



Adsorption characteristics of lead onto soils

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Abstract

The metal adsorption characteristics of fifteen Taiwan soils, exemplified by Pb (II), were evaluated using pH as the major variable. The soil samples were thoroughly characterized for their physical chemical properties and composition, particularly organic matter and metal oxides. The adsorption of Pb (II) followed the Langmuir relation and increased with increasing pH between pH 3.0 and 8.5. The greater adsorption was found for soils with a higher organic matter content at constant pH and metal concentration. To better understand the mechanism of adsorption, the experimental results for Pb (II) were tested in a partition coefficient model to relate the adsorption of the Pb (II) by the different soils with soil components: organic matter, iron oxide, aluminum oxide and manganese oxide. This model was not successful when applied to measurements at the natural soil pH because of the competition of protons with lead for available sites. However, partition coefficients obtained from experimental data were highly correlated with those calculated for a partition coefficient between lead and organic matter alone. Normalization of the partition coefficients, K_d , for the organic matter content of the soils, K_{om} , greatly improved the correlation between the partition coefficient and pH (R^2 increased from 0.602 to 0.855). This suggests that the surficial adsorption sites are principally due to organic matter. For the 24-h equilibration period employed, diffusion of Pb through this superficial organic matter coating to underlying sorptive materials, including metal oxides, is not important in the partitioning of Pb. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Lead is present in the environment because of industrial activities, especially the use of leaded gasoline. Most environmental Pb is originally emitted from the sources in the gas phase and/or adsorbed on particulates, and carried by atmospheric transport resulting in a widespread distribution. Pb adsorbed on aerosols in the atmosphere settles on the ground by rain washout and/or by dry deposition. In several studies it has been concluded that a quantitative relationship exists between lead levels in the dust and in the blood of children [1,2].

In the soil environment, the mobility and the fate of metals is regulated via their partitioning between soil and soil solution [3]. The existence of trace metals in the solid phase is a result of many reactions with adsorption being the most important. The interaction of metal ions with natural soil particles involves multiple mechanisms because various species of the trace element can exist in solution due to complexation with organic and inorganic ligands. All species including free ion can be subject to ion exchange, nonspecific adsorption, (co)precipitation, and surface complexation [4]. Much of the work relating to trace metal sorption by surfaces in natural systems has involved the use of well-defined 'model' surfaces such as clay, aluminum oxides, iron oxides, and manganese oxides. A knowledge of the interactions of Pb with these substances which are present in soil is necessary to develop an understanding of mechanisms for the adsorption of metals.

Gerritse et al. [5], Goings et al. [6] and Jaakkola and Ylaranta [7] have stated that in most temperate soils organic matter, pH, and ionic strength of the soil solution are the major factors in controlling the adsorption of trace metals. The mineral fraction becomes important in governing adsorption when soils have very low organic matter content or high metal oxides content [8].

A strong dependence between soil solution pH and metal adsorption has been reported [9]. Basta and Tabatabai [9] stated that metal adsorption can be described by solution pH alone or in combination with soil properties. Varying contents of organic matter and metal oxides may result in varying capacities for metal sorption onto soils.

Gerritse and Van Driel [10] demonstrated a linear relationship between Cd and Pb adsorption constants and soil organic matter and soil pH for 33 soils. Both Luoma and Davis [11] and Jenne et al. [12] have considered the modeling of metal sorption by incorporating the contributions of different types of binding phases, such as metal oxides and organic matter. A different approach has been taken by Schulte and Beese [13] who showed that, over specified pH intervals, the sorption of cadmium onto different soils could be related to their specific surface areas.

If these approaches are to have general value they should be tested against results from soils in other areas. In this paper, the sorption of lead onto fifteen soils collected in Taiwan is investigated. Both adsorption isotherm and adsorption edge measurements on the soils were conducted. The influence of solution pH and of the concentrations of iron, manganese and aluminum oxides and of organic matter in the soil on Pb sorption were considered. Relationships were developed to predict adsorption of Pb by other soils.

2. Materials and methods

The fifteen soil samples collected in Taiwan for this study are listed in Table 1. They represent a distribution of the major soil types present in Taiwan.

