[DE-FE0032259] Resource Assessment for Carbon Dioxide Storage via Accelerated Carbonation Reaction with Recycled Concrete Aggregates (RCA)

2024 FECM/NETL Carbon Management Research Project Review Meeting

Speaker: Seunghee Kim, Ph.D., P.E., University of Nebraska-Lincoln

August 8, 2024

IN OUR GRIT, OUR GLORY™

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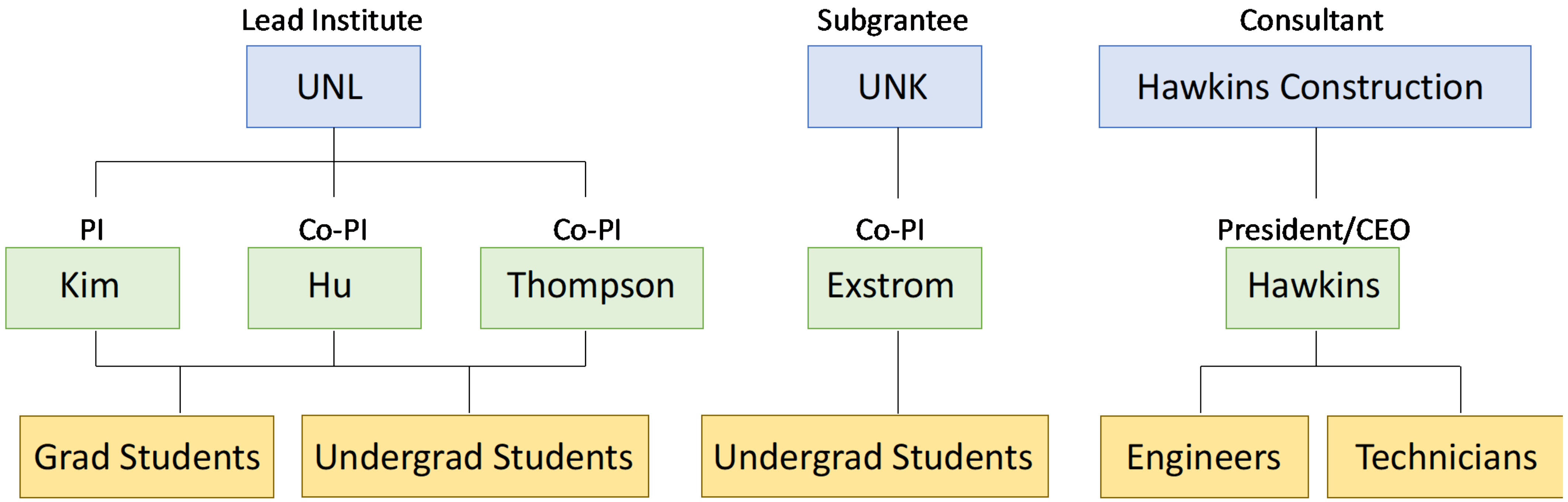
Key Project Participants

- PI: Seunghee Kim, Associate Professor, Department of Civil and Environmental Engineering, University of Nebraska-Lincoln (UNL)
- Co-PI: Jiong Hu, Professor, Department of Civil and Environmental Engineering, UNL
- Co-PI: Eric Thompson, Professor, Economics; Director of the Bureau of Business Research, UNL
- Co-PI: Christopher Exstrom, Professor, Chemistry, University of Nebraska at Kearney (UNK)
- Consultant: Chris Hawkins, President/CEO of Hawkins Construction Company



The organizational chart for project assignments

Project Objectives & Tasks

The Overall Objective

The overall objective is to identify the optimum processes to maximize CO_2 sequestration, enhance the efficiency of carbon mineralization, improve the technology readiness of carbon mineralization, and build and advance the required industrial waste resource base, in particular waste concrete base.

The Scope of Work

Task 1: Project management and planning

Task 2: Field sampling

Task 3: Laboratory analysis of carbonation reactions

Task 4: Resource assessment

Project Performance Dates

Project Performance Dates: July 1, 2023 – June 30, 2025

Table. Milestones of the proposed project.

Task/ Subtask	Milestone Title & Description	Planned Completion Date	Actual Completion Date	Verification Method
1/1.1	Updated project management plan	9/30/2023	9/30/2023	Project management plan file
1/1.1	Kickoff meeting	9/30/2023	9/30/2023	Presentation file
2/2.1-2.2	1. List of collected RCA samples and characterization results	~~3/31/2024~~	4/30/2024	Summary report
3/3.1-3.2	2. Small-scale carbonation reaction tests and the physical and mechanical test results	9/30/2024		Milestone report and presentation file
3/3.3-3.5	3. Large-scale carbonation reaction tests, the prediction of reaction rates and carbon uptake rates, and protocols for optimum CO_2 storage in RCA	3/31/2025		Milestone report and evaluation of derived carbonation and CO_2 uptake rates
4/4.1-4.3	4. RCA resource base, CO_2 storage capacity, and cost and market analysis results	6/30/2025		Final report and presentation file

Funding Summary

Table: Spend plan by fiscal year.

	FY 2023		FY 2024		FY 2025		Total	
	DOE Funds	Cost Share	DOE Funds	Cost Share	DOE Funds	Cost Share	DOE Funds	Cost Share
UNL	64,192	22,432	348,030	88,956	293,130	64,976	705,352	176,364
UNK	13,356	3,119	51,659	12,474	34,771	9,356	99,786	24,949
Total ($)	77,548	25,551	399,689	101,430	327,901	74,332	805,138	201,313
Total Cost Share (%)		24.78%		20.24%		18.48%		20%

