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Stabilization of high mercury contaminated brine purification sludge

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Abstract

The highly leachable mercury contaminants of brine purification sludge (BPS) generated from the Hg-cell electrolysis process in chlorine production can be stabilized in the treatment procedure employing ferric-lignin derivatives (FLD) (Ligmet^{TM} binder) and Portland cement (PC). The stabilization effectiveness has been examined by time-based multiple toxicity characteristic leaching procedure (TCLP) tests and sequential TCLP tests. In a period of 50 days, the multiple TCLP tests showed a variation of less than 90 $\mu g\,l^{-1}$ for the leachable mercury level, and the sequential TCLP tests for the same sample displayed a declining TCLP mercury level. Based on this study, the stabilization of approximately 2000 t of brine purification sludge has been successfully processed with the ferric-lignin derivatives treatment.

Keywords: Brine purification sludge; Leachable mercury; Lignin derivatives; TCLP; Stabilization and solidification

1. Introduction

A former chlor-alkali plant in British Columbia, Canada using the Hg-cell electrolysis process for the chlorine production from the saturated brine solution was permanently shut down in 1991 after 25 years operation. The manufacturing facilities were dismantled at the site. Two of the former caustic tanks were used to store brine purification sludge (BPS) pumped from the brine clarifier during the plant shutdown. The brine purification sludge, consisting of $Mg(OH)_2$, $CaCO_3$, and $BaSO_4$ precipitates, was produced in the process of brine purification using hydroxides, carbonates, and sulfates to remove calcium, magnesium and barium impurities prior to the electrolysis of brine solution for chlorine and caustic soda production. Spent brine containing residual mercury was recycled from the mercury cell to the brine saturation tank and then combined with the new brine. Eventually, BPS contained high levels of total mercury and toxicity characteristic leaching procedure (TCLP, US EPA Method 1311) leachable mercury. Due to BPS being stored in the tank for more than 10 years, the stratigraphy profiles for each tank showed the distribution of different particle size of BPS from <0.037 to 0.59 mm depending on the depth of layer. That is, BPS at the bottom of Tank had a bigger size compared with the top layer of BPS, leading to a wide distribution range for total Hg and TCLP Hg. The total mercury of BPS was approximately 500–7000 mg/kg, primarily consisted of inorganic Hg-contaminants including mercury chlorides and hydroxides, and the TCLP Hg of BPS about 200–400 $\mu g\,l^{-1}$. BPS was classified as environmentally hazardous materials under the Transportation of Dangerous Goods (TDG) Regulations. According to the current land fill regulations [1] for the Province of Alberta, Canada, all Hg-contaminated wastes must meet the standard of 200 $\mu g\,l^{-1}$ TCLP Hg prior to being disposed in a non-hazardous waste landfill. Therefore, it is required to reduce the leachable mercury of BPS to levels acceptable for landfill disposal. To achieve this goal, the means of mercury restoration or stabilization of leachable mercury is normally preferred by the scientists and engineers. So far, we have not found any report yet on successful immobilization of BPS containing high leachable mercury contaminants.

The technologies for recovering mercury from BPS are primarily carried out through the thermal treatment process, such as roast, retort or incineration [2]. However, there are still some challenges facing the mercury recovery during the thermal process. For example, chlorides and hydroxides of mercury and other high salt contents of BPS carry over during the retorting and condensation process, forming impurities. The large amount of water in BPS makes the thermal

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process costly and causes halogens to form acids in the presence of steam, leading to a corrosion problem. Additionally, the adsorbents (such as fly ash, powdered activated carbon, and calcium based acid gas adsorbent) are frequently used to capture the air emission of mercury contaminants from the thermal treatment system, producing a mercury-bearing waste for further treatment. However, it is hard to prevent the unintentional releases of mercury during the thermal recovery process, which may be significant, in spite of carefully designed and implemented mercury emission capture and treatment.

The technologies of solidification/stabilization (S/S) [3] are applied for reducing the mobility of mercury contaminants in the environment by employing additives to trap or immobilize contaminants within solid wastes through both physical and chemical means [4]. In a S/S process, the Hg-contaminated solid wastes [5,6] are mechanically mixed with a stabilizing agent, such as trisodium salt of trimercapto-s-triazine (TMT) [7], sulfur [8], fly ash [9], Portland cement (PC) [10], lignin derivatives [11,12], polymers [13] or other wastes [14–17]. Thus, Hg-contaminants may be immobilized through a chemical bonding [12,16] by the additive, or be enclosed with S/S additive or binder. The solubility and changes of mercury binding forms in contaminated soils have been studied at different pH values [18] after immobilization with alkali-polysulfide and TMT. The S/S effectiveness of leachable mercury is typically determined by the TCLP test. It is normally required for appraising the immobilizing agent at lab-scale prior to the full-scale process due to the matrix complexity for every Hg-contaminated waste.

