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PHYSICAL STABILIZATION TECHNIQUES FOR MITIGATION OF ENVIRONMENTAL POLLUTION FROM DIOXIN CONTAMINATED SOILS

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Summary

Techniques for physically stabilizing dioxin contaminated soils with Portland cement and asphalt have been investigated in the laboratory. The results indicate that these materials can be used to stabilize and prevent dispersion of contaminated soils through wind or water erosion. In particular, these techniques should prove useful where contaminated soils are to be excavated and transported elsewhere for containment or interim storage in a secured facility. Because of the very low aqueous solubility of dioxin, some of the leaching results were inconclusive.

Introduction

Dioxin surfaced as an environmental contaminant of particular concern in the early 1970s as the result of investigative work performed by several government agencies. Early toxicity studies revealed that 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) was extremely toxic in mammalian species. This factor coupled with the growing evidence of relatively frequent environmental occurrence formed the basis for this concern. Investigation of health problems within certain areas of Missouri led to the identification of dioxin as a potential causative agent. This and other events led to additional field surveys which ultimately revealed that polychlorinated dioxin contamination of surface and subsurface soils was fairly widespread, particularly in the state of Missouri.

It is believed that TCDD was first introduced into areas of eastern Missouri via waste oils containing varying levels of TCDD contamination which were sprayed at a number of horse arenas and roadside areas for dust control. At several of the horse arenas, numerous illnesses and deaths occurred among animals, and there were instances of skin lesions and other maladies observed

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in children and adults who were exposed to the oiled arenas. An investigation by the State into the source of these health problems resulted in a sample of the waste oil being sent to the Center for Disease Control (CDC) for analysis. The CDC identified one of the toxic compounds in the waste oil as dioxin.

On December 15, 1983, the U.S. Environmental Protection Agency (EPA) issued a national dioxin strategy for investigating, identifying and cleaning up sites contaminated by TCDD [1]. Within the framework of this strategy was a plan that called for research to be conducted on the technical feasibility and economics of alternative methods for disposal and destruction of wastes and soils contaminated by dioxin. Several projects were initiated in 1984 [2] as part of this strategy. The projects can be categorized as pertaining to TCDD mobility, containment, destruction and stabilization.

A number of investigators have documented the extremely low mobility of TCDD and related chemicals using both laboratory samples and actual field samples [2–8].

Containment of TCDD contaminated soils in underground mines was investigated [9]. Destruction studies were run using incineration in an EPA-developed mobile incinerator [10,11]. Biodegradation was attempted with white rot fungus (*Phanerochaete chrysosporium*) [12–14]. Chemical destruction-/detoxification was studied using alkali polyethylene glycolates [15–18].

Regardless of the low aqueous mobility of dioxin in soils, dispersion still can occur through wind and/or water erosion of the soils themselves. The technology investigated in this study would be applicable in situations where (a) no remedial action is anticipated in the near future, and it is desired to stabilize the site until remedial action is undertaken; and (b) active remedial action is underway using heavy equipment, and unintentional migration of contamination off-site must be eliminated. A study on stabilization was undertaken using soils contaminated with TCDD, from three locations in Missouri. This paper reports on that study.

To prevent migration of the TCDD at these sites and reduce the potential for human exposure, soil stabilization and encapsulation techniques for the contaminated soil were investigated. Portland cement and asphalt were selected for use in this study since each has been used for stabilization of waste materials, both can be easily mixed with soil to produce a stable solidified matrix, the technology and equipment for *in situ* application are readily available for both, and both appear to be cost effective.

The stabilizing materials are also of interest for potential use as a pretreatment for contaminated soils which would require extensive handling or off-site transportation. In this context, *in situ* stabilization of contaminated soil would be used as an initial procedure for dust control and containment immobilization in order to make safer the necessary soil removal, transportation and handling activities.

Within the overall goal of evaluating the effectiveness of existing stabilization technologies for use as an interim remedial measure for dioxin, the following specific objectives were defined:

- Identify promising physical stabilization components.
- Evaluate formulations in the laboratory to:
  - (1) Determine the preferred soil stabilizer using protocols and criteria of the construction industry.
  - (2) Subject the formulations to simulated accelerated weathering
  - (3) Subject the formulations to leach procedures.
- Assess the probability of successful field implementation.

Procedure

Three Missouri sites, each characterized by a high level of dioxin contamination over a relatively large area, were selected as sources of soil for stabilization testing. To increase the applicability of this evaluation, several soil types were obtained to determine the degree of influence that soil variations have on the formulations.

The soils were significantly different in particle size characteristics and other physical characteristics considered important. Table 1 and Fig. 1 outline the key differences.

