

The leaching of lead from lead-based paint in landfill environments

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Abstract

Lead leaching from lead-based paint (LBP) was examined using standardized laboratory protocols and tests with leachate from actual and simulated landfill environments. Two different LBP samples were tested; leaching solutions included leachates from three municipal solid waste (MSW) landfills and three construction and demolition (C&D) debris landfills. The toxicity characteristic leaching procedure (TCLP) and the synthetic precipitation leaching procedure (SPLP) were also performed. Lead concentrations were many times higher using the TCLP compared to the SPLP and the landfill leachates. No significant difference ($\alpha = 0.05$) was observed in leached lead concentrations from the MSW landfill and C&D debris landfill leachates. The impact of other building materials present in LBP debris on lead leaching was examined by testing mixtures of LBP (2%) and different building materials (98%; steel, wood, drywall, concrete). The type of substrate present impacted lead leaching results, with concrete demonstrating the most dramatic impact; the lowest lead concentrations were measured in the presence of concrete under both TCLP and SPLP extractions.

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1. Introduction

In the past, lead was routinely used as a pigment in paints and coatings. Common lead pigments included white lead ($2\text{PbCO}_3 \cdot \text{Pb}(\text{OH})_2$) and red lead (Pb_3O_4 , Pb_2O_4 , $\text{PbO}_2 \cdot 2\text{PbO}$) [1,2]. Concerns stemming from the human health impacts of lead-based paint (LBP) prompted its ban for most applications in the United States in 1978 [3]. Lead from LBP has been associated with health effects such as damage to the brain and nervous system in children, reproductive problems, and high blood pressure [3]. In response to these concerns, the US government has developed several regulations pertaining to LBP. In 1978, the Consumer Product Safety Commission (CPSC) banned residential use of paint containing more than 0.06% lead [3]. In 1996, the United States Environmental Protection Agency (US EPA) and the Department of Housing and Urban Development (HUD) together enacted requirements for disclosure of known LBP used in housing [4]. In 2001, the EPA announced the final rule for identifying lead levels in dust on floors, windowsills and play areas for potential hazards [5].

A major focus of some regulations and policy initiatives has been LBP removal. One major impediment cited for the removal of LBP from structures has been the cost associated with disposing of the removed LBP and associated LBP debris [3]. Solid wastes containing lead are subject to Resource Conservation and Recovery Act (RCRA) regulation. If the amount of lead that leaches from a waste using the toxicity characteristic leaching procedure (TCLP) exceeds the lead toxicity characteristic (TC) limit of 5 mg/L, the solid waste must be managed as a TC hazardous waste (unless otherwise excluded). The management of hazardous waste is often many times more expensive than management of non-hazardous solid waste [3].

In an effort to remove barriers to LBP abatement from residential structures, the EPA has issued several policy clarifications and rule changes. First, the EPA specified that LBP debris removed from a home renovation activity constitutes household waste and is therefore exempt from the definition of hazardous waste [6]. Second, the rules for subtitle D landfills were rewritten to allow LBP debris to be disposed in construction and demolition (C&D) debris landfills [7]. While C&D debris landfills are in many cases unlined, the EPA justified this approach, in part, using results of leaching tests on LBP debris [3]. Laboratory results found that lead leached at much greater concentrations in the TCLP compared to the synthetic precipitation leaching pro-

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cedure (SPLP) [3]. The TCLP, a buffered acetic acid solution, was designed to simulate the acid-forming conditions that may occur in a biologically active MSW landfill. The SPLP, consisting of diluted sulfuric and nitric acids, was designed to simulate leaching as a result of acidic rain. Since C&D debris landfills have generally been considered relatively inert, containing minimal biodegradable wastes which contribute to acid production, the SPLP was thought to better represent true leaching conditions in disposal environments dominated by C&D debris.

This paper presents the results of research examining the leachability of LBP debris in different landfill environments. The goal of this study was to provide data on how lead leaching differs from the standardized protocols often used to represent landfill environments (TCLP, SPLP) compared to leaching using actual and simulated landfill leachates. Since LBP is often only a small fraction of LBP debris, the impacts of several different building material substrates on lead leachability were also examined. The results provide insight regarding the potential fate of lead from LBP debris in a disposal environment, as well as the benefits and limitations of standardized leaching procedures for assessing this fate.

2. Methods and materials

2.1. Sample collection and preparation

Samples of LBP used in this study were collected from two sources. The first source was painted wooden siding from a military barrack at Fort Ord, California (USA). Several pieces of siding were sent to the authors. The wood was observed to have multiple layers of paint, including a tan-colored top coating and a green under coat. Paint was collected from the boards by manually scraping using a hammer and chisel. Care was taken to minimize the wood collected with the paint chips. The paint chips produced satisfied the TCLP size reduction requirement (<9.5 mm). The sample was found to contain an average 35,700 mg lead/kg of paint. In this paper, this paint sample is referred as LBP-A.