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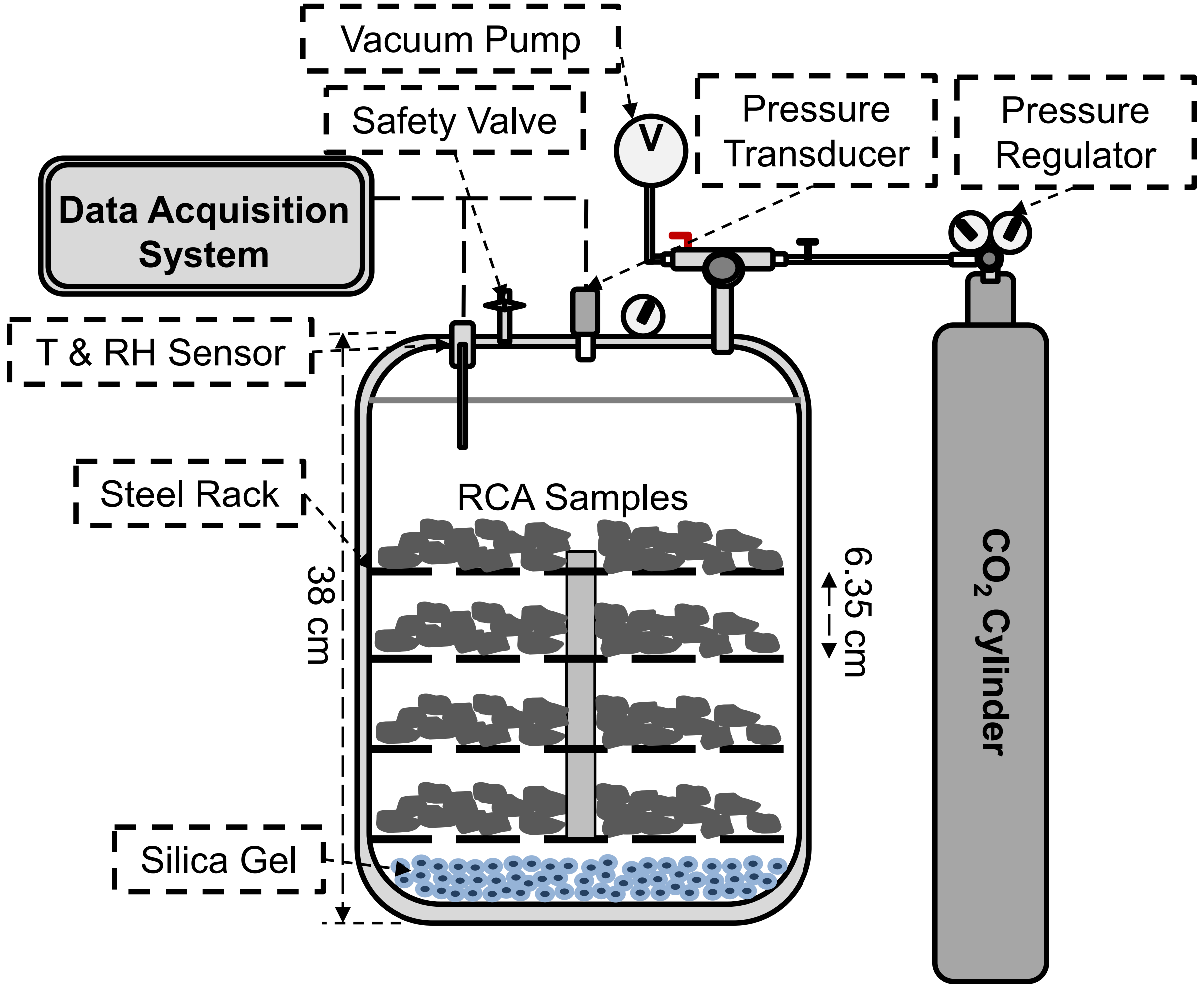
Previous Research: Accelerated Carbonation of RCA in the Small-Scale Reaction Chamber



Assumption on the main reactions:

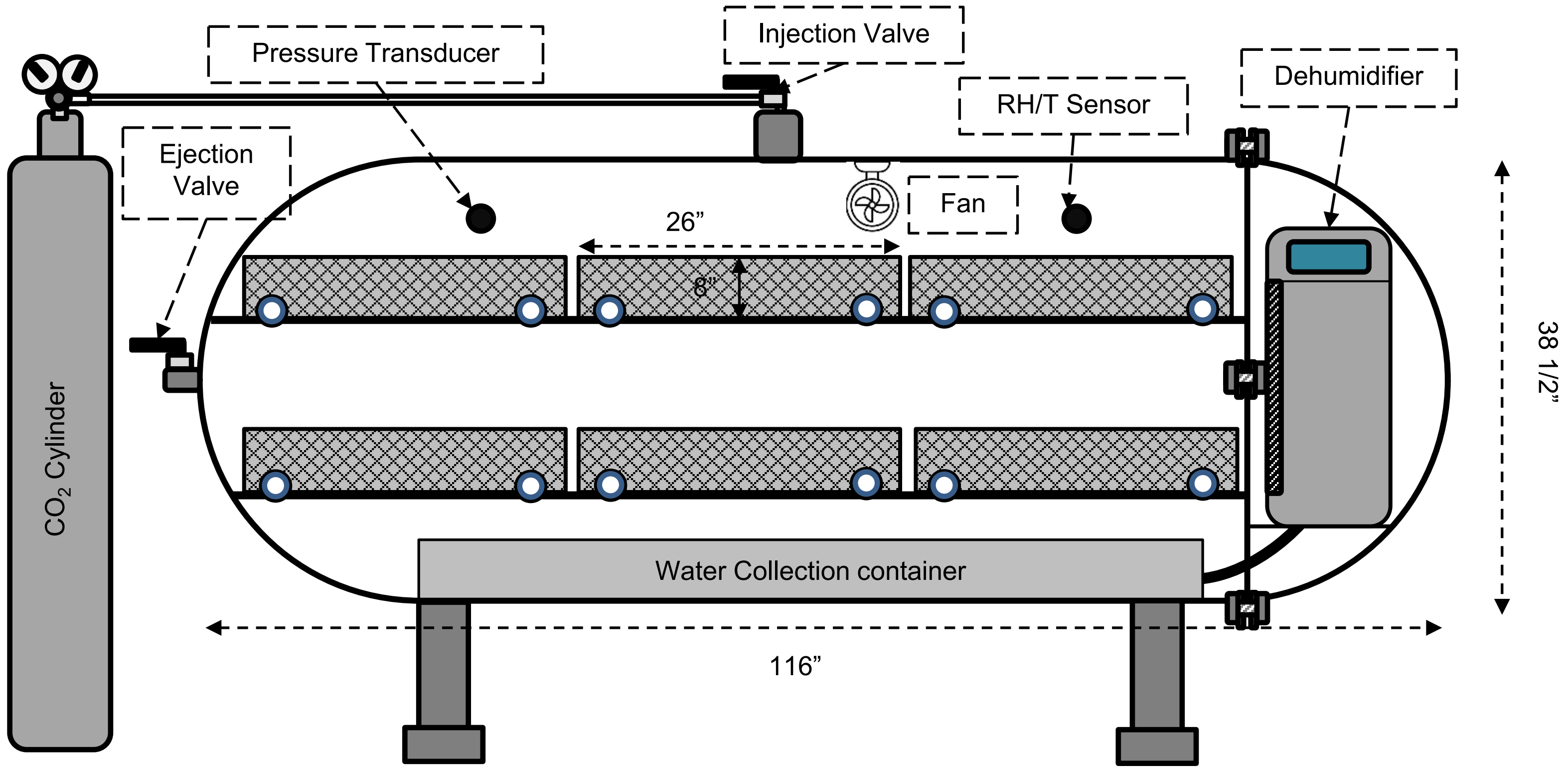
$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

