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Solubility and bioavailability of lead following oral ingestion of vitrified slagged aggregate

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Abstract

The objective of this study was to evaluate the solubility of lead from various lead salts and vitrified slagged aggregate (VSA) in aqueous solutions. The solubility and absorption of lead as lead acetate [$Pb(Ac)_2$], lead chloride [$PbCl_2$], lead superoxide [PbO_2], as well as VSA were studied. Solubility profiles at pH 1, 3, 5 and 7 differed for each compound. Maximal solubility of the lead salts ranged from 2.89×10^5 ppm for $Pb(Ac)_2$ at pH 4 to 6.1×10^3 ppm for PbO_2 at pH 3, with $PbCl_2$, having intermediate values. In each case, the solubility of lead increased as pH decreased from pH 7 to pH 3. However, as pH was lowered further, solubility of lead decreased. Lead from VSA was found to be soluble at a maximal level of 2.3 ppm at pH 3. Mice were administered 10 mg of ground VSA by gavage and monitored for blood lead levels at 1, 4, 8, 12 and 24 h. Peak blood lead levels of 13.8 parts per billion (ppb) were found at 8 h dropping to 3.4 ppb at 24 h after administration. In other experiments, mice were given drinking water containing from approximately 100–1000 ppm of either $PbCl_2$, $Pb(Ac)_2$, or PbO_2 *ad libitum* for 30 consecutive days. The resulting blood lead levels at the end of this period appear to be a function of the concentration of the lead in the drinking water, as well as of the specific salt, with PbO_2 providing the lowest level of lead. These data further indicate that the lead in VSA, which reportedly exists as an oxide, is poorly absorbed from the gastrointestinal tract following gavage.

Introduction

The presence of lead in the environment and in organisms, including humans, is considered a sign of environmental pollution [1]. While the effects of exposure to relatively high concentrations of lead are established, the effects of subclinical exposure on the general population, especially children, are just beginning to be evaluated.

The concentration of lead in surface water is directly related to the sources of contamination, the lead content of sediments, and environmental factors

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(pH, temperature, etc.) [2]. Lead concentrations in household tap water range from 7 to 11 ppb [2], but even higher levels are usually found in "first-draw" samples.

The major modes of lead exposure may occur via ingestion of lead in food, water, or descendent dust [2–4]. In the United States the total daily intake of lead for an adult varies from less than 0.1 mg/day to more than 2 mg/day [5,6]. After absorption of lead in the gut, it is distributed by the vascular system to bone and the soft tissues of the body. Since over 90% of the total body burden accumulates in bone, the blood concentration indicates recent rather than cumulative absorption [7]. Thus, recent exposure to lead either by inhalation or ingestion directly affects the blood concentrations of lead [8,9].

In prolonged exposures to lead resulting in high lead blood levels, there is a decrease in hemoglobin resulting in anemia in both lead workers and children [2]. Threshold levels have been identified for the inhibitory functions of lead on the enzyme activities involved in heme synthesis. In children the blood lead threshold for decreased hemoglobin levels is 40 μg/dl and for anemia, 70 μg/dl [10–13]. The current health standard for children is a blood concentration of 25 μg/dl, below which no adverse effect is presumed.

The widespread use of lead and the evidence for potential adverse effects of lead prompted this study. Lead compounds are encountered on a day to day basis as components of glass containers, paint, some types of gasoline, batteries, food cans, and industrial materials, such as solder, and chemical wastes. In waste treatment processes, such as incineration, where organic materials are converted to CO_2 and H_2O, heavy metals, such as lead which cannot be burned to completion, may be present in an oxidized form.

One specific process is a thermally catalyzed oxidation, vitrification process in which sands, gravels, clays and silicas are converted to a slagged aggregate at temperatures of 1600–2500°F (900–1400°C). The resulting vitrified slagged aggregate (VSA) is devoid of organic contamination and may be used as a commercial building material. The VSA is presumably a type of lead oxide, existing as a complex structural matrix. Because of the proposed construction uses of VSA as well as other potential uses, it is important that the product be carefully studied with respect to release of lead under probable conditions of use. Therefore, the following study was conducted to evaluate the leachability and bioavailability of lead from VSA from an environmental perspective.