This paper represents a S/S method that applies ferric-lignin derivatives (FLD) and Portland cement to treat high Hg-contaminated BPS successfully from lab trials to final full-scale process. The effectiveness of S/S is examined through multiple TCLP tests and sequential TCLP tests. That is, a series of samples were randomly sampled over a period of 50 days for TCLP leachable Hg tests (i.e., multiple TCLP tests). The multiple TCLP tests revealed that the leachable mercury levels varied below 90 $\mu g\,l^{-1}$ for all random samples. The sequential TCLP test is carried out by running first, second and third extraction successively. That is, following the first TCLP test, the remaining solids of the tested sample are extracted by a fresh extraction solution for the second TCLP test. The remaining solids from the second TCLP test are extracted with the third TCLP extraction solution. If the leachable Hg contaminants are immobilized in waste solids, then, the sequential TCLP tests should show a decreasing tendency of TCLP Hg level for the same tested sample. This decreasing tendency indicates that the TCLP Hg contaminants become unleachable even at intensive extraction conditions after stabilization treatment. Thereby, the leachable mercury of BPS can be reduced to an acceptable level (TCLP Hg $< 200\,\mu g\,l^{-1}$) according to the land disposal regulations for Alberta, Canada. While processing BPS with FLD/PC treatment at full-scale, the treated BPS (TCLP Hg $< 60\,\mu g\,l^{-1}$) frequently required 6–7 days to dry in an open area due to the high water content. To aid the drying process, the Hg-contaminated sand (TCLP Hg 189–230 $\mu g\,l^{-1}$) at the site was mixed with the treated BPS at mass ratio of 1:1, leading to a quickly dried matrix with time-based TCLP Hg 22–122 $\mu g\,l^{-1}$. Thus, the treated BPS is now qualified for landfill disposal. As an outcome of this detailed study, about 2000 t BPS and 2000 t of Hg-contaminated sand have been successfully processed and stabilized with FLD/PC treatment.

2. Materials and methods

2.1. Materials

Brine purification sludge was sampled by means of the sampling device equipped with a hollow-pipe (DI 2 in.). A continuous core sample (about 15 kg) was vertically collected at one single spot from the top of the thinner sludge to the bottom of the storage tank. The sample was blended before each test. The mixed BPS contained about 60–63% (w/w) water, and had alkali properties (pH = 9.1–9.7). No metallic mercury was observed in the BPS sample under a microscope at three to five times of magnified scale.

Ferric-lignin derivatives is prepared according to the NORAM procedure [11], which is marketed under the trade name Ligmet^{TM}. FLD is a lignin-based solid with brown color. The freshly prepared FLD contains 12% (w/w) water.

2.2. Analysis

The mercury contents for the TCLP leachates were determined with a mercury analyzer (CETAC M6000)) by the on-site lab which is certified by CAEAL (Canadian Association for Environmental and Analytical Laboratories). For quality control, some samples were analyzed by PSC Analytical Services.

The water content for Hg-contaminated solid wastes was determined by drying about 3 g of sample in a vacuum oven for 2 h at 100 °C. The vapor of Hg contaminants was condensed and collected in a cold water bath for further treatment.

2.3. TCLP (US EPA Method 1311)

The TCLP test is performed to measure the leachable mercury contents in the course of this work, and determine the stability of treated solid wastes. Three pH measurements are recorded according to EPA Method 1311. The value of pH(1) is measured by mixing 5 g of solid sample and 96.5 ml of deionized water in a 250-ml beaker after stirring for 5 min, which represents the acidic or alkali properties of the waste solids. The value of pH(2) is tested by adding 3.5 ml HCl (1 N) to the above described pH(1) solution followed by heating to 50 °C for 10 min, which determines

the alkalinity of the waste solids. Because pH(2) values for all samples in this work are greater than 5, extraction fluid #2 composed of 5.7 ml glacial HAc in 1 l deionized water, is then used for TCLP tests. After 18 h. extraction of waste solids, the pH value of TCLP extraction solution is recorded as pH(3), which represents the neutralization degree of HAc of TCLP extraction by alkalinity of the waste solids.