The second source came from a can of metal primer that contained red lead pigment. The paint can was collected from a household hazardous waste facility and was partially full. Mineral spirits were used to thin the paint, and the liquid paint was applied to a glass surface. Once dry, the paint was scraped with a razorblade scraper and allowed to air dry for 1 week. The scraped paint was then size-reduced to satisfy the TCLP requirement by cutting it into pieces using a pair of scissors. This paint sample will be referred to as LBP-B in this paper. The paint was found to contain an average of 96,600 mg/kg lead. All of the paint chips created were collected in a polyethylene bottle and mixed by shaking.

2.2. Regulatory leaching tests

Both the TCLP (EPA method 1311) and SPLP (EPA method 1312) were performed [8] on the LBP-A and LBP-B samples. The TCLP extraction solution (fluid 1) was prepared by diluting a mixture of 5.7 mL of glacial acetic acid (CH_3COOH)

added to 500 mL of reagent water and 63.4 mL of one normal sodium hydroxide (1N NaOH) to 1 L so that the pH of the solution was 4.93 ± 0.05 . The SPLP extraction fluid was prepared by diluting a 60/40 wt% mixture of concentrated sulfuric acid (H_2SO_4) and concentrated nitric acid (HNO_3) to achieve a pH of 4.20 ± 0.05 .

The paint samples were leached at a 20:1 liquid to solid ratio rotated end over end in plastic bottles using a 30-rpm rotator for 18 ± 2 h. Due to the limited mass of paint available for testing, the procedure was scaled down from the mass described in the regulatory procedures; 4 g of paint was added to 80 mL of leaching solution. Each of the leaching tests was conducted in triplicate. At the end of the agitation period, the pH of each sample was measured and the samples were then filtered through 0.7 μm glass fiber filters. The filtered leachate samples were preserved to a pH <2 by adding few drops of concentrated nitric acid.

2.3. Landfill leachate experiments

Additional leaching tests were conducted on both the LBP-A and LBP-B samples in the manner previously described for the TCLP and SPLP, but instead of the TCLP or SPLP solution, leachates from operating or simulated landfills were used. A similar approach was used by Hooper et al. [9], Jang and Townsend [10] and Dubey et al. [11]; although this technique cannot account for all of the complexities that occur in an actual landfill environment, it does permit a more realistic evaluation of the leaching that can occur as a result of the chemical conditions of the leachate.

Leachates representing both MSW landfills and C&D debris landfills were utilized. The MSW landfill leachate samples were obtained from the leachate collection systems of three lined MSW landfills in Florida. The samples are referred to as MSW-A, MSW-B, and MSW-C. Leachate samples were collected from two lined Class III landfills (samples C&D-A and C&D-B). Liner systems are not required for C&D debris landfills in Florida; Class III landfills represented the closest source of C&D debris landfill leachate. In Florida, Class III landfills receive yard trash, C&D debris, carpet, cardboard, furniture and similar materials [12]. Both of these facilities reported C&D debris as the primary component of their waste stream. Another leachate sample (C&D-C) was collected from a simulated C&D debris landfill being operated as part of another research experiment [13]. Table 1 provides details of all of the leaching solutions used for extractions. The pH measurements are also provided in Table 1 for comparison purposes. Each of the leachate samples was characterized for lead and a number of water quality parameters. Detailed results for water quality parameters are presented elsewhere [14], but as a whole, leachate quality fell within the typical range of reported values in the literature for MSW and C&D landfills.

2.4. Leaching as a function of pH

The impact of pH on lead leaching from LBP-B was examined by leaching the samples at varying pH values, an approach

Table 1
Description of leaching solutions used in the study

Leaching solution	pH of leachates used for LBP-A	pH of leachates used for LBP-B	Comment
TCLP	4.93 ± 0.05	4.93 ± 0.05	Extraction fluid #1 described in EPA method 1311. Buffered acetic acid solution designed to simulate worst-case acid-forming conditions created by anaerobic decomposition in a MSW landfill.
SPLP	4.20 ± 0.05	4.20 ± 0.05	Extraction fluid for east of the Mississippi river in EPA method 1312. Simulated acid rainfall.
MSW-A	6.96	6.88	Leachate Collected from a closed cell of a MSW landfill. Waste of the cell is around 10 years old ^a .
MSW-B	6.97	6.82	Leachate Collected from a closed cell of a MSW landfill. Waste of the cell is around 3 years old ^a .
MSW-C	7.82	7.40	Leachate collected from a closed MSW landfill. Waste is 9–15 years old.
C&D-A	7.29	7.87	Leachate from a Class-III closed landfill.
C&D-B	6.85	6.63	Leachate from an open cell of a Class-III landfill.
C&D-C	6.96	7.44	Leachate from a simulated C&D debris landfill. This simulated landfill is a 20 ft high, 1 ft diameter PVC lysimeter built up on the ground filled with C&D debris for another research (13).

