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# *In situ* stabilisation/solidification: Project lifecycle

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**Abstract**

The successful application of any remedial technology, including stabilisation/solidification, begins with the site investigation. Following a review of the data collected during the site investigation, a treatability study (TS) and pilot study (PS) are prerequisites to full-scale implementation as they show the effects and delivery of binders to the soils, the geochemistry of the soils, and binder dosages necessary for the existing geology. Further, evaluating the data gathered during the TS and PS can help in accurately estimating and executing full-scale operations. Invariably, deviations from the TS and PS regarding soil characteristics and soil chemistry may exist, but the experience gained via the TS and PS aids in making decisions when faced with new and unexpected conditions in the field. This paper will discuss the execution of typical TS and PS applications and their implementation for full-scale treatment. Because the long-term performance durability of design mixes and technology applications are not generally addressed in remediation, post-remediation monitoring and sampling data must be made available to the public to advance the science and art of stabilisation/solidification. As a first step in advancing this technology, this paper follows the lifecycle of stabilisation/ solidification projects from the site investigation through the completion of full-scale work. A 10-year post-remediation sampling event also evidences the long-term viability of the technology.

*Keywords:* Manufactured gas plant; Stabilisation; Pilot study; Treatability study; Deep soil mixing

## 1. Introduction

The lifecycle of any remedial project begins with the discovery of a site. Subsequently, the responsible parties are contacted and are required to perform a remedial investigation (RI) to determine the lateral and vertical extents of contamination, the chemicals present, the general site conditions, and the potential risks to the community and the environment. Following the RI, a feasibility study (FS) that details potential technologies to address site contaminants is conducted. Generally speaking, four technologies (e.g., groundwater pump and treat, excavation and disposal, containment (slurry wall and cap) as well as stabilisation) are studied in the FS as potential remedial alternatives. Additionally, two standard options are routinely considered: administrative controls and no further action. In the United States, this site discovery/RI/FS process is well defined and rigorously followed; therefore, this paper presumes that the RI/FS has been completed and approved by the regulatory agencies and that the selected remedy is stabilisation/ solidification.

*In situ* stabilisation/solidification, or deep soil mixing (DSM), has gained wide acceptance in the environmental remediation market, particularly in the manufactured gas plant (MGP) sector. The authors have performed a number of stabilisation projects involving DSM. In fact, DSM is becoming a remediation technology of choice because it reduces the amount of soils hauled off-site, thereby saving disposal fees and backfill costs; it reduces odours during remediation activities; and overall remediation costs are significantly lower than other remediation technologies, such as thermal desorption and *in situ* chemical oxidation. Moreover, numerous states, including Georgia, South Carolina, New Jersey, Pennsylvania, Massachusetts, and Wisconsin, have embraced the DSM technology when remediating MGP-contaminated materials.

In the United States, remediation of contaminated sites under the Superfund program is dictated by legal instruments such as, the Administrative Order on Consent, and Consent Decree. These documents dictate the schedule, the selected technology based on the findings of the RI/FS, and the post-remediation monitoring activities.

Regardless of the legal mechanism used to initiate and provide oversight for a hazardous waste project, the end objective of *in situ* stabilisation/solidification projects is the same: the permanence of the effective treatment and the elucidation and

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**Nomenclature**

| | |
|---|---|
| ANS | American Nuclear Society |
| ASTM | American Society for Testing and Materials |
| BTEX | benzene, toluene, ethylbenzene, xylene |
| CAA | Clean Air Act |
| cm | centimetre |
| cm/s | centimetre per second |
| $cm^2$ | square centimetres |
| CWA | Clean Water Act |
| DSM | deep soil mixing |
| EPRI | Electric Power Research Institute |
| FS | feasibility study |
| GIS | geographic information system |
| HDPE | high-density polyethylene |
| kg | kilogrammes |
| $kg/m^3$ | kilogrammes per cubic metre |
| kN m | kiloNewton metres |
| kPa | kiloPascal |
| L | litre |
| mm | millimeter |
| $m^3/s$ | cubic metres per second |
| MGP | manufactured gas plant |
| NAPL | nonaqueous-phase liquids |
| ppb | parts per billion |
| ppm | parts per million |
| PAH | polynuclear aromatic hydrocarbon |
| PS | pilot study |
| QA/QC | quality assurance/quality control |
| rpm | revolutions per minute |
| RCRA | Resource Conservation and Recovery Act |
| RI | remedial investigation |
| SPLP | synthetic precipitation leaching procedure |
| SVOC | semivolatile organic compound |
| TCLP | toxicity characteristic leaching procedure |
| TPH | total petroleum hydrocarbons |
| TS | treatability study |
| UCS | unconfined compressive strength |
| U.S. EPA | United States Environmental Protection Agency |
| VOC | volatile organic compound |

dissemination of knowledge concerning the long-term durability of the stabilised mass. When this parameter is considered in the remediation of hazardous waste sites, then the project lifecycle will be complete.

Currently, the project lifecycle is generally overlooked during the remediation of a hazardous waste site. Although there are many reasons for this, it is suggested that the following are the most common:

- The site remediation is driven by regulations, and the parties involved do only what the laws minimally require.
- The site cleanup does not add to the profitability of the company.
- The remediation is usually considered the last step in compliance.
- The responsible companies have already paid out large sums of money to lawyers and engineers in an effort to avoid excessive cleanup costs, and they simply want to stop the expenditures.
- Finally, post-remediation sampling has mostly focused on groundwater at the perimeter of the work rather than on the work itself. Although CERCLA requires 5- and 10-year reviews to assure continued acceptability of the implemented remedy, long-term post-remediation monitoring of a technology application is not currently required by the regulators.

This paper traces the work of two treatability studies, one pilot test, and one case study, all key elements in the lifecycle of a DSM project at MGP sites. Although some of the work of these studies is interrelated, the case study provided is not the end result of the TS or PS discussed. Instead, the TS, PS, and case study are meant to be a mosaic, illustrating different facets of project lifecycle completion.

### *1.1. Manufactured gas plant site history*

Today, a variety of technologies are available to remediate MGP sites due to the complexity of the chemicals associated with the wastes and the close proximity of former MGP sites to densely populated, urban areas. Utility corridors at these sites give MGP wastes preferential pathways to adjacent areas, worsening the extent of contamination and complicating remediation efforts adjacent to and between the active utilities.

Organic contaminants resulting from the processing of coal, wood, and oil into manufactured gas, or town gas, create distinctive environmental impacts at MGP sites. Carcinogenic byproducts, namely polynuclear aromatic hydrocarbons (PAHs), are often found at MGP sites, which are generally located in highly populated areas adjacent to rivers or other watercourse. Thus, the carcinogenic nature of the contaminants coupled with the site's location make MGP sites difficult to delineate and expensive to remediate.

### *1.2. Background*

The legacy of MGP sites dates back to seventeenth century England, with the first uses of town gas. In 1796, town gas was used in Philadelphia, Pennsylvania, and in Richmond, Virginia, in 1803. The first plants were erected in the port cities of Baltimore, Boston, and New York in 1816, 1822, and 1825, respectively. These facilities processed coal, coke, wood, and oil to produce town gas. Over the next 150 years, the MGP industry expanded, with production peaking in the 1920s and 1930s. However, with the introduction of cheap natural gas and the development of the modern gas pipeline industry in the 1940s, the MGP industry began to decline. Sites were closed, and the MGP industry was phased out by the 1960s [1].

With the enactment of the Clean Water Act (CWA), the Clean Air Act (CAA), and the Resource Conservation and Recovery Act (RCRA) in the 1970s, MGP sites became recognised environmental issues due to environmental impacts resulting from cooling and purification processes that produced coal tars, liquors, sludge, and other residuals. In the early 1990s, as a result of the fleets factors case, banks and loan institutions began requiring Phases I and II assessments for the transfer of properties. During this time, several large former MGP sites were discovered to be leaking free product into the environment (i.e., navigable waterways).

It is currently estimated that there are between 36,000 and 55,000 former MGP and coal tar sites in the United States, 88% of which are suspected to have had releases of contaminants to the environment. Cost estimates to clean up the environmental impacts associated with these MGP facilities ranges from £14 billion to £67 billion over the next 30 years [2]. A large number of properties where former MGP sites were located are adjacent to waterways and rivers, generally in high-density residential areas and/or areas earmarked for redevelopment. Because of this proximity to residents, the utility industry has implemented significant efforts over the past decade to assess and contain the environmental liability of these legacy sites. This effort has been prompted in part by the requirement of the Securities and Exchange Commission for companies to document environmental liabilities in their unaudited quarterly financial statements. Still another impetus into the remediation of MGP legacy sites is the promulgation of state and federal regulations. As a result of these regulations, utility companies began active participation in cleanup activities at hundreds of sites across the country. However, subtracting sites determined to require no further action, those addressed by voluntary state cleanup programs, and those for which remediation has already been completed, there still remain between 30,000 and 45,000 sites that have not yet been investigated, approximately 2300 of which are associated with former commercial MGP facilities [2].