$C\text{-}S\text{-}H + CO_2 \rightarrow CaCO_3 + SiO_2 + nH_2O$

Possible main variables on the reaction kinetics:

(1) Pressure, (2) Temperature, (3) Time, (4) Relative humidity

Previous Research: Accelerated Carbonation of RCA in the Large-Scale Reaction Chamber



Carbonation variables:

(1) Pressure: 1 – 60 psi (7 – 414 kPa)

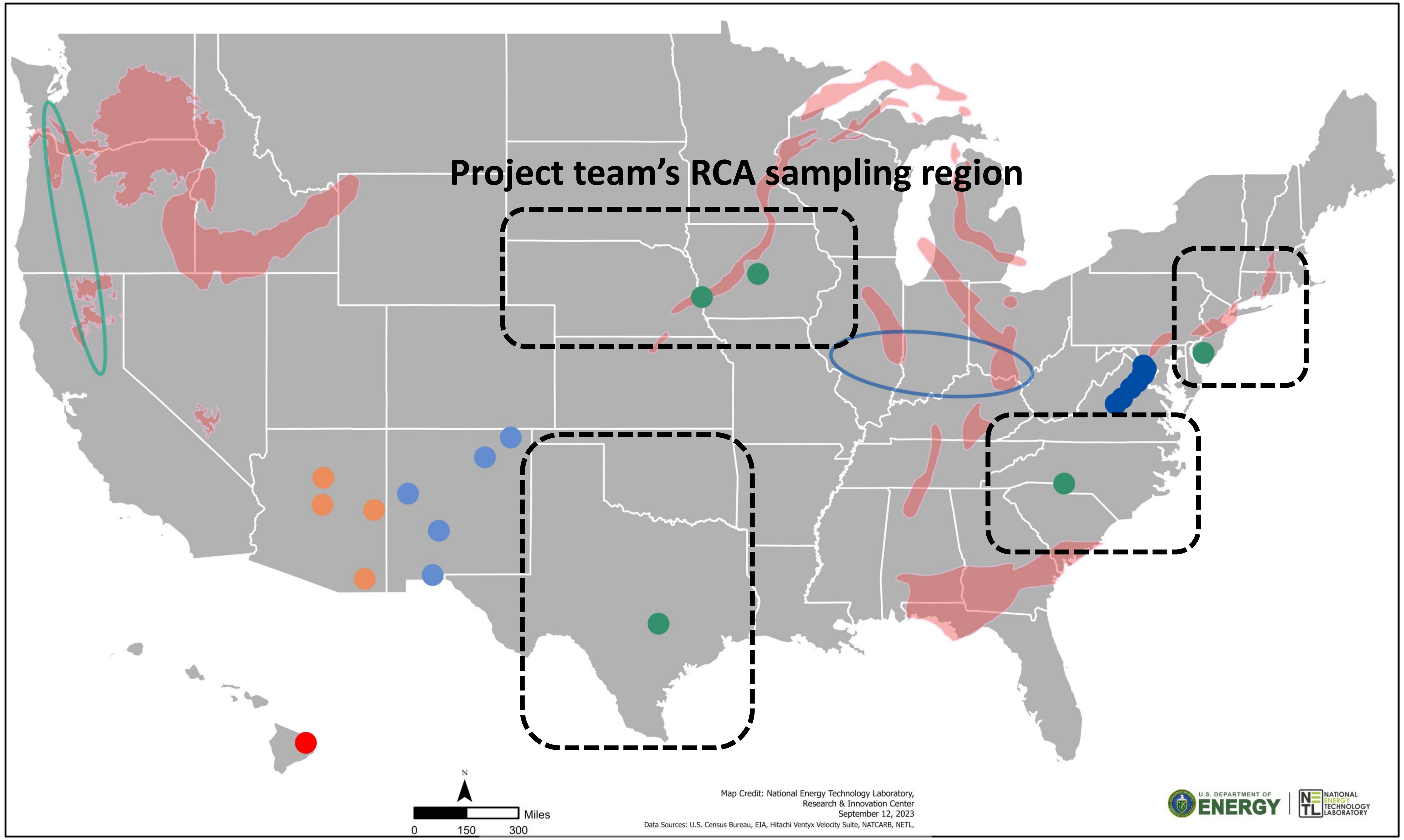
(2) Temperature: ambient, cold, and hot temperature

(3) Reaction time: 1 – 24 hours

(4) Relative humidity: 5 – 80%

(5) Scale (or volumetric CO_2 ratio)

Project Locations



Importance of Project towards advancing DOE Program Goals

Scientific and Technological Merit

- AOI-4 Carbon Storage Technology. Emphasis on classifying RCA with key indices, lab measurements of carbonation reaction, CO_2 uptake rates at different scales, and mechanical & chemical characterization of carbonated RCA.
- The research will provide valuable results for RCA resource base and CO_2 storage potential.
- Potential to achieve a minimum of 20 million tons of permanent CO_2 storage per year.

