Stabilization and Solidification of Contaminated Soils and Sludges Using Cementitious Systems: Selected Case Histories

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Practical stabilization and solidification of soils and sludges exhibiting contamination from heavy metals or organic compounds can be accomplished using readily available, conventional, or byproduct cementitious (hydraulic or pozzolanic) materials, such as portland cement, slag cement, cement kiln dust, lime kiln dust, hydrated lime, and fly ash. Case histories are presented documenting the use of various combinations of cements, fly ash, and byproduct kiln dusts, since the mid-1970s to stabilize and solidify a wide range of contaminated materials. Such materials include PCB-contaminated granular road base, steel industry sludges, contaminated lake-bottom sediments, rotary kiln slag from a secondary lead smelter (acid battery reclaimer), and a very wet former fly ash fill site. Stabilization processes developed have enabled treated materials to satisfy environmental and engineering requirements. Field testing, laboratory stabilization process development, and process implementation (pilot and full-scale) are discussed.

Contaminated land is the legacy of the industrial prosperity and urban development of the past century. People, particularly those in industry, are acutely aware that many waste-handling and management practices followed previously and considered appropriate at the time were not adequate. Soil and groundwater in urban areas worldwide are contaminated with a variety of undesirable compounds that result from industrial processes and disposal of municipal refuse: hydrocarbon products; heavy metals; organic compounds; byproducts such as municipal incinerator ash, fly ash, and bottom ash from coal-fired thermal power generation; industrial and sewage sludges; and other more hazardous materials. As public and scientific awareness of the contamination problem increases, and as economic pressures in urbanized areas push up the value of even severely contaminated real estate, site remediation has become a major technical interest. Although there is a wide variety of remediation options available, only two are currently considered established technologies by the United States Environmental Protection Agency (EPA): high-temperature incineration, and stabilization and solidification. The EPA considers all other technologies for site remediation innovative (1).

REVIEW OF STABILIZATION AND SOLIDIFICATION TREATMENT TECHNOLOGY

Stabilization of contaminated materials generally involves two distinct components, stabilization, whereby the mobile contaminants are complexed to prevent them from dissolving in the groundwater,

and solidification, whereby the stabilized materials are encapsulated to limit exposure and form a monolithic mass protecting them from long-term deterioration in the soil or groundwater in which they are placed. Many concepts involved in stabilization are similar to those involved in the cement and concrete industry, and positive stabilization results can usually be achieved using common cementitious (portland cement, slag cement, hydrated lime), pozzolanic (fly ash, silica fume), or byproduct (cement kiln dust, lime kiln dust) materials.

Methods involved in the stabilization of soils exhibiting high metal concentrations must consider several items to ensure satisfactory stabilization and permanent solidification. Leachable metals must be stabilized by complexing them in their least soluble form. For many common metals, stabilization requires that the pH of the material be limited to a level of minimum solubility for the metals of concern. Most metals are polyvalent, and therefore, amphoteric, which means that the hydroxide compounds formed can act as either acids or bases. At pH levels outside of a relatively narrow band (7 to 11), some hydroxide compounds can break down; the liberated metals become mobile and can enter subsoil or groundwater. Therefore, in stabilizing such a material, it is necessary to provide an environment within a pH band that minimizes solubility of metal hydroxides. The final pH of the stabilized material must remain within this limited pH band also, and the physical characteristics of the stabilized material must resist changes in surface and groundwater conditions and contact water pH to have long-term durability.

In conjunction with the formation of meta-stable metal hydroxide compounds, it may be necessary to complex the metals in more stable forms. For example, metal silicate compounds can be formed that are nearly insoluble across a wide pH range. Several proprietary chemical fixation systems for metals and metal hydroxide wastes involve adding soluble sodium silicates and silicate setting agents to assist the stabilization process (Chemfix, Hazcon, K20/LSC, Sorbond, Petrifix, and Soliditech are some examples). However, portland cement, fly ash, and other supplementary cementitious materials also contain varying amounts of silica; they react with metals and each other to form stable metal silicate compounds. Their interaction is considered in selecting a suitable additive for stabilization. The EPA Superfund Innovative Technology Evaluation program currently is evaluating several stabilization and solidification processes that involve proprietary (silicate-based) additives. Early indications are that the proprietary additives do not significantly improve the effectiveness of stabilization over that of encapsulation (solidification) using cementitious stabilizing agents (2).