Technologies used for the remediation of MGP sites can be straightforward, such as general excavation, or highly complex, requiring a suite of technologies, such as thermal treatment, *in situ* stabilisation, *in situ* chemical oxidation, and slurry walls. Both the owner and contractor must be intimately familiar with the technologies contemplated to ensure they can be readily implemented. To gain this level of knowledge, the development and execution of a TS programme is necessary, as discussed below.

## 2. Treatability study materials and methods

Treatability studies are widely used in the chemical and remediation industries to determine the efficacy of potential treatment processes. The benefits gained from a limited TS outweigh the relatively low costs required for the study. For stabilisation projects, the importance of the data collected is critical in determining compliance with the design goals, the types and quantities of additives or binders to use, and the delivery method necessary to combine the additives into a slurry or dry mix for subsequent injection into the contaminated soils.

To design a study appropriately, it is first necessary to identify and understand the performance criteria, the analytical methods used to measure the performance criteria, the types of additives/binders that can be used, and the sampling protocols to be implemented. Further discussion of these items is provided below.

### 2.1. Performance criteria

The physical performance criteria used in stabilisation of environmental wastes are adapted from the civil engineering and construction disciplines, as they include the same American Society for Testing and Materials (ASTM) methods used when executing construction projects involving geotechnical work. The ASTM methods cited below ensure the physical performance and durability of the stabilised mass with accepted standards. The U.S. Environmental Protection Agency's (U.S. EPA's) test methods for evaluating solid waste, physical/chemical methods are used to confirm the chemical performance requirements.

Performance standards further necessitate that no free liquids be present in the solidified mass. This determination is based on visual observation at the conclusion of the unconfined compressive strength (UCS) testing event. The physical and chemical performance criteria for two recent TSs are presented in Table 1. Note that other sites may have more or less stringent requirements depending on location and extent of contamination.

Additionally, environmental performance standards at MGP sites include total and synthetic precipitation leachability of metals, volatile organic compounds (VOCs), and semivolatile organic compounds (SVOCs). Table 2 presents a summary of these analytical methods.

For the two MGP site TSs included here, nonresidential cleanup standards were selected based on future land use, depth of material, groundwater impacts, and potential human exposure. In some instances, total concentrations of VOCs and SVOCs were also required to be less than the maximum concentration limits for drinking water in adjacent monitoring wells. The specific models used and the calculations performed are beyond the scope of this paper.

### 2.2. Analytical methods

A typical stabilisation TS begins with identification of the performance criteria. These criteria are specified using a variety of methods designed by the ASTM, the U.S. EPA, and the American Nuclear Society (ANS). A listing of the analytical methods can be found in the reference section of the paper.

### 2.3. Selection of additive/binder materials

Knowing the performance criteria and analytical methods allows the preliminary selection of binders. The most common reagent is Portland cement, which is manufactured to meet a variety of physical and chemical requirements. For example, the ASTM Designation C150 [3] provides for eight types of Portland cement; Type I, a general purpose Portland cement, is most applicable in the stabilisation/environmental arena. Its uses typically include pavements and sidewalks, reinforced concrete

Table 1
Treated Columns physical and chemical performance criteria [10]

| Criterion | Method [12–14] | Value | Units |
|---|---|---|---|
| UCS | ASTM D1633 | 345 | kPa |
| Permeability | ASTM D5084 | $1 \times 10^{-5}$ | cm/s |
| Durability | ASTM D4843 | <10 | % |
| Free Liquids | Visual at completion of UCS | None | None |
| Volatiles | | | |
| Benzene | U.S. EPA Method 8260B | 5 | mg/kg |
| Ethylbenzene | | 1600 | mg/kg |
| Toluene | | 680 | mg/kg |
| Xylenes (total) | | 160000 | mg/kg |
| Carbon Disulfide | | 400 | mg/kg |
| Semi-volatiles | | | |
| 2,4-Dimethyphenol | U.S. EPA Method 8270C | 1600 | mg/kg |
| 2-Methylphenol | | 3900 | mg/kg |
| 4-Methylphenol | | 390 | mg/kg |
| Acenaphthalene | | 4700 | mg/kg |
| Acenaphthylene | | 2300 | mg/kg |
| Anthracene | | 23000 | mg/kg |
| Benzo(*a*)anthracene | | 120 | mg/kg |
| Benzo(*a*)pyrene | | 78 | mg/kg |
| Benzo(*b*)fluoranthene | | 780 | mg/kg |
| Benzo(*g*,*h*,*i*)perylene | | 2300 | mg/kg |
| Benzo(*k*)fluoranthene | | 780 | mg/kg |
| Chrysene | | 78400 | mg/kg |
| Dibenzo(*a*,*h*)anthracene | | 78 | mg/kg |
| Fluoranthene | | 82000 | mg/kg |
| Fluorene | | 82000 | mg/kg |
| Indeno(1,2,3-*cd*)pyrene | | 78 | mg/kg |
| Naphthalene | | 100 | mg/kg |
| Phenanthrene | | 61000 | mg/kg |
| Phenol | | 47000 | mg/kg |
| Pyrene | | 61000 | mg/kg |
| Metals | | | |
| Arsenic | U.S. EPA Methods 6010/7471 | | |
| Barium | | 38 | mg/kg |
| Beryllium | | 5400 | mg/kg |
| Cadmium | | 160 | mg/kg |
| Chromium | | 39 | mg/kg |
| Copper | | 1200 | mg/kg |
| Cyanide | | 3100 | mg/kg |
| Lead | | 1600 | mg/kg |
| Mercury | | 1100 | mg/kg |
| Nickel | | 24 | mg/kg |
| Zinc | | 1600 | mg/kg |
| Arsenic | | 23000 | mg/kg |

Table 2
Summary of chemistry methods

| [15–19,21]Criterion | Methods |
|---|---|
| Total VOCs | U.S. EPA Method 8260B |
| Total SVOCs | U.S. EPA Method 8270C |
| SPLP VOCs | U.S. EPA Methods 1311/1312/8260B |
| SPLP SVOCs | U.S. EPA Methods 1311/1312/8270C |
| SPLP cyanide | U.S. EPA Methods 1312/9010B/9014 |
| Total RCRA metals | U.S. EPA Methods 6010/7471 |

buildings, bridges, tanks, reservoirs, sewers, and other masonry structures.

During testing, Portland cement is typically combined with other reagents to create an admixture that demonstrates the desired performance criteria. An admixture is anything other than one of the four basic ingredients (cement, sand, stone, and water) in a concrete mix. Admixtures are generally used to enhance or add desirable properties to concrete, such as strength, reduced leachability of contaminants, durability, ease of handling, controlled setting times, and waterproofing or antiwashout properties. The admixtures of primary importance are pozzolans, bentonite, proprietary chemicals which reduce leaching of contaminants, and water reducers (thinners).

### 2.3.1. *Pozzolans*

Pozzolans are admixtures that include fly ash, silica fume, and other finely ground substances that give cement increased strength, density, and durability. Pozzolans are usually added to cement during the normal course of production because they react, along with the cement, to make concrete harden. In the environmental sector and in the following case study, pozzolans including fly ash and blast furnace slag are most commonly used.

Fly ash can be divided into two major classes, as specified in ASTM C618 [4], depending upon its chemical composition resulting from the type of coal burned: Class F fly ash, which is normally produced from burning anthracite, and Class C fly ash, which is normally produced from burning subbituminous coal and lignite. Class F is rarely cementitious when mixed with water alone [5]. Class C fly ash usually has cementitious properties in addition to pozzolanic properties due to free lime.

The second pozzolan of importance is blast furnace slag, which ASTM defines as “the nonmetallic product consisting essentially of silicates and aluminosilicates of calcium and other bases that are developed in a molten condition simultaneously with iron in the blast furnace” [6]. Three types of slag used in cement production are air-cooled slag, expanded slag, and granulated slag. The durability properties of the air-cooled and expanded slag as well as the hydraulic properties of granulated slag have made it a principal admixture in cement products [6]. Because of its reasonable costs and availability, blast furnace slag was chosen over fly ash as an admixture for use in the TSs discussed below.

### 2.3.2. *Bentonite*

Bentonite is a processed clay material composed principally of the mineral montmorillonite. It has a great affinity for fresh water and, when hydrated, increases its volume more than 7-fold [7]. Bentonite’s self-healing and low permeability properties have made its use widespread in the environmental industry. Lower soil permeabilities can be achieved with small additions of bentonite than would otherwise be possible in mix designs that do not include bentonite. During the treatability tests for the projects discussed herein, a reduction in permeability of two orders of magnitude was achieved when only 0.75% bentonite was added [8].