Five materials were considered for use in this project: Portland cement, emulsified asphalt, asphalt cement, cutback asphalt and sulfur-extended asphalt, however, only the first two were chosen for this study principally because they do not require heating, therefore minimizing the possibility of dioxin vaporization.

TABLE 1

Various soil measurements

Measurement	Soil identification		
	Minker site	Piazza Road	Sontag Road
Atterburg limits			
liquid limit	25	24	36
plastic limit	23	17	30
plasticity	2	7	6
USDA textural classification	Sandy Loam	Sandy Loam	Silt Loam
pH	7.8	6.5	7.7
Sulfate concentration, (%)	0.07	0.13	0.21
App. specific gravity	2.56	2.60	2.52
Dioxin concentration*, (ppb) (2,3,7,8-TCDD isomer)	700	640	32

*For particles $\leqslant 2.0$ mm in diameter. (See text for particle size rationale).

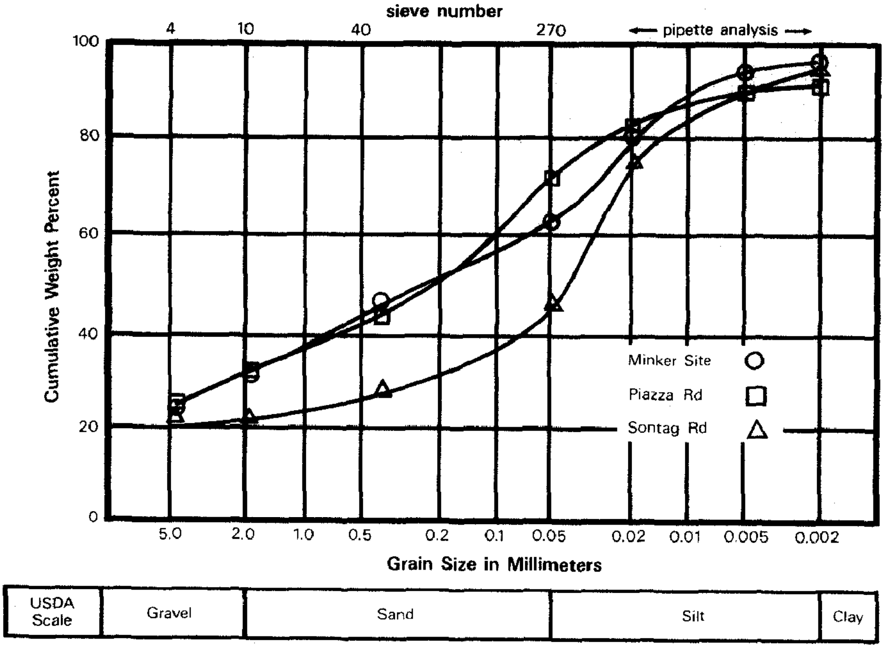

Fig. 1. Semi-log plot of particle size accumulation.

Experimental approach

A brief overview of the experimental approach employed for determining the feasibility and effectiveness of *in situ* stabilization of dioxin-contaminated soils follows.

Formulation of optimized soil-Portland cement mixtures

Development of optimized soil–cement mixtures entailed optimization of the relationship between two key variables, cement content and soil moisture, for each soil type. Initially, each soil was assigned an AASHO (American Association of State and Highway Officials) Group Classification based upon key physical properties. Each soil was then assigned a trial Portland cement content based upon its AASHO Group Classification and empirical data obtained form the Portland Cement Association (PCA) soil–cement applications data base. Soil–cement mixtures were subsequently formulated at the trial cement content, and varying moisture contents, to establish moisture/density relationships. The moisture content which resulted in the greatest density after compaction was considered to be the moisture level at which soil–cement performance was optimized (Fig. 2).

After determination of the optimum soil moisture for each soil type was completed, soil–cement mixtures were formulated at the optimum moisture

