Potential of Using Crushed Rock on Rights-of-Way (ROW) for Carbon Capture

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Executive Summary

Background

When silicate rocks weather, they react with CO_2, converting it into bicarbonate ions, which leads to carbon sequestration. Enhanced weathering (EW) of rocks can be applied to croplands, providing the dual benefits of CO_2 removal and potential improvements in soil fertility. It also boosts ocean and river alkalinity by depositing rock particles into rivers and oceans, further aiding carbon capture efforts.

EW of rocks is emerging as a potential carbon dioxide removal (CDR) strategy with increasing interest from researchers and policymakers. Rocks such as basalt and dunite are particularly effective at capturing CO_2 through weathering, with basalt being the more sustainable and widely available option. These techniques have been studied in various climates, with the highest potential in warm and humid regions. However, there are key challenges to large-scale implementation, including uncertainties in weathering rates, high energy costs associated with rock grinding, and logistical hurdles in material distribution.

California's expansive transportation rights-of-way (ROW) presents a unique opportunity to integrate enhanced rock weathering (ERW) as a carbon sequestration strategy. Caltrans manages significant ROW land that could serve as an experimental and operational platform for deploying ERW techniques. Given California's ambitious climate goals, leveraging ROW lands for ERW could provide both carbon removal benefits and infrastructure resilience if logistical and cost barriers are effectively addressed.

This literature review methodology involves selecting relevant studies, analyzing their quality, and synthesizing key themes and findings to summarize the current state of research and identify gaps for further exploration.

Summary of Findings Relevant to Caltrans

ROW as a Carbon Sequestration Asset:

- Transportation ROWs are underutilized spaces that can support carbon sequestration efforts.
- Studies indicate that ROW afforestation could sequester between 73,543 and 653,987 tons of CO_2 annually in Louisiana[1] alone, suggesting similar potential for California.
- Combining ERW with afforestation could amplify carbon capture while improving soil stability and biodiversity in ROW areas.

Implementation Feasibility and Challenges:

- Weathering Rates: ERW's effectiveness varies by rock type, soil composition, and climate conditions. Long-term field studies are needed to validate sequestration rates in California's diverse environments.
- Material Sourcing and Logistics: Basalt, a commonly used ERW material, is abundant in California. However, optimizing transportation and application strategies is essential to minimize carbon footprint and costs.

[1] This project assessed the CO2 sequestration potential of afforesting ROW lands along four major highways (I10, I20, I49, and US 90). It simulated three forest management scenarios, ranging from no intervention to frequent thinning and replanting.

- Infrastructure Impact: ROW areas need to maintain their primary function for transportation safety and maintenance and research is required to assess how crushed rock application affects soil permeability, erosion control, and road integrity.

Carbon Measurement and Verification:

- Robust monitoring and verification systems are necessary to quantify ERW's carbon sequestration impact accurately.
- Geospatial and remote sensing tools could be leveraged to track carbon uptake and soil changes across Caltrans ROW networks.

Regulatory and Policy Considerations:

- Caltrans can play a leadership role in integrating ERW into California's broader carbon reduction programs.
- Potential policy mechanisms include financial incentives for ERW, carbon credit frameworks, and partnerships with research institutions.

Summary of Research Needs

- Assess the real-world effectiveness of ERW on ROW lands, focusing on carbon sequestration, soil health, and environmental benefits through long-term field trials.
- Identify the best locally sourced materials (e.g., basalt or recycled concrete) for ERW applications and explore integration with existing maintenance workflows.
- Develop standardized systems to track carbon sequestration and soil changes across ROW networks.
- Quantify the combined benefits of ERW and vegetation management for carbon capture and roadside ecosystem improvements.
- Conduct cost-benefit and life cycle analyses to assess the economic feasibility, sustainability, and long-term impact of ERW projects.

Next Steps for Caltrans Implementation

- Pilot Studies: Conduct controlled field trials in ROW areas to assess the feasibility of ERW at different scales.
- Cost-Benefit Analysis: Evaluate the economic trade-offs of implementing ERW versus other carbon sequestration strategies.
- Integration with Maintenance Plans: Develop strategies for incorporating ERW into routine ROW maintenance activities to optimize resource use.
- Collaboration with Stakeholders: Partner with state agencies, research institutions, and industry experts to advance knowledge and implementation of ERW.
- Technology Development: Invest in data collection and monitoring tools to refine carbon measurement methodologies and standardize protocols for ROW-based ERW projects.

Caltrans can position itself as a leader in innovative carbon sequestration practices, contributing significantly to California's climate objectives while enhancing the sustainability of transportation infrastructure.