2.4. Lab-scale trial

A certain amount of 7 (or 10) parts by wt. of brown FLD was manually mixed at room temperature with 100 parts by wt. of gray BPS in a plastic bag until it had a uniform color. After 1 h setting on the lab bench, 50 g of each prepared sample is subjected to an 18 h TCLP extraction. The TCLP leachate filtered through 0.45 μm pore-size filter paper was analyzed for the leachable mercury content. The treated BPS (100 parts by wt.) was further mixed with PC (7 parts by wt.) in a plastic bag. The stabilization effectiveness of final solid wastes was examined with multiple and sequential TCLP methods for analysis of leachable mercury variation.

2.5. Full-scale Trial-1

A total of 3.6 t of BPS were transferred into a mixing bin in four batches by using a front-end loader. The sample for each batch of untreated BPS was collected in a plastic bag for TCLP test. An amount of FLD was applied at a ratio of 10% of the total BPS weight. It took about 10 min for continuously mixing of BPS and FLD with an excavator. Four samples were collected at different locations. The mixing was then continued for another 10 min, and four more samples were collected at different locations again. Then, PC was added at 6% by weight, and mixed with the treated BPS for 5 min. Four more samples were taken from the four different corners of the mixing bin. Each sample was analyzed to determine TCLP leachable mercury content. At time intervals of 2, 3 and 7 days after the treatment with FLD, additional samples were collected for TCLP tests.

2.6. Full-scale Trial-2

Following the similar process of Trial-1, an amount of 1.8 t of BPS was treated by FLD and PC sequentially. For improving the drying rate of treated BPS, the Hg-contaminated sand (1.8 t, TCLP Hg 186-230 $\mu g\,l^{-1}$) at the site was added prior to PC addition.

3. Results and discussion

3.1. Variation of leachable Hg in BPS

The leachable Hg of BPS was determined by TCLP test over 76 days, and the dissolved Hg in disengaging brine water (BW) was also analyzed by Mercury Analyzer instrument. All the analysis data are listed in Table 1, and plotted in Fig. 1. The mixed sample of BPS contained about 59.5–63% (w/w) water, and has alkali properties, pH(1) = 9.1–9.7. It was a jelly form, composed of fine particles with no metallic mercury observed under a microscope at three to five times of magnified scale. The test data showed that BPS was not stable, its TCLP Hg level was continuously increasing, and the dissolved Hg contaminant level in the disengaging clear BW was increasing as well over a period of 76 days.

The reason for BPS instability could be ascribed to the presence of brine salt. In the precipitation process of BPS in the storage tank, the soluble brine salt (NaCl) would preferably stay in the water phase and be concentrated at the top layer as BW. The sample of BPS was taken from the top thin layer to the bottom of the thick layer. The thin layer contained a lot of disengaging BW. This mixture of thin and thick BPS was mixed with the disengaging BW again before the lab tests. Thus, the amount of brine in BPS was increased leading to a new equilibrium between leachable and unleachable mercury. This new equilibrium would take a long time (>76 days) to reach a new balance. As a result, the leachable Hg level was increased by mixing BPS with BW, indicating that the conversion of strongly bonded Hg (unleachable Hg) to the weakly bonded Hg (leachable Hg) was promoted by the higher concentration of brine salt in BW.

Table 1
Test data for BPS and BW

Date	Test #	Sample I.D.	Solid (%)	Setting (days)	TCLP Hg ($\mu g\,l^{-1}$)	pH(1)	pH(2)	pH(3)
11/13/02	1	BS-1	40.5	0	116	9.10	6.03	6.53
11/18/02	2	BS-2	–	5	177	–	–	7.61
11/26/02	3	BS-3	–	13	240	9.37	6.21	6.35
12/09/02	4	BS-4	37.0	26	164	9.66	6.47	6.17
12/11/02	5	BS-5	–	28	177	–	–	6.47
01/09/03	6	BS-6	40.0	57	270	9.62	6.16	6.71
01/28/03	7	BS-7	38.4	76	353	9.35	5.95	6.39
11/13/02	8	BW-1	0	0	97.4	–	–	–
12/11/02	9	BW-2	0	28	166	–	–	–
01/09/03	10	BW-3	0	57	452	–	–	–