#### 2.3.3. Thinners

Thinners reduce the plasticity of the clays drilled and thereby act as a lubricant. The benefits realised include more efficient drilling, a reduction in the frequency and size of clay inclusions, a more homogeneously mixed column, and a reduction in the amount of water added to the slurry. The admixtures in this case include L-175 and Spersene CF provided by Federal Bentonite and PS-1158 supplied by Master Builders. The final selection of mix designs used for the treatability studies discussed herein utilised L-175 thinner [8].

### 2.4. Pre-solidification versus post-solidification sampling

Another important aspect in designing an effective TS is the type of column sampling to be performed. Column sampling can be divided into two broad categories: pre-solidification sampling and post-solidification sampling. Pre-solidification sampling is conducted soon after mixing is complete while the column is still in the liquid state. Post-solidification sampling is conducted after the column hardens.

Both pre-solidification and post-solidification sampling offer certain advantages and disadvantages. For example, pre-solidification sampling is easier, less expensive, and faster while post-solidification sampling requires additional equipment, personnel, and time. Due to these requirements, post-solidification sampling is generally more expensive; however, post-solidification sampling uniquely offers the ability to test the state of the column as it was designed.

Pre-solidification samples can be collected immediately after the column is mixed and the drilling equipment is clear of the area. A sampling device (Fig. 1) mounted by cable to a track hoe is used to collect the sample from anywhere within the mixed column. The sampler is hydraulically actuated to capture the sample at the requisite depth. The sampler stores approximately one 15 cm × 30 cm concrete cylinder, or approximately 6 L of solidified material. Two collection events are necessary to collect the 10–12 8 cm × 15 cm samples required for testing. The sample molding operations can be performed on-site or at an off-site laboratory. A drawback of this pre-solidification sampling technique is that it does not provide in-place data on the column; rather, it provides data regarding the ability of the mixed soils to meet the performance criteria.

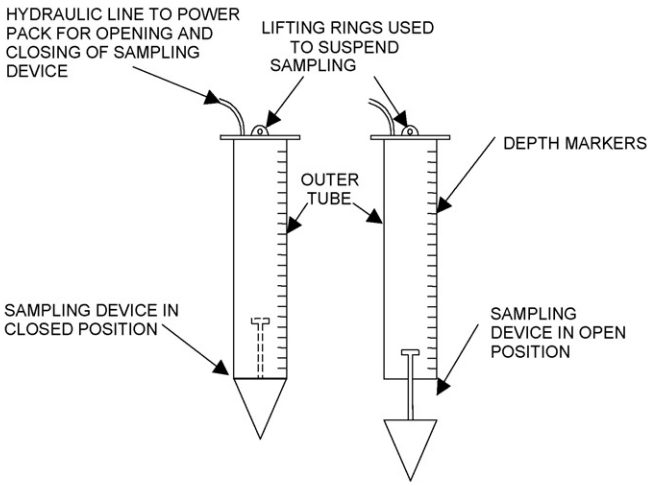

Fig. 1. Hydraulic sampling device.

Post-solidification sampling requires a rotary coring machine with 1.2-m sleeves and a diamond-carbide bit or a Geoprobe® drill rig. Additionally, the selected columns must cure for 3–7 days prior to sampling. Upon collection, the sample cores are examined, and the rock-quality designation and recovery percentages are calculated. The samples are then saw cut to the required size for future testing.

Based on experience, both saw cutting and core drilling introduces imperfections, or “micro-fractures”, on the surface of the samples. These micro-fractures can bias the UCS results low and the permeability results high. The authors have observed failures in up to 10% of the saw-cut samples when compared with identical pre-solidification samples. The micro-fractures provide preferential pathways through which water flows; due to the water flow, fracture planes develop, thus increasing the permeability of the sample and decreasing the strength of the core. Therefore, the true nature of the columns is not analysed. Instead, the actions imparted to the core through sample collection are being analysed. Due to this problem, the authors prefer to collect samples from pre-solidified columns; however, a pilot study programme can consider both sampling techniques to determine which is more appropriate.

### 2.5. Treatability programme results

When the performance criteria, analytical methods, and sampling requirements are known, the selection of additives, sample volume, and mix designs can be determined. Availability and cost are important factors in determining what additives/binders are used in the TS.

Typically, two to three 20-L samples of soil are collected from each site for testing. These samples represent average, special, and worst-case scenarios for the contamination on site. Mix designs are then prepared using approximately 1–2 kg of sample, three to five additives/binders, and five to seven additive rates. Therefore, the total number of mix design samples can approach 35 for each scenario.

Mix design rates usually vary from 5% to 25% addition by weight with limited combinations of cement–cement kiln dust, cement-lime kiln dust, cement-slag, or cement-slag-bentonite. For this particular case study, 31 mix designs were prepared and evaluated, requiring 95 L of material. The samples were subdivided into source areas based on the geology of the site: peat, clay, and sand. Mix designs were then developed for each source area as described in Table 3.

Subsequent to blending soils from each source area with the selected mix designs, each sample was evaluated for the physical performance criteria identified in Table 1. After the mix designs were combined with the soils, they were reevaluated and eliminated from further consideration using the following hierarchy:

- ability to meet all physical performance criteria,
- ability to meet all chemical (leaching) requirements,

Table 3
Several selected design mixes for clay, peat, and sand soils[a,b] [8] (data from treatability study)

| | Mix 21 | Mix 22* | Mix 1 | Mix 28 | Mix 3 | Mix 24[c,d,e] | Mix 26[c,d,e] |
|---|---|---|---|---|---|---|---|
| Soil case | Clay | | Peat | | | Sand | |
| *In situ* bulk density (kg/m$^3$) | 1926 | | 1525 | | | 1958 | |
| Column number (pilot study) | PM13 | PM16 | PM1 | PM7 | PM2 | – | – |
| Theoretical swell volume (%) | 59 | 38 | 41 | 40 | 45 | 47 | 47 |
| Additive addition (mix design) | | | | | | | |
| % Water | 27 | 17 | 20 | 18 | 24 | 22 | 22 |
| % Portland cement | 3.5 | 2.5 | 20 | 6 | 17 | 7 | 2.25 |
| % GGBF slag | 7 | 5 | 0 | 0 | 0 | 0 | 4.5 |
| % C fly ash | 0 | 0 | 0 | 12 | 0 | 0 | 0 |
| % Bentonite | 0 | 0 | 0.50 | 0.25 | 0.75 | 0.2 | 0.2 |
| % Thinner | 0.2 | 0.2 | 0 | 0 | 0 | 0 | 0 |
| Soil proportions (additive addition × *in situ* bulk density) | | | | | | | |
| Water (kg/m$^3$) | 521 | 328 | 305 | 275 | 366 | 431 | 431 |
| Portland cement (kg/m$^3$) | 67 | 48 | 305 | 92 | 259 | 137 | 44 |
| GGBF slag (kg/m$^3$) | 135 | 96 | 0 | 0 | 0 | 0 | 88 |
| C fly ash (kg/m$^3$) | 0 | 0 | 0 | 183 | 0 | 0 | 0 |
| Bentonite (kg/m$^3$) | 0 | 0 | 7.7 | 3.8 | 11.3 | 3.9 | 3.9 |
| Thinner (kg/m$^3$) | 3.9 | 3.9 | 0 | 0 | 0 | 0 | 0 |
| Grout proportions (soil proportions/theoretical swell volume) | | | | | | | |
| Water (kg/m$^3$) | 882 | 865 | 750 | 688 | 813 | 917 | 917 |
| Portland cement (kg/m$^3$) | 114 | 127 | 750 | 230 | 576 | 292 | 143 |
| GGBF slag (kg/m$^3$) | 228 | 254 | 0 | 0 | 0 | 0 | 187 |
| C fly ash (kg/m$^3$) | 0 | 0 | 0 | 458 | 0 | 0 | 0 |
| Bentonite (kg/m$^3$) | 0 | 0 | 18.4 | 9.5 | 25.1 | 8.3 | 8.3 |
| Thinner (kg/m$^3$) | 6.5 | 10.1 | 0 | 0 | 0 | 0 | 0 |
| UCS (7-day) (kPa) | 1213 | 427 | 613 | 76 | 358 | 586 | 380 |
| Permeability (cm/s) | 3.4E−09 | 1.1E−08 | – | – | 3.4E−07 | 3.2E−07 | 3.5E−09 |
| Durability test (relative loss %) | 0.03 | 0.81 | – | – | 0.06 | 0.02 | 1.12 |
| Mixture density (kg/m3) | 1663 | 1140 | 1455 | 1518[c] | 1420 | 1704 | 1700 |
| VOC SPLP reduction (%)[f,g] | 100 | – | – | – | 48 | ND | ND |
| SVOC SPLP reduction (%)[f,g] | 99.94 | – | – | – | 99.98 | 99.97 | 99.94 |
| Cyanide reduction (%)[g,h,i] | 100 | – | – | – | 67 | ND | ND |

(–) samples not analysed.

