



Reduction of suspended solids following hydroclassification of metal-contaminated soils

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Abstract

Remediation of metals-contaminated soil typically uses solidification/stabilization and “dig and haul”. Soil washing and physical separation have been applied to a much lesser extent to reduce soil volumes requiring aggressive treatment and to improve performance of follow-up treatments. In earlier work [J. Hazard. Mater. 66 (1999) 15], we used a simple, vertical-column hydroclassifier, to separate four soils contaminated with heavy metals, defining a “best case” performance for larger-scale (minerals processing) equipment. Such processes, using water-based slurries, generate substantial volumes of water with suspended solids. These typically contain disproportionately high concentrations of heavy metals. Here, we performed an initial screening of settling, coagulation, and centrifugation for reducing suspended solids, and thus suspended metals from soil slurries following processing. The four soils, previously hydroclassified, were sieved to <600 μm, slurried with a 4:1 weight ratio of water, and allowed to settle. Slurry samples were collected at settling times of 0, 0.0833, 1, 5, and 22–24 h. Coagulant (alum) addition and centrifugation were investigated. The slurries were filtered, digested, and analyzed by atomic absorption for lead and chromium content. Two soil slurries clarified in <5 min. In all four cases, 90% of solids and metals settled within 5 h. However, completion may require up to 24 h, or other intervention, i.e. coagulants. The metal concentration in the residual suspended solids increased with settling time, implying an enrichment of metals in finer, suspended particles. Metals dissolved in the slurry water ranged from 3 to 5 mg/l for chromium and lead. This screening study provides guidance for water treatment requirements and treatability studies for the integration of hydroclassification and solids removal. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

1.1. Problem statement

Numerous industrial, construction, and military practices have contaminated soil, and water with heavy metals and organic compounds. Examples include use of lead-based paints, firing ranges, electroplating, and nuclear materials manufacture [1]. Heavy metals frequently disrupt metabolic processes and produce toxic effects in the lungs, kidneys and central nervous system. The non-degradable nature of metals has typically limited the options for remediation to solidification/stabilization, “dig and haul”, and to a lesser extent, soil flushing. Electrokinetic methods have recently been applied in some cases. Remediation costs on the order US\$ 500/m³, and more for radioactive materials, motivate research to minimize volumes requiring costly treatment and to improve the efficiency of those treatments. The physical separation technology referred to in this study used minerals processing technologies to deplete soil fractions of contaminant. Depleted soils should require less aggressive follow-up treatment, improving cost effectiveness. However, processes using water-based slurries generate substantial volumes of water with suspended solids. These typically contain disproportionately high concentrations of heavy metals. Coagulation, settling, and filtration have been used to reduce suspended solids, but these unit operations can represent a large fraction, e.g. 30% of the total process equipment.

1.2. Purpose of this research

This work seeks to improve separations achievable by hydraulic classification, “hydroclassification”, based on the relative size and density of soil and contaminant particles. The specific purpose of the work reported here is to quantify and improve suspended solids and metals removal from effluent process streams representative of hydroclassification.

1.3. Objective and scope

The objectives of our earlier work [2] included the determination of mass and metals distributions into particle size fractions produced by hydroclassification. We investigated four soils from firing ranges, a popping furnace (munitions incinerator), and an electroplating facility. The work reported here integrated with our earlier hydroclassification work to determine: (1) suspended solids and metals in water/soil slurries; (2) the effects of settling time, coagulant addition, and centrifugation; and (3) metals enrichment in the suspended solids during settling. Another objective was to determine metals partitioning to the process water.

2. Background

2.1. Physical separation

Each form of metal contamination exhibits different physical properties: particle size, density and surface charge depending upon the metallic particle, soil characteristics, and

contaminant. As a result, the contamination will not occur uniformly in the soil, but distributed according to these physical properties. Generally, adsorbed metals concentrate on small soil particles [3] having a higher surface area-to-mass ratio. This amplifies metals adsorption as Horowitz [3] illustrates for copper concentration in sediments. Settling may thus enrich the proportion of small particles with time, and the concentration (mg/kg) of metals in the solids remaining in suspension. We addressed this issue by tracking the change in metals concentration (mg/kg) in the remaining suspended solids versus time. These suspended particles and adsorbed metals will, in many cases, require follow-up treatment to meet the discharge limits.

On the other hand, metals contaminants may also occur in soil as discrete particles (fragments and powder) enriched respectively in both large and small particle size fractions. This bimodal metals distribution with particle size, can occur in firing range soils. Following sections provide specific data and implications for remediation with such distributions.