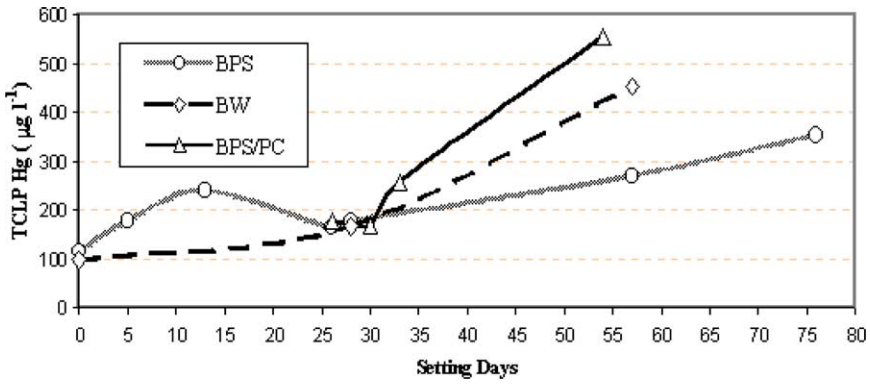

Fig. 1. TCLP Hg vs. setting days (BPS; BW; BPS/PC).

3.2. Portland cement treatment (BPS/PC)

The purpose of mixing PC with BPS is to improve BPS viscosity and particle size and also to determine PC immobilization effects on BPS leachable Hg as well. The test results are listed in Table 2, and plotted in Fig. 1 for the comparison with the TCLP Hg variation of BPS itself. The lab trials (Table 2 and Fig. 1) showed the alkali properties of PC caused the TCLP Hg increase of BPS, displaying the instability of mercury contaminates in BPS. In other words, the alkaline conditions could promote brine salt to slowly weaken the bonding strength of Hg-contaminates in BPS, leading to more and more Hg-contaminants becoming leachable. Therefore, PC is preferably used after immobilizing the leachable mercury of BPS directly with FLD, even though FLD is capable of stabilizing the matrix produced in the treatment BPS/PC.

3.3. Sequence of BPS/PC/FLD treatment

The mercury adsorption properties of FLD have been studied and discussed in the author's previous publication [12,16]. However, this is still a new challenge for FLD to stabilize the leachable mercury in BPS with high salt contents. The results of lab trials showed that FLD demonstrated a greater capacity to adsorb TCLP leachable Hg and a stronger strength of bonding with Hg-contaminants in BPS. Treating the sample of BPS/PC with FLD at 7% dosage, the TCLP Hg was reduced from 256 to 35 $\mu g\,l^{-1}$ (#13 and #15, Table 3). FLD at 10% dosage was capable of reducing TCLP Hg from 554 to 110 $\mu g\,l^{-1}$ (#14 and #26, Table 3).

Based on the results of time-based multiple TCLP tests, FLD demonstrated a stable immobilization of leachable mercury over a period of 42 days. The sequential first, second and third TCLP tests did show a decreasing tendency of TCLP Hg (#15–#25, Table 3). These results could be explicated by the presence of strong bonding strength between FLD and Hg-contaminants in BPS. Furthermore, the results of FLD immobilization were repeatable. For example, the sample of BPS/PC (#14, Table 3) with a high TCLP Hg 554 $\mu g\,l^{-1}$ could be stabilized with FLD at a 10% dosage in a 33-day lab trial (#26–#35, Table 3). Two samples were tested by sequential first, second and third TCLP tests to show a decreasing tendency of TCLP Hg as well.

3.4. Sequence of BPS/FLD/PC treatment

Two potential difficulties could be present in the full-scale S/S process even though the sequence of BPS/PC/FLD treatment had demonstrated the immobilization of the leachable mercury. The completion degree of S/S process mainly relies on effective contact between two solid phases, BPS and FLD. If the solidification of BPS is firstly performed (BPS/PC), then the large particles of solidified BPS with PC may restrict Hg-contaminants to contact FLD effectively. In addition, PC could cause more Hg-contaminants to become leachable leading to a heavier loading for the next FLD treatment. However, these two potential difficulties can be avoided in the sequence of BPS/FLD/PC treatment. In the first step of BPS/FLD, the fine particles of soft BPS are expected to mix with FLD uniformly to ensure an effective contact between weakly bonded Hg-contaminants and FLD.