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After stabilization of metal-contaminated soils and sludges, solidification or fixation of the material often is necessary to facilitate materials handling and minimize contact between the stabilized material and surrounding environment after landfilling. Relatively loose, dry contaminated material may be difficult to safely handle (because of blowing and dusting problems) and require the addition of water. Water itself may leach heavy metals from material and represents another potential waste stream to be considered. Solidification allows the waste and associated moisture to be treated together. Note that it is often necessary to add additional moisture to adjust pH and assist cementitious reactions (hydration). Resulting material then can be landfilled, forming a large impermeable monolithic mass. By this, it is implied that the contact area of the stabilized material with the surrounding soil and surface groundwater is minimized, which greatly reduces the leaching potential of the contaminated material. Updates from the North Atlantic Treaty Organization Committee on Challenges of Modern Society pilot study indicate that reduced leachability of contaminants after stabilization and solidification treatment is largely the result of entrapment (encapsulation) of contaminants within the cementitious matrix, rather than chemical binding to the matrix (2). Encapsulation also can serve to contain organic compounds that may be present in the contaminated soil, although that is a technically controversial issue, particularly with respect to controlling air emissions (volatilization) during treatment, and the lack of standard methods for evaluating the extent to which organics actually have been treated.

Treatment alternatives available for heavy metals contamination are extremely limited. Whereas some reduction of heavy metals using bioremediation and soil washing/metals chelation techniques has been reported, stabilization and solidification methods still represent the best available technology for contamination involving heavy metals.

Various cementitious and byproduct materials are available that have been used successfully in the stabilization of hazardous wastes and contaminated soils. Use of them involves a number of combinations and proportions of contaminated materials, plus stabilizing additives depending on the physical characteristics of the contaminated material (consistency, moisture content, or gradation) and the toxic constituents (solubility potential or concentration). Selecting the process and associated stabilizing agents for a particular material contaminated with heavy metals is largely based on the ability of the fixative to control pH, both in the short-term (for several years) and long-term (for several decades), and thereby minimize solubility of ionic forms of heavy metals and metal hydroxides. Portland cement, slag cement, fly ash, hydrated lime, byproduct kiln dusts, silica fume, and steel slag fines can all be used as stabilizing agents, individually or in combination with other stabilizing agents or chemical fixatives (usually proprietary). The most appropriate stabilizer is selected on the basis of physical and chemical characteristics of the waste and overall treatment economics. The Environment Canada Wastewater Technology Centre, with the support of the EPA and the Ontario Ministry of the Environment, published a proposed evaluation protocol for cement-based solidified wastes (3) that represents the most thorough laboratory assessment of the physical and chemical integrity of stabilized and solidified materials, short- and long-term.

CASE HISTORIES

Since the mid-1970s, a number of projects have documented successful use of conventional or byproduct cementitious (hydraulic or pozzolanic) materials for stabilization and solidification of a wide variety of wastes and contaminated materials. Several projects were selected to represent a range of wastes and contaminated materials and to demonstrate the effective use of cementitious systems for stabilization of heavy metals and organic contaminants and the subsequent solidification of a variety of soil and sludge types and moisture conditions (dry to near fluid). Case histories are presented documenting the use of various combinations of cements, fly ash, and byproduct kiln dusts to stabilize and solidify PCB-contaminated road base, steel industry sludges, contaminated lake-bottom sediments, rotary kiln slag from a secondary lead smelter (acid battery reclaimer), and a very wet former fly ash fill site.

PCB-Contaminated Road Base, Lake Clear, Ontario

In 1981 and 1982, investigations of unusually high concentrations of PCB in fish in Lake Clear led to the discovery that PCB-laden waste oil had been used for dust control on several gravel roads adjacent to the lake. Relatively high levels, in the range of 50 to 700 $\mu g/g$, were identified in the upper levels of the granular roadbase, shoulders, and ditch of two sections of road, the total length of which is about 8 km. The high PCB concentrations at the surface decreased to about 1 $\mu g/g$ at a depth of about 0.5 m. The total volume of contaminated material involved was estimated to be about 6 260 m^3 (4).