Physical separations remediation uses widely applied unit operations of the minerals processing industry. These processes exploit differences in particle size, density, surface, and other properties a contaminant-rich fraction to yield the desired depleted “product” fraction. Ideally, the enriched fraction could be processed for metals recovery, and the depleted fraction returned to the site or remediated with less aggressive (and more economical) methods. We review these at length in *environmental restoration of metal-contaminated soils* [4] describing principles, unit operations, and process trains. In general, these process trains involve a first stage separation of large solids, followed by slurring with water. Further separation is made by screens with fractions directed to the appropriate unit operations, e.g. hydrocyclones. Eventually, a fines-laden effluent stream exits the system and is processed by settling or filtration to yield consolidated solids and a water meeting discharge permit limits. This work focuses on the settling and metals enrichment characteristics of such a stream.

2.2. Hydroclassification

Because many physical separation process trains use gravity-based unit operations such as hydrocyclones, it has become important to assess the potential separation performance. As a treatability study, hydroclassification uses upward flowing water in a small column to elute a series of contaminated soil fractions, again to produce depletion and enrichment of metals among the fractions [2,5]. The separation of soil into nominal size fractions depends on settling phenomena described in part by Stoke’s Law—particles of uniform shape settle through water at a rate proportional to their density and to the square of their diameter [6]. In other physical separations work on explosives-contaminated soils, we observed that all fractions $>63\ \mu\text{m}$ in diameter were easily recovered with settling on the order of seconds to minutes. However, $<20\ \mu\text{m}$ particles remained suspended for more than 1 h; $<2\ \mu\text{m}$ particles, for more than 18 h. Increased settling time directly impacts the sizing of settling tanks, cost and throughput [7]. Accordingly, it is advantageous to coagulate and floc suspended fines to accelerate settling. The physics of colloidal stabilization and coagulant action are authoritatively reviewed in several classic texts by Montgomery [8] and Weber [9]. However, the coagulation and settling removal of solids adds significant expense and complexity to process train. Kuhlman and Greenfield [10] estimate that the chemical costs and also refer to unit operations, such as centrifuges, belt presses, and filter presses, which require capital,

maintenance, and manpower expenses potentially exceeding chemical costs. In this work, we used alum addition and centrifugation as first steps in investigating the enhancement of settling

2.3. Related research: trailer-mounted systems and suspended solids removal

Other investigators have observed these problems and investigated solutions. At the US EPA National Atmospheric Radiation and Engineering Laboratory and at the National Risk Reduction Laboratory investigators developed trailer-mounted systems for physically separating contaminants, and encountered suspended solids problems [4]. In the former case, they treated the effluent suspended solids using a settling tank and a plate-and-frame filter press. This equipment represented about a third (volume-wise) of the total system. Another relevant line of research involves clarification of placer mining effluent. Solids-laden effluent from these operations can foul gravel beds needed for trout reproduction. One group of investigators studied the application of slurry recycling and a settling tank to enhance solids removal [11]. They found that recirculation allowed over 90% solids removal for soils with 2–6% clay. However, turbidity levels remained at several hundred to several thousand NTUs, requiring additional treatment. Another group [12] investigated polyethylene oxide (PEO) polymer addition to a bentonite slurry, followed by screening. They found that PEO produced strong flocs, with screening removing solids and yielding low turbidity water.

3. Experimental design

This work used small quantities of soil (100–200 g) to track the rate of settling and residual solids and metals with time. Coagulant addition allowed detection of differences in settling rate and need for dosing. Centrifugation allowed assessment of this unit operation, and served to detect suspension of metals not susceptible to settling. The experiments were designed to require only readily available bench-top equipment, e.g. shaker, stirrer and centrifuge.

4. Experimental methods and procedures

4.1. Soil samples

The four soils used were as follows: (a) firing range soil 1 (sandy loam by USDA soil texture classification); (b) a soil from near a small arms incinerator (popping furnace) (sandy soil); (c) a soil from near an electroplating operation (sandy soil); and (4) firing range soil 2 (loamy sand).

4.2. Mass, concentration and metals distribution in soil size fractions

These soils were previously hydroclassified [2]. Slurries were subjected to upward flowing water at three terminal velocities to fractionate these soil into nominal particle-size fractions of <63, 63–125, 125–250, and >250 μm (based on quartz particles of 2.65 specific gravity).