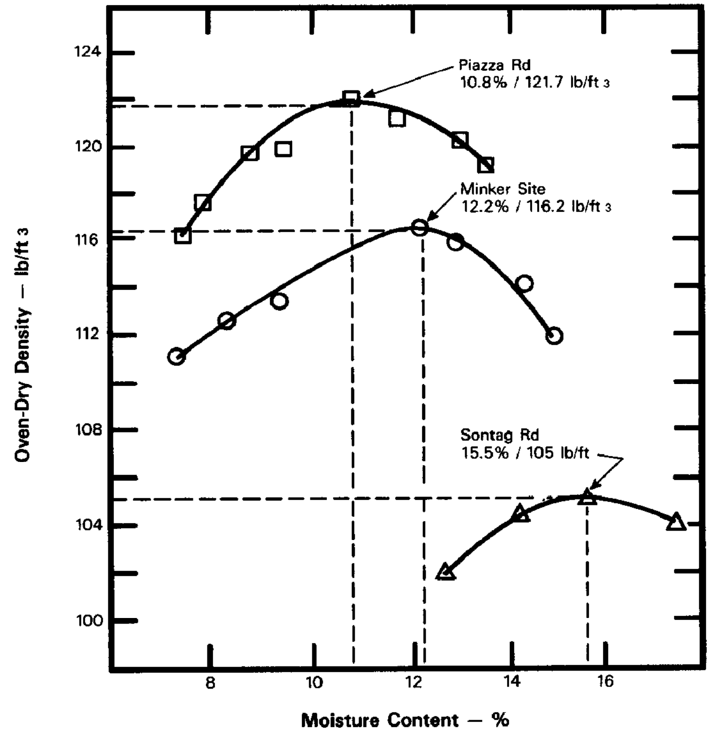

Fig. 2. Soil-cement moisture/density relationships.

and varying cement contents (Table 2). The soil–cement mixtures were then compacted into cylindrical specimens, and allowed to cure for seven days. Once cured, replicate specimens were subjected to one of three evaluations designed to assess the acceptability of the soil–cement mixtues. Freeze/thaw susceptibility determinations (ASTM Method D560) consisted of 12 successive 48-hour cycles in which specimens were alternately subjected to −23 °C storage, followed by ambient temperature thaw (23 hours each). After each thaw cycle was completed, the specimens were abraded with a wire brush to remove any loose particles and cumulative specimen weight loss was used to evaluate the performance of each soil–cement formulation. The second evaluation, wet/dry susceptibility (ASTM Method D559) consisted of 12 successive 48-hour cycles of wetted conditions (specimen immersion for 5 h, followed by a 43 h drying period). In a manner identical to that described for the freeze/thaw test, the specimens were abraded after each cycle and performance was gauged relative to cumulative specimen weight loss. The final evaluation, a 7-day unconfined compressive strength test, provided a quantitative measure of the structural integrity achieved with each formulation. Successful performance required a compressive strength above a minimum acceptance value specified for each soil type.

TABLE 2

Portland cement mix design

Measurement	Soil identification		
	Minker site	Piazza Road	Sontag Road
Soil group classification	A-4	A-2-4	A-4
Trial cement content for moisture/density	10%	7%	10%
Tests			
Freeze/thaw susceptibility	specimen prepared with 7%, 9%, 11%, and 13% cement	specimen prepared with 6%, 8%, 10%, and 12% cement	specimen prepared with 8%, 10%, 12%, and 14% cement
Wet/dry susceptibility	specimen prepared with 7% and 11% cement	specimen prepared with 6% and 10% cement	specimen prepared with 8% and 12% cement
Compressive strength	specimen prepared with 7%, 9%, 11%, and 13% cement	specimen prepared with 6%, 8% and 10% cement	specimen prepared with 10%, 12% and 14% cement
Results			
Optimum moisture, (% water)	12.2	10.8	15.5
Maximum density, (lb/ft^3)*	116.2	121.7	105
Recommended cement content (by wt.%)	7	8	10

*1 $lb/ft^3 = 16.0185\ kg/m^3$.

Formulation of optimized soil-emulsified asphalt mixtures

The formulation procedure used for emulsified asphalt is similar to that described for Portland cement, in that two components are optimized to give the best soil–asphalt properties. The emulsified asphalt mix design procedure utilized in this investigation entailed three basic steps. Initially, each soil was assigned an empirical trial residual asphalt concentration based upon the physical properties of each soil and existing data from emulsified asphalt construction applications. Residual asphalt, defined as that portion of the emulsion which remains after the water carrier has evaporated and the mixture has cured, was initially held constant. Soil–asphalt mixtures prepared at the trial residual asphalt content, but with varying moisture contents, were formulated to determine the water content which resulted in the best asphalt coating of soil particles (Table 3). Emulsified asphalt consisting of micron-sized asphalt particles suspended in an aqueous solution through the use of various types of surfactants and emulsifiers is sensitive to soil moisture and requires a certain soil moisture level to yield good coating. Selection of the optimum moisture