[a] Selected mix designs in table is not all inclusive.

[b] Tables 3 and 11 a derived from two different data sets, the treatability study and pilot study, respectively; therefore, will not match exactly.

[c] Density determined during pilot study.

[d] Pilot study was not conducted on sand mix designs.

[e] Mix 24 and Mix 26 have been updated to include additional data not available at the time of printing Ref. [10].

[f] SLPL reduction (%) = (SPLP(untreated) − SPLP(treated))/SPLP(untreated).

[g] Reduction %—does not include dilution by additives.

[h] Cyanide reduction (%) = (cyanide(untreated) − cyanide(treated))/cyanide(untreated).

[i] Cyanide analytical was non-detect in treated SPLP samples.

- mix designs using identical additives but in greater proportions were eliminated in favor of those using lesser amounts of the same additives (e.g., the selected mix design 8 versus mix designs 5–7),
- availability of reagents,
- costs of reagents.

## 2.6. Results

The results of the TS, including cost considerations for the use of each design mix (not shown), indicated that one mix design for peat (mix design 3), two mix designs for clay (mix designs 8 and 21), and one mix design for sand warranted further study in the pilot programme. In addition, a fifth mix design using Class C fly ash in the peat soils was added to determine the efficacy of using fly ash and compressed air. The TS incorporated a progressive analytical regimen; only when the physical performance criteria were met were the chemical/environmental parameters analysed.

### 2.6.1. Clay case results

Eight *in situ* stabilisation/solidification mixtures were formulated for the clay composite sample in this phase of testing. In general, the amount of cement required for the clay mixtures was slightly greater than that used in the sand case, ranging from 12% to 15%. Additionally, thinner was incorporated into the majority of grout mixes to help break down the stiff clays, and higher water contents were added to improve material mixing. However, this created greater amounts of swell when compared to the sand case samples.

UCS after 7 days of curing was greater than 690 kPa for the cement mixes and ranged from 220 to 496 kPa for the blast furnace slag mixes. Hydraulic conductivities for all samples analysed ranged from $10^{-9}$ to $10^{-8}$ cm/s. Based on these results, mix designs 8 and 21 were initially considered because both mixtures met all the physical requirements; however, mix design 8 used more cement and was therefore a more expensive alternative than mix design 21 and therefore mix design 21 was used in the pilot test. Mix design 22 was later modified because of excessive swell, leading to development of mix design 22*. Mix design 22* reduced the amount of water from 29% to 17% and replaced the admixture Spersene with 0.20% L175 [9]. Results of the mix designs 21 and 22* for the clay soils are summarized in Table 3.

### 2.6.2. *Peat case results*

Nine *in situ* stabilisation/solidification mixtures were formulated for the peat composite sample: three cement-grout mixtures and six blast-furnace-slag mixtures. Appropriate setting was achieved for all cement-grout mixtures although at a greater content than either the sand or clay mixes (>15%). Set times ranged from 1 to 5 days. After 7 days, UCS for the three mixes ranged from 358 to 613 kPa, with hydraulic conductivities in the range of $10^{-7}$ cm/s.

None of the blast-furnace-slag mixes proved successful at treating the peat composite samples. The competition between organics in the peat and organics in the blast furnace slag for the available lime in the cement did not allow the blast-furnace-slag grouts to set; therefore, the blast-furnace-slag mixtures were eliminated from further consideration. Subsequently, mix designs 1 and 3 were chosen for pilot-scale work with an additional mix design using fly ash (M28) added prior to pilot-scale implementation. Results of the peat design mixes meeting the performance criteria are found in Table 3.

### 2.6.3. *Sand case results*

Because the sand source at this site was very similar to the sand source at another site where work was being performed, the mix design in use at that site was used. The sand case results presented are those determined during previous treatability testing at that site. The decision to use the previous treatability testing results saved both time and money for this study, the subsequent PS, and full-scale work. Table 3 presents the sand design mixes.

## 3. Pilot study results

Following selection of the design mixes during the TS, the project lifecycle proceeds to development of the PS [10]. The principal purpose of the PS is to scale up the design mixes developed during treatability testing for application under actual field conditions. Mix designs approved for the PS are selected based on ability to meet the performance criteria, availability, and costs. Additionally, the PS is used to determine the operational parameters for the DSM drill platform. The most important operational parameters include the following:

- mixing-tool diameter;
- cycle time;
- rotational speed;
- penetration and withdrawal rates;
- optimisation of grout density and viscosity to accommodate existing soil conditions;
- exposure of pilot-test columns for visual inspections to determine:
  - ○ lateral stability,
  - ○ voids,
  - ○ inclusions,
  - ○ homogeneity of mix;
- development of the work platform;
- consideration of column sampling.

The development of the PS begins with the work plans, which dictate the approved additives, the type of drill platform being deployed, and the type and quantity of data to be collected. The location of the batch plant, utilities, and drill platform are finalised in the field. Data collection begins with the surveyed locations of the columns being drilled. Data are collected and organised on Microsoft® Excel spreadsheets and ultimately populated into a geographic information system (GIS) platform that, with a click on any numbered column, provides 28 process parameters and comments about the drilling performance or sample collection.

Table 4 summarises the GIS data available for review. Numerous field sheets are used to collect data to ensure that the slurry

Table 4
GIS process parameters (example)

| | |
|---|---|
| Column number | R21 |
| Date | 27 May 2003 |
| DSM platform (elevation in m) | 39.01 |
| Design top of DSM (elevation in m) | 37.80 |
| Actual top of DSM (elevation in m) | 37.80 |
| Design bottom of DSM (elevation in m) | 31.85 |
| Actual bottom of DSM (elevation in m) | 31.85 |
| Design depth (m) | 5.90 |
| Actual depth (m) | 5.90 |
| Start time | 1403 |
| Stop time | 1424 |
| Mix time (min) | 0:21 |
| No. of passes | 2 |
| No. of overlaps | 5 |
| Treatment volume ($m^3$) | 31 |
| Weight of soil (tonnes) | 61.9 |
| Soil classification design | Sand |
| Soil classification actual | Sand |
| Water % (design) | 18% |
| Cement design (tonnes) | 4.0 |
| Actual cement injected (tonnes) | 5.0 |
| Actual % of cement | 8.0% |
| Bentonite design (tonnes) | 0.31 |
| Bentonite added (tonnes) | 0.32 |
| Design mud balance ($kg/m^3$) | 1236 |
| Actual mud balance ($kg/m^3$) | 1257 |
| Design grout (L) | 12521 |
| Actual grout (L) | 12547 |

*Notes*: Began drilling on 19 May 2003 and redrilled on 27 May 2003 to design depth.

Table 5
Typical cement usage log (example only)

| Date | BoL #[a] | Total cement batched (tonnes) | Thinner used (L) | Thinner received (L) | Cement received (tonnes) |
|---|---|---|---|---|---|
| 8 April 2004 | 598309 | 0 | 0 | 66600 | 23.4 |
| | 598357 | 0 | 0 | 0 | 24.0 |
| 9 April 2004 | 598364 | 0 | 0 | 0 | 24.3 |
| | 598397 | 0 | 0 | 0 | 26.9 |
| 12 April 2004 | | 23.8 | 1609 | 0 | 0 |
| 13 April 2004 | 598465 | 14.1 | 1136 | 0 | 23.7 |
| | 598468 | 0 | 0 | 0 | 24.1 |
| 14 April 2004 | 598482 | 28.7 | 2160 | 0 | 24.2 |
| | 598487 | 0 | 0 | 0 | 23.3 |
| | 598502 | 0 | 0 | 0 | 23.9 |
| 15 April 2004 | 598541 | 57.2 | 4353 | 0 | 24.5 |
| 16 April 2004 | 598584 | 54.4 | 1136 | 0 | 24.4 |

[a] BoL #, bill of lading number.