Detailed Findings

Background

Enhanced weathering (EW) of rocks is gaining attention as a promising carbon dioxide removal (CDR) strategy, with studies evaluating its global potential, costs, challenges, and co-benefits. Rocks like dunite and basalt are particularly effective in capturing CO_2, with dunite being more cost-efficient. Warm and humid regions, such as India, Brazil, and Southeast Asia, hold the highest potential for EW due to favorable conditions. Despite its promise, challenges include uncertainties in weathering rates, the energy-intensive nature of rock grinding, and logistical concerns.

Environmental and health impacts of EW are heavily influenced by the energy mix of the countries implementing it. Rock grinding is the most resource-intensive stage, but transitioning to cleaner energy significantly enhances the sustainability of the process. Enhanced weathering has also shown potential to improve soil health and crop productivity while mitigating ocean acidification. Supply chain optimization, including transportation efficiency, is crucial for scaling EW, with studies highlighting its feasibility when local quarry materials are utilized.

Other innovative applications include using engineered soils with crushed concrete and dolerite, which sequester carbon effectively while maintaining soil stability in infrastructure projects. Additionally, roadside soils and rights-of-way (ROW) offer viable options for localized carbon sequestration through techniques like afforestation, planting shrubs, and minimizing soil disturbance. These methods could sequester significant amounts of CO_2 annually, although their offset potential remains modest compared to total emissions.

Despite its potential, enhanced weathering faces challenges such as high energy costs, uncertainties in long-term weathering rates, and gaps in understanding environmental impacts. Research highlights the importance of multi-year trials to assess soil carbon dynamics, standardized measurement techniques for carbon removal verification, and the use of innovative materials and modeling to accelerate weathering rates. As a complement to other negative emissions technologies, EW could play a critical role in global decarbonization strategies, particularly when integrated into agricultural and infrastructure systems.

Enhanced Rock Weathering (ERW) for Carbon Sequestration

Global Potential and Applications of ERW

- Potential and Costs of Carbon Dioxide Removal by Enhanced Weathering of Rocks[2]
  This study examines the feasibility, potential, and costs of using enhanced weathering (EW) of rocks as a carbon dioxide removal (CDR) strategy. This process accelerates the natural chemical weathering of silicate minerals to absorb atmospheric CO2 and store it as bicarbonates in the ocean. The researchers assessed two types of rocks: dunite, which offers high CO2 sequestration potential, and basalt, a more abundant and sustainable alternative with lower environmental risks and additional agricultural benefits, though its sequestration potential is lower. Warm and humid regions, including India, Brazil, Southeast Asia, and China, are identified as the most suitable deployment areas, accounting for about 75% of the global potential due to favorable

[2] https://iopscience.iop.org/article/10.1088/1748-9326/aaa9c4

climate conditions. The study emphasizes the importance of grain size and weathering rates, with smaller grain sizes increasing efficiency but also raising energy demands and costs.

The costs are influenced by factors like mining, grinding to specific grain sizes, transportation, and spreading on croplands. Achieving finer grain sizes increases energy demands but boosts weathering efficiency. While EW is more expensive than afforestation and bioenergy with carbon capture and storage, it remains significantly cheaper than direct air capture (DAC). The scalability of EW is highlighted, with the potential to offset 4 Gt CO2 annually using global croplands. However, uncertainties remain regarding weathering rates, environmental impacts, and the integration of biological and hydrological processes. The study concludes that EW is a promising CDR option, particularly for tropical regions, but calls for further research to refine models, quantify co-benefits like soil fertility improvements, and address challenges related to large-scale implementation.

- The Potential of Enhanced Weathering in the UK[3]
  This study evaluates the feasibility of implementing ERW in the UK, focusing on its capacity to sequester up to 30 MtCO2 annually by 2050. The study emphasizes the benefits of improved soil health and agricultural productivity alongside climate mitigation. However, it identifies significant challenges, including the high costs of quarrying and crushing silicate rocks, limited availability of long-term field trials, and the need for standardized carbon measurement protocols. These barriers must be addressed to realize ERW's full potential as a climate mitigation strategy.

Environmental and Life-Cycle Impacts

- Environmental and Health Impacts of Atmospheric CO2 Removal by Enhanced Rock Weathering[4]
  The study evaluates the environmental and health impacts of ERW across 12 countries. Key findings show that rock grinding is the largest contributor to environmental impacts, while transitioning to cleaner energy systems significantly reduces resource depletion, ecosystem loss, and human health risks. ERW is found to be competitive with other CDR strategies, requiring less water and energy while avoiding land-use conflicts seen in bioenergy and afforestation approaches. Countries with high-carbon electricity, such as China, India, and Germany, show the greatest potential for impact reductions under a low-carbon energy scenario.