The soils were air dried, and agglomerates were broken by hand and by using a wooden mallet. Particles larger than 2 mm were removed by sieving. All further tests were performed on soils with particles less than 2 mm in size. Organic matter was measured by the Walkley–Black wet combustion method; soil pH was determined in water; soil particle size distribution was determined by a sedimentation (hydrometer) method [14]. Using the methods developed by Iyengar et al. [15] soil metal oxides were extracted by the ammonium oxalate method and the free metal was determined by atomic absorption spectrophotometry. Natural Pb contamination of soils was also checked, and no significant amount of lead was found.

Batch equilibration studies were conducted for lead (II) for each of the fifteen soils. The soil suspensions were 1.00 ± 0.01 g per 100 ml. Ionic strength was maintained at 0.01 M with NaNO_3 . Lead nitrate was added at a concentration of 1×10^{-4} M. Ten to twelve pH values covering the range from 2.5 to 8.5 were used, and room temperature ($25 \pm 2^\circ\text{C}$) was maintained. The pH values of the samples were adjusted by adding NaOH or HNO_3 as required. Samples were shaken at 150 strokes per minute on a reciprocating shaker for 24 h. The pH values were determined after shaking the samples for 24 h. The samples were then filtered through 25-mm diameter, 0.45- μm membrane filters (Gelman Sciences, Ann Arbor, MI). The lead concentrations in the filtered solutions were determined using an atomic absorption spectrophotometer (AA 908, GBC, Australia).

Table 1
Properties of various Taiwanese soils

Soil name	^a pH in water	Clay (%)	Oxides			Organic matter (%)
			Fe_2O_3 (%)	Al_2O_3 (%)	MnO_2 (%)	
Beichatianshan silty loam	3.9	44.5	1.029	0.496	0.046	8.3
Changhua loamy sand	3.5	16.1	0.121	0.079	0.017	0.8
Chiayi sandy loam	6.8	9.7	0.638	0.443	0.001	1.1
Guanyin sandy loam	5.6	9.5	0.784	1.374	0.021	2.3
Huwei loam	7.4	20.2	0.810	0.638	0.060	5.4
Jente clay loam	4.8	28.0	0.584	0.748	0.055	5.1
Kaohsiung silty loam	7.1	20.8	0.505	0.410	0.038	4.0
Keelung silty clay	6.6	27.1	0.860	0.721	0.095	5.5
Lichochoen sand	4.2	6.5	0.746	0.248	0.010	0.4
Luzhu sandy loam	4.9	7.8	1.095	0.161	0.001	1.8
Tacha silty loam	5.2	13.6	0.778	1.154	0.042	11.2
Taichung silty loam	6.6	6.4	0.417	0.144	0.003	1.3
Tenchung silty loam	6.7	24.3	0.917	0.620	0.022	3.0
Yuenlin silty clay loam	6.4	34.2	1.442	1.271	0.024	6.7
Yunlin silty loam	6.9	9.5	0.243	0.133	0.009	1.6

^aSoil pH was determined after 30 min stirring, and then 1 h standing.

Samples for the adsorption isotherm experiments were prepared by adding 1.0 g soil in 100 ml of 0.01 M NaNO₃. The pH was adjusted in order to approach the desired pHs, 4.5 and 6.0 for Pb. The initial lead concentrations ranged from 5.0×10^{-7} to 2×10^{-3} moles/l, and the equilibration time was 24 h at room temperature ($25 \pm 2^\circ\text{C}$). After 24 h, the pH was readjusted to the initial value and the samples were filtered through 0.45 μm membrane filters. It was found that the changes in pH after 24 h are small (all these adjustments were only within ± 0.3 pH). The amount of adsorbed lead was calculated as the difference between the amount added initially and that remaining in solution.

3. Results and discussion

3.1. Soil characteristics

A summary of soil characteristics is presented in Table 1. The soils ranged from sandy to clay loam, with clay contents varying from 6.4% to 44.5%. The soil pH ranged from 3.5 to 7.4 in water solution. The organic matter ranged from 0.4% to 11.2%. The Yuenlin silty clay loam has the highest Fe oxide content (1.442%); the Guanyin sandy loam has the highest Al oxide content (1.374%) and the Keelung silty clay has the highest Mn oxide content (0.095%) among the soils.