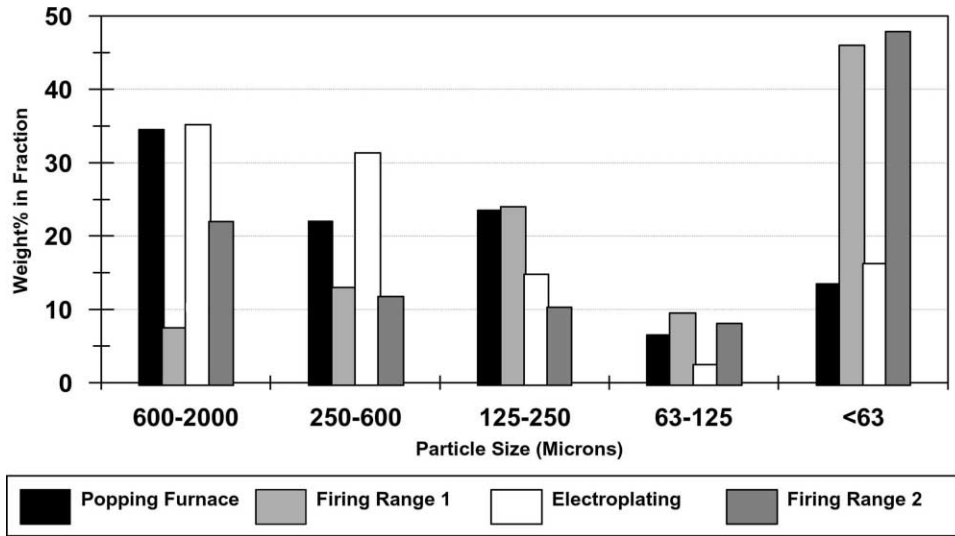


Fig. 1. Weight percentage in size fractions resulting from hydroclassification.

Hydroclassification revealed that the popping furnace and electroplating soils were sandy, as shown in Fig. 1, with <15 and 18% respectively in the silt/clay range (<63 μm). In contrast, the two firing range soils yielded 45–48% <63 μm material (Fig. 1). Wet sieving confirmed that the size range separations were substantially achieved. For the particle-size fractions, we determined the mass, metal distributions and concentrations.

The furnace and firing range soils 1 and 2 contained predominantly lead. The furnace soil had a concentration of over 100,000 mg/kg in the 600–2000 μm fraction and 40,000 mg/kg or less in the other size fractions. The firing range soil 1 had a more dramatic metal concentration profile, with over 550,000 mg/kg in the 600–2000 μm fraction. Lead fragments were clearly visible. Concentrations in the other fractions included 50,000 mg/kg in the 250–600 and over 30,000 mg/kg in the <63 μm fraction. Firing range soil 1 showed similar bimodal patterns, with the highest concentrations at the size range extremes. The electroplating soil contained chromium as the predominant metal, with concentrations ranging from 1000 to 41,000 mg/kg (<63 μm fraction). The metal distribution data are presented in Fig. 2 for the <600 μm fraction. Examining the <600 μm material better reflects the distribution from hydroclassification, and reduces variability.

Lead reported to all fractions of <600 μm soil (Fig. 2), with the 250–600 μm fraction containing approximately 30–50 wt.% of the total heavy metal in the <600 μm fraction.

For the firing range soil 1, the lead distribution for the <600 μm material exhibited a bimodal distribution (Fig. 2) with approximately 30 wt.% in the 250–600 μm , and 65 wt.% in the <63 μm fractions respectively. For the electroplating soil, approximately 85 wt.% of the chromium and 66 wt.% of the lead were distributed to the <63 μm fraction. For the firing range soil 2, the soil fractions also exhibited a bimodal distribution of lead similar to that of the firing range soil 1, with approximately 34 wt.% in the 250–600 μm and 46 wt.% in the <63 μm fractions, respectively.

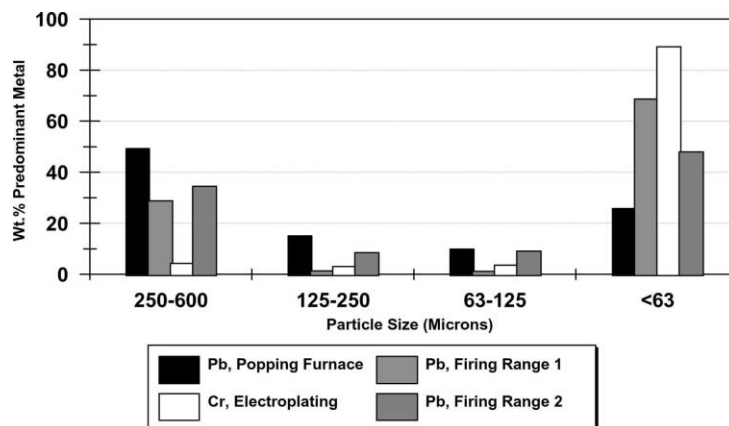


Fig. 2. Weight percentage distribution of predominant metal resulting from hydroclassification.