Novelty of the Project

- In-house, fabricated, lab- and large-scale reaction chambers (one-ton capacity).
- Specially designed physical, mechanical, and chemical test sets: deliver quality control (QC) measures and products for the construction industry and green market.
- Collaboration between academia and industry.

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Project Execution Plan

Task 1.0 Project Management and Planning

Subtask 1.1 – Project management plan

Subtask 1.2 – Diversity, Equity, and Inclusion

Task 2.0 Field Sampling

Subtask 2.1 – Acquisition of RCA

From different locations with temp-humidity

Source code for concrete mixture

Origin of infrastructure, size, and gradation

Subtask 2.2 – Characterization of RCA

Physical/mechanical properties of RCA

Residual mortar content (RMC)

Chemical composition (XRD, TGA, etc.)

→ several groups of RCA

Task 3.0 Lab Analysis of the Carbonation Reactions

Subtask 3.1 – Measurement of reaction kinetics at small-scale reaction chamber

Different RCA groups, CO_2 pressure, temperature

Subtask 3.2 – Measurement of physical and mechanical properties of CO_2-treated RCA

Physical/mechanical/chemical tests

Subtask 3.3 – Measurement of reaction kinetics at large-scale reaction chamber

Subtask 3.4 – Prediction of reaction rates and carbon uptake rates at anticipated field conditions

Solid-gas kinetic models, CO_2 mass consumption

Subtask 3.5 – Development of Protocols for Optimum CO_2 sequestration of RCA

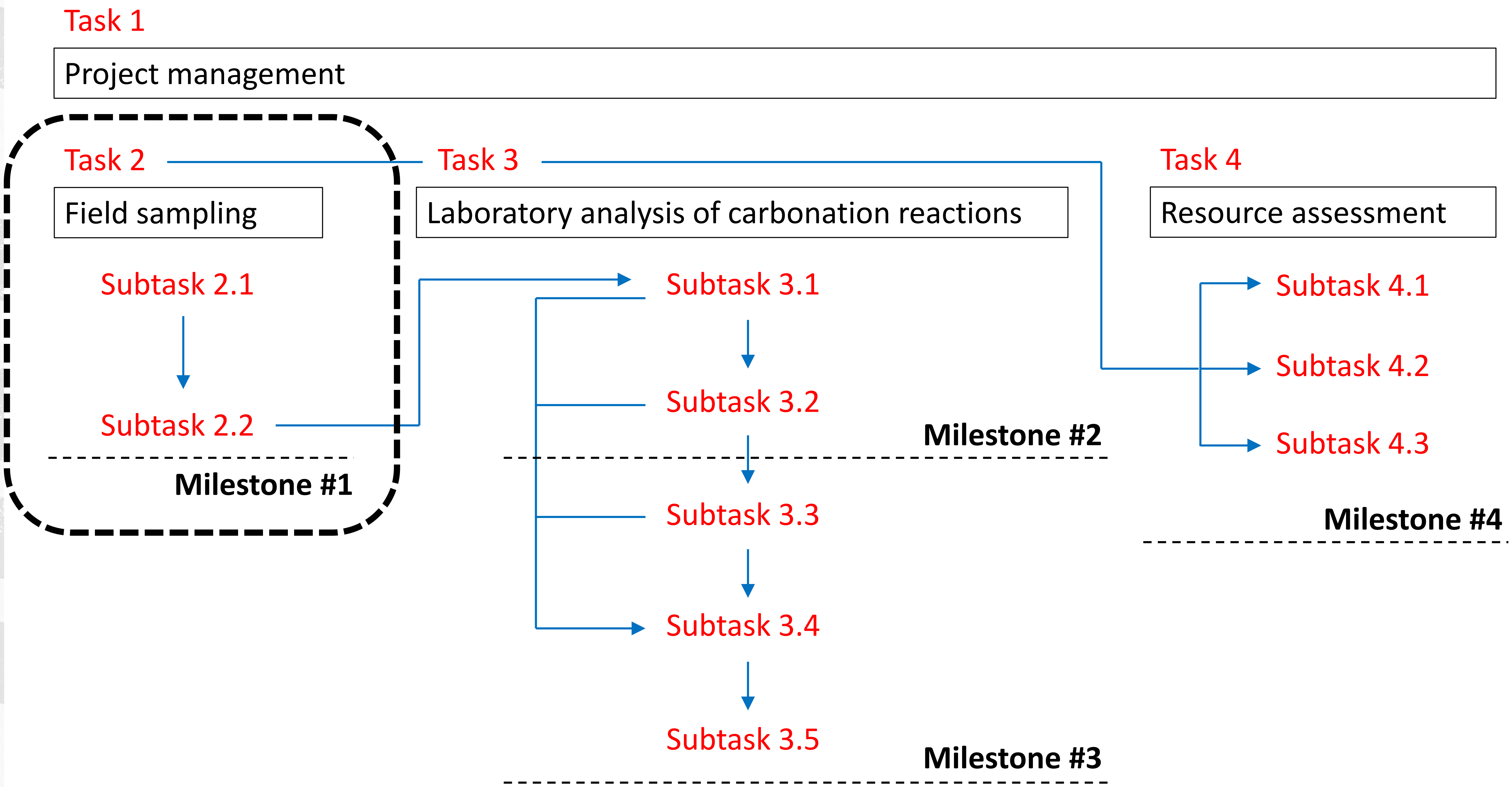
Task 4.0 Resource Assessment

Subtask 4.1 – Resource assessment of RCA: expected resources of each RCA groups

Subtask 4.2 – CO_2 storage potential

Subtask 4.3 – Cost and market analysis: Industrial wastes and mineralization process

Project Schedule & Key Milestones



Expected Outcomes and Impacts

- Improve the quality of the RCA resource base and carbon sequestration capacity via the carbonation of RCA in the *ex-situ* mineralization setting.
- First set of quantitative test data on carbonation reaction rates and carbon uptake rates with different RCA groups.
- Potential to disrupt the $19 billion stone aggregate industry in an environmentally positive manner.
- Reduced burden on the construction and demolition waste management.
- Target cost: $15-18 per ton for Carbonated RCA *vs*. $22-28 per ton for natural limestone aggregates.