Table 2
Test data for PC effects on TCLP Hg of BPS

Date	Test #	Sample I.D.	Solid (%)	Setting (days)	TCLP Hg ($\mu g\,l^{-1}$)	pH(1)	pH(2)	pH(3)
12/09/02	11	BS100/PC7	58.5	0	179	12.01	8.65	7.06
12/13/02	12	#11	57.3	4	169	12.14	9.21	6.77
12/16/02	13	#11	56.7	7	256	12.15	8.32	6.82
01/06/03	14	#11	54.6	28	554	10.94	5.68	6.78

Table 3
Data for treatment sequence of BPS/PC/FLD

Date	Test #	Sample I.D.	Solid (%)	Composition (g)		Setting (days)	TCLP Hg ($\mu g\,l^{-1}$)	pH(1)	pH(2)	pH(3)
				BPS	FLD					
12/16/02	13	BPS100/PC7	56.7				256	12.2	8.3	6.8
12/20/02	15	#13/FLD7	–	#13; 300 g	21 g	0	35	11.6	8.3	6.9
01/06/03	16	#15	49.9	–	–	17	92	12.0	8.0	6.6
01/09/03	17		–	First TCLP solution setting for 72 h			67	–	–	6.6
01/09/03	18		–	Decant first TCLP solution (915 g), second TCLP			55	–	–	–
01/13/03	19		–	Second TCLP solution setting for 72 h			41	–	–	5.9
01/13/03	20		–	Decant second TCLP solution (915 g), third TCLP			26	–	–	–
01/16/03	21	#15	–	–	–	27	114	–	–	6.4
01/31/02	22	#15	48.9	–	–	42	117	12.1	6.8	6.9
02/04/03	23		–	First TCLP solution setting for 4 days			117	–	–	6.8
02/05/03	24		–	Decant first TCLP solution (915 g), second TCLP			63	–	–	6.2
02/06/03	25		–	Decant second TCLP solution (915 g), third TCLP			40	–	–	4.9
01/06/03	14	BS100/PC7	54.6				554	10.9	5.7	6.8
01/09/03	26	#14/FLD10	–	#14; 250 g	25 g	0	110	11.3	5.8	6.5
01/13/03	27	#26	–	–	–	4	58	11.6	6.2	6.4
01/16/03	28		–	First TCLP solution setting for 72 h			60	–	–	6.9
01/16/03	29		–	Decant first TCLP solution (915 g), second TCLP			60	–	–	6.4
01/20/03	30		–	Second TCLP solution setting for 72 h			47	–	–	6.1
01/20/03	31		–	Decant second TCLP solution (915 g), third TCLP			36	–	–	5.6
01/23/03	32	#26	42.0	–	–	14	96	11.4	6.6	6.4
02/11/03	33	#26	41.6	–	–	33	105	11.4	7.2	6.5
02/12/03	34		–	Decant first TCLP solution (915 g), second TCLP			51	–	–	6.2
02/12/03	35		–	Decant second TCLP solution (915 g), third TCLP			45	–	–	5.8

The mixture of BPS/FLD is watery and sloppy, which can be further solidified with PC. The results for the sequence of BPS/FLD/PC treatment are listed in Table 4 and plotted in Fig. 2.

The presence of strong bonding strength between FLD and Hg-contaminants in BPS matrix could be supported by the multiple and sequential TCLP tests. The time-based multiple TCLP tests displayed a small variation of leachable Hg level within a range of 34–84 $\mu g\,l^{-1}$ over a period of 50 days (#43–#55, Table 4), showing a good stability of immobilized Hg-contaminants with FLD in BPS. Two samples were randomly collected at a time interval of 29 days for sequential first, second and third TCLP tests (#44–#48, #51–#53, Table 4), separately. The stabilized structures for both samples were not destroyed, showing the stability under acidic conditions for a longer extraction time than regular 18 h for standard TCLP test. Furthermore, neither obvious increase nor decrease of TCLP Hg level was observed