  Compared to other large-scale CDR strategies, ERW demonstrates significant sustainability advantages. It requires less energy than direct air capture and significantly less water than bioenergy with carbon capture and storage or afforestation. Furthermore, ERW integrates with agricultural practices, avoiding land-use competition and supporting crop productivity. The study emphasizes that clean energy transitions are critical to ERW's success, making it a viable solution for climate mitigation when coupled with decarbonized energy systems. Policymakers are encouraged to consider ERW as part of national net-zero strategies, leveraging its lower environmental footprint while balancing CO2 removal goals. Further research is recommended to optimize ERW processes, explore applying recycled materials for ERW, and refine life-cycle assessments to enhance its sustainability and scalability.

[3] https://www.sciencedirect.com/science/article/abs/pii/S1750583612001466
[4] https://www.nature.com/articles/s43247-022-00436-3

- [Life Cycle Impact and Cost Analysis of Quarry Materials for Land-Based Enhanced Weathering in Northern California](https://www.sciencedirect.com/science/article/pii/S0959652624032062?via%3Dihub)[5]
  This research provides a detailed analysis of the life-cycle impact and cost assessment for utilizing quarry materials in land-based enhanced weathering for carbon dioxide removal in Northern California. The study evaluates the economic and environmental implications of sourcing, transporting, and applying olivine-bearing and other silicate rocks such as dacite and andesite to agricultural lands. The report emphasizes the potential for local quarry materials to be competitive with commercial carbon capture technologies while minimizing transport-related emissions. The analysis integrates life-cycle assessment with economic modeling, exploring factors such as particle size, weathering rates, transport distances, and local environmental conditions. Results suggest that while olivine-bearing rocks perform best, regional materials like andesite and dacite are less effective but still economically viable under specific scenarios. Transportation and grinding processes are significant contributors to emissions and costs, making proximity to agricultural sites critical for feasibility. The study also highlights operational challenges, such as energy-intensive comminution (the process of crushing and grinding rocks into fine particles) and potential particulate emissions, which require careful management.

Field Trials

- [Reduced Accrual of Mineral-Associated Organic Matter After Two Years of Enhanced Rock Weathering](https://link.springer.com/article/10.1007/s10533-024-01160-0)[6]
  The study explores the effects of ERW using crushed silicate rock on soil organic matter (SOM) and carbon cycling in three cropland field trials in California's Central Valley. Over two years, the study found that while total soil organic carbon (SOC) and nitrogen (SON) stocks did not decrease significantly, the mineral-associated organic matter (MAOM) pool—a critical and slower-cycling component of SOM—showed reduced accrual rates in the upper 0–10 cm soil layer in ERW-treated plots compared to controls. This suggests that ERW may impact soil carbon dynamics, with lower MAOM-C and MAOM-N stocks in the surface soils despite no net loss of total SOM. These results highlight the need for further studies to understand the biogeochemical mechanisms and to assess long-term impacts of ERW on soil fertility and carbon sequestration.

  The study also investigated microbial communities and observed reduced active microbial biomass in surface soils treated with crushed rock, correlating with the reduced MAOM accrual rates. While some microbial taxa showed increased abundance under ERW, overall microbial community composition did not differ significantly between treatments. The findings indicate complex interactions between crushed rock amendments, microbial activity, and SOM cycling. Future research should focus on long-term field trials across diverse soil types and climates, including the integration of SOM effects into carbon accounting frameworks to ensure accurate assessment of ERW's potential as a scalable carbon removal strategy.

[5] https://www.sciencedirect.com/science/article/pii/S0959652624032062?via%3Dihub
[6] https://link.springer.com/article/10.1007/s10533-024-01160-0

Modeling and Methodological Critiques

- Advancing Enhanced Weathering Modeling in Soils[7]
  Current models assessing EW face challenges due to uncertainties in soil processes and the lack of robust comparisons with experimental data. To address this, the researchers in this study developed a dynamic Soil Model for Enhanced Weathering (SMEW), which integrates ecohydrological and biogeochemical processes. By comparing SMEW with four experimental datasets, ranging from simple incubation systems to mesocosm experiments, the study highlights its ability to replicate key dynamics like soil moisture, pH, and inorganic carbon. However, findings suggest that weathering rates are much slower than previously assumed. The results underscore the complexity of EW processes, particularly the interplay between soil hydrology and biogeochemistry, which affects CO_2 sequestration efficiency. The study identifies significant gaps between theoretical models and observed dissolution rates, emphasizing the need for further experimental and field-scale research.