The solubility and absorption of lead as lead acetate, lead chloride, lead superoxide, as well as VSA were evaluated. Solubility profiles at pH 1, 3, 5, and 7 were studied for each compound. The bioavailability of lead was determined using aqueous solutions of different lead salts as drinking water, namely: lead acetate, lead chloride and lead superoxide. VSA was also administered by gastric gavage into adult male mice, to observe the biological uptake of lead into the blood compartment.

Materials and methods

Solubility studies

Lead acetate (157 mg) was dissolved in 100 ml of 5% HCl to yield a final stock solution with a lead concentration of 1000 ppm. This stock solution was then diluted with 5% HCl to prepare standard solutions of 500, 250, 125, 62.5, 31.25, and 15.625 ppm. The standard solutions were analyzed by Inductively Coupled Plasma Spectrometry (ICP) (Applied Research Laboratory/Model 3410 ICP with Minitorch) at a wavelength of 220.35 nm.

Aqueous solutions of lead were prepared by adding 1 gram of lead salt to 20 ml of deionized distilled water at pH 1, 3, 5 and 7 (adjusting with acetic acid or hydrochloric acid). Solutions were prepared for: (1) lead acetate, (2) lead chloride, (3) lead superoxide, as well as for (4) unground- and ground-slagged aggregate. Each of the solutions was vortexed and pH value was determined with an Orion EA 940 pH analyzer, allowed to sit overnight at room temperature before being centrifuged at 3000–4000 *g* for 10 min. The supernatant was collected and the pH value measured. The supernatant was then analyzed for lead by ICP spectrometry at a wavelength of 220.35 nm.

For pH adjustment studies, saturated lead solutions were prepared by addition of more than 2 g of lead acetate into 2 ml of deionized distilled water. The pH values of the resulting solutions were adjusted with glacial acetic acid or ammonium hydroxide to approximately 1, 3, 5 and 7 resulting in a saturated solution of lead acetate at each of the four pHs. Saturated solutions at these pHs were also prepared for the other lead salts by dissolving 1 g of either lead chloride, lead superoxide, unground- and ground-slagged aggregate in 20 ml of deionized distilled water in the same way, with the exception that the pH of the lead chloride solution was adjusted with hydrochloric acid or ammonium hydroxide as needed rather than with acetic acid.

For evaluation of the combined effects of trituration and pH modification on solubility of lead from slagged aggregate, one gram of small VSA (unground and ground) or large VSA (unground and ground) was placed in each of 20 ml of pH 3 water as well as in deionized distilled water. The flasks were shaken for 10 minutes and pH measured.

Each of the solutions was allowed to sit undisturbed overnight at room temperature and the pH of supernatants measured again. The solutions were centrifuged and the supernatants were then analyzed by ICP spectrometry at a wavelength of 220.35 nm.

Absorption/bioavailability studies

To determine the bioavailability of lead, mice were either given lead solutions as drinking water or gavaged with VSA. Adult male CD-1 mice (12 weeks of age) were purchased from Charles River Breeding Laboratories, Wilmington, MA. They were housed in the vivarium under a controlled environment

with a constant temperature of 23°C and a 14:10 hour light:dark cycle. All mice received Purina rodent chow (Ralston Purina Co., St. Louis, MO) and drinking water *ad libitum.*

The animals were weight matched and distributed into 4 groups with 5–6 animals per group. The following drinking solutions were administered: Group I animals – 1.83 g of lead acetate trihydrate was dissolved in 1000 ml of deionized distilled water and was pH adjusted with glacial acetic acid to 4.8–5.0. Group II animals – 1.34 g of lead chloride was dissolved in 1000 ml of deionized distilled water. Group III animals – 1.07 g of lead superoxide was dissolved in 1000 ml of deionized distilled water. Group IV animals, which was the control group, was given deionized distilled water, only. All animals were maintained under these conditions for a period of 30 days. Water consumption was measured twice a week and corrections were made for water evaporation. Body weight was recorded weekly during the experiment. After final exposure, animals were sacrificed and whole blood was obtained via cardiac puncture using a sterile disposable needle and collection into Microtainer Brand tubes with EDTA (Beckton and Dickinson Company). Blood samples were analyzed by graphite furnace atomic absorption spectrometry (GFAA) [14]. For this purpose, blood samples were first diluted with five volumes of a solution of Triton X-100 (octyl phenoxy polyethoxyethanol) (0.5 ml/l) and diammonium hydrogen phosphate (ammonium phosphate dibasic) (5 g/l).