Effective hydroclassification requires producing a depleted fraction, needing less rigorous follow-up treatment, e.g. stabilization/solidification, and an enriched one, preferably with a small volume facilitating disposal, or a concentration facilitating recovery of the contaminant metal. For the firing range soils 1 and 2, approximately 90% of the lead mass was contained in lead fragments in the $>2000\ \mu\text{m}$ fraction. Figs. 1 and 2 together show the 63–250 μm fraction of the firing range soil 1 is substantially depleted of lead, with only about 0.3% of the lead in approximately 35 wt.% of the original $<2000\ \mu\text{m}$ material. This fraction could be more easily stabilized, and metal recovered from the $>600\ \mu\text{m}$ fraction. The firing range soil 2 and popping furnace soil displayed much less depletion in the intermediate size fractions, and thus limited benefit from hydroclassification. In contrast, the electroplating soil exhibited a pronounced enrichment of the $<63\ \mu\text{m}$ fraction—approximately 90% of the chromium in 31 wt.% of the soil, with a concentration of about 4 wt.%. Hydroclassification appears advantageous for this soil.

4.3. Sample preparation

For the settling experiments, approximately 200 g of each well-homogenized soil was mixed in a weight ratio 4:1, water:soil in a 4 l plastic container. This was agitated for 1 h on an linear shaker at 200 oscillations/min. After this vigorous wash, we wet sieved the slurry through a 30-mesh US standard sieve (ASTM, E-11) with openings of 600 μm . During sieving, the samples were sprayed with deionized water through a nozzle. Material passing the 30-mesh sieve was subjected to settling.

4.4. Settling experiments

For each soil sample, the slurry passing the 30-mesh screen ($<600\ \mu\text{m}$) was agitated in a 4 l clear plastic container (Section 4.3) using a Lightnin laboratory stirrer set at 500 rpm. During agitation (0 settling time), a 50 ml sample was removed in a plastic centrifuge tube.

Stirring was stopped, and the slurry remained in the container for settling. A 50 ml sample was removed at times of 0.083, 1, 5, and 22–24 h, carefully inserting a pipette 1 cm below the surface to avoid disturbing the settling slurry. The collected samples were placed in 50 ml plastic containers. Two additional samples were taken at 1 h. One was a 100 ml sample placed in a 250 ml clear plastic centrifuge bottle. Alum was added at 50 mg/l, and settling continued for 18–20 h. The other additional sample was placed in a 50 ml plastic centrifuge bottle and centrifuged (Fisher Scientific, Marathon 3200 bench-top centrifuge) for 20 min at 3500 rpm.

4.5. Analysis

Each of the slurry samples was passed through 0.45 μm filter. The filter solids were dried and weighed to obtain mass. The concentration of suspended solids (mg/l) was calculated from the filtered solids. These solids and filters were then microwave digested. The digest was diluted and analyzed for lead, aluminum, and chromium content by atomic absorption (in accordance with US EPA procedure 3051). This allowed calculation of suspended metals (mg/l) of slurry and the metals concentration in the suspended solids (mg/kg). The filtrates were analyzed by the same method, excluding digestion.

5. Results

In the field, physical separation by hydroclassification, and water treatment, are performed as an integrated process. Our earlier paper [2] presented results of the hydroclassification, and Figs. 1 and 2 in this paper provide the most significant results of mass and metals distribution among the nominal size fractions. The results of our recent settling work include: (1) the suspended solids as a function of settling time, coagulant addition, and centrifugation; (2) suspended metals; (3) enrichment of metals in suspended solids; and (4) dissolution of metals into the water phase.