The remediation approach accepted by the Ontario Ministry of the Environment was to subexcavate the contaminated material and incorporate it into a very low permeability monolithic mass and place it in a suitably designed site. The following criteria were established for the remediation:

- Contaminated soil was to be stabilized into a solid mass having a permeability of less than 1×10^{-7} cm/sec;
- Any off-site migration was to be within acceptable limits (PCB concentration in groundwater less than Ontario Drinking Water Quality Objective of 3 $\mu g/l$); and
- If considered appropriate after technical evaluation, the disposal site was to be on an identified parcel of crown land about 600 m from the lake.

To meet the disposal criteria for the estimated 6 260 m^3 of contaminated material, a laboratory mix design and bench scale testing program was completed by the authors, with the overall objectives of (a) encapsulating the PCB-contaminated soil into a monolithic, durable mass to prevent the loss of free particles and (b) reducing the permeability of the mass to less than 1×10^{-7} cm/sec. A series of test specimens was prepared using normal Type 10 portland cement, bentonite, and cement-bentonite as prospective stabilizing and solidification agents. Small samples were mixed by hand in the laboratory and compacted (tamped) into 100-mm high by 100-mm diameter tobacco tins, sealed with a twist lid, placed in double plastic bags to maintain moisture conditions, and allowed to cure. Unconfined compressive strength development at 20°C was monitored using a pocket penetrometer. After a curing period, samples were submitted to an environmental laboratory for distilled water leach and Ontario Regulation 309 (acid) leachate extraction analyses.

On the basis of laboratory tests, it was concluded that satisfactory stabilization and solidification (acceptable reduction of leachable compounds and adequate solidification of the mixture) was achieved using 10 percent of portland cement by mass of dry soil. The mixture, when compacted to at least 95 percent Standard Proctor Maximum Dry Density, exhibited the desired very low perme-

ability and sufficient compressive strength to give good resistance to weathering and erosion. An alternative mix consisting of 12 percent cement kiln dust and 3 percent portland cement was also developed and confirmed to meet the basic design criteria after minor adjustments to the mix proportions.

Following the positive evaluation of the laboratory mix design and bench scale testing, a full-scale remedial work program was implemented. The subexcavation of the contaminated soils and road reconstruction were completed under one contract, and the mixing and disposal of the stabilized material were conducted under a separate contract. Tendering for the mixing and disposal of the contaminated material allowed the bidder to select the stabilization and solidification mixture, and the alternative 12 percent cement kiln dust to 3 percent portland cement mix was used. Contaminated soil was mixed with the stabilizing agents in advance using a central plant, then the mixture was transported, placed, and compacted at the disposal site using conventional soil-cement procedures. Before the contaminated soil was processed in the plant, any oversized rocks and boulders were removed by screening. The screened rocks and grubbing material were placed in layers in the middle of the compacted monofill. Contaminated materials and the stabilization and solidification mixture were monitored continuously using a field laboratory, measuring moisture content, compressive strength development (pocket penetrometer), and field compaction. The 4:1 cement kiln dust to portland cement ratio was maintained throughout, and the total amount of cement kiln dust and portland cement adjusted (increased) to ensure that a satisfactory moisture content was maintained for proper compaction (95 percent Standard Proctor Maximum Dry Density minimum).

The final volume of the stabilized and solidified monofill was measured to be 8 100 m^3, with the increase in volume of 1 840 m^3 (about 29 percent) attributed to the stabilizing agents and some native material picked up when cleaning up the work area. Of the 8 100 m^3, approximately 4 260 m^3 was contaminated material processed through the mixing plant, and the remaining 3 840 m^3 was oversized rocks, boulders, and grubbing material.

The average PCB concentration of the contaminated soil after screening was determined to be about 21.5 μ/g. The monofill was situated at least 2m above the groundwater table in the unsaturated soil zone and, as such, was not in direct contact with the groundwater system. The monofill design promoted surface runoff and minimized infiltration by mounding and construction of a conventional soil-cement cap; solidification prevented the migration of PCB by subsurface movement of fines. The low permeability of the monofill further limits infiltration and hence minimizes the potential for leaching of PCB in the long term.

Theoretical computations were made to estimate the amount of PCB that could move off site under actual site conditions. Based on a PCB solubility of 0.4 μg/1 for the average concentrations of contaminated soil representative of the monofill mass, it was calculated that the probable concentration of PCB in the groundwater following beneath the monofill was between 0.01 and 0.05 μg/1, which is well below the Ontario drinking water objective, 3 μg/1. Cost of remediation was about $850,000, using established technology and readily available equipment and procedures. The Ontario Ministry of the Environment considered the remediation an acceptable solution to containing PCB residues in Lake Clear.

