabilization of the contaminants found at MGP sites.

In situ S/S techniques were considered for the three sites discussed in this report with mixed success. The following subsections briefly summarize the results of the work at each site.

Former MGP Site in Georgia

During the early 1990s, the remediation of a former MGP site in Georgia was successfully performed using in situ S/S. Based on strength and permeability testing, the remediation of the site was performed using a 10% by weight cement mixture for solidification of the contaminated soils at the site and a 20% by weight cement mixture for a riverside containment wall. After remediation a public park and riverfront walkway were constructed as part of the site restoration. The site groundwater was monitored during 11 rounds of sampling and analysis after completion of the remediation, and the results showed that the levels of the constituents of concern at the site were below their respective MCLs.

Former MGP Site in Wisconsin

During 1997 and 1998, a treatability study was performed to assess the efficacy of using in situ S/S to remediate a former MGP site in Wisconsin. Similar to the site in Georgia, as little as 8.5% cement was shown to effectively solidify the tarry soils at the site. In addition, fly ash was added to the soils to attempt to stabilize the contaminants within the solidified mass. The results suggested that fly ash did not significantly reduce the leaching of PAHs and total cyanide from the treated soils. In addition, it appeared that volatile constituents (BTEX compounds) were mostly lost to the air during the mixing process. Because of the high costs for implementing S/S at the Wisconsin former MGP site and concerns regarding the proposed future uses of the site, an alternative remedial method, chemical oxidation, was selected.

Former MGP Site in Pennsylvania

In 1998, a treatability study was performed to assess the efficacy of using in situ S/S to remediate a former MGP site in Pennsylvania. Again, cement was chosen as the main additive to achieve successful solidification of the MGP soils. The strength and permeability tests showed that the addition of 20% cement was required. In addition, additives were tested to attempt to stabilize contaminants within the solidified soils. The addition of 1.5% Organically Modified Clay (OMC) to the mixture demonstrated an ability to bind organic compounds within the solidified mass. The treatability study determined that a risk assessment should be performed to determine which soils need to be treated using the OMC and cement mixture and which soils can be solidified using only the cement. As of this writing, no active remediation has been performed at the site and further investigation work and risk assessments are being performed to determine a risk-based solution for the site within the framework of the current state regulations.

Summary

The results of the three case studies indicate that the S/S process has significant potential for remediation of former MGP sites, particularly where conventional excavate and treat technologies cannot be employed easily or are cost-prohibitive. The treatability studies indicate the MGP soils can be successfully solidified and treated by selecting the proper additives for soil mixing, resulting in a structurally sound treatment zone that does not readily leach contaminants. The key to implementing in situ S/S is to perform a site-specific treatability study to determine the ability of the additives to meet regulatory guidelines and project-specific goals, based on the desired final use for the site. As a result, the S/S process should be considered as a viable remedial alternative during feasibility studies at former MGP sites.

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Printed on recycled paper in the United States of America

1000727

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