- Are Enhanced Rock Weathering Rates Overestimated?[8]
  This study discusses the potential overestimation of CDR rates through ERW due to geochemical and mineralogical complexities. It highlights three key pitfalls that contribute to inflated CDR calculations: initially fast dissolution rates of reactive minerals that diminish over time, the dominance of accessory carbonate dissolution in generating cation fluxes misattributed to silicate weathering, and the use of cation measurements that do not directly correlate with carbon sequestration. These issues risk undermining the credibility of ERW as a climate mitigation strategy by overestimating the effectiveness and reliability of the approach. To address these concerns, the study recommends incorporating long-term experimental setups to track sustained reactivity, screening feedstocks for carbonate content to ensure accurate attribution of carbon capture, and directly measuring carbon-based outcomes rather than relying on proxy indicators like cation flux. The researchers in this study emphasize the need for robust, interdisciplinary research and transparent, open-access data to enhance understanding and trust in ERW methodologies, ensuring accurate reporting and verifiable carbon credits for climate action.

Transportation Rights-of-Way (ROW) and Carbon Sequestration

ROW-Based Carbon Sequestration Potential

- Geotechnical Requirements for Capturing CO2 Through Highways Land[9]
  This study investigates the potential of roadside verges and central reserves in Britain for carbon capture and storage through the formation of calcium carbonate ($CaCO_3$) in soil. Roadside verges, constituting 238,000 hectares, and central reserves, spanning 31,200 miles, have untapped potential for passive carbon sequestration. By incorporating calcium-rich materials like recycled concrete or dolerite into soil, CO_2 from the atmosphere can be absorbed and stored as stable carbonates. Engineering these areas during construction or upgrades could help the UK achieve its ambitious CO_2 reduction target by 2050. This approach aligns with broader sustainability goals by contributing to carbon mitigation and enhancing ecosystem services.

[7] https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2024MS004224
[8] https://www.frontiersin.org/journals/climate/articles/10.3389/fclim.2024.1510747/full
[9] https://geomatejournal.com/geomate/article/view/1263/1098

However, challenges remain in balancing CO2 capture with soil permeability to prevent issues like flooding. Engineering roadside verges and reserves for carbon sequestration must also account for ecosystem benefits such as biodiversity and flood regulation. Vegetated roadside verges, which facilitate carbonate formation, could be integral to green infrastructure efforts, supporting goals like pollinator conservation and urban cooling. The study underscores the need for careful design and resource management, including the use of recycled materials and cost-effective transportation, to optimize economic and environmental outcomes. Ultimately, the research presents a promising framework for integrating carbon capture into road infrastructure as part of broader climate change mitigation strategies.

- Removal of Atmospheric CO2 by Engineered Soils in Infrastructure Projects[10]
  This research explores the use of engineered soils with crushed concrete and dolerite in infrastructure projects to capture CO2 through enhanced rock weathering and pedogenic carbonate precipitation. Seasonal temperature significantly influenced carbon accumulation, while rainfall sometimes caused losses. Geotechnical tests showed no adverse effects on soil strength or drainage, ensuring suitability for construction without increasing flood risks. The study highlights applications in highways, urban redevelopment, land reclamation, green infrastructure, and flood mitigation systems. These projects leverage existing supply chains and readily available materials like quarry fines and crushed concrete, enabling scalable CO2 removal while meeting construction needs and contributing to climate change mitigation.

- Enhancing the Carbon Dioxide Sequestering Capacity of Louisiana Highway Right-of-Way Lands[11]
  This report examines the potential of large-scale afforestation projects along Louisiana's highway ROWs, which cover 10,305 acres across major highways like I-10, I-20, and I-49. The study models three forest management scenarios with varying planting densities and thinning frequencies, demonstrating that these areas could sequester between 73,543 and 653,987 tons of CO2 annually by 2050. The report emphasizes the importance of detailed planning, including inventorying ROW lands, evaluating tree species for growth, carbon uptake, and storm survivability, and aligning efforts with the climate initiatives. Soil carbon sequestration and reforestation logistics, such as sapling provisioning and maintenance, are also discussed as critical factors for long-term success. The findings suggest that afforestation of ROW lands could significantly offset greenhouse gas emissions and provide economic and ecological benefits, making it a viable natural climate solution.

- Carbon Sequestration by Roadside Filter Strips and Swales: A Field Study[12]
  This field study evaluates the effectiveness of vegetative filter strips and wetland swales in capturing carbon along highways in North Carolina. Results indicate that wetland swales store significantly more carbon than dry swales, demonstrating the importance of hydrological conditions in enhancing soil carbon storage. Additionally, these systems offer co-benefits such as improved stormwater management, reduced runoff, and enhanced biodiversity. The findings suggest that while vegetative filter strips and wetland swales can act as valuable carbon sinks, their capacity is overestimated in broader Federal Highway Administration models. The study underscores the importance of accurately quantifying carbon sequestration rates in specific urban land uses to guide policies and support climate change mitigation strategies.