^a MSW-A and MSW-B are the leachate collected from two different cells of the same landfill.

commonly used when characterizing the leachability of waste products [15–19]. The LBP samples were leached using extraction solutions at different pH at a 20:1 liquid to solid ratio in polyethylene bottles (rotated end over end in a 30-rpm rotator for 16 h, excluding the time spent for measuring and adjusting the pH).

De-ionized water was adjusted to different pH values (ranging from pH 1 through pH 13) by using either sodium hydroxide (NaOH) or nitric acid (HNO₃) as needed. Leaching began with a lower liquid volume than required in order to allow some volume for pH adjustment. During the first few hours the pH of each sample was adjusted at 15-min intervals. Later in the test adjustment frequencies were decreased based on the degree of pH variation. Additional DI water was added to make a liquid to solid ratio of 20:1 and extracted for 16 additional hours at 30 rpm. When complete, the final pH was measured and the samples were filtered and preserved in the similar manner as for TCLP and SPLP.

2.5. Impact of substrate material on lead leaching

LBP debris contains both LBP as well as the construction materials associated with the paint. In some cases, only the LBP is removed, but in other cases, the LBP-coated debris is removed and becomes the waste material that must be managed. The building materials present in the debris may influence leaching test results and thus impact how the debris must be managed.

The impact of a substrate material on LBP leaching from LBP-B was evaluated with wood, drywall, concrete, and steel. Each material was first size-reduced. A piece of southern yellow pine dimensional lumber was drilled with a power drill (using an 8.7-mm drill bit), with the drill cuttings being collected as the samples. A compound snip was used to cut a sheet of steel into

pieces less than 9.5 mm. Drywall was reduced to small pieces to meet TCLP requirement by slightly hammering the gypsum and tearing the paper manually. Crushed concrete was collected from a concrete recycling facility and passed through a 12.5-mm sieve.

The wood siding from which the LBP-A samples were obtained was found to have approximately 6 g of paint per 100 g of painted wood. This fraction would be expected to be lower in more dense substrates such as steel or concrete. In an effort to keep the same mass of lead in each test and to provide reasonable paint content, 98 g from each size-reduced construction material was leached separately with 2 g of LBP chips in 2 L of SPLP and TCLP solutions in triplicate. While the presence of more or less lead would impact lead leaching results, the objective was to compare the impact on lead leaching from the substrates. As a control, 2 g of paint chips without a substrate material were leached in 2 L of SPLP and TCLP solutions using the same procedure.

2.6. Leachate digestion and analysis

Each of the leachate samples collected in this study were digested using EPA Method 3010 A [8], an acid digestion for analysis by inductively coupled plasma atomic emission spectroscopy (ICP-AES). The LBP-A and LBP-B samples were also digested for total lead content using EPA Method 3050B [8]. All of the digested samples were then analyzed using ICP-AES, a Thermo Jarrell Ash 61E Trace Analyzer. The detection limit for lead was 4 µg/L. Samples were leached and analyzed in triplicate, duplicates and blank samples were included as appropriate. The recoveries of blank spike, matrix spike and calibration check samples were within 87–109%. Statistical analysis was performed on the data set using student *t*-test as appropriate at 95% confidence limits.

Table 2
Lead leaching results from LBP with TCLP and SPLP

Leaching solution	LBP-A			LBP-B		
	Initial pH	Final pH	Lead leaching (mg/L)	Initial pH	Final pH	Lead leaching (mg/L)
TCLP	4.92	5.51	209, 205, 212	4.93	5.14	587, 577, 519
SPLP	4.24	6.51	9.66, 8.95, 52.1	4.21	5.65	103, 107, 110

3. Results and discussion

3.1. Comparison of TCLP and SPLP results

The results of the TCLP and SPLP leaching tests for the LBP-A and LBP-B samples are presented in Table 2. The concentration for each of the triplicate analyses is provided. The results are presented in this manner because of the noticeable degree of variability observed among few triplicate runs. This highlights the extreme variability that may be encountered when working with LBP debris, a fact that has been highlighted in the past [3]. Leaching results from the LBP-B sample were more uniform (it was from one paint source, while the LBP-A sample originated from wooden siding coated with multiple layers of paint). Due to less variability observed in the LBP-B sample, it was selected for the more detailed subsequent experiments (pH and substrate impact testing).