Standard blood solutions were prepared by spiking blood containing 1.3 mg/ml of disodium EDTA with 1000 ppm of aqueous lead solution to yield seven standards (15.625, 31.25, 62.5, 125, 250, 500, and 1000 ppb of lead). Calibration standards were prepared by diluting 1 ml of the blood standard solutions with 5 ml of Triton X-100 (0.5 ml/l) and diammonium hydrogen phosphate (5 g/l).

After dilution, the blood samples and standards were analyzed at a lamp current of 8.0 mA and a wavelength of 283.3 nm. Drinking water solutions were analyzed by ICP spectrometry at a wavelength of 220.35 nm.

To evaluate bioavailability of lead from VSA, ten mg of ground VSA was placed in each of ten test tubes with 0.25 ml of deionized distilled water (pH 7.25) and allowed to sit overnight. Twenty adult male mice were randomly divided into 2 groups with 10 animals per group. The suspensions were vortexed and drawn up into a syringe and introduced by gavage into the 10 mice. For controls, 0.25 ml of deionized distilled water (pH 7.25) was introduced to each of 10 animals. Blood samples were obtained after induction of anesthesia with ether from 2 males of each group at the end of 1, 4, 8, 12, and 24 hours. Each blood sample was taken by cardiac puncture with a sterile disposable needle and syringe and immediately transferred into Microtainer Brand purple top tubes containing EDTA (Beckton and Dickinson Company). The body weight of each mouse was measured and recorded. Blood samples were analyzed by atomic absorption (GFAA) spectrometry.

Results

Solubility studies

Saturated lead solutions of lead acetate, lead chloride, and lead superoxide, as well as that for unground- and ground-VSA were adjusted to pH ranges of approximately 1, 3, 5 and 7. In the case of lead acetate the initial adjusted pH was 1.81. In comparison with the adjusted initial pH, the overnight pH changes in each solution only differed slightly (<0.95). Solubility profiles at a pH of approximately 1, 3, 5 and 7 differed for each compound. As shown in Table 1, lead acetate had the highest solubility of all, followed in order by lead chloride, lead superoxide and VSA. In each case, the solubility of lead increased as pH decreased from pH 7 to pH 3. However, as pH was lowered further, solubility of lead decreased (Fig. 1). Lead from unground- and ground-VSA were found to be soluble at a maximal level of 2.3 ppm and 2.8 ppm at around pH 3, respectively (Table 2).

Saturated lead solutions of lead acetate, lead chloride, lead superoxide, as well as unground- and ground-VSA were made in deionized distilled water with pH 7.63. The initial pHs of the solutions of the three lead salts were different

TABLE 1

Effect of pH adjustment on solubility of lead salts and VSA

Compound	Adjusted initial pH	Overnight pH	Lead conc. (ppm)
	1.81	1.92	156,909.00
$Pb(Ac)_2$*	3.30	3.23	277,368.00
	4.96	4.01	289,474.50
	6.66	6.38	73,488.00
	1.23	1.25	5,211.72
$PbCl_2$**	2.92	2.91	9,398.00
	4.90	4.42	2,388.52
	6.78	6.01	21.10
	1.20	1.00	2,417.10
PbO_2*	3.04	2.43	6,139.40
	5.16	4.23	4.938.40
	6.87	6.97	2,474.50
	0.99	0.82	1.57
Unground*	3.10	3.16	2.35
Aggregate	5.00	5.89	<0.10
	6.72	6.69	<0.10

*Glacial acetic acid added to adjust pH.