3.2. Adsorption isotherms

The adsorption of Pb to soils can be characterized by an adsorption isotherm which is a plot of adsorption quantity against aqueous equilibrium concentration of lead at fixed temperature, pH, and applied pressure. The adsorption isotherms allow the partition coefficient data to be extrapolated to high lead loading data. The adsorption data obtained from isotherm experiments were fitted to Langmuir adsorption isotherms using nonlinear regression. The form of the isotherm equation used was:

$$\Gamma = \frac{\Gamma_m \times K \times [\text{Pb}]}{1 + K \times [\text{Pb}]} \quad (1)$$

where Γ = lead concentration in soil ($\mu\text{g/g}$); $[\text{Pb}]$ = lead concentration in water (mg/l); Γ_m = maximum sorbed lead concentration ($\mu\text{g/g}$); K = constant ($1/\text{mg}$).

A nonlinear-program [16] was applied to perform the regression. Table 2 shows the parameters of the nonlinear regression of $[\text{Pb}]$ vs. Γ as well as Γ_m and K according to the Langmuir equation. At any single pH the maximum sorbed Pb concentration, Γ_m , for the fifteen Taiwan soils varied widely but correlated with the soil organic matter content significantly for pH 4.5 and 6.0 ($R^2 = 0.913, 0.967$ respectively) (Fig. 1). The sorption maximum Γ_m generally increased with soil organic matter content and no significant correlation was found with the soil Fe, Al, and Mn oxides. The Tacha silty loam had the greatest maximum adsorption quantity (43.9 mg/g), and the Lichocheh sand had the smallest maximum adsorption quantity (1.1 mg/g) at pH 4.5. The difference may be attributed to the high organic content of the Tacha silty loam compared with the organic content of Lichocheh sand. Among all soils tested, the Tacha silty loam has the highest

Table 2

Parameters for the nonlinear regression of Γ against [Pb] using the Langmuir equation for the adsorption of Pb on 15 Taiwan soils at two pH values

Soil name	pH 4.5			pH 6.0		
	Γ_m ($\mu\text{g/g}$)	K (l/mg)	R^2	Γ_m ($\mu\text{g/g}$)	K (l/mg)	R^2
Beichatianshan silty loam	34 818	0.089	0.992	90 238	0.215	0.993
Changhua loamy sand	1167	0.046	0.992	2863	0.298	0.996
Chiayi sandy loam	1257	0.039	0.989	3162	0.308	0.992
Guanyin sandy loam	4231	0.134	0.996	15 020	0.285	0.989
Huwei loam	13 916	0.304	0.989	48 629	0.925	0.998
Jente clay loam	10 155	0.038	0.987	44 217	0.098	0.997
Kaohsiung silty loam	8670	0.125	0.993	29 390	0.254	0.994
Keelung silty clay	27 739	0.009	0.996	63 861	0.105	0.991
Luzhu sandy loam	4165	0.037	0.988	13 896	0.078	0.995
Tacha silty loam	43 948	0.123	0.996	143 213	0.436	0.991
Taichung silty loam	3278	0.016	0.996	12 711	0.217	0.995
Tenchung silty loam	5183	0.074	0.997	21 036	0.268	0.993
Lichochoen sand	1136	0.021	0.992	2728	0.284	0.988
Yuenlin silty clay loam	29 355	0.018	0.994	66 315	0.137	0.992
Yunlin silty loam	3862	0.022	0.997	13 007	0.245	0.994

organic content (Table 1). The relationship between the strength of binding, measured by a combination of K and Γ_m , and both pH and organic matter content is less clear and batch equilibrium experiments were performed to explore this relationship.