TABLE 3

Emulsified asphalt mix design

Measurement	Soil identification		
	Minker site	Piazza Road	Sontag Road
Emulsion type	SS-1h	SS-1h	SS-1h
Percentage asphalt residue in emulsion	59.6	59.6	59.6
Trial-residual asphalt content, (%)	7.0	8.5	9.0
Tests			
Coating -			
moisture content giving best asphalt coating	mixtures prepared with 11% to 16% moisture	8% to 12% moisture	16% to 20% moisture
Compaction -			
moisture content giving highest density and/or Marshall stability	mixtures with 9% to 15% moisture compacted into specimens	6% to 12% moisture	15% to 20% moisture
Residual asphalt -			
specimen properties measured at various asphalt percentages	specimen prepared with 6%, 7%, 8%, 9%, and 10% residual asphalt	7.5% and 8.5% residual asphalt	7%, 8%, 9%, and 10% residual asphalt
Results			
Coating	15% moisture	12% moisture	20% moisture
Compaction	14% moisture	10% moisture	18% moisture
Recommended residual asphalt Content	9% asphalt residue	9% asphalt residue	9% asphalt residue

content was based upon visual observation of soil coating efficiencies at various moisture levels.

Soil–asphalt mixtures formulated at the trial residual asphalt content and the optimal coating moisture were then compacted into solid specimens after a certain percentage of the moisture had been allowed to evaporate away from the mixture (a procedure referred to as dryback). The percent dryback, starting with zero percent, was increased until compacted specimens reached a maximum density or stability. Generally, the soil water content that gave the best coating was too high to achieve optimum density upon compaction, and a dryback of one or more percent was required.

In the final step of the formulation process, soil–asphalt mixtures at varying residual asphalt concentrations and the optimum soil moisture content were prepared, allowed to dryback to the appropriate moisture content, and compacted into cylindrical specimens. The specimens were allowed to cure for one day in the mold at ambient temperature, then removed from the mold and allowed to cure for an additional day at 100°F (~38°C). Four replicate specimens were prepared at each residual asphalt content, with two evaluated dry and two evaluated after exposure to water. The dry and soaked specimens were tested for Marshall stability (a type of compressive strength measurement), dry bulk density, and moisture content. Comparison of results from dry and soaked specimens provided additional critical performance data, included "soaked stability loss" and "absorbed moisture loss".

Weathering of stabilized soil

After critical formulation parameters had been optimized for the Portland cement and emulsified asphalt stabilization agents, triplicate specimens of soil–cement and soil–asphalt were prepared for each of the three soils to evaluate performance relative to immobilization of the dioxin contaminant. Once cured, all specimens were subjected to accelerated-rate, simulated environmental weathering in the laboratory. Soil–stabilizer specimens were subjected to twelve successive freeze/thaw cycles, followed by twelve successive wet/dry cycles, to simulate natural seasonal weathering cycles. The freeze/thaw and wet/dry environmental weathering simulation procedures were slight modifications of those used previously for Portland cement mix design work, in that the specimens were not abraded with a wire brush between cycles. Although the abrasion step was a critical aspect of the Portland cement mix design procedure, such rigorous abrasion was not considered to be a realistic simulation of the abrasive forces likely encountered after field implementation. Omission of active abrasion from the repetitive wet/dry and freeze/thaw weathering simulation procedure was considered to be more representative of naturally occurring environmental stresses.

Evaluation of weathered soil–stabilizer specimens

Native soils and weathered soil–stabilizer specimens were subjected to an aqueous leaching procedure designed to simulate that occurring naturally in the environment via surface water and groundwater mechanisms (EPA Solid Waste Leaching Procedure; SW-924). This protocol employed four sequential leaching cycles of roughly 18 h duration each, with fresh leaching medium (neutral deionized water) introduced at the initiation of each cycle. Aqueous leachates generated from stabilized and unstabilized soils were analyzed for dissolved dioxin levels to determine the effectiveness of stabilization techniques at inhibiting dioxin mobility via solubilization mechanisms. Additionally, particles which became dissociated from the parent specimen during weathering and leaching processes were collected and analyzed for particle size distribution. Comparison of the level of erodable particles (<53 μm) generated from stabilized soils with those present in unstabilized soils was considered to be an extremely important indicator of stabilization effectiveness, as water and airborne transport of contaminated soil particles represent significant mechanisms for dioxin mobilization and concomitant human exposure.

Results

Soil-cement formulations

The strength and durability of soil–cement formulations were assessed by the amount of weight loss after freeze/thaw cycles and wet/dry cycles, and by compressive strength. The results are summarized in Table 4.