The LBP-B sample leached more lead than LBP-A in both the TCLP and the SPLP (Table 2). Lead concentrations from LBP-B sample ranged from 519 to 587 mg/L with the TCLP and 103 to 110 mg/L with the SPLP. The LBP-A samples ranged in lead concentration from 205 to 212 mg/L and 8.95 to 52.1 mg/L with the TCLP and SPLP, respectively. The pH increased in all tests, with a greater increase in pH in the SPLP relative to the TCLP. This is expected as the TCLP solution is a buffered weak acid solution, while the SPLP is an un-buffered acid solution. As presented, the LBP-B sample had a greater lead content (96,600 mg/kg) than the LBP-A (35,700 mg/kg). Comparing the percent leaching from the samples under TCLP and SPLP, it was found that the fraction of lead leaching from the two samples was very similar: lead leached at 11.5–11.9% and 10.7–12.1% under TCLP for LBP-A and LBP-B samples, respectively. The fraction of lead leached using the SPLP was 0.5–2.9% for the LBP-A sample and 2.1–2.3% for the LBP-B sample.

Both paint samples leached many times more lead using the TCLP than the SPLP. With the LBP-A sample, the TCLP leached

approximately five times more lead, while for LBP-B, the TCLP leached 10 times more (neglecting the 52.1 mg/L value) as compared to SPLP. The observation that TCLP leaches more lead from LBP debris when compared to SPLP supports previous observations [10,19]. The difference in leaching between TCLP and SPLP was cited in the background to the 1998 EPA proposed rule for disposal of LBP debris; EPA observed that the lead concentrations from leaching of LBP debris samples were approximately 10 times more in TCLP than SPLP [3]. Ferguson and McBride [20] found that lead leached 50 times more from contaminated soil using the TCLP compared to the SPLP. Another study based on leaching of printed wire boards and cathode ray tubes found TCLP to leach approximately 175 times more lead than SPLP [10].

The difference in lead leaching between the TCLP and SPLP results from two factors: the type of acid used and the pH of the leaching solution during the test. TCLP is a weak acid solution while SPLP is a strong acid solution. The acetic acid in the TCLP can cause a greater degree of lead leaching, because acetate chelates strongly with lead, enhancing dissolution and complexation [21]. A difference in the leaching solution pH is the other reason for a disparity; the buffered nature of the TCLP solution results in less pH increase during the extraction compared to the SPLP. In this study, the pH of the LBP-B sample changed from 4.93 to 5.14 during the TCLP while the pH of the LBP-A sample changed from 4.92 to 5.51. Results from the SPLP found that the LBP-B sample pH changed from 4.21 to 5.65, while the LBP-A sample pH changed from 4.24 to 6.51 (Table 2).

As has been described in the literature [18,22], and as will be shown later for the LBP-B sample, lead leaching is heavily influenced by pH. The greater difference between TCLP and SPLP in sample LBP-A was in part due to the large pH difference compared to that observed for LBP-B. These results show that both the pH and the organic acid content contribute to the difference in lead leaching from LBP in SPLP and TCLP.

Table 3
Lead leaching from LBP with different landfill leachates

Leaching solution	LBP-A			LBP-B		
	Initial pH	Final pH	Lead leaching (mg/L)	Initial pH	Final pH	Lead leaching (mg/L)
MSW-A	6.96	7.01	19.3, 17.6, 15.3	6.87	6.77	35.3, 44.7, 50.5
MSW-B	6.97	7.02	9.93, 8.85, 8.44	6.82	6.72	16.7, 16.1, 14.6
MSW-C	7.82	7.52	22.6, 20.7, 22.5	7.4	7.1	21.3, 20.6, 25.7
C&D-A	7.29	7.21	8.30, 12.3, 106	7.87	7.31	13.6, 13.7, 13.5
C&D-B	6.85	6.79	5.35, 5.70, 47.0	6.63	5.95	20.6, 18.9, 18.9
C&D-C	6.96	7.07	16.8, 8.63, 20.4	7.44	7.2	6.56, 7.23, 7.11

3.2. Leaching with landfill leachate

The leaching results for the LBP-A and LBP-B samples with different landfill leachates are presented in Table 3. The high variability associated with the LBP-A sample is again illustrated for several samples. Extraction with MSW-A as leaching fluid leached the highest (35.3–50.5 mg/L) while with C&D-C leached the least (8.63–20.4 mg/L). The extractions with MSW leachate did not, however, leach more than extractions with C&D in all cases; extraction with C&D-B leached more than that with MSW-B. Upon statistical analysis, the results showed there was no significant difference in leaching of LBP-B with MSW and C&D landfill leachates. It is noted, however, that this statistical analysis is based on leachates from only six landfills (three MSW and three C&D debris landfills). Although the final pH was higher for MSW-A samples as compared to C&D-B samples, higher lead leaching was observed from MSW-A extractions. This indicates that although pH is one of the most important factor controlling lead leaching (as presented in detail in subsequent section), other factors beside pH are contributing to some extent in the degree of lead leaching.