Table 6
Soil data spreadsheet

| Date | Mix design | Wet density ($kg/m^3$) | Moisture (%) | Dry density ($kg/m^3$) |
|---|---|---|---|---|
| 13 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 13 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 14 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 14 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 14 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 14 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 14 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 14 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 14 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 15 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 15 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 15 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 15 April 2004 | 6 | 1743 | 37.8 | 1265 |
| 15 April 2004 | 6 | 1743 | 37.8 | 1265 |

Table 7
Column data spreadsheet

| Column ID | Northing | Elevation (m) | Depth (m) | Grout (L) |
|---|---|---|---|---|
| MM-11 | 874.8731 | 67.5 | 4.9 | 15356 |
| NN-9 | 264.1735 | 67.5 | 4.7 | 12089 |
| OO-8 | 264.6643 | 67.3 | 3.5 | 12643 |
| PP-6 | 262.3170 | 67.2 | 3.5 | 11976 |
| OO-7 | 261.8608 | 67.3 | 4.1 | 12415 |
| PP-5 | 259.5098 | 67.2 | 3.5 | 13636 |
| LL-12 | 266.1082 | 67.5 | 4.2 | – |
| MM-10 | 263.7526 | 67.4 | 4.6 | 15746 |
| NN-8 | 261.4029 | 67.4 | 4.5 | – |
| OO-6 | 259.0495 | 67.2 | 3.2 | 13213 |
| OO-5 | 256.2438 | 67.2 | 3.2 | 13191 |

(–) data not available.

meets the design specifications of the mix. This begins with the cement log, which is used to record shipments of cement and admixtures received and used. Table 5 shows a portion of a typical cement usage log. Along with the cement usage log, a stabilisation master spreadsheet is used to record *in situ* soil conditions, such as moisture content and density (Table 6), and column data, such as the top elevation and the volume treated (Table 7). Additionally, the spreadsheet contains treatment data (Table 8) that document the cycle time, number of passes, and volume of slurry received. Please note that the tables presented herein are only examples and do not include all information that is recorded. They identify the type of information that is important to the contractor and owner to ensure compliance with the project requirements.

### *3.1. Mixing tool and column geometry*

The diameter of the DSM mixing tool is critical in determining the volume of each column and the number of columns to be drilled for the project. The effective area of a 2.4-m diameter tool is 3.9 $m^2$ while a 3.7-m diameter tool has an effective area of 8.7 $m^2$. An example of a typical mixing tool is shown in Fig. 2.

The geometry of the site and columns in relation to each other is also very important. There are numerous column geome-

Table 8
Treatment data spreadsheet [10]

| Total mixing time | Equiv. passes | Desired ratio cement (%) | Total required grout (L) | Actual grout (L) | Actual ratio (%) |
|---|---|---|---|---|---|
| 0:50 | 4 | 12 | 12305 | 15355 | 19.8 |
| 0:35 | 4 | 12 | 11798 | 12089 | 2.4 |
| 0:35 | 4 | 12 | 8815 | 12641 | 30.3 |
| 0:25 | 4 | 12 | 9042 | 11956 | 24.4 |
| 0:25 | 4 | 12 | 10537 | 12415 | 15.1 |
| 0:17 | 4 | 12 | 8967 | 10636 | 15.7 |
| 0:20 | 4 | 12 | – | – | – |
| 0:09 | 4 | 12 | 10579 | 15746 | 32.8 |
| 0:09 | 4 | 12 | 11673 | 13100 | 10.9 |
| 0:09 | 4 | 12 | 11412 | 13191 | 13.5 |
| 0:09 | 4 | 12 | 7903 | 10753 | 26.5 |
| 0:09 | 4 | 12 | 8505 | 10522 | 19.2 |
| 0:09 | 4 | 12 | 7699 | 10011 | 23.1 |
| 0:09 | 4 | 12 | 8168 | 9955 | 18.0 |

(–) data not available.

Fig. 2. Typical DSM mixing tool.

tries that can be used for stabilisation work; however, the most efficient geometry minimises the overlap of each column, thus reducing areas that receive additional additive and mixing time. Fig. 3 illustrates the most economical and efficient column geometry. Using this geometry, a 0.4-ha area requiring stabilisation with a 1.8-m diameter tool requires 1900 columns compared to 470 columns for a 3.7-m diameter tool.

### 3.2. Mixing parameters

Cycle time and rotational speed are important in determining costs for full-scale work. Cycle time dictates the total amount of time necessary to drill one column. Typically, a 4.6-m deep column takes 45 min to drill and requires two to four passes of the auger over the length of the column at a rotational speed of 6–8 rpm. However, with a large-diameter tool, it is difficult to maintain the proper rotational speed and penetration rate because of the tool's size. Furthermore, as the column depth increases, additional torque is required to achieve the specified depth. The greater the torque required, the slower the rotational speed and advance rate.

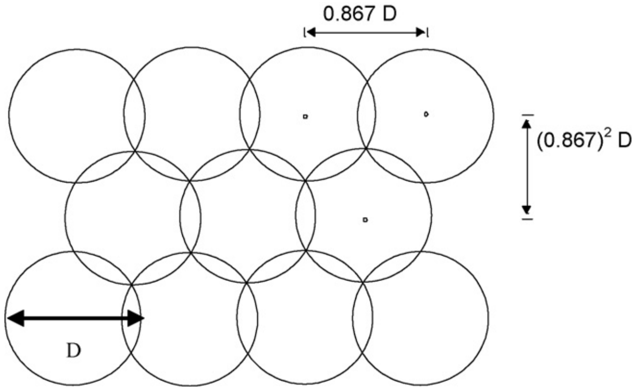

Fig. 3. Typical column geometry.

Fig. 4. Example of mixed column geometry.

An indirect measure of cycle time and rotational speed is the homogeneity of the unexcavated mixed column as shown in Fig. 4. During the pilot-scale test, cycle time ranged from 20 to 127 min per column, or an average of 54 min per column. Based on experience with similar soils, it was anticipated that production cycle time would be lowered to 40–45 min per column for full-scale implementation.

The pilot test offers the only opportunity for the owner and contractor to verify the thoroughness of the mixing by physically observing an unearthed column and noting the frequency of voids, inclusions, unmixed slurry, and free product as well as the overall stability of the column. It is also an excellent way to determine the amount of swell generated by actual drilling conditions. One can then directly correlate the physical observations with the penetration rate, rotational speed, cycle time, and mix design used.

During the pilot test, the mix design is optimised. Additional data are collected for in-place moisture content and density. These results are compared to the treatability results, allowing the mix design to be altered during pilot production as needed. Typically, the slurry that is delivered to a column is altered based on field data, drilling performance, and quantity of swell produced. The slurry will be thinned or thickened based on the moisture content of the soils, and additional grout will be pumped after the predetermined volume of the design mix has been utilized, as long as drilling continues. Thus, the slower the drilling, the more slurry is used. This is important when estimating performance costs.

### 3.3. Batch plant

The batch plant is assembled with a grout-flow meter (Fig. 5) to determine the overall volume of material injected. Another important parameter is the grout density, which can be measured by a simple instrument, such as a mud balance, or by more sophisticated instruments, such as an ultrasonic densiometer. Grout density is typically measured with a mud balance in general compliance with API recommended practice 13B-1 [22].

The amount of swell created is inversely proportional to the strength requirement of the column. That is, the greater the

Fig. 5. Grout-flow meter in operation.

strength requirement for the column, the more additive/admixture is required. The more additive/admixture required, the more water is required, creating more swell. One way to minimise this increase is to use a water reducer; however, the creation of swell is not eliminated.

During the development of the treatability study for this particular case, the amount of swell generated was between 40% and 60% [11]. The pilot study work plan accommodated this additional material by sequencing the excavation such that approximately 0.9–1.2 m of soil was left atop the saturated soil where the drill platform was positioned. Prior to drilling, the soils directly over each column were removed, thus creating a basin to collect the majority of the swell. Swell that could not be contained in the basin was subsequently disposed at an appropriate landfill.

## 3.4. *Pilot study implementation*

Using the five viable mix designs that met the performance and cost criteria in the TS, 23 pilot columns were designed: 14 for the peat material and 9 for the clay materials [10]. Details are provided below.

### 3.4.1. *Basic grout mixtures*

As indicated above, five mix designs were selected for the field PS. Three of the mixes were developed during the DSM laboratory study, including Mixtures 1 and 3 for peat soils and Mixture 21 for the clay soils. The other two mix designs were modifications of those developed during the bench-scale treatability study. Mixture 22* was a slightly modified version of Mixture 22, and Mixture 28, a fly ash–cement mixture, was developed after completing the laboratory study. In addition to each of these basic grout mixtures, variations of each were developed for implementation during the study. Variations in the amounts of water, bentonite, cement, and thinners were explored to find the most viable grout mix for full-scale DSM. In all, a total of 20 variations of the five basic grout mixtures were formulated, as shown in Table 9.