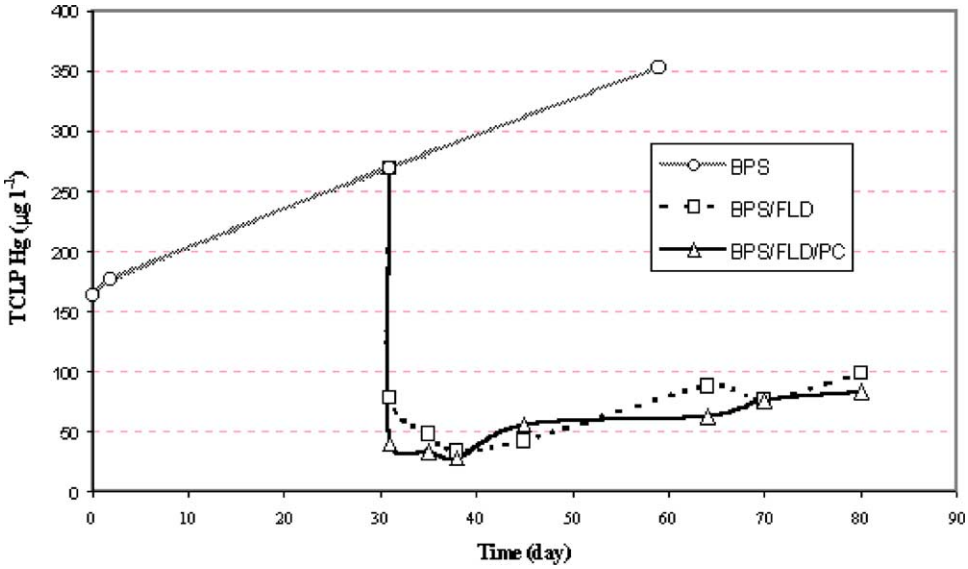

Fig. 2. Stabilization effect of BPS/FLD/PC treatment.

Table 4
Data for treatment sequence of BPS/FLD/PC

Date	Test #	Sample I.D.	Solid (%)	Composition (g)		Setting (days)	TCLP Hg ($\mu g\,l^{-1}$)	pH(1)	pH(2)	pH(3)
				BPS	FLD or PC					
01/09/03	6	BS-6	40.0				270	9.6	6.2	6.7
01/09/03	36	#6/FLD10	53.0	#6, 1000 g	FLD, 100 g	0	79	11.8	6.6	6.7
01/13/03	37	#36	42.6	–	–	4	49	11.8	6.4	6.7
01/16/03	38	#36	48.8	–	–	7	34	10.7	6.1	6.5
01/23/03	39	#36	49.0	–	–	14	43	11.2	6.1	6.4
02/11/03	40	#36	50.7	–	–	33	88	11.1	6.9	6.8
02/18/03	41	#36	49.2	–	–	40	76	10.9	6.6	6.7
02/28/03	42	#36	51.9	–	–	50	99	10.7	6.8	6.8
01/09/03	43	#36/PC7	47.3	#36, 500 g	PC, 35 g	0	40	12.0	8.3	6.6
01/13/03	44	#43	46.8	–	–	4	34	12.1	6.2	6.5
01/16/03	45		–	First TCLP solution setting for 72 h			32	–	–	6.7
01/16/03	46		–	Decant first TCLP solution (915 g), second TCLP			72*	–	–	6.4
01/20/03	47		–	Second TCLP solution setting for 72 h			50	–	–	6.1
01/20/03	48		–	Decant second TCLP solution (915 g), third TCLP			39	–	–	4.9
01/16/03	49	#43	54.9	–	–	7	28	12.0	8.6	6.7
01/23/03	50	#43	56.4	–	–	14	56	12.1	9.3	6.6
02/11/03	51	#43	57.3	–	–	33	63	12.1	9.9	6.7
02/11/03	52		–	Decant first TCLP solution (915 g), second TCLP			41	–	–	6.5
02/12/03	53		–	Decant second TCLP solution (915 g), third TCLP			35	–	–	5.8
02/18/03	54	#43	57.1	–	–	40	76	11.8	8.6	7.1
02/28/03	55	#43	60.4	–	–	50	84	11.7	8.5	6.5
01/28/03	7	BS-7	38.4				353	9.4	6.0	6.4
01/28/03	56	#7/FLD7	40.8	#7, 600 g	FLD, 42 g	0	50	11.8	7.1	6.6
01/31/03	57	#56	48.0	–	–	3	50	11.0	6.3	6.6
02/11/03	58	#56	56.1	–	–	14	41	9.2	5.8	6.7
01/28/03	59	#56/PC7	44.7	#56, 300 g	PC, 21 g	0	22	12.0	10.5	7.8
01/31/03	60	#59	62.2	–	–	3	25	12.2	11.3	7.3
02/11/03	61	#59	84.8	–	–	14	67	11.4	8.2	7.2
01/28/03	62	#7/FLD7/PC7	44.3	#7, 300 g; FLD, 21 g; PC, 25.5 g		0	35	12.0	11.1	7.2
01/31/03	63	#62	56.0	–	–	3	33	12.2	11.2	6.6
02/11/03	64	#62	79.1	–	–	14	70	12.2	9.4	6.6

Note: *Gas was released from the solid matrix, causing TCLP extract under gas pressure.

in comparison with the immobilization results between BPS/FLD and BPS/FLD/PC (#56–#61, #62–#64, Table 4, Fig. 2). This result further confirmed the expectation that the immobilization of leachable mercury was accomplished in the first step of BPS/FLD through the effective contacts between weakly bonded Hg-contaminants and FLD.