Steel Industry Sludges and Contaminated Lake-Bottom Sediments

Expansion of a steel plant in Hamilton, Ontario, required the removal of a large quantity of a very soft, water-laden sludge and sediment mixture from an old harbor area and slip and its replacement with suitable fill to provide a construction site (5). Some treatment of the sludge sediment to meet landfill disposal requirements was required, and various stabilization methods were evaluated in the laboratory and small field trials before one was adopted. It was determined that the sludge sediment could be satisfactorily stabilized to meet both environmental (solubility of potential toxic constituents in accordance with Ontario Regulation 309) and engineering (bearing capacity) requirements for industrial fill applications. Thus, the reclamation process adopted for the old harbor area involved removing the sludge sediment by stone fill displacement below the water surface, dredging, stabilization, and either disposal to landfill or return to the site for fill above the water table. Other applications of the process also were developed, for use in stabilizing very soft sediments, basic oxygen furnace clarifier sludge, dust high in trace elements, or contaminated dredge spoils, for example.

Geotechnical studies indicated that the sludge sediment was fairly consistent in appearance along the harbor and slip; it was very loose, oily, black, organic, metallic (mainly from iron oxide) waste mixed with lake-bottom sediment, and its moisture content was highly variable (29 to 75 percent mass of water to total mass), as was its bulk density (1300 to 1650 kg/m^3) and loss on ignition (7 to 31 percent). Although most of the site's contaminants were of industrial origin (rolling mills), at early stages the slip received municipal sewage. The result was a rather unpleasant and variable industrial sludge and sediment mixture.

To give various strengths and rates of strength gain to the highly variable sludge and sediment, stabilization involved a number of possible combinations and proportions of sludges and sediments and stabilizing agents, such as fly ash, byproduct kiln dusts, steel slag fines, portland cement, and slag cement. Byproduct materials were used when possible, and either little or no portland cement was added, to minimize costs. Because the project involved nearly 300,000 m^3 of sludge and sediment, a wide range of byproducts was evaluated to ensure supply continuity.

Construction soil stabilization (soil-cement) concepts were adopted, which involve initial drying of the very wet sludges and sediments using high surface area materials (fly ash, kiln dusts), and then pozzolanic or hydraulic reactions as required. For disposal to landfill, just some drying and fairly low strengths (shear strength $\approx$ 0.01 to 0.02 MPa, equivalent to soft clay) were desirable, whereas for fill, initial handling strength and then high strength development (shear strength > 0.1 MPa, equivalent to a very stiff clay) were required.

A simple laboratory program, similar to that described for the Lake Clear remediation, was developed so that a wide range of stabilizing agents and addition rates could be considered for field trials and costing. The approach is considered more representative of conditions in a large mass of solidifying material than open curing, for which significant strength development may result from simple drying instead of cementitious reactions. Supplemental tests monitored pH, moisture content, temperature and bulk relative density. Typical laboratory stabilization trials for a 46 percent moisture content sludge and sediment are summarized in Table 1.

The laboratory stabilization trial results meeting the strength requirements for landfill or fill indicate that, whereas high organic content was not stopping pozzolanic and hydraulic reactions, it was probably inhibiting them. Quick (unslaked) lime kiln dust is much more efficient in this respect than is ordinary calcitic or dolomitic lime kiln dust, and slag cements require a fair degree of alkaline activation. The 1980 additive costs were $2.00 to $4.00 per tonne of final stabilized material.

TABLE 1 Laboratory Stabilization Trials

Wt. % Sediment (wet)	Mass % Additives	Penetrometer Strength, MPa			
		1 Day	7 Day	14 Day	21 Day
80	15 lime kiln dust (quick) 5 portland cement	0.29	0.43	>0.43	>0.43
80	15 lime kiln dust (quick) 5 slag cement	0.25	0.31	0.41	0.43
80	15 cement kiln dust (bypass) 5 portland cement	0.04	0.42	0.43	>0.43
80	15 lime kiln dust 5 portland cement	0.12	0.20	0.22	0.24
80	15 fly ash (~ 8% carbon) 5 lime kiln dust (quick)	0.07	0.12	0.17	0.18
75	15 lime kiln dust 10 fly ash (~ 8% carbon)	0.16	0.27	0.30	0.34
75	20 cement kiln dust 5 portland cement	0.02	0.20	0.43	>0.43
75	15 fly ash (~ 8% carbon) 5 lime kiln dust 5 portland cement	0.12	0.24	0.43	>0.43
75	15 fly ash (~ 8% carbon) 5 lime kiln dust 5 slag cement	0.04	0.12	0.15	0.32