### 3.4.2. *Grout mixing*

Grout is mixed in batches to maximise and simplify quality control, with one to four batches required for each test column. Grout batches are developed based on the dimensions of the column to be stabilised and the *in situ* density of the materials. Using a cement grout mixer, reagents are mixed with water to create the grout for each mix design. The flow of water is monitored with an in-line turbine meter while reagents are weighed prior to introduction into the mixer.

The batch tank is equipped with a high-shear, lightning mixer/agitator to maintain a homogeneous grout mix. The total volume of the batch tank is 5.2 $m^3$; however, to allow adequate freeboard, the working volume of the tank is limited to approximately 3.8 $m^3$. After the correct proportions are added to the batch tank, the high-shear mixer completes the blending process. The operator takes a grout sample and tests the density using a mud balance. The weight of the batch is recorded on the batch plant log and the sample transferred to a mixing tank.

A Magnum centrifugal pump transfers the batch to separate mixing tanks until it is needed for *in situ* treatment. The amount of grout pumped to the DSM rig is measured using the grout-flow meter. A typical “batch” consists of 3028 L of grout. Each batch is made and pumped into a secondary tank in less than 10 min. While the first batch is mixing in the second tank, another batch is made. Four batches are prepared prior to pumping the grout to the drill rig. The grout is constantly mixed prior to pumping to the drill rig.

### 3.4.3. *Grout density and pumping*

Grout density is a primary quality control parameter during full-scale DSM implementation, providing more consistent and reliable results than the use of weigh hoppers or other weighing devices. Grout density can be rapidly checked to verify the proportioning of reagents in the mix design without interrupting the mixing process. Density is also important in determining the workability of the grout mixture, that is, if the grout is pumpable. Using a progressive cavity pump, grout must be pumped to the top of the Kelly bar on the DSM rig for stabilisation of each column. The pump is capable of transferring liquids with densities less than 1605 kg/$m^3$ and apparent viscosities less than 0.05 Pa s.

The predetermined grout volume is pumped to injection ports located along the length of the blades of the mixing tool and into each treatment column to blend with the contaminated soils. The grout volume is calculated based on the diameter, depth, and overlap portions of each treatment column.

### 3.4.4. *Soil-mixing equipment*

Soil-mixing equipment included a multibladed, rotating mixing tool with a 2.4-m diameter. The mixing tool was attached to a 24-m long by 36-$cm^2$ hollow drill stem (Kelly bar) with a bolted flange.

The Kelly bar and tool was supported by a high-torque transmission attached to a crawler-mounted lift crane. The range of torque exerted by the transmission for normal mixing operations was between 135.6 and 542.4 kN m. The centre of the drill stem to the pivot point in the centre of the crane was approximately 10.7 m. The mixing rig always operated

Table 9
Selected pilot study mix designs [10]

| Pilot mix ID | Soil class | Lab mix ID | Water (%) | Cement (%) | Bentonite (peat) thinner (clay) | Fly ash (peat) blast furnace slag |
|---|---|---|---|---|---|---|
| PM1 | Peat | 1.0 | 27.1 | 23.2 | 0.58 | 0 |
| PM2 | Peat | 3.0 | 28.8 | 18.1 | 0.80 | 0 |
| PM3 | Peat | 3.1 | 22.8 | 17.2 | 0.25 | 0 |
| PM4 | Peat | 3.1 | 15.3 | 15.3 | 0.22 | 0 |
| PM5 | Peat | 3.2 | 20.2 | 17.1 | 0.25 | 0 |
| PM6 | Peat | 3.5 | 18.9 | 10.4 | 0.24 | 0 |
| PM7 | Peat | 28.1 | 22.7 | 6.0 | 0.25 | 12.0 |
| PM8 | Peat | 28.2 | 18.8 | 7.7 | 0.25 | 16.0 |
| PM9 | Peat | 3.3 | 23.3 | 15.0 | 0.25 | 0 |
| PM10 | Peat | 3.4 | 20.0 | 13.0 | 0.25 | 0 |
| PM11 | Peat | 3.6 | 18.2 | 16.9 | 0.25 | 0 |
| PM12 | Peat | 3.7 | 17.6 | 17.0 | 0.25 | 0 |
| PM13 | Clay | 21.0 | 31.0 | 4.0 | 0.22 | 7.9 |
| PM14 | Clay | 21.1 | 24.0 | 4.4 | 0.25 | 8.8 |
| PM15 | Clay | 21.2 | 19.0 | 4.0 | 0.23 | 8.0 |
| PM16 | Clay | 22.0 | 22.0 | 3.1 | 0.25 | 6.3 |
| PM17 | Clay | 22.1 | 25.0 | 2.5 | 0.20 | 5.0 |
| PM18 | Clay | 22.2 | 29.0 | 2.5 | 0.40 | 5.0 |
| PM19 | Clay | 22.3 | 14.0 | 2.3 | 0.18 | 4.6 |
| PM20 | Clay | 21.1 | 21.0 | 3.5 | 0.20 | 7.0 |

on a wooden platform consisting of 0.3 m × 1.2 m × 8.5 × m (thick × wide × long) hardwood mats butted together. The mats provided stability, maintained vertically plumb mixing, and minimised contamination of drill rig tracks. In addition, the drill platform could be equipped with a hood to minimise VOC emissions. Fig. 6 shows the drilling rig deployed, and Fig. 7 shows a drill rig equipped with a hood for emissions control.

### 3.4.5. *Horizontal and vertical control*

The northing and easting coordinates of each column centre were tabulated using AutoCAD® and the Georgia State Plane coordinate system. Standard total station survey equipment was used to locate the centre point of each column in the horizontal plane. The centre point of each column was staked after the pre-DSM elevation platform was excavated, and the column number was recorded on the stake. Personnel on the ground signaled the operator to verify the correct location of the mixing tool.

The tool was mounted rigidly to the Kelly bar, creating a fixed distance between the tool and a given point on the bar. The bar was marked to indicate the distance from the lowest cutting point on the tool. By marking the Kelly bar in 0.3-m increments, the depth and vertical rate of mixing were observed as the column construction progressed. The bottom elevation of each column was determined by deducting the measured column depth from the preexisting surface elevation.

*3.4.5.1. DSM column installation.* Fourteen DSM columns were installed in the peat soils and nine columns in the clay

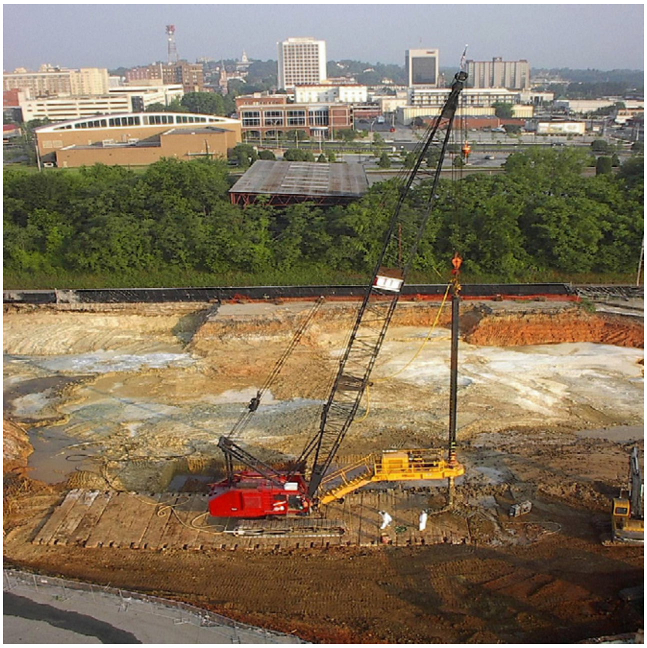

Fig. 6. DSM rig in action.

Fig. 7. Drill rig equipped with a hood.

soils. Each column was used to test one or more operational variables, including the grout mixture proportions, the mixing method, the use of air as a drilling aid, the ability to penetrate saprolite, the excavation depth, the confirmatory sample collection methods, and the swell. All peat columns were completed using a 2.4-m diameter auger while clay columns utilised both a 2.4- and a 1.8-m diameter auger. After completion, analytical samples were collected and analysed for the various performance criteria.

*3.4.5.2. Sample selection.* Seven of the 12-peat mix designs failed to meet the UCS performance criteria of 345 kPa. Of the remaining five mix designs (column samples PM1, PM2, PM3, PM9, and PM10), the mix design for column PM3 was eliminated because of the inherent difficulty of the formulation and its implementability in the field. The remaining four designs passed the environmental performance criteria. Based on their success, water addition rates ranging from 20% to 29%, a minimum of 15% cement additive, and a 0.25% admixture of bentonite were chosen for use in the full-scale mix design. For cost effectiveness, the amount of cement was minimised; thus the approved mix design was a variation of the laboratory mix design 3.