In these assessments the acceptance criteria developed and utilized by industry research groups were adopted for use as minimum acceptance values for key parameters such as durability, structural strength, and water sensitivity of compacted mixtures. These criteria were originally developed for applications in which the soil–cement or soil–asphalt mix would serve as a base or sub-base in road construction, or for contruction of embankments and dams. Although the stabilized Missouri soils will undoubtedly never be required to function under such abrasive or stressful conditions, utilization of industry acceptance criteria for the current application should provide a safety margin which will help ensure that adequate longevity is obtained. Additionally, key parameters which are the focus of construction industry performance evaluations (durability, strength, and water sensitivity) are directly related to weathering resistance, a significant concern in the soil stabilization application. Equally important, Portland Cement Association and Asphalt Institute accep-

TABLE 4

Summary of soil-cement strength/durability results

Soil collection site	Cement content (wt.%)	Freeze/thaw weight loss (%)		Wet/dry weight loss (%)		Compressive strength (psi)[a]		Selected optimum cement content (%)
		Criterion maximum	Test mean	Criterion maximum	Test mean	Criterion minimum	Test mean	
Minker residence	7	10	3.9	10	1.6	250	358	
	9	10	3.8	10	N[b]	250	567	7
	11	10	5.0	10	2.8	250	746	
	13	10	3.8	10	N	250	269	
Piazza Road	6	14	6.4	14	8.4	285	249[c]	
	8	14	5.2	14	N	285	358	8
	10	14	4.9	14	3.0	285	388	
	12	14	4.4	14	N	285	N	
Sontag Road	8	10	16.1[c]	10	4.1	190	N	
	10	10	7.6	10	N	190	229	10
	12	10	5.5	10	3.4	190	298	
	14	10	4.9	10	N	190	388	

[a] 1 psi ~ 0.07 bar.

[b] Samples not prepared based on the formula optimization outline.

[c] Did not meet criterion.

tance criteria are based upon a great deal of data derived from experience gained through field implementation. Comparable formulation data specific to the current application are virtually non-existent, and development of such data would require collection of field data for years. Consequently, it was clearly advantageous to utilize the well-developed existing acceptance criteria for evaluation of soil–stabilizer performance.

Soil-emulsified asphalt formulations

The strength and durability of soil–emulsified asphalt formulations was assessed by soaked Marshall stability (500 pounds minimum acceptable), stability loss of a soaked specimen compared to an unsoaked specimen (50% maximum acceptable), and absorbed moisture (4% maximum acceptable).

The use of emulsified asphalt alone was not an effective technique for stabilization of the soils used in this testing. The search for an effective modification included consultation with Asphalt Institute engineers and a review of existing literature, with the conclusion that pretreatment of the soil with lime would improve the emulsified asphalt performance substantially. Lime pretreatment of soil reduces the swell characteristics and the effective surface area, as well as providing an increase in strength due to pozzolanic reactions. The lime pretreatment selected for this study consisted of adding 1.5% of lime by weight to the soil with mixing water. This was followed by homogenization of the mixutre for one minute prior to the addition of the asphalt emulsion.

The results are shown in Table 5 for formulations without lime modification and with lime modification. Unacceptable values are indicated with an asterisk.

Soil–stabilizer weathering and dioxin containment

Two potentially significant mechanisms for environmental transport of dioxin associated with contaminated soils are aqueous solubilization and erosion of contaminated particulates. Consequently, comparison of dioxin leachability and the level of easily erodable contaminated particles (i.e., small particles susceptible to entrainment and transport by natural erosive forces) before and after stabilization was utilized as the basis for evaluating the effectiveness of soil stabilization techniques.

Prior to experimental determination of dioxin leachability, stabilized soil specimens formulated at optimized conditions were subjected to an accelerated-rate, simulated weathering process. The weathering simulation, utilized to evaluate the influence of environmental exposure on soil–stabilizer performance and durability, frequently resulted in deterioration of the structural integrity of soil–stabilizer specimens in a fashion consistent with that due to natural aging. Degradation in structural integrity typically resulted in dissociation of material from the parent soil–stabilizer specimen during the weathering simulation. Determination of the size and amount of dissociated material provided a means for direct comparison of specimen durability, as well as a

TABLE 5

Soil-emulsified asphalt evaluations

Soil specimen	Asphalt content (%)	Soaked marshall stability (LB)		W/O LIME	W/LIME	W/O LIME	W/LIME
		W/O LIME	W/LIME				
		(minimum acceptable=500 lb)		(max. acceptable=50%)		(max. acceptable=4%)	
Minker	6	662	1832	83.0*	44.1	10.4*	5.2*
	7	556	1784	86.9*	31.8	10.1*	5.1*
	8	602	1642	82.2*	34.4	11.8*	4.5*
	9	582	1423	80.2*	3.6	11.9*	2.4
	10	724	1365	77.8*	38.2	11.0*	4.7*
	11	N	1541	N	26.1	N	5.9*
Piazza	5.5	475*	N	91.3*	N	9.8*	N
	6.5	454*	N	87.8*	N	8.3*	N
	7.5	553	2202	81.3*	48.4	7.5*	4.9*
	8.5	986	2096	68.7*	45.9	6.2*	4.1*
	9.5	624	N	77.6*	N	7.3*	N
Sontag	7	N	1160	N	28.5	N	6.2*
	8	N	1276	N	34.0	N	7.4*
	9	N	1195	N	26.7	N	6.9*
	10	N	1216	N	6.6	N	7.1*

* = Unacceptable.