Project Success Criteria

Task/ Subtask	Decision Point Description	Date	Success Criteria
1	Decision regarding revision of Project Management Plan	9/30/2023	New Project Management Plan submitted if necessary.
2.1-2.2	Field sampling – acquisition and characterization of RCA	6/30/2024	Source materials are classified with residual mortar content, chemical composition, and other relevant physical/ mechanical indices.
3.1-3.3	Determination of carbonated RCA properties	3/31/2025	Improvements in the physical, mechanical, and environmental characteristics of source materials after the carbonation reaction are demonstrated.
3.4-3.5	Derivation of carbonation reaction rate and CO_2 uptake rate	3/31/2025	Carbonation reaction rates at anticipated in-situ conditions are derived. Potential carbon uptake rates at the presumed mass-scale operation are estimated.
4.1	Resource assessment of RCA	6/30/2025	The location, quantity, availability, and accessibility of RCA resources by each classified quality group are identified.
4.2	CO_2 storage potential	6/30/2025	CO_2 storage potential ($MtCO_2$ stored or sequestered) of identified RCA resource groups is assessed.
4.3	Cost and market analysis	6/30/2025	The cost analysis of carbonation operation, as well as supply, demand, and market analysis are completed.

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Status of Project Objectives and Tasks

Subtask 2.1: Acquisition of representative RCA samples

Sources and information of collected RCA samples

Aggregate ID	Location	Aggregate Source
NLS	Omaha, Nebraska	Limestone
NSG	Omaha, Nebraska	Sand and Gravel
NE-1	Omaha, Nebraska	Highway
NE-2	Valley, Nebraska	Commercial buildings
IA	Ankeny, Iowa	Multiple sources
NY	Hillburn, New York	Commercial buildings
NC	Charlotte, North Carolina	Commercial buildings


NLS


NSG


NE-1


NE-2


IA


NY


NC

Status of Project Objectives and Tasks

Subtask 2.2: Characterization of RCA

Test methods for basic properties of RCA

Tests	Standard	Before Carbonation	After Carbonation
Gradation	ASTM C136	CA and FA combined	N/A
Specific Gravity	ASTM C127/ C128	CA and FA	CA
Water Absorption	ASTM C127/ C128	CA and FA	CA
Residual Mortar Content (RMC)	- Mamirov et al. (2022)	CA (all sizes)	N/A
Freeze/Thaw (F/T) Mass Loss	- CSA 23.2-24A	CA (½”)	CA (½”)
Aggregate Compression Test (ACT)	-	CA (All sizes)	CA (½”)
Aggregate Crushing Value (ACV)	- Mamirov et al. (2022)	CA (All sizes)	CA (½”)
TGA, XRD	Scrivener at al. (2016)	CA	CA
Paste Content	Zhao et al. (2022)	CA	N/A

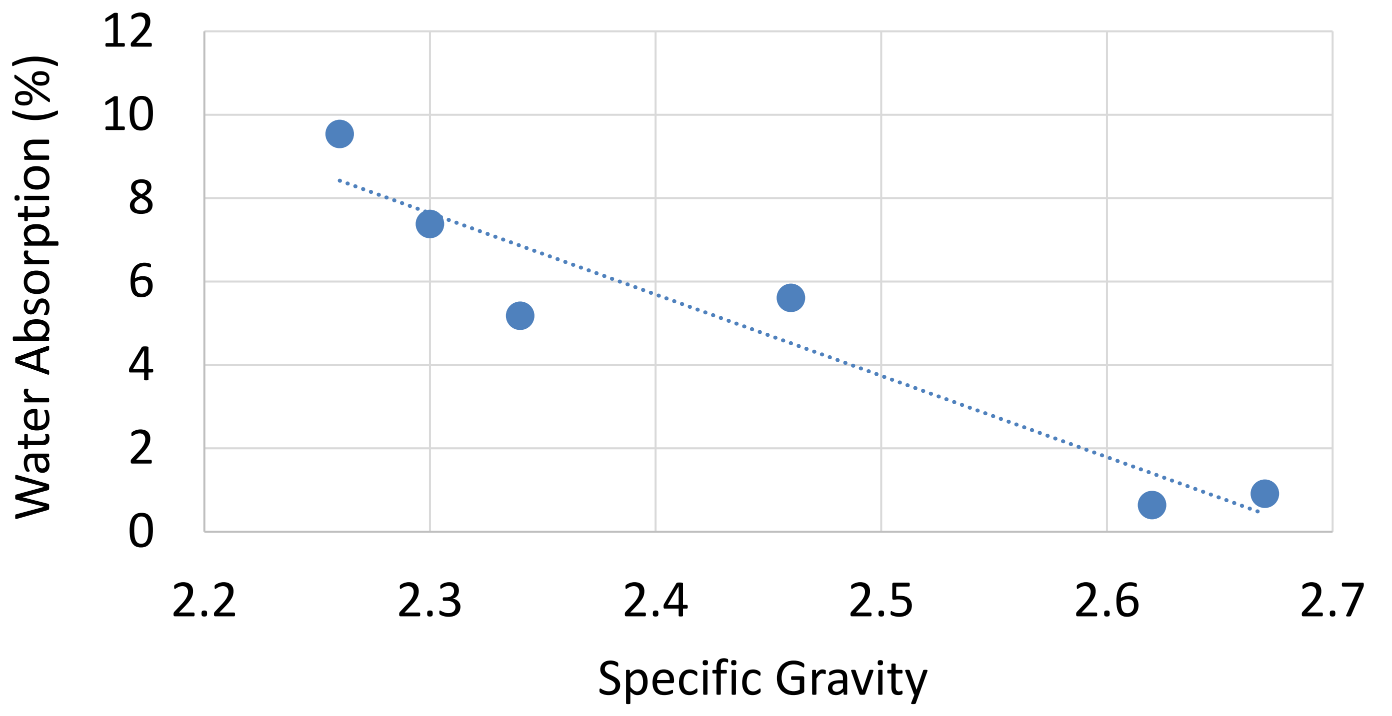
Note: CA: coarse aggregates, FA: fine aggregates