Six of the eight clay mix designs passed the physical performance criteria for UCS and permeability. Columns PM17 and PM18 failed to meet the UCS criterion; therefore, subsequent testing was terminated. Although they passed the UCS and permeability performance criteria, samples from pilot columns PM14 and PM19 were terminated because of the complexity of the mix designs' implementability in the field. Column samples PM13, PM15, PM16, and PM20, which are variations of laboratory mix design 21, remained. Again, the additives were minimised within the range tested; therefore, the full-scale mix design required a water addition rate of 18–31%, a minimum of 3.5% cement additive, 7% blast furnace slag, and a 0.20% admixture of L175 thinner. The minimisation of additives reduced costs.

As noted in Table 3-footnote(d), a sand soil PS was not performed. However, for completeness, the sand soil full-scale design mix is presented with the peat and clay soil mix designs in Table 10.

### 3.5. Comparison of treatability and pilot test results

The analytical results of the untreated samples, the selected mix designs and the columns that were subjected to the selected mix designs for peat and clay are shown in Table 11. In general the pilot study column's SPLP results were consistent with the results of the treatability study.

## 4. Discussion—deep soil mixing environmental case study

Following a successful TS and PS, the next step in the *in situ* stabilisation/solidification project lifecycle is full-scale implementation. The following case study illustrates the long-term effectiveness of *in situ* stabilisation/solidification, thus completing the project lifecycle.

### 4.1. Deep soil mixing of contaminated soils at the former Columbus MGP site

DSM has been practised for many years, primarily in the geotechnical and deep foundations arenas; however, in the late 1980s and early 1990s, DSM crossed over into the environmental arena. To date, approximately 46 environmental DSM projects have been completed, of which Compass Environmental Inc., has performed 9.

The former Columbus MGP site, located along the Chattahoochee River waterfront in the central business district of Columbus, Georgia, was acquired by the City of Columbus as part of a downtown waterfront revitalisation and restoration plan. The city planned to redevelop the land as a park and riverfront walk. The schedule for remediation of the former MGP site was critical as the park had to be completed in time for the city's Columbus day festival.

The 1.6-ha site was filled extensively since the 1930s, especially along the western site boundary, to raise the riverbank. The initial site investigations revealed pockets of coal tar and oil in the fill. The primary MGP-affected soils, however, were encountered below the water table in the alluvium underlying the fill. Analytical results indicated the presence MGP-related contaminants, including VOCs and PAHs. The reported maximum total VOC and PAH concentrations were 262,870 and 2,385,900 ppb, respectively. Oil and grease concentrations in soil were as high as 5500 ppm. Table 12 shows the timeline for the project.

### 4.2. Treatment technology description

The *in situ* stabilisation process used an auger system to drill into affected soils and uniformly mix the soils with cement additive. The mix design specified 10% by weight addition of Type I Portland cement and a 25% addition for the western soil cement wall along the Chattahoochee River. The depth of each auger hole was projected based on extensive site assessment data, and the column volume was calculated. The required amount of additive for each column could then be determined and regulated. The additive was mixed into slurry at the batch plant and pumped to the rig. The water:cement ratio varied across the site but was typically about 1.5:1.

Treatment equipment included a 2.5-m diameter auger advanced using a 91-tonne drill rig capable of developing a torque of 271 kN m. Cement additive was introduced through the hollow-stem auger to three exit ports in the bottom of the auger.

The cement grout was produced in a high-shear colloidal lightning mixing plant. The 3800-L mixer had the capability of producing up to 39 $m^3$/s.

Water was obtained from a nearby fire hydrant and pumped to the batch plant. The flow of water was metered to achieve the required mix design. Grout was then transferred to the soil-mixing rig.

### 4.3. Treatability testing

A TS was performed to determine the appropriate dosage of Type I Portland cement additive. Test mixes were evaluated

Table 10
Approved design mixes for full-scale DSM [10] (data from pilot study)[a]

| | Mix 21 | Mix 3 | Mix 26[b] |
|---|---|---|---|
| Soil case | Clay | Peat | Sand |
| *In situ* bulk density (kg/m$^3$) | 1926 | 1525 | 1958 |
| Column number | PM13 | PM2 | – |
| Theoretical swell volume (%) | 59 | 45 | 59 |
| Additive addition | | | |
| % Water | 18–31 | 20–29 | 16 |
| % Portland cement | 3.5 | 15.0 | 1.5 |
| % GGBF slag | 7 | 50 | 4.5 |
| % C fly ash | 0 | 0 | 0 |
| % Bentonite | 0 | 0 | 0.5 |
| % Thinner | 0.2 | 0.2 | 0 |
| Soil proportions (additive addition × *in situ* bulk density) | | | |
| Water (kg/m$^3$) | 347 | 366 | 313 |
| Portland cement (kg/m$^3$) | 67.1 | 259 | 29 |
| GGBF slag (kg/m$^3$) | 135 | 0 | 88 |
| C fly ash (kg/m$^3$) | 0 | 0 | 0 |
| Bentonite (kg/m$^3$) | 0 | 11 | 0 |
| Thinner (kg/m$^3$) | 3.9 | 0 | 0 |
| Grout proportions (soil proportions/theoretical swell volume) | | | |
| Water (kg/m$^3$) | 587 | 813 | 530 |
| Portland cement (kg/m$^3$) | 114 | 575 | 49 |
| GGBF slag (kg/m$^3$) | 228 | 0 | 149 |
| C fly ash (kg/m$^3$) | 0 | 0 | 0 |
| Bentonite (kg/m$^3$) | 0 | 25 | 0 |
| Thinner (kg/m$^3$) | 6.5 | 0 | 0 |
| UCS (7-day) (kPa) [ASTM 2166] [19] | 786 | 503 | 379 |
| Permeability (cm/s) [ASTM 5084] | 1.0E−07 | 2.7E−07 | 3.5E−08 |
| Durability test (relative loss %) [ASTM 4843] | 0.48 | 0.06 | 1.12 |
| Mixture density (kg/m$^3$) | 1670 | 1420 | 1700 |
| Reduction (%) VOC SPLP[c,d,e] [U.S. EPA Method 1312/8260B] | >55 | Increase | – |
| Reduction (%) SVOC SPLP[c,d] [U.S. EPA Method 1312/8270C] | >99.9 | >99 | 99.94 |
| Reduction (%) cyanide[c,d,e,f] [U.S. EPA Method 1312/9010B] | >75 | >67 | – |

[a] Tables 3 and 10 are derived from two different data sets, the treatability study and pilot study, respectively; therefore, will not match.

[b] Mix 26 is are slight variation of the mix design tested in the lab. Design based on similar project.

[c] Reduction %—does not include dilution by additives.

[d] SLPL reduction (%) = (SPLP(untreated) − SPLP(treated))/SPLP(untreated).

[e] Cyanide and VOCs were non-detect in both the treated and untreated samples.

[f] Cyanide reduction (%) = (cyanide(untreated) − cyanide(treated))/cyanide(untreated).

for their ability to achieve design values of UCS, permeability, and PAH content of toxicity characteristic leaching procedure (TCLP) extract (see Table 13 for DSM performance criteria). Based on the results of the study, a design mix of 10% by weight addition of cement was specified for the stabilisation with a rich mix of 25% to be used for the western soil cement wall. Pilot-scale testing of the treatability results was not conducted. A decision mandated by schedule and contractor's scope of work.

## 4.4. Field operations

### 4.4.1. Excavation

Overburden fill soils were excavated from the general site elevation of 71.32 m to approximate elevations of 67.28 and 64.62 m, a maximum of 7 m. The overburden consisted primarily of imported fill that was placed after MGP operations ceased. The fill materials therefore were less impacted than the

Table 11
Comparison of SPLP results from the treatability and pilot study [23]

| Analytical parameter | Soil matrix | Untreated sample | Lab mix design no. | Test column | Test column | Test column | Test column |
|---|---|---|---|---|---|---|---|
| SPLP VOC, sVOC, CN- | Clay (mg/L) | 4501 | M3 (0.97) | PM1 (3.37) | PM2 (3.50) | PM9 (3.22) | PM10 (1.11) |
| SPLP VOC, sVOC, CN- | Peat (mg/L) | 2762 | M21 (1.70) | PM13 (2.86) | PM15 (2.70) | PM16 (16.04) | PM20 (1.91) |
| SPLP VOC, sVOC, CN- | Sand (mg/L) | 1600 | M11 (0.5) | pNp | pNp | pNp | pNp |

pNp, pilot study not performed for sand matrix.