The LBP-B leached less lead in the six landfill leachates than both the regulatory tests (TCLP and SPLP). The TCLP was found to leach approximately 10–80 times more lead than the landfill leachates. The SPLP was found to leach approximately 2–15 times more lead than landfill leachates. The reason for the lower concentrations of lead leached with the landfill leachates than the TCLP may be due to low level of acetic acid present in those landfill leachates compared to the TCLP. The acetic acid concentration of C&D-B leachate was 2.5 mg/L and was less than 0.3 mg/L for all other leachates; the acetic acid concentration of the TCLP solution is 5990 mg/L. Previous studies have also reported that lead concentrations leached from printed wire boards (PWBs) and cathode ray tubes (CRTs) with MSW leachates were less than those from the TCLP [10]. The higher leaching of lead with SPLP as compared to that from MSW and C&D leachates was due to a lower final pH in SPLP (5.65) as compared to leachates (pH 5.95–7.31). Impact of pH on lead leachability is presented in detail in the next section.

3.3. Leaching as a function of pH

Fig. 1 graphically presents the results of lead leaching as a function of pH for the LBP-B sample. The results show the dramatic impact pH has on lead leachability. Lead leached at the greatest concentrations at high and low pH values with nearly 100% lead leachability observed near pH 13. This trend has been observed in lead from other wastes as well [17–19]. In a study on the dissolution of lead paint in aqueous solutions, Barnes and Davis [23] observed that lead leached more under very acidic conditions, and leached the least between pH 9 and 10.

At low pH values, elemental lead is unstable and readily dissolves (Pb^{2+}) at both low and high pE values [24]. At neutral and slightly alkaline pH values, lead forms compounds such as PbSO_4 , PbCO_3 and $\text{Pb}(\text{OH})_2$ (at high pE) and PbS (at low pE) depending on the other chemical species present. For the scenario depicted in Fig. 1, the lead concentration in the solution

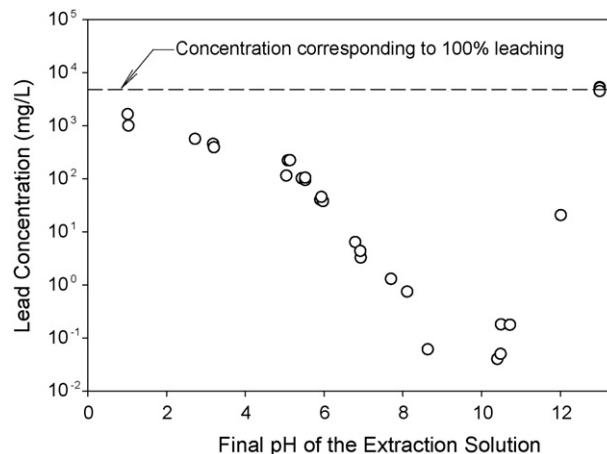


Fig. 1. Lead leaching from LBP-B as a function of pH.

decreased as the pH is increased indicating the precipitation of Pb^{2+} as $\text{Pb}(\text{OH})_2$. At very high pH values ($\text{pH} > 12$), $\text{Pb}(\text{OH})_2$ reacts with excess OH^- present in solution to form the dissolved species of lead $\text{Pb}(\text{OH})_3^-$ [24].

Since the slope of the lead concentration curve between pH 4 and 9 is relatively steep, there is a considerable difference in lead leaching results for a small change of pH. This is an important factor to be considered for the condition of real landfills because most landfill leachates have a pH between 6 and 8 [25]. The results of LBP leaching with different landfill leachates followed the pH trend to some extent, with other factors also contributing to lead leaching as presented in detail in the previous section. The SPLP results followed a similar trend as the pH study. The SPLP average final pH for LBP-B sample was 5.65 with lead leaching from triplicate samples in the range of 103–110 mg/L (see Table 2). At a similar pH (pH 5.52), lead leaching in the pH study was 105 mg/L (see Fig. 1), suggesting that pH is the major factor controlling lead leachability in the case of the SPLP. However, the TCLP concentrations for lead are approximately 2.5 times more than the results that could be predicted from the impact of pH alone. The final average pH in TCLP for LBP-B sample was 5.14 with lead concentration in the leachate observed in the range of 519–587 mg/L (see Table 2). At the similar pH value of 5.13 in the pH study (see Fig. 1) the lead concentration measured was 224 mg/L. This indicates that the lead reaction with the acetic acid in TCLP also plays an important role in addition to pH.