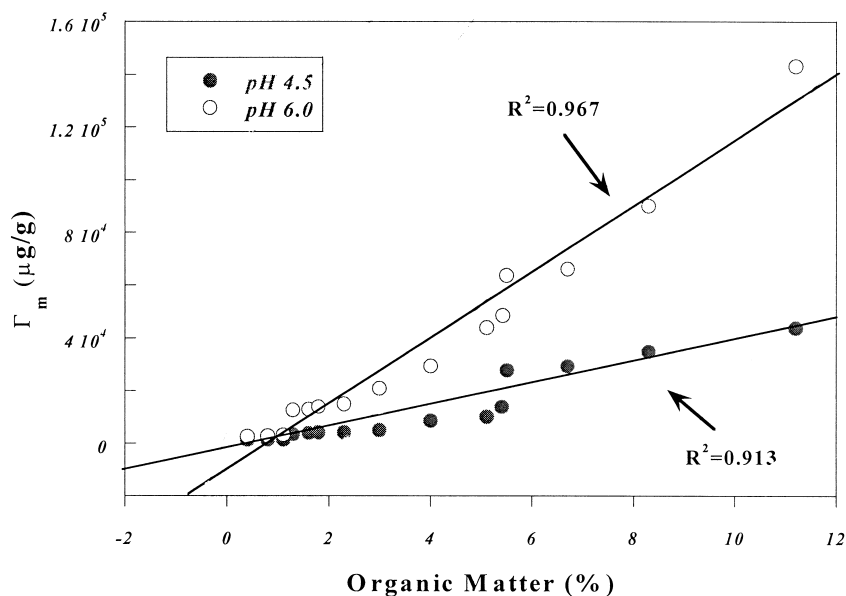


Fig. 1. The regression of organic matter vs. maximum sorbed Pb concentration (Γ_m).

3.3. Batch equilibration

The most important factor in controlling the partitioning of a metal to soil is the solution pH [17]. The amount of Pb (II) adsorbed on the soils increased sharply with pH, up to pH 5 to 6 and reached a maximum at pH 8.0 with only marginal increase between pH 6 and 8 for Tacha silty loam and Lichoche sand (for clarity representative data on 9 of the soils is presented in Fig. 2). The high dependence of Pb adsorption on pH can be explained by the fact that pH will affect the surface charge of the adsorbent and the degree of ionization and the speciation of adsorbate [18].

The soils vary in their metal binding strength. Among all soil properties in our study, organic content appears to be the most important parameter in correlating with Pb adsorption. The range of adsorption is illustrated by comparison of the Tacha silty loam, with the greatest organic content, which displayed the greatest extent of metal adsorption of all the soils with Lichoche sand which has the least metal adsorption capacity and the least organic content (Fig. 2). Partition coefficients may be used to facilitate a quantitative test of the relationship of adsorption and soil properties.

3.4. Partition coefficients

The ratio of the Pb concentration in the soil to the concentration in the solution phase is defined by partition coefficient (K_d).

$$K_d = \frac{[\text{Pb}]_s}{[\text{Pb}]_w} \quad (2)$$

Where $[\text{Pb}]_s$ = lead concentration in soil ($\mu\text{g/g}$); $[\text{Pb}]_w$ = lead concentration in water ($\mu\text{g/ml}$).

The sorbed lead concentration in soil was assumed to be the difference between the Pb added and that remaining in solution at the end of 24 h.

These K_d values vary greatly from soil to soil. The adsorption edge data (shown in Fig. 2 for nine representative soils) were used to establish K_d values at fixed pH and plot $\log K_d$ vs. pH for all 15 soils (Fig. 3). The slope of Fig. 3 is about 0.39, which indicates that only 0.39 mole of protons are released for each mole of Pb sorbed to the soil. Although it is clear from Fig. 3 that pH is the major factor controlling the partitioning, the variation in K_d at pH around 5.0 from our data set is approximately 1.5 log units, or a factor of 30. Thus, to achieve a given aqueous phase concentration, the lead concentration that could be present in two soils at the same pH could also vary by a factor of 30. Hence, pH is the most important parameter, but it is not the sole one. The goal is to predict partitioning to a higher degree than when pH is the only variable considered.

In an attempt to better predict the partitioning of Pb to soil, a general partitioning model for the sorption of Pb by soil surface substances at fixed pH was developed. A preliminary statistical analysis of the variation of lead adsorption with measured soil properties was made. Clay content and surface area showed poor relationship with