[10] https://www.sciencedirect.com/science/article/pii/S0301479722005898?via%3Dihub
[11] https://www.ltrc.lsu.edu/pdf/2022/22-3TIRE.pdf
[12] https://ascelibrary.org/doi/10.1061/9780784413197.028

- [Evaluating Management Options to Increase Roadside Carbon Sequestration](https://cesticc.uaf.edu/media/280608/RoadsideCarbonStudy.pdf)[13]
  This report investigates three management techniques to increase soil organic carbon (SOC): raising mowing heights, planting woody shrubs such as rubber rabbitbrush, and adding legumes to perennial grass seed mixes. The study conducted experiments across three sites in southwestern Montana along I-90, using 1-square-meter test plots to measure the effects of these management practices on SOC, biomass, and soil respiration rates over two years. Results indicated that minimizing soil disturbance is the most effective strategy for medium- to long-term carbon storage, while the other practices showed mixed or limited benefits. The report concludes that while increasing mowing height and introducing legumes or shrubs may influence carbon storage, minimizing soil disturbance in ROW zones remains the most effective and reliable practice. The findings also highlight the importance of balancing safety and ecological considerations in roadside management to maximize carbon sequestration.

- [Guidebook for Designing and Managing Rights-of-Way for Carbon Sequestration and Biomass Generation](https://nap.nationalacademies.org/catalog/22154/guidebook-for-designing-and-managing-rights-of-way-for-carbon-sequestration-and-biomass-generation)[14]
  This guide provides practical strategies for leveraging ROW vegetation to enhance carbon sequestration and biomass production. It discusses methods for optimizing planting design, species selection, and maintenance practices to balance transportation infrastructure needs with environmental goals. The guide emphasizes ROWs as multifunctional landscapes that can serve as carbon sinks while producing renewable biomass. It provides state Departments of Transportation (DOTs) with a framework to assess the feasibility of implementing projects aimed at generating saleable carbon offsets or biomass feedstocks for bioenergy markets.

  The guide also introduces a Feasibility Toolkit to assist DOTs in evaluating site-specific opportunities, potential carbon sequestration, and financial implications. It highlights the role of emerging carbon offset markets and bioenergy initiatives, urging DOTs to periodically re-evaluate conditions for implementing projects in light of technological advancements and policy changes. Motivated by increasing operational costs, declining revenues, and climate change mitigation goals, the guide encourages DOTs to balance monetary benefits with broader environmental and social objectives. By leveraging decision-making tools and understanding market dynamics, DOTs can pursue projects that align with their operational priorities and sustainability goals.

Carbon Sequestration Through Engineered Materials

Development of Synthetic Minerals for Carbon Capture

- [Synthesizing Fast Weathering Silicate Minerals and Doping with Micronutrients for Carbon Capture](https://atrium.lib.uoguelph.ca/items/0e45d508-afaf-4bbd-8170-235670119c64)[15]
  This doctoral thesis focuses on synthesizing fast-weathering silicate minerals like akermanite (from steel slag) and calcio-olivine (used in cement production) through solid-state sintering methods. These synthetic minerals are doped with plant micronutrients, enabling dual functionality: capturing CO2 and improving soil fertility. The study highlights the term “fast-weathering” to describe materials capable of rapid cation release (e.g., calcium and

[13] https://cesticc.uaf.edu/media/280608/RoadsideCarbonStudy.pdf
[14] https://nap.nationalacademies.org/catalog/22154/guidebook-for-designing-and-managing-rights-of-way-for-carbon-sequestration-and-biomass-generation
[15] https://atrium.lib.uoguelph.ca/items/0e45d508-afaf-4bbd-8170-235670119c64

magnesium), which accelerates CO2 sequestration into stable carbonate forms. The research also investigates the co-utilization of saline brine and industrial CO2 streams to produce sodium bicarbonate, a potential oceanic carbon storage solution, using a modified Solvay process. Advanced characterization techniques like X-ray diffraction (XRD), scanning electron microscopy (SEM), and inductively coupled plasma mass spectrometry (ICP-MS) confirm the performance of these minerals. Machine learning models are employed to predict weathering rates, revealing that calcio-olivine outperforms akermanite in CO2 capture efficiency. This work bridges gaps in synthetic mineral design and highlights its scalability for land-based and oceanic carbon removal technologies.

Engineered Soils in Infrastructure for CO2 Capture

- Removal of Atmospheric CO2 by Engineered Soils in Infrastructure Projects[16]
  This research investigates the integration of engineered soils containing crushed concrete and dolerite into infrastructure projects to capture and store atmospheric CO2 through enhanced rock weathering and pedogenic carbonate precipitation. Fourteen experimental plots were tested to analyze carbon sequestration potential and geotechnical properties over two years, showing that concrete plots captured more carbon compared to dolerite plots. Carbon and oxygen isotope analyses confirmed the formation of pedogenic carbonates. Seasonal temperature significantly influenced carbonate accumulation, while rainfall contributed to carbonate loss. Geotechnical assessments showed no negative impacts on soil penetration resistance or drainage, ensuring the feasibility of incorporating these soils into infrastructure without increased flooding risks.