Subtask 2.2: Characterization of RCA

Specific gravity and water absorption

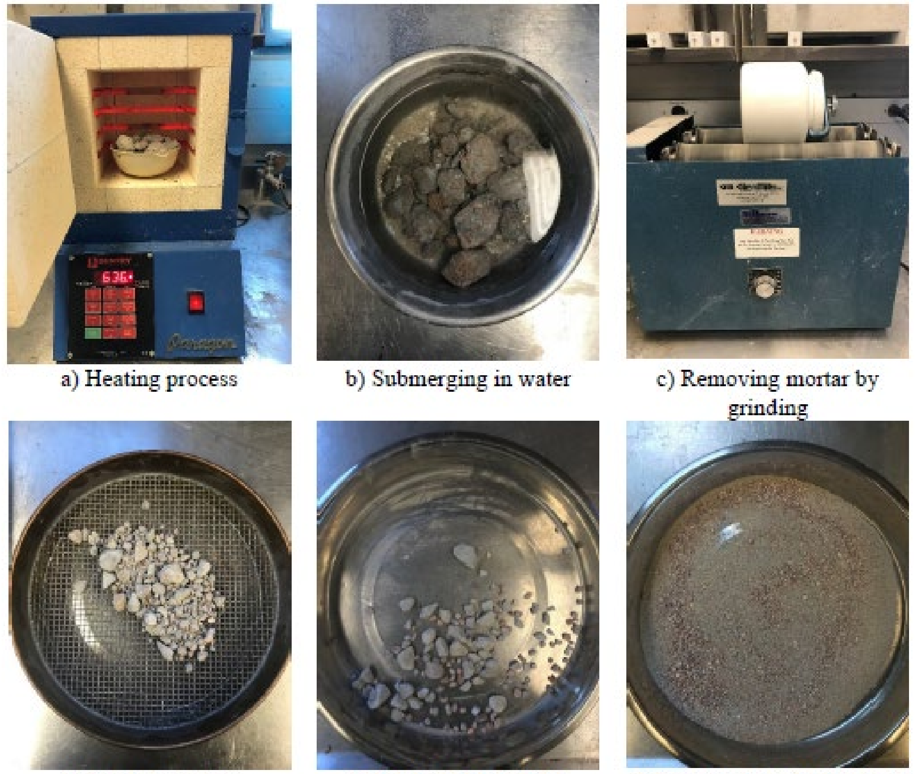
Aggregates	Specific Gravity	Water Absorption (%)
NSG	2.62	0.64
NLS	2.67	0.91
NE-1	2.34 (2.38/ 2.30) *	5.18 (4.86/ 5.55) *
NE-2	2.30 (2.34/ 2.27) *	7.38 (7.09/ 7.69) *
IA	2.26 (2.32/ 2.18) *	9.54 (9.20/ 9.99) *
NY	2.46	5.61
NC	2.60	3.61

Note: *Coarse aggregates/Fine aggregates



Status of Project Objectives and Tasks

Subtask 2.2: Characterization of RCA

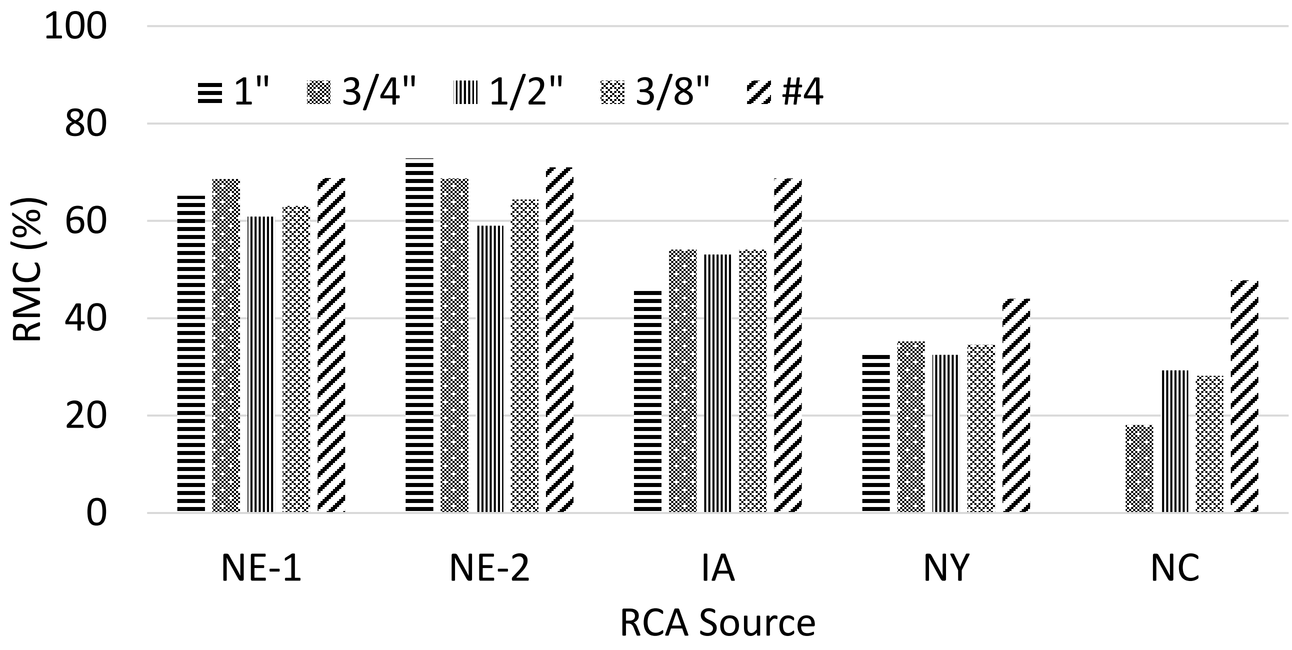


a) Heating process
b) Submerging in water
c) Removing mortar by grinding
d) Sieving process
e) Original NA in RCA
f) Removed residual mortar