3.5. Full-scale trials

Two full-scale trials were carried out at site following the procedures for full-scale Trial-1 and -2. The test data for Trial-1 and -2 are recorded in Tables 5 and 6, respectively. Consistently with the lab results, the full-scale trials (Trial-1 and -2) have shown the capability of FLD to immobilize leachable Hg in BPS.

Trial-1 showed that about 188 $\mu g\,l^{-1}$ TCLP Hg of BPS could be immobilized by FLD at 9.4% dosage. The dilution factor for the applied dosage (9.4%) apparently was not the key factor to reduce the leachable Hg level from the initial 188 $\mu g\,l^{-1}$ to final 55.9 $\mu g\,l^{-1}$. After mixing with the excavator for 10 min, a very short time was required for FLD to immobilize the leachable Hg. No significant difference was observed in the stabilization of leachable Hg between the mixing times of 10 and 20 min (see Table 5). Similar to the lab trials, the immobilization of TCLP Hg was accomplished in the step of BPS/FLD, and no effectiveness of PC on the stabilization of leachable Hg was observed. The time-based stability test showed that the leachable Hg level varied in a narrow range of 17.2–59.0 $\mu g\,l^{-1}$ in a period of 7 days.

Trial-2 employed 1.8 t of Hg-contaminated sand to replace about 50% volume of BPS used in Trial-1. Applying the same dosage of FLD as that in Trial-1, the leachable Hg (212 $\mu g\,l^{-1}$) of sand was then immobilized by FLD as well as BPS. In addition, the presence of sand in the final treated matrix did save the required time for drying. Similar to Trial-1, the time-based stability test showed that the leachable Hg level varied in a narrow range of 22.3–72.8 $\mu g\,l^{-1}$ in a period of 8 days.

3.6. Commercial process

Based on the study of lab-scale and full-scale trials, the sequence of BPS/FLD/PC treatment for BPS stabilization

Table 5
The records for full-scale Trial-1 (21/4/03)

Items	Weight (kg)	Solids (%)	TCLP leachable Hg ($\mu g\,l^{-1}$)
Untreated Hg-contaminated BPS	3600	37.8[c]	188[c]
First batch of BPS	900	41.5	211
Second batch of BPS	900	41.9	196
Third batch of BPS	900	34.3	115
Forth batch of BPS	900	33.3	228
Applied FDL[a]	340		
Mixing FDL and BPS for 10 min with excavator		42.3[c]	55.9[c]
Random sampling at Location A/B/C/D		43.0/43.0/41.8/41.3	41.2/64.7/74.7/42.9
Continue to mix for 10 min more with excavator		43.1[c]	37.0[c]
Random sampling at Location A/B/C/D		42.2/44.1/44.0/42.1	36.1/29.5/44.7/37.6
Applied PC[b]	240		
Mixing for 5 min with excavator		47.7[c]	57.2[c]
Random sampling at Location A/B/C/D		45.8/48.2/48.7/47.9	17.6/44.8/86.5/79.9
Stabilization test of leachable Hg			
Sampling after 2 days of treatment		45.1/47.5	17.3/59.0
Sampling after 3 days of treatment		47.0	20.9
Sampling after 7 days of treatment		47.8	17.2

[a] FLD/BPS = 9.4/100 by weight.
[b] PC/(BPS + FLD) = 6.1/100.
[c] Average data of tested sample.

has been developed from concept to the commercially available process. As an outcome of this work, the stabilization of 2000 t of BPS and 2000 t of Hg-contaminated sand has been completed at the remediation site and qualified for landfill disposal.

In the course of BPS stabilization process [19], 155 samples were taken for TCLP Hg test to ensure the stabilization quality of treated waste. An average of $63.1 \pm 3\sigma\ \mu g\,l^{-1}$ (σ = 23.4, standard deviation) TCLP Hg for all tested samples, having a 99.7% confidence level, is consistent with the results obtained from the lab trials. All the analytical data for TCLP Hg were plotted in Fig. 3 according to the statistic method. The TCLP Hg distribution for the stabilized waste showed that the FLD immobilization under the described conditions was capable of reducing the leachable mercury level of BPS to 86.5, 110 and 133 $\mu g\,l^{-1}$ corresponding to the confidence level of 68.3, 95.5 and 99.7% respectively. Only one datum of TCLP Hg (180 $\mu g\,l^{-1}$) exceeded the upper quality control level (i.e., 99.7% confidence level). Consequentially, this material was further treated again before it was released for disposal. This commercial case has also demonstrated a good consistency of handling materials and repeatability of FLD stabilization during the whole process.