  The study emphasizes the use of engineered soils in various infrastructure projects, including highways and roadsides, urban development and brownfield redevelopment, land reclamation, green infrastructure such as parks and vegetated slopes, and drainage or flood mitigation systems. These projects provide opportunities for large-scale CO2 removal while maintaining construction and hydrological performance. Readily available materials like quarry fines and crushed concrete align with existing supply chains, enabling practical application on a large scale. Such designs could contribute significantly to net-zero emission goals while promoting sustainable construction practices.

Pollutant Sequestration Using Waste Materials

- Nitrogen Dioxide Sequestration Using Demolished Concrete[17]
  The report explores the potential for utilizing demolished concrete to sequester nitrogen dioxide (NO_2) and its application in sustainable transportation infrastructure. Concrete is a heavily used construction material, yet its production generates significant environmental pollution, including NOx emissions from cement kilns. This research aims to address this challenge by using crushed demolished concrete aggregates (CCA) to adsorb NO_2. Results indicate the feasibility of this innovative approach to mitigating emissions from cement production and transportation-related sources, contributing to resource conservation and improved air quality. However, the research underscores the need for further investigations to optimize conditions for maximum NO_2 adsorption and to understand the combined effects of NO_2 and SO_2 removal.

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[16] https://www.sciencedirect.com/science/article/pii/S0301479722005898?via%3Dihub
[17] https://rosap.ntl.bts.gov/view/dot/31144

Crushed Concrete Aggregates (CCA) have diverse applications in transportation infrastructure and environmental sustainability. They can be used in road construction as base or subbase layers, in bridges for structural components, and in airport and marine installations, offering strength and durability while reducing the need for virgin materials. By recycling demolished concrete, CCA minimizes landfill use and contributes to solid waste management solutions. Additionally, it can be recycled into new concrete, potentially serving as a corrosion inhibitor to extend the lifespan of reinforced concrete or as a set accelerator in time-sensitive projects. CCA also finds use in urban planning as construction fill or in drainage systems due to its permeability, further reducing the environmental impact of infrastructure development and supporting resource conservation.

Soil Carbon Dynamics and Land Management

Land Cover and Soil Carbon Sequestration

- Landscape-Level Differences in Soil Carbon and Nitrogen[18]
  This study examined how land cover and topography independently and jointly influence soil carbon and nitrogen storage at the Oak Ridge Reservation in Tennessee. They found that soil carbon and nitrogen stocks were generally higher under pastures compared to forests and transitional vegetation, with the majority of carbon stored in the top 20 cm of soil. Pastures exhibited greater nitrogen availability and lower carbon-to-nitrogen ratios, suggesting a higher potential for long-term carbon sequestration in mineral-associated organic matter—a more stable form of carbon. While topography had a secondary effect compared to land cover, valleys tended to have higher subsurface carbon and nitrogen stocks.

  The implications for carbon sequestration strategies are significant, as land management practices that enhance pasture cover could boost soil carbon storage. However, the study also highlighted complexities like residual effects of historical land use, which influence current soil carbon dynamics, and the challenges in quantifying soil carbon due to spatial variability. The researchers underscore the importance of understanding how different land covers and topographies contribute to soil carbon and nitrogen dynamics, particularly when considering strategies for mitigating carbon dioxide emissions and managing land for carbon sequestration.

Enhanced Weathering and Soil Organic Matter

- Reduced Accrual of Mineral-Associated Organic Matter After Two Years of Enhanced Rock Weathering[19]
  Field trials in California assess how crushed meta-basalt affects soil organic carbon (SOC) and nitrogen dynamics in irrigated cropland soils. After two years of ERW application, the study finds a reduction in MAOM stocks in the upper 10 cm of soil compared to control plots. However, total SOC levels remained stable, suggesting that particulate organic matter (POM) compensates for MAOM losses. The study raises critical questions about the interactions between ERW, soil organic matter pools, and microbial activity. It emphasizes the need for long-term monitoring and multi-site trials to evaluate ERW's broader implications for soil carbon cycling and nitrogen availability across varying environmental contexts.

[18] https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2002GB001918
[19] https://link.springer.com/article/10.1007/s10533-024-01160-0

Land Management for Improved Soil Carbon Storage

- Evaluating Management Options to Increase Roadside Carbon Sequestration[20]
  This Montana-based study evaluates land management strategies designed to enhance soil carbon storage along roadsides. Practices such as increasing mowing height, integrating nitrogen-fixing legumes, and planting shrubs were tested for their impact on soil carbon dynamics. Results reveal that minimizing soil disturbance is critical for maintaining long-term carbon stocks. Additionally, integrating diverse vegetation improves soil structure and organic matter accumulation. The research highlights the potential of such management practices to boost roadside carbon sequestration while enhancing ecosystem services, such as erosion control and biodiversity support.