**Hydrochloric acid added to adjust pH.

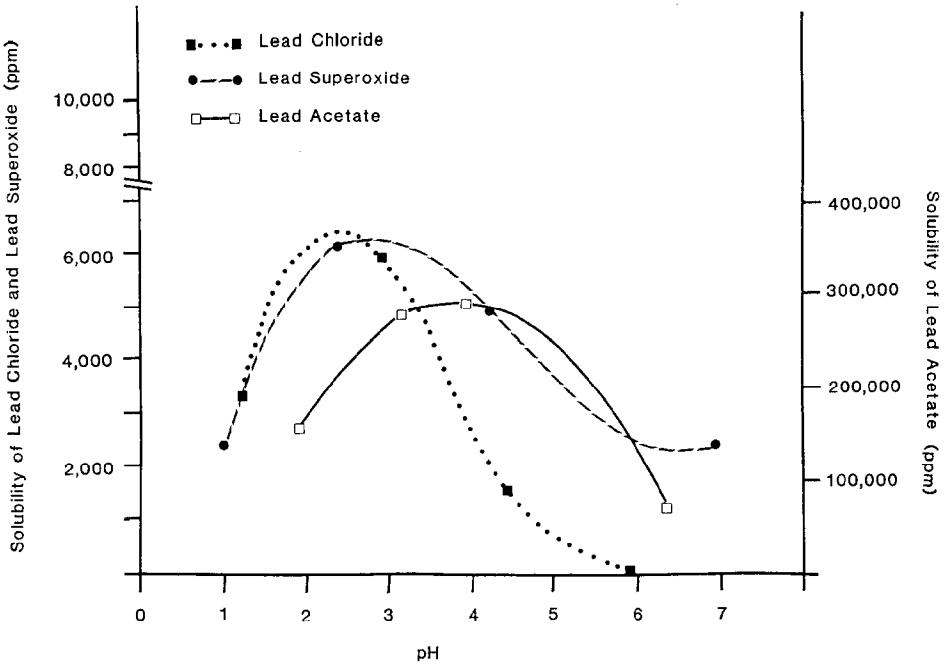

Fig. 1. Solubility of lead acetate, lead chloride and lead superoxide as a function of pH. Solutions of each salt were prepared in distilled water and adjusted to pHs of 1, 3, 5 and 7. The left ordinate represents the solubility of lead chloride and lead superoxide in parts per million. The right ordinate represents the solubility of lead acetate in parts per million. The abscissa represents the pH of the solution at 15 hours following preparation. Each value represents the mean of three experiments.

TABLE 2

Effect of trituration of VSA on solubility

Compound	Adjusted initial pH	Overnight pH	Lead conc. (ppm)
	0.99	0.82	1.57
Unground	3.10	3.16	2.35
Aggregate	5.00	5.89	<0.10
	6.72	6.69	<0.10
	1.03	1.16	2.50
Ground	3.10	3.21	2.80
Aggregate	5.13	5.99	<0.10
	6.80	7.18	<0.10

TABLE 3

Effects of trituration and pH on solubility of lead from VSA

Initial solution pH	Unground aggregate (ppm)	Ground aggregate (ppm)
3.0±0.5	0.38	0.54
	0.70	1.02
	1.44	1.50
	2.15	2.80
	Mean±S.E.M. 1.17±0.40	1.47±0.49
7.0±0.5	0.10	0.10
	0.10	0.11
	0.13	0.13
	Mean±S.E.M. 0.11±0.009	0.11±0.008

[1]Not significantly different between unground and ground aggregates, at pH 3.0±0.5 ($p>0.05$) and pH 7.0±0.5 ($p>0.05$).
[2]Significantly different between pH 3.0±0.5 and pH 7.0±0.5 for both unground aggregate ($p<0.05$), and ground aggregate ($p<0.05$).

from blank water pH, but that of both unground- and ground-VSA were not significantly different. Maximal solubility of the lead salts ranged from 289,474 ppm for lead acetate at pH 4.01 to 6,139 ppm for lead superoxide at pH 2.43, with lead chloride having intermediate values (Table 1). Particle size of the VSA, determined by comparing unground- and ground-VSA, had no effect on solubility of lead which was consistently less than 0.10 ppm (Table 2).

The solubilities of lead from VSA of different particle sizes were higher at pH 3.0 (1.17±0.40 ppm in unground VSA and 1.47±0.49 ppm in ground VSA) than at pHs around 7 (0.11±0.009 ppm in unground VSA and 0.11±0.008 ppm in ground VSA) (Table 3). But there was no significant increase in solubility caused by trituration ($p>0.05$). Furthermore, the trituration effect on solubility at pH 7.0 was also negligible being less than 0.1 ppm.