5.1. Suspended solids

Fig. 3 illustrates the change in suspended solids versus time for the firing range soil 2. Note the almost exponential drop in solids from approximately 70,000 to 1561 mg/l at 5 h settling. After 23 h settling, the solids had dropped below a measurable quantity. Fig. 4 combines data for the firing range soil 2 and all other samples. The firing range soil 1 and electroplating samples clarified dramatically in <5 min. The electroplating sample exhibited a continued suspended solids content, even for the centrifuged sample. This suggests either an experimental error, or the presence of suspended solids not susceptible to gravitational settling. On the other hand, the firing range soil 2 and popping furnace soil required between 1 and 5 h to substantially clarify (>90% solids removal). Completion to below detectable quantities required up to 23 h. Given the rapid settling of the first two soil slurries, alum addition (20 mg/l) did not produce noticeable differences. Addition to the last two slurries may have produced some benefit. However, turbidity (visual observation) remained high despite the addition of a relatively high dosage (50 mg/l) of alum. Given the continued turbidity, settling with alum was continued to 18–20 h. At this time the suspended solids

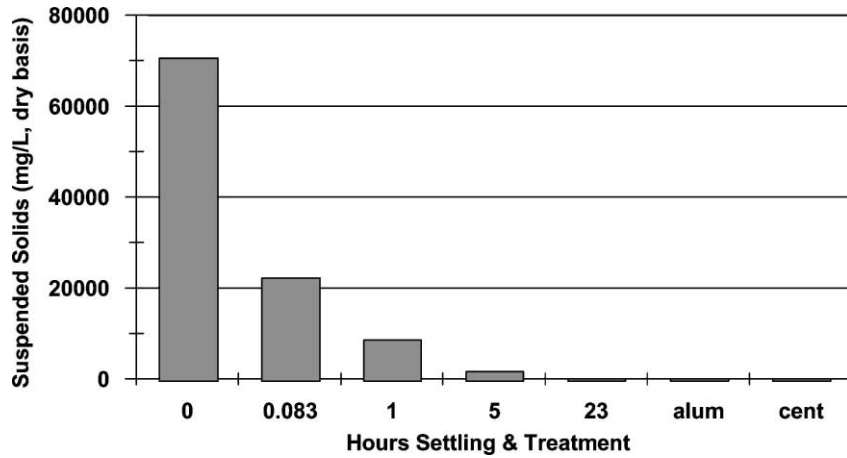


Fig. 3. Suspended solids (mg/l) vs. settling time for firing range soil 2.

were low, but comparable to that for settling without alum (Fig. 4). Thus, at the dosage used, the alum may have produced only a marginal benefit. The slurry samples that settled for 1 h, and were then centrifuged, exhibited no filterable solids or detectable metals.

5.2. Suspended metals

Fig. 5 illustrates the change in suspended lead (mg/l) versus time for the firing range soil 2. The decrease is more linear than for the solids removal. Fig. 6 combines data for

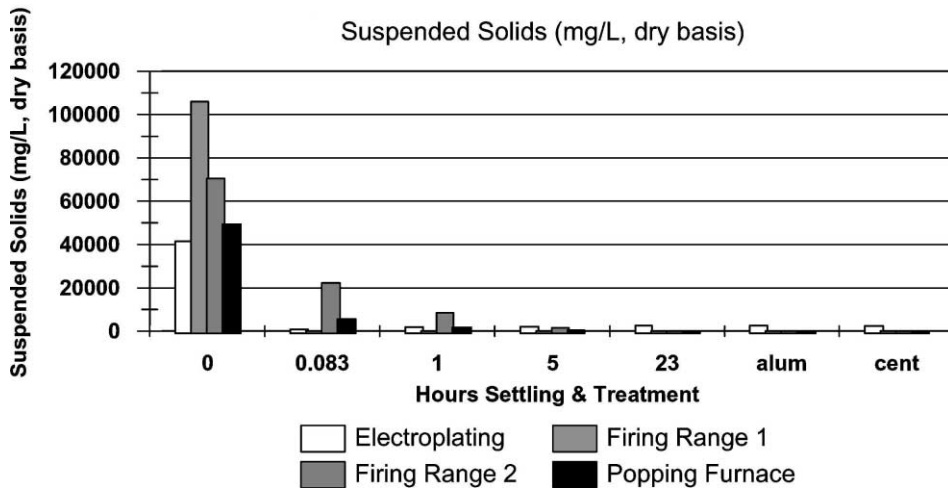


Fig. 4. Suspended solids vs. settling time and treatment.