Table 6
The records for full-scale Trial-2 (24/4/03)

Items	Weight (kg)	Solids (%)	TCLP leachable Hg ($\mu g\,l^{-1}$)
Untreated Hg-contaminated BPS	1800	37.6[b]	252[b]
First batch of BPS	600	35.2	228
Second batch of BPS	600	39.8	145
Third batch of BPS	600	37.8	384
Addition of FDL[a] to BPS and mixing for 10 min with excavator	316		
Addition of untreated Hg-contaminated sand	1800	85.3[b]	212[b]
First batch of sand	600	91.2	230
Second batch of sand	600	75.4	219
Third batch of sand	600	89.4	186
Applied PC[a]	240		
Mixing for 5 min with excavator		65.6[b]	53.8[b]
Random sampling at Location A/B/C/D	56.8/69.5/67.8/68.4		32.7/122/32.0/28.4
Stabilization test of leachable Hg			
Sampling after 2 days of treatment		67.9	28.8
Sampling after 5 days of treatment		60.6	23.2/22.3
Sampling after 8 days of treatment		71.7	72.8

[a] FLD/(BPS + sand) = 8.8/100 by weight.
[b] PC/(BPS + FLD + sand) = 6.1/100.

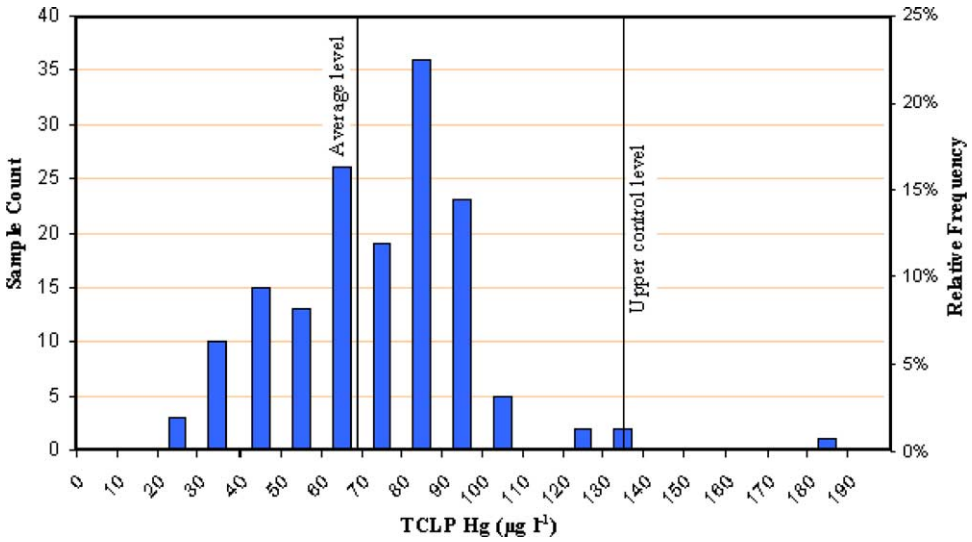

Fig. 3. TCLP Hg distribution for treated waste.

4. Conclusion

As an alternative S/S method, the sequence of BPS/FLD/PC treatment has shown an economical and simple process for the stabilization of BPS. This paper provides a detailed study on monitoring the stability of immobilized TCLP Hg with FLD in BPS by means of the time-based multiple TCLP tests and sequential TCLP tests. Over a period of 50 days, the time-based TCLP Hg varied within a range of 34–84 $\mu g\,l^{-1}$, and sequential first, second and third TCLP tests for an individual sample displayed a decreasing tendency of TCLP Hg. Hence, FLD has demonstrated the capability to immobilize the leachable Hg contaminants through the strong bonding strength with Hg-contaminants in BPS.

The FLD technology has provided an alternative solution for BPS treatment, which should be of benefit to the environmental protection. In addition, the application of FLD technology reduced the BPS treatment and disposal costs by approximately $3 million CND compared to alternative third party proprietary options. The cost for the sequence of BPS/FLD/PC treatment was about $90 CND for per metric tonne wastes.

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