Residual mortar content (RMC)

Aggregates	RMC (%)				
	1”	¾”	½”	3/8”	#4
NE-1	65.14	68.60	60.88	63.07	68.80
NE-2	72.85	68.73	59.00	64.40	71.00
IA	45.99	54.11	53.10	54.12	68.74
NY	33.08	35.24	32.47	34.56	44.02
NC	-	18.10	29.31	28.19	

Method: thermal shock method (Mamirov et al., 2022)



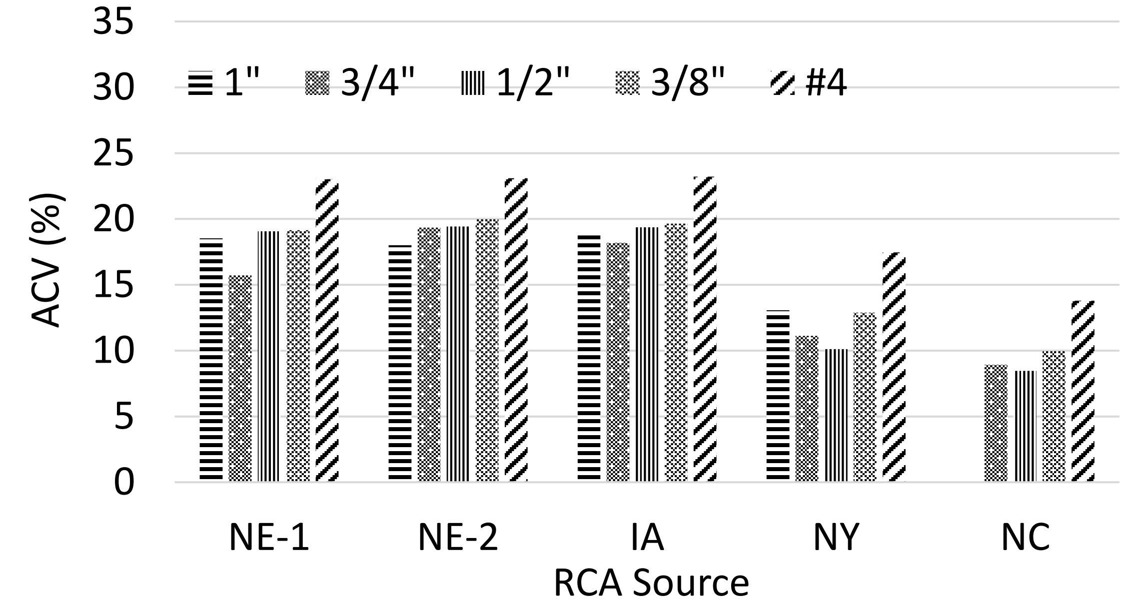
Status of Project Objectives and Tasks

Subtask 2.2: Characterization of RCA

Aggregate crushing value (ACV)

Aggregates	ACV %				
	1”	¾”	½”	3/8”	#4
NLS	-	-	-	7.67	-
NE-1	18.53	15.71	19.06	19.15	23.02
NE-2	18.01	19.34	19.43	19.97	23.10
IA	18.75	18.19	19.37	19.65	23.22
NY	13.06	11.12	10.11	12.88	17.46
NC	-	8.93	8.46	9.96	1[illegible]