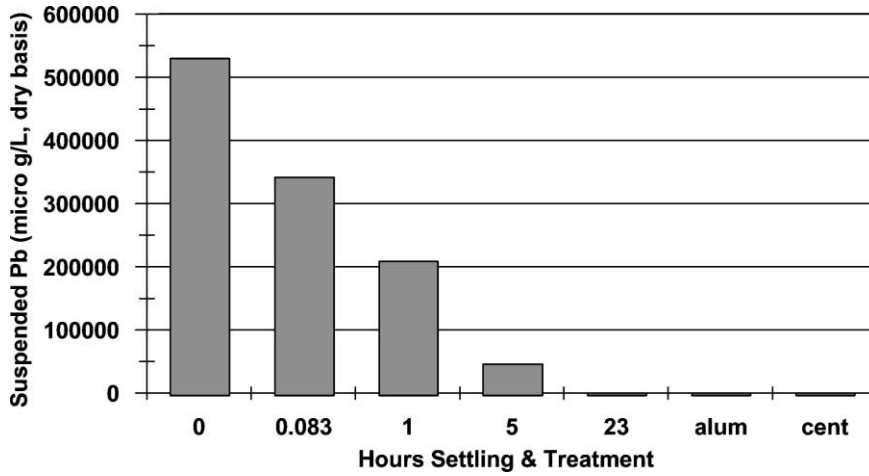


Fig. 5. Suspended lead (mg/l) vs. settling time for firing range soil 2.

the firing range soil 2 and all other samples. Consistent with the solids reduction, the firing range soil 1 and electroplating samples exhibited dramatic reductions in <5 min. Suspended metals decreased by 100 and 97%, respectively. On the other hand, the firing range soil 2 and popping furnace soil slurries required up to 5 h settling to reduce suspended metals by 90% (from over 500,000 to 45688 and 44317 $\mu\text{g/l}$, respectively). Settling for about 23 h was needed to reduce metals to non-detectable levels. Alum addition and centrifugation produced metals removal consistent with the solids removal noted above. Despite significant removal

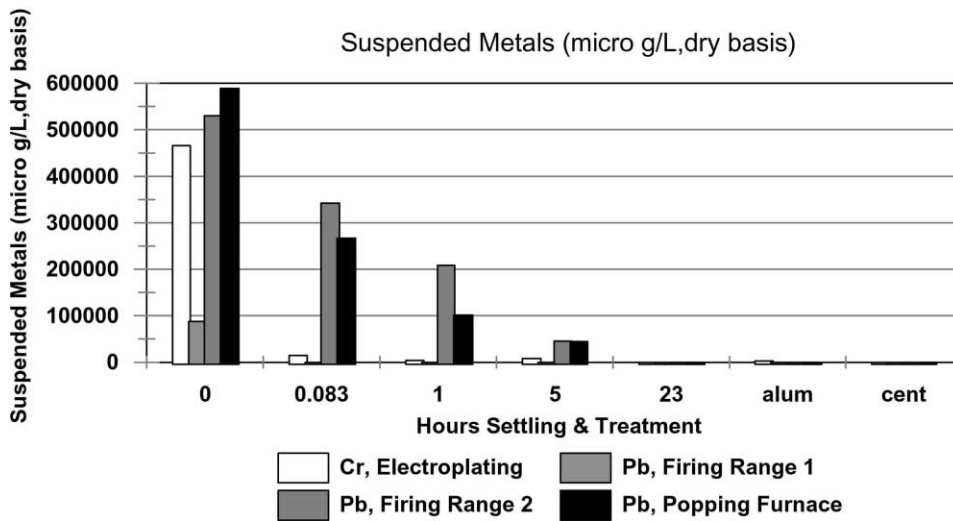


Fig. 6. Suspended metals vs. settling time and treatment.

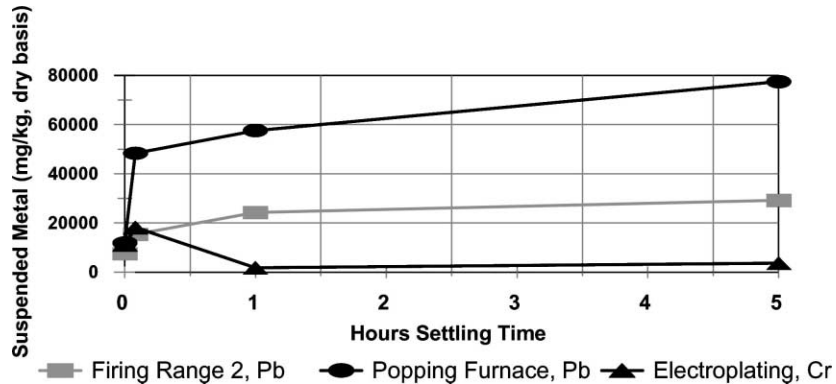


Fig. 7. Concentration of suspended metals in the suspended solids as a function of settling time.

by settling, the metals concentrations observed for the firing range soil 2 and popping furnace soil, would greatly exceed discharge limits, even after hours of settling. These concerns are addressed in the Section 5.3 on dissolved metals.