Changing the pH of the solution from 7.0 to 3.0 resulted in significant differences in solubilities of both unground and ground VSAs. The solubility increased from 0.11±0.009 to 1.17±0.40 in unground VSA after the pH was lowered from 7.0 to 3.0. The increased solubility of lead from ground VSA was approximately the same going from 0.11±0.008 to 1.47±0.49 ppm (Table 3).

Absorption/bioavailability studies

Lead salts were also added to drinking water and the lead concentrations measured with ICP spectrometry as shown in Table 4. The lead concentration of control drinking water was negligible, while those from prepared solutions

TABLE 4

The relationship between total lead consumption and blood concentration[a]

Solution	A	B	C	D	E[b]
Control	0	11.6	30	0	1.38±0.26
PbO_2	102.79	10.4	30	32,070	51.66±6.35
$PbCl_2$	1,035.08	8.5	30	263,945	184.64±11.25
$Pb(Ac)_2$	1,228.97	8.0	30	294,953	251.70±56.12

[a]Legend: A - Lead concentration in drinking water (ppm); B - consumed water volume per day per mouse (ml/day); C - administration period (day); D - total consumed lead amount (μg) = A × B × C; and E - blood lead concentration (ppb).
[b]Blood concentrations are shown in mean ± S.E.M.

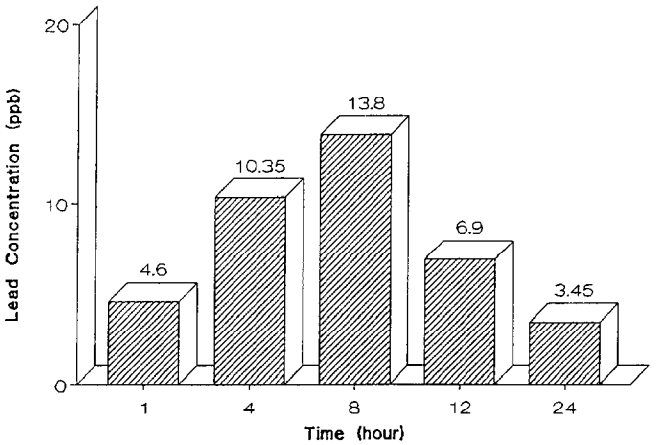

Fig. 2. Absorption of lead from vitrified slagged aggregates following gavage. Ordinate represents lead concentrations in blood in parts per billion at 1, 4, 8, 12, and 24 hours following administration.

of lead chloride, lead acetate and lead superoxide were 1035, 1229 and 103 ppm, respectively.

The average quantity of drinking water consumed by control mice each day was found to be 11.6 ml. The average daily consumption of drinking water contained lead was 10.4 ml of PbO_2, 8.5 ml of $PbCl_2$ and 8.0 ml of $Pb(Ac)_2$. After 30 days, the total lead consumed by each group was 32,070 μg for the PbO_2 group, 263,945 μg for the $PbCl_2$ group, and 294,953 μg for the $Pb(Ac)_2$ group (Table 4).

The GFAA-measured lead concentrations in blood of each group of 5–6 mice was 1.38±0.26 ppb in the control group, 51.66±6.35 ppb in the PbO_2 group, 184.64±11.25 ppb in the $PbCl_2$ group, and 251.70±56.12 ppb in the $Pb(Ac)_2$ group (Table 4).

Male CD-1 mice (35–40 g) were administered 10 mg of ground VSA and blood lead levels were monitored at various intervals. Blood was obtained by

cardiac puncture at different time points as shown in Fig. 2. The lead concentrations in blood increased rapidly after administration to 4.5 ppb at 1 hour, 10.35 ppb at 4 hours, reaching a peak value of 13.8 ppb at 8 hours. The blood lead levels then dropped to 6.9 ppb at 12 hours and 3.45 ppb at 24 hours after administration.

Discussion

The three basic questions addressed in these studies were:

(1) What is the effect of pH on the solubility of lead as $Pb(Ac)_2$, $PbCl_2$, PbO_2 and as VSA?

(2) What is the effect of smaller particle size with respect to solubility of lead from VSA?