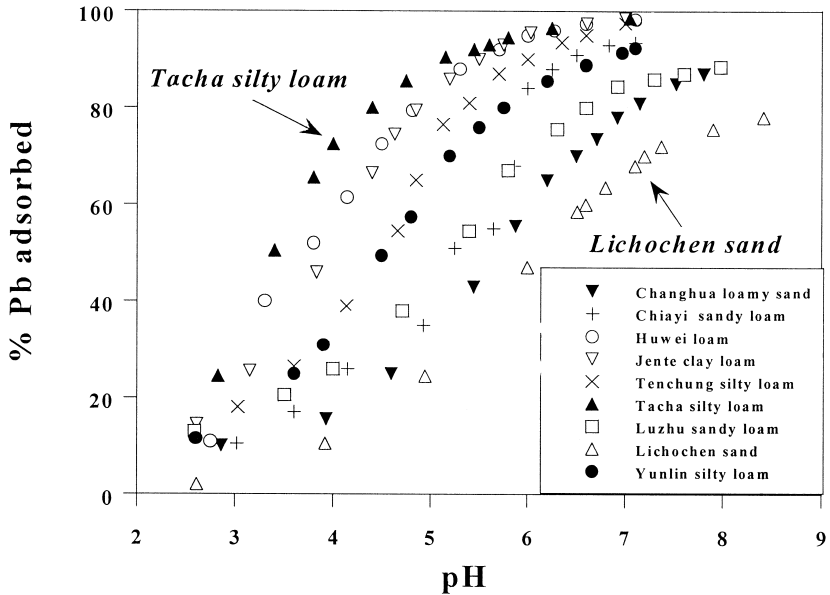


Fig. 2. Adsorption of lead (1×10^{-4} M initial concentration) onto nine representative soils. Soil/water = 1 g/100 ml; $I = 0.01$ M NaNO_3 ; $T = 25^\circ\text{C}$.

adsorption. Based on this analysis, the major adsorbing sites for binding Pb (II) are considered to be Fe_2O_3 , Al_2O_3 , Mn_2O_3 , and organic matter. The model uses fixed ionic strength and fixed initial metal concentration.

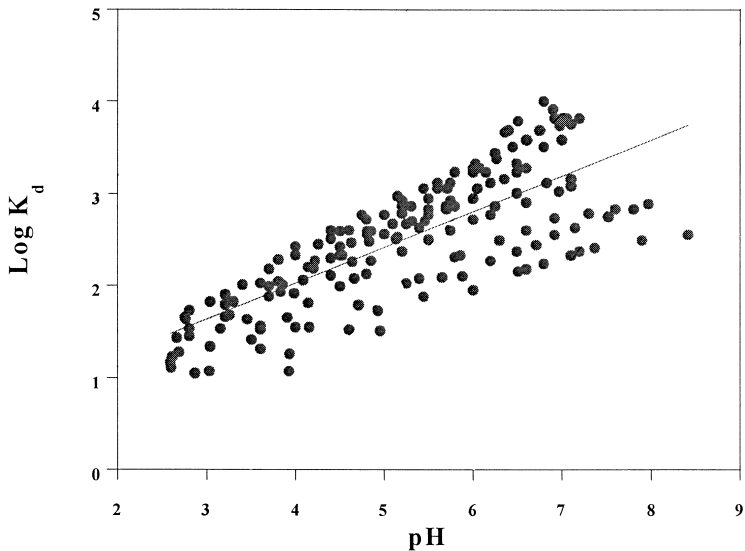


Fig. 3. $\text{Log } K_d$ as a function of pH for adsorption of Pb onto 15 Taiwan soils. Soil/water = 1 g/100 ml; $I = 0.01$ M NaNO_3 ; $T = 25^\circ\text{C}$. Regression equation: $\log K_d = 0.4664 + 0.389 \text{ pH}$; $R^2 = 0.5982$.

A typical reaction between lead and a sorption phase can be written as Eq. (3):



$$K_{\equiv \text{Site} - \text{Pb}} = \frac{[\equiv \text{Site} - \text{Pb}]}{[\equiv \text{Site}][\text{Pb}]} \quad (4)$$

where $K_{\equiv \text{Site} - \text{Pb}}$ is the conditional stability constant of this reaction; $\equiv \text{Site}$ is a binding site onto iron, aluminum, manganese oxide and organic matter; $\equiv \text{Site} - \text{Pb}$ is the quantity of lead sorbed by the binding site.

The total quantity of the lead sorbed by the soil particle, $[\equiv \text{Site} - \text{Pb}]$, is the sum of the quantities of the Pb sorbed by the individual sorption phases as is expressed in Eq. (5):

$$[\equiv \text{Site} - \text{Pb}] = [\text{FeO}_x - \text{Pb}] + [\text{AlO}_x - \text{Pb}] + [\text{MnO}_x - \text{Pb}] + [\text{OM}_x - \text{Pb}] \quad (5)$$

Equilibrium free lead concentration in solution, then can be obtained by combining Eq. (4) with Eq. (5) to give Eq. (6):

$$[\text{Pb}] = \frac{[\equiv \text{Site} - \text{Pb}]}{\{K_{\text{FeO}_x} - \text{Pb}[\text{FeO}_x] + K_{\text{AlO}_x} - \text{Pb}[\text{AlO}_x] + K_{\text{MnO}_x} - \text{Pb}[\text{MnO}_x] + K_{\text{OM}} - \text{Pb}[\text{OM}]\}} \quad (6)$$

Rearranging Eq. (6):

$$\frac{[\text{Pb}]}{[\equiv \text{Site} - \text{Pb}]_{\text{tot}}} = \frac{1}{\sum K_{\equiv \text{Site}_i} [\equiv \text{Site}_i]} = \frac{1}{K_d} \quad (7)$$

Therefore the partition coefficient is

$$K_d = \sum K_{\equiv \text{Site}_i} - \text{Pb} [\equiv \text{Site}_i] \quad (8)$$

where $[\equiv \text{Site}_i]$ is site concentration of a particular class of sites.