Summary of Findings

The growing urgency of climate change mitigation has led to innovative approaches for carbon sequestration, with rights-of-way (ROW) along highways and transportation infrastructures emerging as a significant opportunity. ROW lands, which are often underutilized strips of vegetated land adjacent to transportation infrastructure, provide an ideal setting for strategies like afforestation and enhanced rock weathering (ERW). These approaches could transform ROW lands into valuable carbon sinks while offering co-benefits for infrastructure and ecosystem services.

Afforestation in ROW lands not only captures carbon but also provides other benefits like erosion control, stormwater management, and biodiversity enhancement. While some studies primarily examine afforestation, enhanced rock weathering (ERW) presents an additional opportunity to maximize carbon sequestration on ROW lands. ERW involves applying crushed silicate rocks, such as basalt or dolerite, which react with atmospheric CO2 to form stable carbonate minerals like calcium carbonate. ROW lands are particularly well-suited for ERW because of their accessibility, minimal competing land use, and the distributed nature of these spaces. However, the application of crushed rock for ERW on ROW lands presents challenges and uncertainties, including:

- **Weathering Rates:** ERW effectiveness depends on the dissolution rates of silicate minerals, which can vary significantly based on rock type, soil properties, and environmental conditions. Research indicates that weathering rates are often slower than predicted, necessitating long-term studies to validate their carbon capture potential.
- **Cost and Logistics:** Transporting and applying crushed rock to distributed ROW lands can be resource-intensive. Optimizing logistics and reducing costs is critical for large-scale implementation.
- **Carbon Measurement and Verification:** Robust monitoring systems are needed to accurately measure carbon sequestration and ensure the credibility of carbon credits generated by ERW.

The integration of ERW and afforestation on ROW lands represents a promising pathway for achieving significant carbon sequestration. While afforestation provides a proven method to capture and store carbon biologically, ERW offers a complementary geochemical mechanism that could enhance carbon removal efficiency. As Louisiana and other regions consider using ROW lands for carbon capture, further research is essential to address uncertainties in ERW performance, optimize application strategies, and integrate these solutions with broader transportation and land management goals.

[20] https://cesticc.uaf.edu/media/280608/RoadsideCarbonStudy.pdf

Gaps in Findings

Limited Field Trials on ROW Lands:

- While ROW lands are highlighted as underutilized spaces with carbon capture potential, most studies focus on afforestation (e.g., Louisiana's ROW lands) rather than the application of crushed rock for ERW.
- Field trials specifically testing the effectiveness of crushed rock on ROW soils, vegetation, and infrastructure compatibility are scarce.

Uncertainty in Weathering Rates:

- ERW studies emphasize significant uncertainties in weathering rates under field conditions, which may differ from laboratory predictions. Factors such as soil type, precipitation, and temperature variability influence the efficiency of CO2 capture.
- Long-term studies are needed to determine the sustained carbon capture potential of crushed rock in ROW contexts.

Monitoring and Verification Challenges:

- Measuring the actual amount of CO2 sequestered through ERW in ROW lands remains a challenge. Carbon monitoring and verification methods for ROW settings are not standardized, raising concerns about the reliability of reported carbon offsets.

Environmental and Economic Trade-offs:

- Crushing and transporting rock to distributed ROW sites involves energy-intensive processes that can offset some carbon benefits. The environmental and financial costs of ERW logistics, especially for ROW applications, are not well-documented.

ERW and Afforestation:

- While afforestation and ERW have been studied independently, there is limited exploration of their combined potential on ROW lands. Understanding how vegetation and crushed rock interact in carbon capture processes is an area requiring further investigation.

Soil Impacts of Crushed Rock Application:

- Research gaps exist in understanding how crushed rock affects soil properties (e.g., porosity, drainage, and nutrient availability) in ROW settings. Long-term impacts on soil health and ecosystem stability need further study.

Next Steps

Long-Term Field Trials: Assess the real-world efficacy of ERW in ROW settings.

- Carbon Sequestration Rates: Study weathering rates of different silicate rocks (e.g., basalt, dolerite) under varied climatic and soil conditions along ROW lands.
- Soil and Ecosystem Impacts: Measure changes in soil chemistry, biodiversity, and overall ecosystem health after rock application.
- Infrastructure Effects: Evaluate whether crushed rock improves soil stability and reduces erosion near highways.