3.4. Impact from substrate of LBP on lead leaching

Figs. 2 and 3 present the average lead concentrations and pH values measured in the leaching experiment conducted for the LBP-B along with different substrates. In general lead leaching with TCLP was higher than with the SPLP, similar to the observations without substrates. The TCLP results in Fig. 2 show that lead leached most in the absence of any substrate and the average lead concentration for all the substrate conditions except concrete exceeded the TC limit (5 mg/L). As presented in previous section, pH is a major factor controlling lead leachability. Comparing the final pH and corresponding lead concentrations for

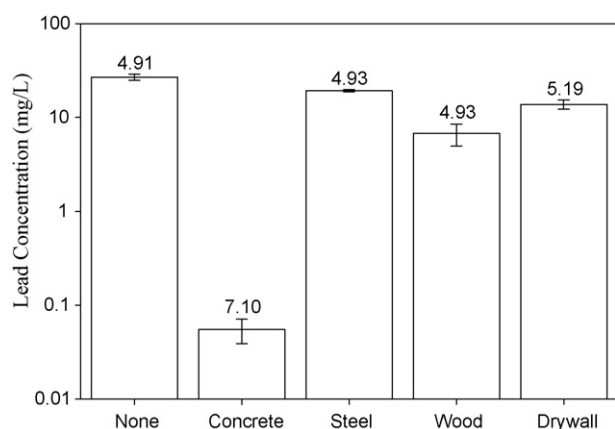


Fig. 2. Lead leaching from LBP-B as a function of substrate material (extraction fluid-TCLP).

different substrate, it was observed that the highest and lowest lead concentrations (26.9 and 0.06 mg/L) were observed for the sample with no substrate and for the sample with concrete, with these two samples having the lowest (pH 4.91, no substrate) and highest (pH 7.10, concrete) values of final pH, respectively. For the other samples, although the final pH measurements of the leachates using wood and steel as substrates were both 4.93, leached lead concentrations were different (6.74 and 19.3 mg/L, respectively). The sample with drywall had a final pH of 5.19 with lead concentration as 13.8 mg/L. Lower lead leaching was observed in presence of steel compared to no substrate with similar pH values. This observation follows the trend earlier studies have documented that the lead leaching is inhibited in presence of steel for different lead containing waste samples [26,27].

Comparing the final pH values and the corresponding lead concentrations in the leaching experiment with substrates under TCLP with that of the pH impact study (presented in earlier section), lead concentrations with different substrates followed the trend as expected based on pH impact except that for the sample with wood as a substrate material. A lower concentration of lead was observed from the TCLP leaching tests with wood as compared to the value expected from the impact of pH alone. It is hypothesized that in the case of wood, lead may be adsorbed

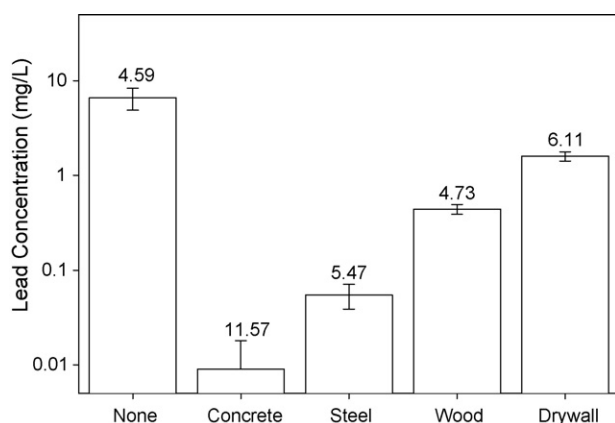


Fig. 3. Lead leaching from LBP-B as a function of substrate material (extraction fluid-SPLP).

on the binding sites of the wood particles and hence filtered out after the extraction test. Statistical analysis indicates that the lead TCLP concentrations leached with the different substrates were significantly different from each other.