N = Samples not prepared for this testing based on the formula optimization outline.

mechanism for evaluating stabilizer effectiveness. The mass of dissociated particulate material in the size interval readily amenable to erosion (<53 μm) was compared with that in the unstabilized soil to evaluate the effectiveness of soil stabilization relative to this important transport mechanism. Additionally, because mass–volume ratios typically influence partitioning phenomena significantly, separate leachability studies were conducted with the dissociated particulate material to evaluate effects of this relationship.

The weathering simulation, which entailed twelve repetitive freeze/thaw cycles followed by twelve repetitive wet/dry cycles, resulted in significant degradation of soil–cement specimens as measured by the mass of material dissociated from parent soil–cement specimens. Although the extent of specimen degradation was variable among replicates for a given soil type, it was a consistent effect, as degradation occurred in all soil–cement specimens. Soil–cement degradation observed for each soil, or the cumulative mass of soil–cement material dissociated from the parent specimen over the course of the two-month simulated weathering period, can be summarized as follows:

Site	Soil–cement specimen loss (% by weight)			
Minker Residence	4.4%	15.9%	16.7%	(mean = 12.3%)
Piazza Road	12.7%	10.9%	11.4%	(mean = 11.7%)
Sontag Road	23.3%	23.5%	14.4%	(mean = 20.4%)

Examination of these data reveals that specimen loss was roughly equivalent for the Minker and Piazza Road soils, but was substantially higher for the Sontag Road soil–cement. These data are consistent with those obtained previously, in that both physical characterization data and soil–stabilizer formulation data indicated that the Sontag Road soil was least suitable for cement or asphalt stabilization. It should also be noted that the Sontag Road specimen began deteriorating very early in the weathering process (after approximately 5–7 freeze/thaw cycles), whereas deterioration in the Minker and Piazza Road specimen was not visible until the final 4–6 cycles of the wet/dry susceptibility test. Although the issue of soil–stabilizer durability, and the relationship between dioxin containment and strength/durability will be discussed subsequently, it should be noted that very little dissociation of soil–stabilizer material was observed to occur in any of the soil–asphalt specimens.

Weathered soil–stabilizer specimens, dissociated particulate material and native soil samples were subjected to an aqueous leaching procedure designed to simulate that occurring naturally via surface water infiltration/run-off and groundwater migration. Leachability data (i.e., mobilization of dioxin from the soil particles to the aqueous leachate phase) obtained from unstabilized, native soils provided the frame of reference for evaluating the effectiveness of soil stabilization via comparison with comparable data from soil–stabilizer specimens.

Leachability data obtained for each of the unstabilized, native soils reveal that very little dioxin was leached from any of the Missouri soils. Data interpretation was complicated by the fact that dioxin levels were routinely at or below the analytical limit of detection (LOD).

Dioxin leachate levels observed for the Missouri soils (1–2 ppt) were consistent with those predicted from solubility considerations. TCDD, an extremely hydrophobic molecule, is highly insoluble in aqueous systems, and will partition preferentially toward virtually any other medium.

Several experiments were conducted with the Minker soil at varying leachate ratios to resolve the question of whether dioxin was at saturation levels in the leachate, or whether the leachate concentration was driven by this relationship. In the initial experiment, unstabilized soil was leached at a 1 : 1.5 solid to liquid ratio, consistent with that used for the soil–cement specimen.

Results obtained from this leachability experiment, designed to determine if the leachate systems were being driven by dioxin solubility limitations (whereby leached dioxin levels should remain unchanged) or by the solid : leachate ratio (whereby with greater soil mass the leachate dioxin level should increase substantially) showed that dioxin levels in the leachates were again statistically identical to previous data (2–3 ppt), providing strong evidence that the leachate system was solubility limited. Unfortunately, these data also confirmed the fact that all existing soil–cement stabilization data must be considered inconclusive. The apparent solubility limitation rendered all conclusions ambiguous, thereby precluding either conclusion (i.e., it could not be concluded that cement stabilization was either effective or ineffective in reducing dioxin leachability).