Optimization of Rock Types and Application Methods

- Rock Suitability: Explore the carbonation potential and economic feasibility of various rock types, including locally available silicates and recycled materials like crushed concrete.
- Application Techniques: Research novel methods or integration with existing ROW maintenance workflows to reduce costs and maximize efficiency.
- Particle Size: Investigate the role of rock particle size in enhancing surface area and weathering rates.

Carbon Monitoring and Verification Systems

- Measurement Techniques: Use advanced tools to track mineral carbonation.
- Geospatial Technologies: Integrate remote sensing for large-scale monitoring of carbon sequestration across ROW networks.
- Standardized Protocols: Create guidelines for reporting and verifying carbon credits from ROW-based ERW.

Interactions Between ERW and Vegetation

- Nutrient Cycling: Investigate how silicate rocks influence nutrient availability and soil fertility, potentially benefiting afforestation efforts.
- Vegetation Growth: Examine how ERW impacts vegetation health, biomass accumulation, and carbon storage in combination with planting schemes.
- Soil Microbial Activity: Study how microbial communities in ROW soils respond to crushed rock and their role in accelerating weathering processes.

Scalability and Sustainability of ERW in ROW

- Life Cycle Analysis: Quantify the environmental impacts of rock mining, transportation, and application versus the carbon sequestered.
- Cost-Benefit Analysis: Compare the financial costs of ERW with other ROW management and carbon capture strategies.
- Water Use and Pollution: Investigate whether ERW impacts water quality or drainage systems near highways.

Policy and Governance Research

- Incentive Programs: Develop financial mechanisms like carbon credits or subsidies to support ERW implementation on ROW lands.
- Regulatory Frameworks: Study how ERW can be integrated into the state carbon reduction plans.

- Stakeholder Collaboration: Research best practices for engaging transportation agencies, local governments, and private sector partners.

Pilot Programs and Scalable Models

- Regional Pilots: Launch demonstration projects on ROW lands in diverse regions to study variability in outcomes.
- Scalability Studies: Develop models to assess the feasibility of expanding ERW to larger ROW networks.
- Community Engagement: Involve local communities in pilot projects to have public comments and address concerns.

Technological Innovation in ERW

- Advanced Models: Use advanced predictive models to optimize rock selection and forecast weathering rates based on site conditions.
- Enhanced Crushing Technologies: Research methods to reduce the energy intensity of rock grinding, which can offset some carbon benefits.
- Data Integration: Build platforms to integrate field data, lab results, and climate models for better decision-making.

Caltrans Potential Contributions

Caltrans has a unique opportunity to lead the implementation of ERW on ROW lands, contributing significantly to California's climate goals. By facilitating long-term field trials, Caltrans can provide access to ROW sites and partner with researchers to assess the effectiveness of ERW in real-world conditions. Caltrans can optimize the use of locally sourced materials, such as basalt or recycled concrete, and integrate ERW into existing maintenance workflows. Leveraging its geospatial and monitoring infrastructure, Caltrans can develop standardized systems for tracking carbon sequestration and soil changes across ROW networks. Additionally, combining ERW with vegetation management plans offers dual benefits of carbon capture and enhanced roadside ecosystems. By conducting cost-benefit analyses and life cycle assessments, Caltrans can ensure the sustainability and economic feasibility of these projects. As a policy leader, Caltrans can advocate for the inclusion of ERW in California's carbon offset programs and secure funding for pilot initiatives. These pilots can serve as scalable models for integrating ERW into ROW lands statewide, showcasing its potential to mitigate climate change while supporting infrastructure resilience and ecological health. Through innovation, collaboration, and public engagement, Caltrans can set a benchmark for transportation agencies nationwide in leveraging ROW lands for carbon capture.

Implementation Mechanisms

Pilot Projects and Demonstration Sites

- Establish test sites across varied California ROW landscapes to assess ERW effectiveness under different conditions.
- Partner with academic and research institutions for data collection and analysis.
- Utilize existing infrastructure to minimize additional construction and land-use conflicts.

ROW-Specific ERW Optimization

- Utilize local rock sources to minimize transportation emissions and costs.
- Integrate ERW with vegetation management practices to maximize co-benefits.
- Develop site-specific application techniques to enhance weathering efficiency while maintaining soil stability.

Advanced Carbon Monitoring and Data Integration

- Deploy geospatial and remote sensing technologies to monitor ERW effectiveness.
- Develop predictive models for ERW's long-term impact on California's transportation networks.
- Standardize data collection methodologies to ensure compatibility with state and federal carbon reporting frameworks.

Stakeholder Collaboration and Funding Strategies

- Work with state agencies and federal bodies to secure grants and funding incentives.
- Engage in pilot projects and research collaborations.
- Explore market-based solutions such as carbon credit trading to enhance financial viability.