SPLP also leached the most (6.6 mg/L) when there was no substrate material with the lowest final pH (4.59) observed; the sample with concrete leached the least (0.008 mg/L) with the highest final pH of 11.6. For other substrates, the amount of lead leached was highest for drywall (1.23 mg/L) followed by wood (0.44 mg/L) and steel (0.06 mg/L) with final pH of extraction solution as 6.11, 4.73 and 5.47, respectively (see Fig. 3). Comparing the lead concentrations observed with SPLP as compared to what would be expected based on pH impact alone, it was found that the sample with wood and steel as substrate showed less lead leaching and the one with drywall showed more. As stated in the previous paragraph, lead does have a tendency to get adsorbed on binding sites of organic matter (wood in this case), resulting in lower lead concentrations in solution in the SPLP leachate with wood as substrate. The exact cause of higher lead leaching with drywall as a substrate as compared to what is expected from impact of pH alone needs further exploration. The presence of organic matter as paper from drywall may have helped in lead mobilization in solution as organic dissolved complexes. Statistical analyses suggest that the lead concentrations from the different substrates were significantly different from each other when SPLP was used as the leaching solution.

3.5. Integration of results and implications

The TCLP extracted more lead from the LBP samples than the SPLP, a result previously observed on other lead-containing wastes, including LBP debris. Two primary factors cause this difference: the lower pH during the TCLP (although it is not initially lower than SPLP, it remains lower because of its buffered nature) and the interaction of lead with acetate. Previous dramatic differences in TCLP and SPLP results prompted the US EPA to suggest that lead would be more mobile in MSW landfills compared to C&D debris landfills. This assertion was not supported with the data obtained herein where LBP was leached with MSW and C&D landfill leachates; lead concentrations from the SPLP were found more representative of both leachate conditions. The MSW leachate samples were typical of those encountered at modern lined MSW landfills: the pH was higher than the TCLP and the acetic acid concentration was much lower. While landfills do go through an “acid phase” where the pH is lower and acid concentrations are higher, “methane forming” conditions where the pH is near neutral and acid concentrations are lower are more typical. While limited in terms of the numbers of sites tested, the results of this evaluation suggest that lead leachability from LBP paint is more similar between MSW and C&D debris landfills than would be indicated by the dramatic differences between TCLP and SPLP. It is very likely that other factors, such as biological reducing conditions which occur in both MSW and C&D debris landfills, play a larger role in the fate of lead in landfills.

The type of substrate in contact with lead paint impacts leaching test results. This is important because characterizing

heterogeneous debris for lead leaching may involve selective testing of the fraction containing the lead paint, and a correction to account for the mass of other materials (without lead paint) in the debris. The substrates can impact lead leaching by altering pH (e.g., the pH increase with concrete resulted in less lead leaching) and by interacting with the lead in solution (e.g., the apparent interaction of wood particles with lead). The impact of iron was less than might be expected based on results in other studies [26,27]. In these other studies, the dissolution (oxidation) of elemental lead ($\text{Pb} \rightarrow \text{Pb}^{2+}$) was suppressed by the more electrochemically favored dissolution of iron ($\text{Fe} \rightarrow \text{Fe}^{2+}$). In the case of LBP, most of the lead in the paint will exist in the oxidized form, thus this phenomenon will play much less of a role.

4. Conclusion

Lead leachability from LBP under a variety of leaching conditions was examined. The TCLP leached lead at concentrations many times greater than the SPLP, a consequence of the different chemical nature of the two leaching tests. From the results observed for a limited number of landfills, no statistical significant difference was observed between the lead leachability with actual MSW and C&D debris landfill leachates. In this experiment, the SPLP was more representative of both the MSW and C&D debris landfills than the TCLP in terms of lead leachability from LBP debris. When the impact of different paint substrates was examined, concrete was found to reduce lead leachability by the greatest extent; wood, steel, and drywall reduced the amount of lead leaching to a lesser extent. The results suggest that simply equating the TCLP to conditions in a MSW landfill and the SPLP to conditions in a C&D debris landfill may not be appropriate for LBP debris. Additional work is needed to assess the more complicated phenomena known to occur in actual landfill settings such as sorption, entrainment, precipitation and biological reduction.