Eq. (8) was applied to the lead adsorption data for the Taiwan soils. For each of the fifteen soils, the adsorbed Pb is divided by the soluble Pb to obtain experimental partition coefficients at each fixed pH and at the soil natural pH by interpolation of the adsorption edge curves. These partition coefficients were regressed stepwise against site concentrations for the component considered: organic matter, iron oxide, aluminum oxide, and manganese oxide using Eq. (8) to obtain conditional formation constants for each phase. The concentrations of organic matter and of the metal oxides were considered to be proportional to their site concentrations. Separate regression was done omitting one or more sorption phases. These formation constants were then used to calculate predicted partition coefficients. The equation shown in Table 3 is an example which utilizes formation constants for the binding of Pb (II) by organic matter, iron oxide, aluminum oxide and manganese oxide to predict K_d . All observed and predicted K_d of pH 3.0, 4.0 and 5.0 are listed in Table 4. Huwei loam, for example, contains 5.4% organic matter, 0.810% iron oxide, 0.638% aluminum oxide and 0.060% manganese oxide. The predicted K_d value (138.3 ml/g) at pH 4.0 is almost identical to that observed (136.0 ml/g). The success of the model including different components can be

Table 3

The conditional formation constants, considering one, two, and three components in the model at pH 4.0

Component considered	Conditional formation constants				R^2
	$K_{\text{OM-Pb}}$	$K_{\text{FeO}_x\text{-Pb}}$	$K_{\text{AlO}_x\text{-Pb}}$	$K_{\text{MnO}_x\text{-Pb}}$	
OM ^a	24.90	–	–	–	0.941
OM and FeO _x	21.04	28.37	–	–	0.973
OM, FeO _x and AlO _x	25.26	22.36	12.98	–	0.976
OM, FeO _x , AlO _x and MnO _x	19.66	22.05	12.47	105.57	0.977

^aOrganic matter content.Sample calculation of predicted K_d by considering four components: $K_d = 19.66[\text{OM}] + 22.05[\text{FeO}_x] + 12.47[\text{AlO}_x] + 105.57[\text{MnO}_x]$.

evaluated by the goodness of fit values, R^2 , for regression of experimental partition coefficients against partition coefficients calculated from the conditional formation constants. The very low R^2 values (0.002 to 0.586) shown in Table 5 at soil natural pH indicate that only poor correlation was found for the relation of the partition coefficient to the concentration single or multiple potential binding sites when the natural soil pH was considered. The reason can be attributed to the fact that the effect of pH, demonstrated to be a major variable, is not considered in this equation.

Table 5 also shows the comparisons of the results predicted by the model with the experimental data for three different pH values (3.0, 4.0, and 5.0). The single component that gives the best correlation is organic matter ($R^2 = 0.941$ for pH 4.0). A small improvement is obtained by including aluminum oxide ($R^2 = 0.973$ for pH 4.0) while only slight improvement is obtained with four components (organic matter, iron, aluminum and manganese oxide) ($R^2 = 0.977$ for pH 4.0). At each fixed pH, this model

Table 4

The observed and predicted K_d at pH 3.0, 4.0 and 5.0 (ml/g)