Soil masses of 0.1 g for unstabilized Minker soil, and 1.0 g for Minker soil–cement, were selected for use in a final attempt to evaluate the effectiveness of Portland cement for immobilizing the dioxin contaminant. Results obtained from these two leachability studies were inconclusive, as dioxin was not detected in any of the resultant leachates from either stabilized or unstabilized soil matrices. Consequently, no definitive conclusions could be drawn from the leachability experimentation. As will be discussed subsequently, however, soil stabilization with Portland cement did effectively retard the potential for environmental migration of dioxin-contaminated soil particles via water and airborne erosion.

Although inconclusive data were obtained for the Piazza Road and Sontag Road soils, leachability data obtained for the Minker site provide solid evidence that soil stabilization with emulsified asphalt was, in fact, effective in reducing the environmental mobility of dioxin via aqueous solubilization. Examination of leachability data for the Minker soil reveals that dioxin was detected in two of three replicates for the native soil, but was not detected in any of the replicates for either the compacted or uncompacted soil–asphalt materials.

Leachability results obtained for native and asphalt stabilized Minker soils showed that the mean leachate level obtained for the compacted soil–asphalt specimen was statistically lower than that obtained for the unstabilized soils at the 95% significance level. Consequently, these data definitively demonstrate that use of compacted emulsified asphalt for stabilization of the Minker soil effectively reduced the aqueous leachability of the dioxin contaminants.

While comparable effectiveness could not be defended statistically for the uncompacted soil–asphalt material, leachability results obtained for these samples, as well as those obtained for soil–asphalt specimen from Piazza Road and Sontag Road soils, clearly suggest that emulsified asphalt is an effective technique for immobilizing the dioxin contaminant. Although the experimental and analytical problems/limitations discussed previously preclude derivation of definitive conclusions, the absence of the dioxin at detectable levels in virtually all soil–asphalt leachates implies that soil stabilization effectively reduced solubilization of the dioxin contaminant.

Erodable soil particulates as an indication of soil–stabilizer performance

As discussed previously, stabilization of dioxin-contaminated soils was considered to have promise relative to reduction in the level of erodable soil particulates, defined for the purpose of this investigation as material <53 μm which is readily entrained and transported by surface water run-off or wind, was an evaluation parameter utilized to assess the effectiveness of soil stabilization. Measurements of the level of erodable particulates were performed after the soil–stabilizer specimen had been subjected to the simulated weathering process. The rationale for considering erosion an important factor was that a significant amount of dioxin would be bound to small soil particles (silt- and clay-sized aggregates), and that environmental transport of such particulates represented a greatly enhanced potential for human exposure. To verify the validity of this rationale, an aliquot of the native Minker soil was fractioned, and fractions of appropriate size intervals were analyzed for dioxin to establish the relationship between particle size and dioxin contaminant loading. In addition, representative samples of the size interval of greatest interest (i.e., the easily erodable <53 μm interval) were analyzed for each of the native soils.

The profile obtained for the Minker soil, selected as a representative example of the three soils investigated, revealed that a significant amount of the dioxin contaminant is, in fact, associated with the <53 μm size interval, as postulated. Soil particles <53 μm yielded a mean dioxin loading of 877 ng/g, as compared with a value of 702 ng/g obtained for the "whole" soil (i.e., all soil material <4.76 mm). This value translates to a contribution equivalent to 69% of the total mass of dioxin present in the "whole" soil. The validity of this hypothesis is further supported by results obtained from dioxin analyses of silt- and clay-sized particles for the Sontag Road and Piazza Road soils. These two soils also exhibited dioxin contaminant concentration levels for the <53 μm size interval which were greater than those for the corresponding "whole" soils (i.e., the 0–4.76 mm fraction), indicating that greater than 50% of the total amount of dioxin was associated with the easily erodable soil particles.

Based upon formulation of soil–cement specimens at the laboratory-derived mix design values, specimen deterioration and loss of soil–cement material occurred with all three soils. Soil–cement specimen loss ranged from approximately 12% (Minker and Piazza Road) to 20% (Sontag Road), with particulate material in the sand-, silt- and clay-size intervals (i.e., <2.0 mm) accounting for roughly 50% of the total mass of dissociated material for all three soils. The levels of easily erodable particulate material (<53 μm) dissociated from the monolithic specimen over the course of the weathering simulation were significant, and can be summarized as follows:

Collection site	Mass of <53 μm material dissociated (g)	Percentage dissociated
Minker Residence	21.1	1.2
Piazza Road	10.8	0.6
Sontag Road	35.3	2.2

As was observed in the dioxin leachability investigations, soil stabilization with emulsified asphalt was also very effective in reducing the level of easily erodable contaminated particulates. After extensive weathering of the soil–asphalt specimen, very little deterioration of the matrix was observed for any of the soils evaluated. The amount of soil–asphalt material dissociated from the parent specimen over the course of the simulated weathering process was negligible ($<0.1\%$) for both the Minker and Sontag Road specimen, and only 3.3% was lost from the Piazza Road soil–asphalt specimen. The deterioration profile obtained for the Piazza Road soil–asphalt specimen showed that less than 6% of the dissociated material was in the <53 μm size interval, which translates to only 0.2% of the intial specimen. These data indicate that emulsified asphalt was essentially 100% effective in reducing the level of easily erodable soil particles for the Minker and Sontag Road soils, and resulted in a 98% reduction in the level of contaminated material in this size interval for the Piazza Road soil.