Note that the data for firing range soil 2 and popping furnace soil indicate the suspended solids were removed proportionally faster than the suspended metals. In the first 5 min, almost 70% of the solids settled for the firing range soil 2. However, only 37% of the metals settled. For the popping furnace soil, approximately 95% of the solids settles, but only just over 50% of the metals settled. Both these cases indicate that virtually all the $>63 \mu\text{m}$ material settled within the first 5 min, and the $<63 \mu\text{m}$ material began to fractionate, leaving suspended solids enriched in lead. The more dramatic rise for the popping furnace soil is consistent with the higher lead concentration in the smallest size ranges leading to the $<63 \mu\text{m}$ fraction (Fig. 2). This suggests that, while the absolute amount of suspended solids is being reduced with time, the remaining solids are growing more concentrated in metal. Fig. 7 illustrates these observations, showing that the suspended metals content for the firing range soil 2 and popping furnace soil rise sharply during the first few minutes of settling. The data from the electroplating soil seem to contravene this observation. However, the chromium concentration rises here too for the first settling time of 5 min. Subsequent values may be affected because the values are at a very low level, perhaps reflecting experimental error or association of metals with a more buoyant soil component, i.e. organic matter. The firing range soil 1 did not produce detectable metals beyond the first sampling time.

5.3. Dissolved metals

Analysis of the filtrates after 1 h of settling indicated 3–5 mg/l dissolved lead in the process water. Tests for aluminum indicated 0.72–2.66 mg/l, roughly proportional to the alum addition. No dissolved chromium was detected. An important factor in metals dissolution is pH. The firing range soil 1 had a pH of approximately 6.5; the others, 7. The process water had a pH of approximately 6.5. These pH levels (as well as the relatively low dissolved solids, $<150 \text{ mg/kg}$) would tend to favor immobilization of adsorb metals.

These dissolved concentrations must be evaluated in light of concentration limits for metals discharge. The sanitation districts of Los Angeles county set limits of 10 and 40 mg/l for chromium and lead discharge for wastewater [13]. However, King County, Washington sets more stringent limits of 2.75 and 2 mg/l respectively, as daily averages [14]. King County also sets a settleable solids limit of 7.0 ml/l. The data convincingly show how suspended solids can easily cause limits to be exceeded. Regarding settleable solids, the firing range soil 1 and electroplating soil would easily meet this standard within 5 min of settling. The popping furnace soil might take a few minutes longer; the firing range soil 2, more than 1 h of settling. Clearly, suspended metals in the water would be the limiting factor here, not the suspended solids. The data do not suggest a serious problem with dissolved metals, but enough to justify checking this parameter in treatability studies.

6. Conclusions

6.1. Integration of bench-scale hydroclassification and settling

Integrating small-scale hydroclassification and settling experiments reveals the potential for physical separation applied to a specific contaminant/soil mixture. The primary goal is to produce a contaminant depleted fraction. Small-scale experiments help estimate system performance, solid/liquid flowrates, residence times, and water treatment requirements. Differences in separation are revealed for soil texture, contaminant morphology and association with the soil.

6.2. Settling performance and particle size distribution

Basing settling performance on proportions of ($<63 \mu\text{m}$) material may lead to an incorrect prediction. Settling behavior depends most directly on the percentage of the finest soil, components, i.e. $<2.0 \mu\text{m}$ and in particular clays. While the firing range soil 1 and electroplating soil were nominally fine and coarse respectively, they both settled rapidly. The other two soils, nominally one coarse and the other fine, settled slowly. This apparent inconsistency results from the fact that the rapidly settling soils came from localized high energy environments. The firing range soil 1 came from a flat, poorly vegetated area over which storm runoff moved rapidly. The electroplating soil came from a site near the Pacific Ocean. While superficially described as coarse and fine, they both certainly experienced hydraulic classification in situ that removed the finest particles.

Looking to future work, our results suggest more quantitative experiments, on a variety of soil/contaminant combinations, relating soil particle size distribution, settling performance, and metal enrichment. Empirical jar tests are needed to optimize coagulant, coagulant aid, and pH conditions to best facilitate settling. Furthermore, site remediation requires intensified processing system (compact, low residence time and portable) for removing suspended fines. Several approaches appear promising, with a good model being the recycling and polymer addition to placer mining fines [11,12]. The use of microsand or a microcarrier (MC) coated with colloids may also prove effective [15,16].