(3) What is the bioavailability of lead following oral ingestion of VSA?

Experiments were conducted to evaluate the effects of pH on the solubility of lead in aqueous solutions. In one series, the solubility of individual lead salts was determined by adding 1 gram of either $Pb(Ac)_2$, $PbCl_2$ or PbO_2 to 20 ml of deionized distilled water. Although some solutions were unsaturated with respect to lead, it was found, as expected, that $Pb(Ac)_2$ was more soluble than $PbCl_2$ which in turn was more soluble than PbO_2. In other experiments, the pHs of the solutions were adjusted to approximately 1, 3, 5, or 7 by addition of acetic acid, hydrochloric acid or ammonium hydroxide, as needed.

It was found that the solubility of $Pb(Ac)_2$ was much lower at pH 7 than at pH 3 and pH 5. As pH was lowered below 3, the solubility began to decrease. In the cases of $PbCl_2$ and PbO_2, the solubilities were greater at pHs around 3 to 4 than they were at pH 7.

In the case of VSA, the solubility of lead was minimal presumably because it exists in an oxidized form in a complex matrix which limits its release and thus reduces its solubility.

In the studies designed to evaluate the effects of particle size on solubility, VSA was ground with a mortar and pestle to yield a fine sand like product which was compared to a matched VSA which was not ground as such.

The solubilities of lead were not significantly different between these two groups as addition of either unground- or ground-VSA to water at pH 7.63 resulted in so little lead in solution that it was not measurable. This is an indication of the complex vitrification matrix, which exists limiting the release of lead. When acidity of the solution was increased by dropping the pH to around 3.0, the solubility of lead increased and was detectable. However, the solubility of 1.17 ± 0.4 ppm for the unground VSA was not significantly different ($p > 0.05$) from that for the ground VSA which was found to be 1.47 ± 0.49 ppm. There were some variations in solubility seen for similar preparations treated identically. The differences observed for identical preparations indicate non-homogeneity of the VSA with respect to lead content. When total

lead content of the VSA was determined by strong acid extraction it was found to be 2800 to 3300 ppm. Thus, release of lead and subsequent solubilization of lead from the ground VSA is minimal.

An important question is whether the accidental ingestion of VSA would deliver a body burden of lead that would be expected to produce adverse health effects.

The absorption of lead into the body occurs mainly by inhalation and ingestion. Based on the above solubility studies for lead salts and VSA, it is reasonable to conclude that the route which could deliver the most lead is the oral route since the acidity of the stomach would be in the range of pH 1.5–2.5. This route has been studied at length for other lead compounds and it has been reported that gastrointestinal absorption of lead is a function of age with absorption being approximately 8% in adults and 40% in infants [15].

A potentially important pathway for ingestion of lead is direct ingestion by small children who tend to lick their hands which may be contaminated with dust containing lead. A positive correlation between the lead in dust and that found in wipes from children's hands has been found [16]. Since this VSA is intended for use as a commercial building product, the gavage experiments conducted in the present investigation were designed to evaluate the extent of absorption of lead from VSA that could be accidentally ingested.

Following gavage of mice with 10 mg of ground VSA, peak blood lead levels of 13.8 ppb were found at 8 hours dropping to 3.45 ppb at 24 hours after administration (Fig. 2). These results indicate that the lead in VSA, which reportedly exists as an oxide, is poorly absorbed from the gastrointestinal tract following gavage. VSA releases lead at low levels which are unlikely to produce acute toxicity. By extrapolation, the upper health-based limit of 400 ppb in a 70 kg human could be achieved from an exposure as direct (and unlikely) as ingestion of 541 g of VSA.

A child of 2 years and weighing 33 pounds (15 kg) would require 67.5 g of aggregate to reach the 25 μg/dl level [2]. Using 200 mg as the maximal quantity of soil or aggregate such a child would be expected to ingest [17], the expected blood level would be only 0.74 ppb at 8 hours. Thus, these data indicate that absorption of lead from VSA following oral ingestion is of little or no health concern since bioavailability is minimal.

Finally, it appears as expected, that blood levels in mice are a function of the concentration of the lead in drinking water, but may be more dependent upon the specific lead salt used, with PbO_2 providing the lowest level of lead of the three standard lead salts.

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