Larger bench scale testing was completed; it involved preparation of several large 90-kg samples and various stabilizing agents using an Eirich R-7 mixer that, using only drum rotation, simulated a large stabilization plant pugmill. Sealed curing and curing under a 0.8-m head of water were completed at a 7°C to 13°C temperature range to simulate cooler field conditions. The results supported the smaller-scale test methodology adopted.

Solubility of toxic constituents in the industrial sludge and contaminated sediment was evaluated using a very severe, modified Organization for Economic Cooperation and Development solubility test procedure (6) that determines the dissolution rate for each constituent of interest. The procedure involves leaching 1 g of sludge and sediment per 0.05 l of distilled water during five 24-hr cycles of vigorous (3 Hz) shaking, with the supernatant drawn off and filtered between cycles and submitted for chemical analysis.

Solubility test results indicated that stabilization reduced trace element constituent levels in all cases except Cu and Pb, but these were still well below the maximum allowable despite the very severe nature of the test, and the stabilized material was fully acceptable from an environmental viewpoint.

Pilot-scale and full-scale field implementations resulted in a final stabilization and solidification process consisting of (a) a chute that allowed excavated material to be fed into a standard ready-mix truck; (b) central additive storage silos for storing and adding the stabilization agents, with the most reactive agent added last to allow for visual control of initial stiffening; and (c) mixing and transporting for discharge at a designated location where strength monitoring was completed on the stabilized material. The ready-mix truck operation proved so efficient during pilot-scale testing that it was adopted in place of a large base stabilization plant for full scale implementation.

At its peak, six 14-yd³ ready-mix trucks were used with about 1,000 t of sludge and sediment stabilized in an 8-hr shift. Optimum

stabilizing agents (based on economics and availability, after first confirming strength development and stabilization capabilities) were determined to be 8 to 12 percent highly reactive byproduct quick (unslaked) lime kiln dust, and 3 to 5 percent slag cement (replacing portland cement). After successful stabilization of the harbor and slip materials, the process was used to stabilize very soft sediments from another area of the plant, and a similar fixed plant process was developed to stabilize basic oxygen furnace clarifier sludge on a continuous basis. In each case, the stabilized product was approved by the Ontario Ministry of the Environment for fill applications or landfilling, on the basis of a former unsaturated column leachate method (since replaced by the Ontario Regulation 309 Leachate Extraction Procedure). It was estimated that the cost of stabilization and solidification (in 1980 dollars) was about $8.00/t using byproduct stabilizing agents.

Rotary Kiln Slag from Secondary Lead Smelter (Acid Battery Reclaimer)

An acid battery reclaiming plant uses a long rotary kiln and soda ash lead-reduction approach to recover lead from spent batteries. The secondary lead smelting operation has a very low environmental impact; its SO_2 emissions are carefully controlled. Feed materials—primarily lead sulphate, lead oxide, and lead sulphide resulting from crushing of 3.5 million spent lead storage batteries per annum, with soda ash and iron added to capture sulphur in the rotary kiln slag plus coke as a reducing agent/energy source—are fed gravimetrically into the long rotary kiln operating at a temperature of about 1100°C. Resulting molten salt lead is tapped out into 60-tonne holding kettles, with the slag overflowing at the hot end of the kiln and into slag pots to cool. About 31 to 32 percent slag is produced per unit of bullion on average, or about 45 tonnes of rotary kiln slag per day (≈16,500 t/year).

Rotary kiln slag differs from conventional iron silicate lead slag produced by other primary and secondary smelters; it is low in silicates and iron, high in sulphur and sodium, and quite soft and friable. Shortly after being turned out of the slag pot, rotary kiln slag cools to a hard state in large chunks. The fresh slag reacts immediately on contact with air, oxidizing from the surface inward (expending heat). After several weeks of exposure to air and precipitation, rotary kiln slag breaks down to a consistency similar to very moist cohesive soil. The somewhat alkaline rotary kiln slag does not meet Quebec Ministry of the Environment landfill disposal requirements for solid waste (7), being slightly high in leachate test lead, and it is physically unstable until fully broken down, that is, after several weeks to months of exposure to air and precipitation. Rotary kiln slag is completely dry when turned out, but it retains about 60 percent moisture when fully broken down in an outdoor stockpile.

