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PART V: Heavy Metals

Chapter 7

THE RELATIONSHIP BETWEEN SOIL PARTICLE SIZE AND LEAD CONCENTRATION

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ABSTRACT

Many studies regarding heavy metal concentration in contaminated soils have observed increased concentrations in the smaller-sized particles. This phenomenon has been attributed to differences in organic matter, contaminant source, and particle surface area. The relationship between particle size and lead concentration in soils was explored. Data from four published studies were considered; the sources of lead contamination were lead smelting, metal manufacturing, and combustion of leaded automotive fuels. These four studies reported lead concentrations in different soil fractions, separated by particle size, or diameter. A total of 14 soil samples were evaluated, with each having 3 to 6 different particle-size fractions. The particle sizes ranged from less than 63 microns to between 850 to 2000 microns. Lead concentrations were plotted versus mid-range diameters. Data for each of the 14 soil samples were approximately linear on a log-log plot. Trend lines for each soil sample revealed strikingly similar slopes for all 14. The slopes ranged from -0.59 to -0.25, with a mean of -0.37. Correlation coefficients ranged from 0.75 to 0.999. This relationship suggests that soil lead concentrations are nearly proportional to the diameter raised to the power -0.37. Stated differently, soil lead concentrations within a given soil sample can be approximated as being inversely proportional to the cube-root of the particle diameter.

Keywords: soil, particle size, lead, heavy metals

1. INTRODUCTION

Lead is ubiquitous within our environment. Human activities have provided many sources of lead contamination, from the ancient art of lead smelting, to the more recent practice of adding

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lead to automotive fuels. The stable nature of lead ensures that it remains in the environment once it is emitted.

Unfortunately, lead has very toxic properties, and can lead to developmental damage lasting for a lifetime. Children are the most vulnerable group; their mental and behavioral development is irreversibly altered by exposure to lead. The past use of lead in automotive fuels ensures that most of today’s adults have been significantly exposed to lead as children.

Since smaller particles are more readily suspended in the atmosphere and dispersed by winds, studies have looked at the relationship between soil particle size and lead concentration. The oft-observed increase in concentration as the particle size decreases has summarily been explained by the increase in surface area on a per unit-mass basis. However, this relationship has not been studied in detail, and consideration of data in the literature contradicts this theory.

1.1 Studies Reported in the Literature

Several studies have looked at lead concentration for a few ranges of particle sizes. Tawinteung, et al. (2005) studied soils in Thailand which had been contaminated by industrial sources during lead recycling and smelting. They sieved five separate soil samples into three fractions by particle size, and analyzed each fraction for lead. Weiss, et al. (2006) studied lead in a sample of roadside soil in the US, separated into five fractions by particle size. Yarlagadda, et al. (1995) studied the lead concentration in three soil samples from the site of a metal manufacturing facility in New York City. They separated the soil samples into six fractions by particle size. Momani (2006) studied four soil samples from roadside soils in Jordan, where leaded gasoline was in continued use. He separated each sample into four fractions by particle size. In each of these four studies, the lead concentration increased with decreasing particle size.

One additional study did find the opposite relation, exhibiting decreasing concentration with decreasing particle size (Bright, 2006). However, this study analyzed soils that had been weathered for 70 years since the contamination source had ended. These soils may have become dispersed and diluted by fresh soils transported by wind. Therefore, this study has not been included in the current work.

1.2 Theory

Soil particle surfaces are highly reactive. As a result, adsorption is considered to be the most significant process responsible for the uptake of lead by soil. If soil contacts a liquid solution containing lead, the amount which is adsorbed is dependent upon the concentration of lead in the solution, the soil-solution contact time, and the amount of surface area of the soil. Additional variables include the amount of mixing that occurs, and its effect on convection, or mass transfer through the boundary layer surrounding the soil particles. For the current work, the rate of convection is considered to be very large relative to the rate of adsorption, so that convection does not impede adsorption. Once convective resistance is ignored, the flux (rate of adsorption per unit surface area) is simply described as proportional to the difference between the lead concentrations in the solution and on the particle surface.
\[
(mass \ flux) \propto C_{Pb,\text{soln}} (1) C_{Pb,\text{surf}}
\]

If the concentration on the surface is small relative to that of the solution, then this expression can be simplified even further.

\[
(mass \ flux) \propto C_{Pb,\text{soln}} \tag{2}
\]

Finally, if the volume of solution is very large relative to the amount of soil, then the solution concentration remains constant, making the flux constant as well. The amount adsorbed can now be determined as the product of flux, surface area, and soil-solution contact time.