6.3. Settling enrichment of metals

Within minutes, settling removes substantially all sand fractions and begins to segregate the silt and clay fractions. For those soils with significant fines fractions, the data suggest a strong potential for producing metals enrichment of the residual suspended solids. From a processing standpoint, this phenomena slows the rate of removal of suspended metals relative to removal of solids.

6.4. Metals dissolution in process water

Regarding dissolution, the firing range and popping furnace soils exhibited dissolution of lead into the process water (3–5 mg/l) after the initial mixing and 1 h settling. This was consistent with mobilization by small-scale TCLP extractions performed with the earlier hydroclassification work. The electroplating soil exhibited no detectable dissolution of chromium—again consistent with the low mobility of chromium, even though the <63 μm fraction had a concentration over 40,000 mg/kg. While the electroplating soil was not tested for lead dissolution, earlier small-scale TCLP testing indicated a mobility orders of magnitude less than that for lead in the other soils.

All three types of the soils which exhibited some dissolution contained lead primarily in a particulate and physically dispersed form (although corrosion may have contributed to mobilization and readsorption). On the other hand, metals were introduced in solution form to the electroplating soil. The data suggest that the highly dispersed surface adsorption occurring in the electroplating soil explains the extremely low mobility of the chromium relative to the lead in the other samples.

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References

- [1] R.M. Bricka, C.W. Williford Jr., L.W. Jones, Technology Assessment of Currently Available and Developmental Techniques for Heavy Metals-Contaminated Soils Treatment. Technical Report No. IRRP-93-4, US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, USA, 1993.
- [2] C.W. Williford Jr., Z. Li, Z. Wang, R.M. Bricka, Vertical column hydroclassification of metal-contaminated soils, *J. Hazard. Mater.* 66 (1999) 15–30.
- [3] A.J. Horowitz, a Primer on Sediment-Trace Element Chemistry, 2nd Edition, Lewis Publishers, Chelsea, MI, 1991, pp. 1–61.
- [4] I.K. Iskandar, Environmental Restoration of Metals-Contaminated Soils, CRC Press, Boca Raton, FL, 1999, pp. 160–161 (Chapter 7).

- [5] S. Hay, W.S. Richardson, C. Cox, Wayne Interim Storage Site: Particle Size Fractionation and Radionuclide Characterization of Soil, A Preliminary Report for the Environmental Protection Agency and New Jersey Department of Environmental Protection, US EPA National Air and Radiation Environmental Laboratory, Montgomery, AL, 1991.
- [6] W.L. McCabe, J.C. Smith, P. Harriott, Unit Operations of Chemical Engineering, 5th Edition, McGraw-Hill, New York, 1993, pp. 156–162.
- [7] Metcalf and Eddy, in: G. Tchobanoglous, F.L. Burton (Eds.), McGraw-Hill, New York, 1991, pp. 220–240.
- [8] J.M. Montgomery, Consulting Engineers, Water Treatment Principles and Design, Wiley/Interscience, New York, 1985, pp. 116–134.
- [9] W.J. Weber, Physicochemical Processes, Wiley, New York, 1972, pp. 61–109.
- [10] M.I. Kuhlman, T.M. Greenfield, Simplified soil washing process for a variety of soils, *J. Hazard. Mater.* 66 (1999) 31–45.
- [11] R.A. Johnson, J.H. Chapman, R.M. Lipchak, Recycling techniques to reduce sediment discharge in placer mining operations, *JWPCF* 59 (1987) 274–283.
- [12] S.K. Sharma, B.J. Scheiner, Effect of Physico-Chemical Parameters on Dewatering: A Case Study, Fluid/Particle Separation, *J. Am. Filtration Soc.*, Vol. 4, No. 3, September 1991, pp. 162–166.
- [13] Sanitation districts of Los Angeles County, web page: <http://www.lacsd.org/iw/LIMITS.htm>, 2000.
- [14] King County, Washington, web page: <http://www.metrokc.gov/recelec/archives/policies/put813pr.htm>, 2000.
- [15] C.-Y. Fan, Y. Ding, S.-L. Liao, R. Field, P.C. Chan, R. Dresnack, High Rate Microcarrier-Weighted Coagulation for Treating Wet Weather Flow, US EPA and New Jersey Institute of Technology personnel, web page: <http://www.epa.gov/ednrmrl/repository/epa-600-x-99-033/presentation.pdf>.
- [16] E. Guibelin, Actiflo process: a highly compact and efficient process to prevent water pollution by storm waters, *Water Sci. Technol.* 30 (1) (1994).