A bench scale testing program was developed to stabilize and solidify rotary kiln slag. A series of laboratory trials was completed for the aged, stored slag and the relatively unoxidized fresh slag to determine the optimum stabilization and solidification processes necessary to fully oxidize the slag, reduce the leaching of heavy metals, and durably solidify the material to meet Quebec Ministry of the Environment's requirements.

A series of laboratory trials was completed using several stabilizing agents and solidifiers, including portland cement (Type 10 and Type 50), fly ash, and hydrated lime, in various combinations and proportions. Initially, small samples were prepared in the same fashion as described for the Lake Clear and industrial sludge and

contaminated sediment projects. Because lead, and lead hydroxide solubility is particularly sensitive to changes in pH, as indicated in Figure 1 (*8*), the pH of the stabilized material must be maintained within a narrow range of about 9 to 11. Stabilization trials for the stored slag and fresh slag were completed separately, recognizing that the relatively unoxidized fresh slag had to be pretreated (aged) before stabilization and solidification.

The stored slag was variable in moisture content (approximately 35 to 60 percent by dry mass) and in physical characteristics, suggesting that the degree of aging throughout the stockpiled material was inconsistent. Forty stabilization trials were conducted to develop an optimum stabilization recipe based on pH, unconfined compressive strength development, appearance (density, porosity, permeability), and durability.

As a result of the trials, stabilization and solidification mixes incorporating fly ash were eliminated, (pH was too high and it had inadequate strength development. Larger 2-kg samples were prepared by mechanical mixing, using mixtures incorporating Type 10 portland cement with and without hydrated lime. For these trials, the moisture content of the stored slag was increased to 60 percent by mass to control pH and provide additional moisture to assist in oxidizing any unreacted slag pieces that were still present in the stored slag.

Throughout the testing program, samples were subjected to environmental analysis in accordance with Quebec Ministry of the Environment's leachate extraction test procedures. It is an agitated acid leachate extraction procedure similar to the USEPA EPTox procedure and the Ontario Regulation 309 Leachate Extraction Procedure. Test results indicated that stabilization and solidification using 10 percent Type 10 portland cement by wet mass of stored slag resulted in a material satisfying the Quebec ministry's requirements for solid waste.

Fresh slag presented a separate set of challenges. The presence of unreacted pieces in the fresh slag required that a prestabilization and solidification step be introduced into the process to rapidly age the slag before treatment, otherwise the material would not be stable, and subsequent slag expansion destroyed the cementitious matrix. Laboratory testing indicated that the fresh slag could be quickly broken down by adding water in stages (a maximum of about 90 percent by dry mass), in conjunction with regular mixing of the wetted slag to expose it to air. After about one week, the condition of the fresh slag was similar to that of the stored slag, allowing the fresh slag to be stabilized and solidified in the same way as the stored slag, using 10 percent Type 10 portland cement.
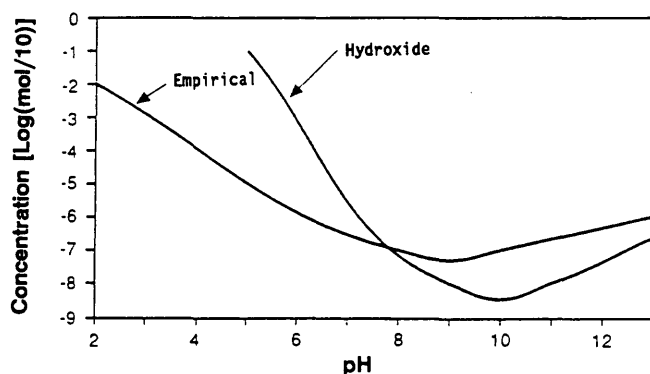
The laboratory bench scale testing program was completed in June 1991. Pilot-scale field testing was completed at the plant in the fall of 1991, with similarly positive results for the stabilization and solidification. Results of the pilot-scale field testing indicated that the process for aging fresh slag needed refinement.

