学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

Enhanced Rock Weathering in Acid Mine Drainage and Sandy Soil Systems: Assessments of CO_2 Removal Potential and Co-benefits
(酸性鉱山廃水および砂質土壌における岩石風化促進: CO_2 除去ポテンシャルとコベフィットの評価)

Enhanced Rock Weathering (ERW) is increasingly recognized as a scalable carbon dioxide removal (CDR) strategy offering important environmental co-benefits such as soil fertility restoration and averting ocean acidification. This dissertation explores the mechanistic, modeled, and field-based performance of ERW in two underexamined geochemical environments: (1) acid mine drainage (AMD) channels and (2) degraded sandy soils, by integrating geochemical modeling, laboratory dissolution studies, field validations, and a robust monitoring framework to assess both the CDR potential and co-beneficial effects of silicate mineral amendments.

Chapter 1 introduces the scientific motivation, defining ERW as a nature-based negative emissions technology (NET) that accelerates the natural weathering of silicate minerals by pulverization to sequester atmospheric CO_2 as stable bicarbonate in aqueous systems. It presents the dual research focus on AMD and sandy soils, which represent geochemically reactive and underutilized environments for ERW deployment. The chapter outlines the overarching objectives and methodological framework, principles and the comprehensive overviews of NET and ERW, and field, and modeling approaches.

Chapter 2 provides a comprehensive literature review, tracing the evolution of rock weathering studies and the emergence of ERW within the broader context of CDR strategies. It identifies key factors influencing ERW effectiveness, such as pH, mineral composition, particle size, and hydrological settings. The chapter also highlights knowledge gaps in ERW deployment in acidic environments like AMD systems and underexplored settings like degraded tropical sandy soils, motivating unique research trajectory of this dissertation.

Chapter 3 presents the research methodology and framework underpinning this dissertation, combining geochemical modeling, laboratory experiments, and field validations. Thermodynamic data were carefully prepared and calibrated to reflect site-specific mineralogy and solution chemistry, supporting accurate simulations of mineral stability and dissolution processes. Reactive transport modeling employed governing equations that couple fluid flow, solute transport, and chemical reactions, incorporating specific surface area estimations based on particle size distributions. Analytical methods included petrological characterization via microscopy and X-ray diffraction, hydrochemical analyses for major ions, pH, and trace elements, and field measurements to monitor water chemistry and validate model predictions. This integrated approach ensured robust assessment of ERW mechanisms and carbon sequestration potential across diverse environmental conditions.

Chapter 4 presents modeling results showing that highly acidic AMD systems (pH 2–4) significantly enhance basalt weathering kinetics. Basalt particle sizes of 10 μm demonstrated CO_2 sequestration potentials of up to 3,660 tCO_2 per year per channel, with substantial improvements in water quality including pH increases above 3.1 and high arsenic attenuation potential via co-precipitation with Fe (III) oxyhydroxy-sulfate mineral, specifically the schwertmannite. Simulations also indicated that soil systems, although less reactive due to neutral pH, provide stable environments for nutrient release and moderate CDR values of ~8 tCO_2/ha/year from 24 tons basalt dissolution per hectare per year.

Chapter 5 validates these model predictions through a year-long field application in AMD channels at an abandoned mine site in Hakodate, Hokkaido, Japan. Ground basalt deployments ($D_{50} \approx 1.5$ mm) resulted in 40–80% dissolution over 358 days. Concurrently, water pH increased by 0.5–1.7 units and arsenic removal efficiencies ranged from 25% to 30%. These findings confirm the practical feasibility of ERW as a dual-purpose strategy for passive water treatment and CO_2 drawdown in mining-impacted landscapes.

Chapter 6 extends field trials to sandy soils in Central Myanmar. While weathering rates were slower due to neutral soil pH and limited water retention, basalt application yielded measurable mineralogical improvements to the soils. Soil pH rose by ~1.5 to ~2 units, calcium and magnesium availability increased, and cation exchange capacity improved, supporting both soil fertility and long-term carbon stabilization potential through secondary carbonate precipitation and bicarbonate retention.

Chapter 7 provides a general discussion synthesizing all results. It emphasizes that ERW efficacy is highly context-dependent, influenced by pH, mineralogy, flow conditions, and particle size. Acidic aqueous systems like AMD channels offer ideal conditions for rapid mineral dissolution and high CDR rates, whereas tropical sandy soils provide agricultural co-benefits with modest but meaningful carbon sequestration potential. Limitations such as the scalability of field deployment, long-term stability of carbon sinks, and dissolution rate variability across mineral types are also critically assessed. The chapter further proposes a robust Monitoring, Reporting, and Verification (MRV) framework, integrating a proposal to apply isotopic tracers (e.g., δ^{13}C-DIC), field-based indicators, and IoT-based water quality sensors for real-time tracking of pH, EC, and trace metal concentrations—supporting transparent, accountable ERW project validation in the future.

Chapter 8 concludes that ERW is both scientifically and practically viable as a multifunctional environmental technology. It holds promise not only for easy CO_2 sequestration foot-printing but also for the remediation of acidified waste waters and the fertility enhancement of degraded sandy soils. The dissertation advocates for scaled-up ERW trials and long-term performance tracking using proposed MRV-compatible protocols. These findings contribute to advancing ERW from experimental trials to actionable climate and land management solutions in post-mining and agriculturally marginal regions.

In conclusion, this dissertation demonstrates that Enhanced Rock Weathering offers a versatile and effective strategy for simultaneous climate mitigation and environmental restoration across diverse geochemical landscapes. By bridging modeling, experimentation, and field validation, it establishes a foundational framework for optimizing ERW deployment and monitoring in both acid mine drainage and degraded sandy soil systems. These integrated insights pave the way toward scalable implementation of ERW as a critical component of sustainable carbon management and ecosystem rehabilitation worldwide.