Table 12
Timeline

| Date | Work performed |
|---|---|
| November 1991 | Site mobilisation |
| December 1991 to April 1992 | Excavation |
| January 1992 to May 1992 | *In situ* vertical auger soil treatment performed |
| May 1992 to June 1992 | Backfill and site restoration |
| June 1992 | Liner installation |
| June 1922 to present | Post-remediation monitoring |
| October1992 | Columbus day festival |

soils at and below the water table. All excavation was planned to be above groundwater level. After placement of the western soil cement wall, the riverbank west of the wall was further lowered to an approximate 58.83-m elevation. Added quality assurance/quality control (QA/QC) measures were implemented during this excavation to ensure continued protection of the river environment. Georgia Power maintained the river level below elevation 57.91 m by manipulating upstream lock and dam operations. A total of about 86,000 $m^3$ of soil was removed in the excavation phase.

It was imperative that MGP-affected soils were segregated from unaffected soils in this phase. Prior to excavation of each lift, the fill surface was visually inspected. In some cases, the soil could be identified as affected based on odour or marked discoloration. In the absence of clear visual indications, the site was divided into sections, and grab samples were taken to form a composite representative of each grid. The samples were analysed for total petroleum hydrocarbons (TPH), PAH, and benzene, toluene, ethylbenzene, and xylene (BTEX) content. The criteria for classification of the fill as affected material are listed in Table 14.

Obviously affected soils were removed to the on-site staging/holding area for subsequent stabilisation. Other soils were hauled to an off-site storage area and segregated by area of excavation until analytical results became available. Materials determined to be affected were then returned to the site for stabilisation with the *in situ* soils. The clean fill was retained at the off-site storage area for future use as backfill over the cap liner material.

### 4.4.2. *Deep soil mixing*

*In situ* stabilisation operations were initiated along the eastern site boundary, using equipment similar to that described in Section 3.4.4. The rich-mix soil-cement wall (Fig. 8) along the west side was completed next to enable the riverfront contractor to begin work. The wall was approximately 114-m long, with each overlapping 2.4-m diameter column keyed 1 metre into the saprolite. Once the wall was stabilised, affected soils west of the wall (between the wall and the river) were excavated from an approximate 64.62-m elevation to a 58.83-m elevation and placed on the east side of the wall for subsequent stabilisation with the *in situ* soils. Shotcrete was sprayed on the lower portion of the exposed riverside of the wall to ensure sealing of the saprolite/bedrock interface.

Table 14
Criteria for affected soil

| Parameter | Value (mg/kg) |
|---|---|
| Total PAH content | >200 |
| Carcinogenic PAH content | >100 |
| BTEX content | >100 |
| Total TPH content | >500 |

Fig. 8. Exposed stabilised soil-cement wall.

Stabilisation then progressed across the site, as shown in Fig. 9. Treatment extended in different site areas from 68.28- and 64.62-m elevations down to 57.91-m elevations; the deepest auger holes were 11 m. Georgia Power maintained the river level below 60.96-m elevations during the *in situ* stabilisation operations.

Prescreening in-place soils increased productivity and operation efficiency and reduced maintenance and equipment breakdowns that lead to on-time completion of the work. A total of 1823 overlapping 2.4-m diameter columns were placed, with a

Table 13
DSM performance criteria[a]

| Parameter | General stabilisation (10% design mix) | Soil/cement wall (25% design mix) |
|---|---|---|
| Unconfined compressive strength [ASTM D2166] [20] (kPa) | 413 | 413 |
| Permeability [ASTM D5084] (cm/s) | $1 \times 10^{-5}$ | $1 \times 10^{-6}$ |
| PAH content [U.S. EPA Method 1311/8270] [21] (mg/L) | 10 | 10 |

Unconfined compressive strength at 28 days.

[a] All regulatory requirements were achieved in accordance with the project specifications.

Fig. 9. ISS of the Columbus MGP site.

Fig. 10. Completed city park.

total stabilised soil volume of more than 62,700 $m^3$. The production duration was 20 weeks.

QC testing was performed on the stabilised columns to verify compliance with the performance criteria for UCS, permeability, and PAH content of TCLP extract, as shown in Tables 13 and 15. A total of 333 columns were sampled; the column numbers and sample depths were randomly selected. Samples were collected from freshly mixed materials using a 25-cm sampling tube device. All samples were subjected to UCS testing; penetration resistance at 1 day provided an early indication that the required 28-day strength of 413 kPa would be achieved. Permeability and leachable PAH analyses were performed on 10% of the samples. All analytical results met or exceeded design specifications.

### 4.5. Site restoration

Upon completion of *in situ* stabilisation, the stabilised area was covered with 0.3 m of unaffected soil, compacted, and sloped to drain. A 60-mm high-density polyethylene (HDPE) liner material was then placed over the entire stabilised area, as part of the cap.

Unaffected soils previously excavated and stored off-site were returned to the site for use as backfill. Backfill was placed over the liner in lifts and compacted to 90% of the Standard Proctor maximum dry density. The City of Columbus completed the area fill with topsoil to final grade in order to construct the new city park (Fig. 10). The remaining surplus of unaffected soil was used as daily cover at the city's municipal landfill.

Table 15
Key parameters

| Parameter | Value |
|---|---|
| Additives and dosage | Portland Type 1: 10% (w/w) for monolith 25% (w/w) for gravity wall |
| Curing time (day) | 28 |
| Penetration rate | 0.3–1.2 m/min during penetration and withdrawal |
| Compressive strength [ASTM D 2166] (kPa) | 413 |
| Volume increase (%) | 20 (on average) |
| Permeability [ASTM D 5084] (cm/s) | $\leq 1 \times 10^{-6}$ |

### 4.6. Results

The company engineered, managed, and performed remediation of 62,700 $m^3$ of contaminated soils at the Columbus MGP Site. At the time, 1992, this was largest environmental DSM stabilisation project ever undertaken in the United States.

### 4.7. Post-remediation monitoring

Georgia Power Company implemented a post-remediation monitoring plan to confirm and document the effectiveness of the remedial action and monitor for potential releases of MGP-related constituents from the site. Eight monitoring wells were installed around the site periphery. Seven of these were screened in the water table aquifer above the saprolite, and the remaining well penetrated the underlying bedrock.

The wells were sampled regularly, and the groundwater samples were analysed for VOCs, PAHs, and total cyanide. The wells were also checked visually for the presence of nonaqueous phase liquids (NAPL). Sampling occurred quarterly for the first year and semiannually for the next 4 years. No statistically significant levels of MGP-related constituents were recorded during the 5-year period, and monitoring was discontinued.

In addition, Electric Power Research Institute (EPRI), in association with Southern Company, Georgia Power and Louisiana State University, performed a 10-year assessment study of the site. EPRI recently published these results [12].

The results of the 10-year post-remediation study demonstrated "that the present integrity of the solidified mass is in excellent condition" [12]. The liner also showed superior performance as test results for "thickness, puncture strength, and density of the sampled liner" showed the same strength characteristics as when it was originally placed. Finally, there is "no evidence to suggest that the integrity of the stabilised mass would diminish over time." To date, the groundwater "continues to remain clean at the site" [12]. All of these data attest to the viability of *in situ* stabilisation/solidification as a long-term solution for the remediation of MGP wastes.

## 5. Conclusions

The TS, if properly executed, will narrow the types and amounts of additives used for pilot-scale testing in the field. It will also allow time to explore pricing, delivery, and availability of the additives/binders and to develop a better understanding of the physical and chemical properties of the contaminated wastes. The study described herein narrowed a field of more than 35 potential mix designs to 6.

The TS forces the owner, engineer, and contractor to address the physical and chemical aspects of the wastes, as well as the additives and binders that will eventually be selected for the full-scale work methodically. During the TS, the engineer and contractor can decide how best to deliver the additives in addition to finding the most abundant and cost-effective binders. A more detailed cost estimate may also be developed at this time since the additive can be as much as 30–50% of the stabilisation costs.

The six mix designs from the treatability study were then developed into 23 column mix designs for testing during the pilot-scale evaluation.

During implementation of the TS and PS detailed in this paper, a full-scale DSM project was ongoing at a similar site. During the similar project work, valuable information was gathered that directly led to improvements and cost-cutting measures for the project discussed herein. The PS confirmed the results of the TS and allowed the project team to further refine the mix designs selected. Based on past experience conducting similar projects, operational flexibility is a must. The mix designs that were developed during the TS and finalised in the PS were changed a final time prior to commencing work.

During the development of the project costs, the design team located a cement supply that could be shipped by rail and was cheaper than the mix designs that were previously developed. Also, during the performance of the work, while moisture contents and soil densities were collected, the water content in the mix design was constantly altered to optimise the dose of the reagents and to minimise swell.

As the detailed case study of the former Columbus MGP site shows, *in situ* stabilisation/solidification is a viable, long-term solution for the remediation of MGP wastes.

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