Soil name	pH 3.0		pH 4.0		pH 5.0	
	Obs.Kd	Pred.Kd	Obs.Kd	Pred. Kd	Obs. Kd	Pred. Kd
Beichatianshan silty loam	59.7	47.7	203.5	196.9	417.6	499.9
Changhua loamy sand	10.8	6.47	18.6	21.2	51.2	59.4
Chiayi sandy loam	11.0	16.7	29.9	41.3	164.2	195.7
Guanyin sandy loam	34.9	40.3	83.4	81.8	575.8	506.9
Huwei loam	47.9	40.5	136.0	138.3	468.9	423.3
Jente clay loam	36.3	39.2	121.2	128.2	418.3	430.6
Kaohsiung silty loam	36.1	27.5	113.6	98.9	321.2	290.7
Keelung silty clay	53.2	45.8	142.6	146.1	493.0	456.9
Lichochoen sand	15.5	12.7	11.9	28.5	136.7	122.8
Luzhu sandy loam	23.5	17.5	54.3	61.6	130.2	167.0
Tacha silty loam	63.9	66.3	243.3	256.2	797.9	774.8
Taichung silty loam	14.3	10.3	35.5	36.8	87.4	109.2
Tenchung silty loam	26.7	30.1	109.1	89.3	345.7	331.4
Yuenlin silty clay loam	55.8	57.9	189.2	181.9	631.5	673.9
Yunlin silty loam	16.8	10.2	53.5	39.4	127.0	109.1

Table 5

Comparison of R^2 for regression of experimental partition coefficients against predicted values obtained from conditional formation constants.

Component considered	R^2			
	Natural pH	pH 3.0	pH 4.0	pH 5.0
OM ^a	0.002	0.905	0.941	0.936
Fe	0.107	0.197	0.296	0.263
Al	0.425	0.154	0.345	0.182
Mn	0.510	0.107	0.121	0.074
OM and Al	0.543	0.923	0.973	0.972
OM, Fe and Al	0.584	0.926	0.976	0.975
OM, Fe, Al and Mn	0.586	0.929	0.977	0.975

^aOrganic matter content.

The regressions were performed at three pH values and at the natural pH of each of the soils by considering one, two, three and four components in the model Eq. (8).

fits the experimental data very well by considering organic matter as the only sorption phase ($R^2 > 0.900$). The results indicate that organic matter is the most important single phase in a predictive model. Adding a second phase gains only a marginal improvement at great cost in the form of required additional information.

To reduce the variance in the pH-dependent K_d 's that are shown in Fig. 3, the K_d values were normalized to the organic matter content of the soils. Normalization of K_d to the amount of organic matter is commonly done for hydrophobic organic compounds [18,19]. The organic matter normalized partition coefficients, K_{om} , for the 15 soils are presented in Table 6 and a plot of $\log K_{om}$ vs. pH for the 15 soils is shown in Fig. 4.

Table 6

The organic matter normalized partition coefficients for 15 Taiwan soils at three different pH values

Soil name	OM ^a	K_{om} (organic matter normalized K_d)		
	(%)	pH 3.0	pH 4.0	pH 5.0
Beichatianshan silty loam	8.3	719	2452	8645
Changhua loamy sand	0.8	1352	2325	6401
Chiayi sandy loam	1.1	1003	2718	5835
Guanyin sandy loam	2.3	1084	3625	11990
Huwei loam	5.4	887	2518	8684
Jente clay loam	5.1	712	2376	8202
Kaohsiung silty loam	4	903	2841	9031
Keelung silty clay	5.5	967	2592	9146
Lichochoen sand	0.4	388	2967	9173
Luzhu sandy loam	1.8	1306	3015	13066
Tacha silty loam	11.2	571	2172	7124
Taichung silty loam	1.3	1099	2728	6727
Tenchung silty loam	3	889	3637	11523
Yuenlin silty clay loam	6.7	832	2824	9426
Yunlin silty loam	1.6	1047	3346	11065

^aOrganic matter content.

