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Use of spent hand warmer and ration heater wastes for stabilization of lead in shooting range soil

SEONGWON JEONG AND KYOUNGPHILE NAM
Seoul National University

Abstract

Military shooting ranges are characterized by the continuous accumulation of lead (Pb) derived from ammunition, resulting in severe soil contamination and potential human exposure risks. Reducing Pb mobility and bioaccessibility is essential to prevent off-site dispersion and minimize risks to military personnel. However, conventional remediation methods are often impractical in active military facilities, making *in situ* stabilization using reactive amendments a feasible alternative. This study investigated the effectiveness and mechanisms of Pb stabilization using recycled military wastes, including spent hand warmers (Fe oxide–based) and ration heater materials ($Mg(OH)_2$–based), as stabilizing agents. Soil spiked with Pb at 3,000 mg/kg was amended with spent hand warmer and ration heater materials at mass ratios of 1–10 relative to Pb (w/w) and incubated for 7 days. Stabilization performance was evaluated using the Synthetic Precipitation Leaching Procedure (SPLP, U.S. EPA Method 1312) and the Solubility/Bioavailability Research Consortium assay (SBRC, U.S. EPA Method 1340). Sequential extraction (Tessier et al., 1979), X-ray diffraction (XRD), electron probe microanalysis (EPMA), and zeta potential measurements were conducted to determine changes in Pb speciation and identify stabilization mechanisms. SPLP results showed that Pb leachability decreased from 13% in the control to below 1% in both hand warmer– and ration heater–amended soils. Similarly, SBRC-extractable Pb decreased from 86% in the control to 56 and 74%, respectively, indicating substantial reductions in Pb bioaccessibility. Sequential extraction revealed that the exchangeable fraction decreased from 65 to 28% in hand warmer–amended soils, accompanied by increases in carbonate and Fe–Mn oxide fractions. Due to the negative surface charge of the spent hand warmer over pH 4–9, spatial associations between Pb and Fe were observed by EPMA, providing evidence for Pb adsorption onto Fe oxide surfaces as a dominant stabilization mechanism. In soils amended with spent ration heater, the exchangeable fraction decreased markedly to 2%, while the carbonate fraction increased from 15.8 to 65.5%. Application of spent ration heater increased soil pH to 9.5–10, and EPMA revealed discrete Pb-rich precipitates, indicating that precipitation of $Pb(OH)_2$ was a dominant immobilization mechanism.