Former Fly Ash Fill Site

In 1967 or thereabouts, approximately 100,000 m^3 of Type C (low CaO) fly ash from Ontario Hydro's coal-fired thermal generating station was placed in a former sand and gravel pit situated in the northeast corner of metropolitan Toronto. The fly ash was innocuous from an environmental point of view (almost inert fill, with the exception of slightly elevated arsenic and boron levels). However, under Ontario Regulation 309 and its nonregistrable, nonhazardous limits, the fly ash is very loose and wet; as such, it is not suitable for the proposed construction of a large and prestigious commercial/industrial development. Reconditioning the fly ash fill is necessary if the material is to be used as engineered fill below road and parking lot areas.

Testing of the fly ash confirmed that its in situ moisture content was about 45 to 50 percent, and its consistency ranged from dry to near fluid.

Because of its relatively low CaO content, the fly ash fill material, although pozzolanic, does not possess significant hydraulic properties. Laboratory trials were conducted in spring 1991 to determine a reconditioning process for the material so that it could be used economically for engineered fill applications at the site.

Laboratory trials were conducted on large, bulk samples of the fly ash obtained from the site with a large backhoe. Field samples were double bagged to preserve their moisture condition, then carefully split into smaller representative subsamples for laboratory trials. A series of small-scale trials was completed using portland cement, hydrated lime, and lime kiln dust initially identified as potential stabilizing and solidifying agents. The test method used was similar to that previously described using 100-mm high × 100-mm diameter cans, with strength development (rate and unconfined compressive strength using a pocket penetrometer) of interest for engineered fill use, and pH measured for environmental reasons. Note that the fly ash fill area was already alkaline, and a significant increase in pH was not desirable.

Test observations indicated that portland cement and hydrated lime were not suitable stabilizing and solidifying agents. At even low addition levels (<5 percent), the fly ash mixtures set very rapidly (within hours) to strengths greater than 0.4 MPa. For engineered fill applications at this site, it was desirable to have a mixture that remained workable until it could be placed and compacted using conventional construction equipment with a final, unconfined compressive strength similar to stiff clay, so it could be excavated later if future construction was necessary.

Byproduct dolomitic lime kiln dust proved most effective. Additional trials were completed to refine the addition levels, and it was determined that 8 percent lime kiln dust (by wet mass) resulted in a satisfactory engineered fill mixture that could be readily handled (placed and compacted using conventional equipment), which possessed adequate strength (approximately 0.3 MPa after about 2 days and 0.4 MPa after four weeks). The reconditioned fly-ash mix, although possessing relatively high unconfined compressive strength, could be broken up by hand, indicating that it could be re-excavated easily using conventional construction equipment.

FIGURE 1   Solubility of lead versus pH in a cement/fly ash stabilization and solidification system (*8*).

A sample of the reconditioned fly ash was subjected to environmental analysis (Ontario Regulation 309 Leachate Extraction Procedure) for comparison with Ontario requirements for drinking water and wastes. Although the boron level was slightly elevated, fluoride and selenium, the leachate from the stabilized and solidified reconditioned fly ash, satisfied Ontario drinking water standards and was well within the nonregistrable, nonhazardous designation for wastes.

On the basis of the reconditioning results and leachate analyses, the fly ash was classified as a special waste and accepted by the Ontario Ministry of the Environment for use as engineered fill at the site. The reconditioned fly ash may be used beneath parking lot and roadway areas outside the building footprint. It is anticipated that pilot-scale and full-scale reconditioning of the fly ash will proceed on-site in 1992, as the site is developed.

CLOSING COMMENTS

Results of more than 15 years of experience confirm that cementitious systems—portland cement, fly ash, hydrated lime and byproduct materials, such as cement and lime kiln dusts, silica fume and slag cement—can be used to durably stabilize and solidify a wide variety of soils, sludges, sediments, and other wastes containing unacceptable levels of organic and inorganic toxic constituents. Such systems can be designed using relatively simple laboratory procedures, based on a thorough understanding of the cementitious components involved and their reactions with the waste materials and toxic constituents. The systems also can be practically implemented using conventional, readily available materials and equipment. New protocols for evaluating cement-based solidified wastes will greatly assist in the assessment of the longevity of stabilization and solidification remediation (particularly with respect to contaminated ma-

terials containing organic compounds); such protocols are expected to further support EPA current position that stabilization and solidification is an accepted technology for the treatment of contaminated materials.

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