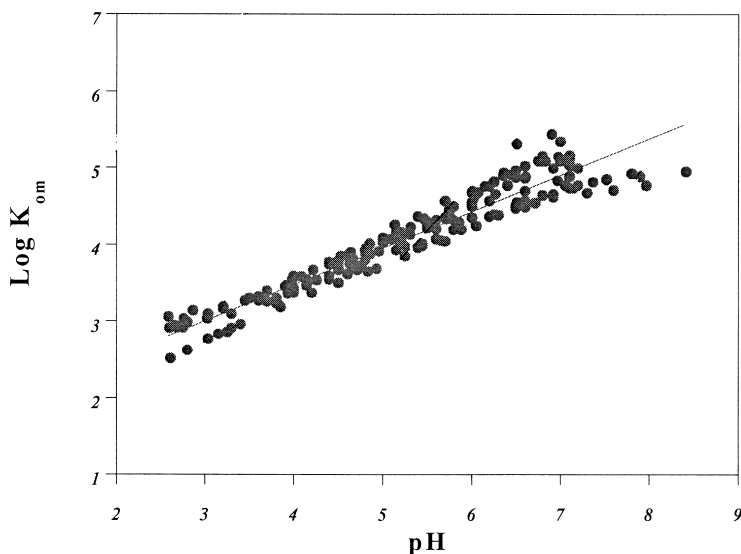


Fig. 4. Log K_{om} (organic normalized K_d) as a function of pH for adsorption of lead onto fifteen Taiwan soils. Soil/water = 1 g/100 ml; I = 0.01 M NaNO₃; T = 25°C. Regression equation: $\log K_{om} = 1.47 + 0.4955 \text{ pH}$; $R^2 = 0.858$.

The data collapse to form a single curve in which the scatter is far less than was present in Fig. 3. The regression parameters for Figs. 3 and 4 are given in Table 7. From Table 7, the pH vs. K_{om} curve always has a higher R^2 value than does the pH vs. K_d curve. Oepen et al. [19] stated that the small amount of organic matter is not sufficient to mask the adsorption effect of clay minerals, thus sorption to clay minerals becomes more important. Similar results can be found in Table 7, the R^2 values increase from 0.602 to 0.788 for pH vs. K_d curve after deleting the samples with organic matter less than 1%. The improvement of correlation for pH vs. K_{om} curve was also found by deleting samples at pH extremes. Organic matter binding Pb within the soil will dissolve into soil solution at extremely high pH and will lose a large amount of bound Pb.

Table 7

Comparison of regression coefficients for Fig. 3 plotted with pH vs. K_d and Fig. 4 plotted with pH vs. K_{om}

	n^a	Slope	Intercept	R^2
pH vs. K_d	178 ^b	0.400	0.400	0.602
pH vs. K_{om}	178 ^b	0.495	1.457	0.855
pH vs. K_d	156 ^c	0.473	0.157	0.788
pH vs. K_{om}	156 ^c	0.508	1.436	0.933
pH vs. K_d	160 ^d	0.429	0.293	0.587
pH vs. K_{om}	160 ^d	0.506	1.426	0.941

^a n : Sample numbers.

^b All data sets.

^c The samples with organic matter content less than 1% have been deleted.

^d The samples with pH less than 3.0 and greater than 8.0 have been deleted.

In the 24-h adsorption experiments, only the organic matter, and not the metal oxides, were involved in the sorption of the added lead. This conclusion regarding the partitioning of lead in our work is in contradiction to that obtained from sequential fractionation data that shows a distribution of lead among various sorption phases. Organic matter coating clay minerals has been found to have an important influence on binding capacity for polar and non-polar compounds [19]. The fractionation of soils that are field-contaminated and therefore aged. A possible explanation for the discrepancy is that the organic matter is a superficial coating of the soil and, in the 24-h period that we used to equilibrate the samples, diffusion of the lead to the underlying metal oxide and other sorption phases was not important in controlling the partitioning of the lead between the soil and the solution phases. In a like manner, desorption will be controlled by the equilibrium of Pb between the soil organic matter and soil water. The underlying material serves as a reservoir of Pb. The uptake and release of Pb by these underlying metal oxide and other sorptive phases is a diffusion-controlled process. Further long-term adsorption experiments are needed to verify this hypothesis.

4. Conclusions

(1) The results of both adsorption edge and adsorption isotherm studies showed that Pb adsorption is highly pH dependent. Different soils have different adsorption abilities. Among all soil properties, the organic matter plays the most important role in controlling lead sorption onto soils.

(2) The partition coefficient, which is related to the percentage of lead adsorbed, increases with rising pH values.

(3) A model for the sorption of metal by soil surface substances at fixed pH was developed. The results showed that the conditional partition coefficients were highly correlated with the organic matter content at a fixed pH, i.e., the same proton concentration.

(4) The R^2 of the regression line was improved from 0.602 to 0.855 when $\log K_{om}$ vs. pH rather than $\log K_d$ vs. pH was considered for the 178 measurements for the fifteen soils that were investigated.

(5) Comparison of batch samples equilibrated for 24-h with aged, field samples suggests diffusion of lead through a superficial organic matter coating is slow and underlying sorptive materials, including metal oxides, are unimportant in the short-term partitioning of Pb.

(6) The maximum sorbed lead concentrations, I_m , from adsorption isotherm studies and the partition coefficients predicted from the model are useful in establishing a soil standard that is applicable to different localities.

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