\[
(mass \ adsorbed) = (flux) \times (surface \ area) \times (contact \ time) \tag{3}
\]

For a given mass of soil, the concentration of lead in the soil can be calculated from the amount adsorbed.

\[
C_{Pb} = \frac{mass \ adsorbed}{mass \ of \ soil} = \frac{mass \ adsorbed}{mass \ of \ soil} = (flux) \times \left( \frac{surface \ area}{mass \ of \ soil} \right) \times (time) \tag{4}
\]

Stated differently, the concentration of lead in the soil is proportional to the specific surface area, or surface area per unit mass, \( \hat{A} \).

\[
C_{Pb} \propto \hat{A} \tag{5}
\]

Two types of surface area are considered, external and internal. The external surface area of a single particle can be approximated as the surface area of a sphere. The internal surface area is the area associated with pores and micropores throughout the soil particle. Lead adsorbs to internal surface areas after diffusing through the pores; consequently, adsorption onto internal surface areas is slower than adsorption onto the external surface. The total surface area (external + internal) does not change with particle diameter. Assuming a constant flux in this case, and applying equation 5, the concentration of lead in soil is predicted to be independent of particle diameter, since (based on total surface area) is independent of particle diameter. This model will not be used, because i) the assumption of constant flux is very poor with regard to internal surface area, and ii) evidence indicates that concentration of lead in soil is not independent of particle size.

The model used for the current work assumes spherical particles with no internal surface area and no convective resistance. The specific surface area based on external area can be calculated by considering a single soil particle.

\[
\hat{A} = \frac{surface \ area \ of \ the \ particle}{mass \ of \ the \ particle} = \frac{surface \ area \ of \ the \ particle}{\rho_p V_p} \tag{6}
\]
where \( \rho_p \) and \( V_p \) are the density and volume of the particle, respectively. Substituting for the surface area and volume of a sphere, the equation for the specific surface area is obtained.

\[
\hat{A} = \frac{\pi d_p^2}{\rho_p \frac{\pi}{6} d_p^3} = \frac{6}{\rho_p d_p}
\]  

(7)

where \( d_p \) is the diameter of the particle. From this relation, it is clear that specific surface area is inversely proportional to the particle diameter. Consequently, since the soil lead concentration is proportional to the specific surface area (equation 5), then it is also inversely proportional to the particle diameter.

\[
C_{pb} \propto d_p^{-1}
\]

(8)

If this simple model is correct, then the log-log plot of \( C_{pb} \) vs \( d_p \) will be linear, with a slope of -1.

2. MATERIALS AND METHODS

Data from four published studies were considered; the sources of lead contamination were lead smelting, metal manufacturing, and combustion of leaded automotive fuels. These four studies reported lead concentrations in different soil fractions, separated by particle size, or diameter. A total of 14 soil samples were evaluated, with each having 3 to 6 different particle-size fractions. The particle sizes ranged from less than 63 microns to between 850 to 2000 microns. Lead concentrations were plotted versus mid-range diameters on log-log plots. Linear regression was used to determine the slope of the best-fit line for each sample. The mean and range of all 14 slopes were determined.

3. RESULTS AND DISCUSSION

Data from four literature studies are plotted in Figure 1. Each soil sample in each study has been plotted separately on the log-log plot. Trend lines have been added for each soil sample. The height of each line is an indication of the level of contamination of the soil.
Data for each of the 14 soil samples are approximately linear in the log-log plots in Figure 1. This indicates that the data fit a power-law trend line. Trend lines for each soil sample revealed strikingly similar slopes for all 14, regardless of the soil location, contamination source, or the study reporting it. The slopes range from -0.59 to -0.25, with a mean of -0.37, and a median of -0.36. The standard deviation is 0.10, and the 95% confidence interval on the slope is -0.43 to -0.31. Correlation coefficients ranged from 0.75 to 0.999. This relationship suggests that soil lead concentrations are nearly proportional to the diameter raised to the power -0.37.

4. CONCLUSION

The striking similarity in the data from all four studies indicates that similar physical or chemical phenomena are responsible for the partitioning of lead preferentially onto smaller particles. All samples also display a power-law relation of lead concentration to particle diameter. However, since the exponent of the particle diameter is not 1.0, then the simplifying assumptions which were made to obtain this model are not valid. The assumptions which are most likely to have caused this discrepancy are i) no internal surface area; and ii) no convective resistance. Therefore, the phenomenon of increasing lead concentration with decreasing soil particle size cannot be simply explained by an increase in available surface area. Further work must be done to characterize the effects of internal surface area and convective resistance to mass transfer.
5. REFERENCES