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References

- [1] J. Gooch, *Lead-Based Paint Handbook*, Plenum Press, New York, 1993, pp. 95–97.
- [2] Oil and Color Chemists' Association, Australia, *Surface Coating*, vol. 1 *Raw Materials and Their Usage*, second ed., Chapman and Hall, New York, 1983, 299–300.
- [3] US EPA. Federal Register, FR 63(243), 70190–70233, United States Environmental Protection Agency, Washington, DC, 1998.
- [4] US EPA. Federal Register, FR 61(45), 9064–9088, United States Environmental Protection Agency, Washington, DC, 1996.
- [5] US EPA. Federal Register, FR 66(4), 1205–1240, United States Environmental Protection Agency, Washington D.C., 2001.
- [6] US EPA. Memorandum, Regulatory States of Waste Generated by Contractors and Residents from Lead Based Paint Activities Conducted in Households, 31 July 2000, United States Environmental Protection Agency, Washington D.C., 2000.
- [7] US EPA. Federal Register, FR 68(117), 36487–36495, United States Environmental Protection Agency, Washington, DC, 2003.
- [8] US EPA. Test Methods for Evaluating Solid Waste, SW-846, third ed., Office of Solid Waste and Emergency Response, United States Environmental Protection Agency, Washington D.C., 2003.
- [9] K. Hooper, M. Iskander, G. Sivia, F. Hussein, J. Hsu, M. Deguzman, Z. Odion, F. Ileazy, M. Petreas, B. Simmons, Toxicity characteristic leaching procedure fails to extract oxoanion-forming elements that are extracted by municipal solid waste leachates, *Environ. Sci. Technol.* 32 (23) (1998) 3825–3830.
- [10] Y. Jang, T. Townsend, Leaching of lead from computer printed wire boards and cathode ray tubes by municipal solid waste landfill leachates, *Environ. Sci. Technol.* 37 (20) (2003) 4778–4784.
- [11] B. Dubey, T. Townsend, H. Solo-Gabriele, Comparing arsenic leachability in landfill leachate and in TCLP, in: *Proceedings 2004, Nineteenth International Conference on Solid Waste Technology and Management*, Philadelphia, March 21–24, 2004, pp. 567–576.
- [12] FAC Solid Waste Management Facilities, Florida Administrative Code, Chapters 62–701, Florida Department of Environmental Protection Agency, Tallahassee, FL, 2003.
- [13] J. Jambeck, *The Disposal of CCA-Treated Wood in Simulated Landfills: Potential Impacts*, Ph.D. Dissertation, University of Florida, Gainesville, FL, 2004.
- [14] L. Wadanambi, *Issues Surrounding Heavy Metals in Landfills: Lead Based Paint Leaching and Concentrations in Florida Landfill Leachate*, M.E. Thesis, University of Florida, Gainesville, FL, 2004.
- [15] J. Warner, K. Solomon, Acidity as a factor of leaching in leaching of copper, chromium and arsenic from CCA-treated dimensional lumber, *Environ. Toxicol. Chem.* 9 (1990) 1331–1337.
- [16] P. Cooper, Leaching of CCA from treated wood: pH effects, *Forest Prod. J.* 41 (1) (1991) 30–32.
- [17] H. Van der Sloot, L. Heasman, P. Quevauviller, *Harmonization of Leaching Test*, Elsevier Science B.V., Amsterdam, 1997.
- [18] T. Tolaymat, *Leaching Tests for Assessing Management Options for Industrial Waste: A Case Study Using Ash from the Combustion of Wood and Tires*, Ph.D. Dissertation, University of Florida, Gainesville, FL, 2003.
- [19] B. Dubey, T. Townsend, Arsenic and lead leaching from the waste derived fertilizer ironite, *Environ. Sci. Technol.* 38 (20) (2004) 5400–5404.
- [20] E.L. Ferguson, M. McBride, Lead contaminated soil disposal in non hazardous waste landfills: ground water effects and policy implications, in: *Proceedings of the International Conference on Solid waste Technology and Management*, Winder University School Eng, Chester, PA, USA, 1999, pp. 1032–1039.
- [21] P. Flyhammar, K. Hakansson, The mobilization of heavy metals in partly stabilized MSW during oxidation, in: *Proceedings Sardina 99, 7th International Waste Management and Landfill Symposium*, S. Margherita di Pula, Cagliari, Italy, 4–8 October, 1999, pp. 213–218.
- [22] D. Kosson, H. Van der Sloot, F. Sanchez, A. Garrabrants, An integrated framework for evaluating leaching in waste management and utilization of secondary materials, *Environ. Eng. Sci.* 19 (2002) 159–204.
- [23] G. Barnes, A. Davis, Dissolution of lead based paint in aqueous solutions, *J. Environ. Eng. ASCE* 122 (7) (1996) 663–665.
- [24] W. Stumm, J. Morgan, *Aquatic Chemistry: An Introduction Emphasizing Chemical Equilibria in Natural Waters*, third ed., Wiley-Interscience, A Division of John Wiley & Sons, Inc., New York, 1996, pp. 318–327.
- [25] T. Christensen, P. Kjeldsen, P. Bjerg, D. Jensen, J. Christensen, A. Baun, H. Albrechtsen, G. Heron, Biogeochemistry of landfill leachate plumes, *Appl. Geochem.* 16 (2001) 659–718.
- [26] D. Kendall, Toxicity characteristic leaching procedure and iron treatment of brass foundry waste, *Environ. Sci. Technol.* 37 (2003) 367–371.
- [27] K. Vann, S. Musson, T. Townsend, Factors affecting TCLP lead leachability from computer CPUs, *Waste Manage.* 26 (3) (2006) 293–298.