Cost estimates

Rough cost estimates which included the cost for stabilizer materials, equipment, and labor/supervision; but excluding costs associated with safety and health equipment gave the following results. For soil–cement formulations having cement contents in the range of 7% to 10%, the cost per cubic yard is

$11 to $13. For a 9% soil–asphalt formulation with 1.5% lime modification, the cost per cubic yard is $47.

Conclusions and recommendations

Although several inherent experimental and/or analytical limitations often complicated data interpretation and did not support statistically defensible conclusions in all instances, data obtained in this investigation do validate a number of conclusions. The most significant findings and conclusions can be summarized as follows:

- Optimized mixtures of soil and Portland cement produced soil–cement specimens of acceptable strength and durability based upon construction industry derived performance criteria for all three soils evaluated.
- Mixtures of soil and emulsified asphalt could not be formulated with any of the three soils which met acceptance criteria for all three soils.
- Soil–cement specimens subjected to simulated enrironmental weathering processes appeared to deteriorate significantly, in that cumulative loss of specimen mass ranged from 12–20%. However, existing laboratory data and evidence from field applications which have been in place for over 30 years, indicate that an additional increase in Portland cement content of 2% will yield soil–cement specimens of more than adequate strength and durability.
- Soil–emulsified asphalt specimens appeared to be quite resistant to environmental stress and weathering, as only negligible deterioration of the soil–asphalt matrix was observed over the course of the weathering simulation.
- Inconclusive data were frequently obtained relative to the effectiveness of soil stabilization techniques in reducing the leachability of the dioxin contaminant. Interpretation of leachability data was often complicated by the extremely limited aqueous solubility of dioxin, which restricted maximum leachate levels to a concentration only slightly above the detection limit for dioxin. Consequently, it was extremely difficult to identify and document differences between dioxin contaminant levels generated from stabilized and unstabilized soils. As such, stabilization of contaminated soils with Portland cement could not be determined to be either effective, or ineffective, toward immobilizing the dioxin contaminant via aqueous solubilization meachanisms.
- Although comparable problems existed with the design, conduct and interpretation of emulsified asphalt leachability experimentation, data obtained from these investigations definitively demonstrated the technique to be effective on the Minker soil. Further, 11 of 12 leachates from asphalt stabilized soils yielded undetectable dioxin contaminant levels, providing additional evidence that this approach was effective in reducing dioxin leachability for all three soil types.

- Soil stabilization with Portland cement and emulsified asphalt proved to be effective in reducing the level of easily erodable contaminated soil particles. Erodable particulate material (a second potentially significant human exposure mechanism), measured after completion of the weathering process was substantially reduced with Portland cement stabilization, and was virtually eliminated with emulsified asphalt stabilization. Additionally, available data suggests that uncompacted emulsified asphalt could be used as an effective pretreatment technique for containment of the dioxin contaminant when removal, extensive handling and/or off-site transportation if required.

Based upon the data obtained from this investigation, recommendations for further investigation include:

- Continued investigation of Portland cement as an *in situ* soil stabilization technique to obtain conclusive evidence of its effectiveness relative to immobilization of the dioxin contaminant via solubilization mechanisms. Based upon data obtained in this investigation, an effective experimental design would include: formulation at cement contents 2% greater than those used in this investigation to assess the impact of this approach on both environmental strength/durability and dioxin leachability; and the use of a larger bench-scale leachability system in an attempt to overcome the dioxin solubility/detection limit complication.
- Continued investigation of soil stabilization with emulsified asphalt and lime-modified soils, in both expanded-scale laboratory studies and pilot-scale field evaluations, to further document the effectiveness of this technique, and to evaluate the feasibility of *in situ* stabilization on a more realistic scale.
- Experimental evaluation of the effectiveness of a combined soil stabilization approach using Portland cement with an asphalt coating on the soil–cement surfaces. This approach would be particularly attractive, in that it combines the strengths of both stabilization techniques, while maximizing cost-effectiveness through exploitation of the relatively inexpensive Portland cement base.

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