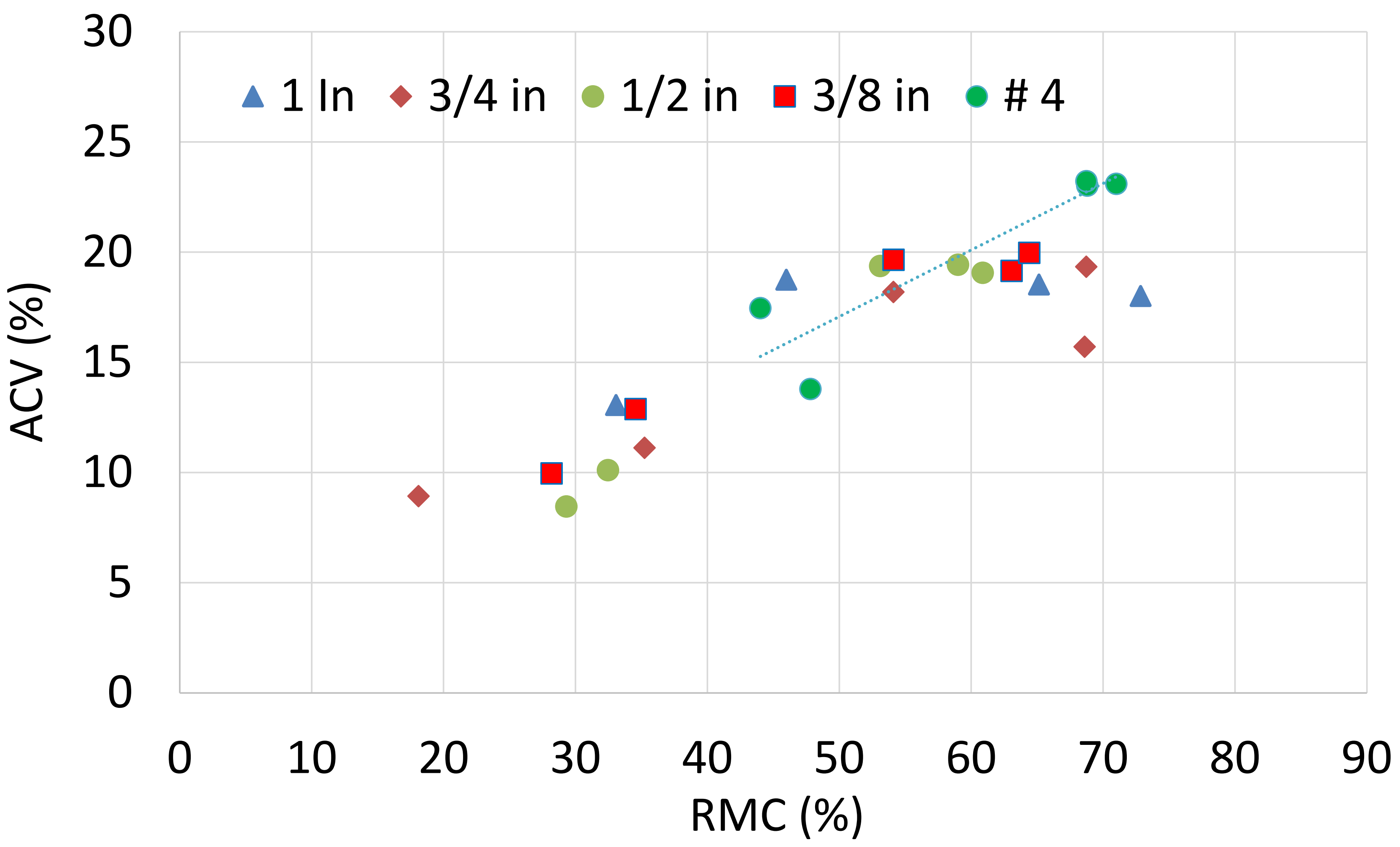

a) Placing sample in a steel ring
b) Applying load
c) Sample appearance after crushing process
d) Vibrating a sample
e) Sieving a sample
f) Crushed amount



Status of Project Objectives and Tasks

Subtask 2.2: Characterization of RCA

Correlation between RMC and ACV

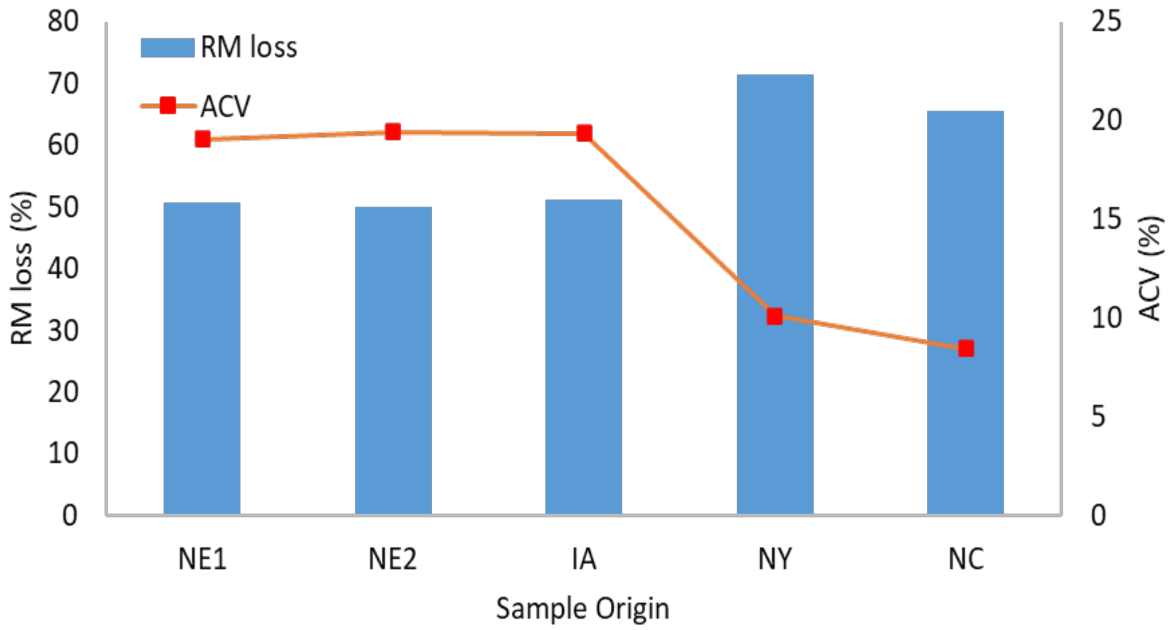


Status of Project Objectives and Tasks

Subtask 2.2: Characterization of RCA

Freeze/Thaw (F/T) mass loss

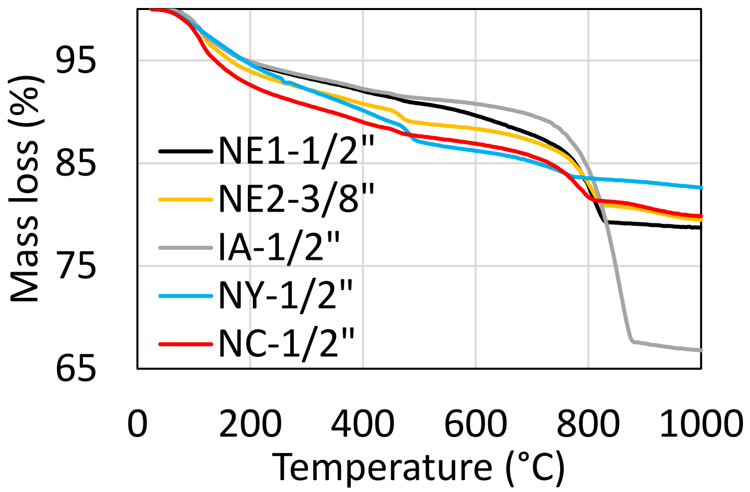
Aggregates (with 1/2" size)	ACV (%)	RMC (%)	F/T mass loss (%)
NLS	7.67	-	4.88
NE-1	19.06	60.88	30.84
NE-2	19.43	59.00	29.52
IA	19.37	53.10	27.13
NY	10.11	32.47	23.17
NC	8.46	29.31	19.23

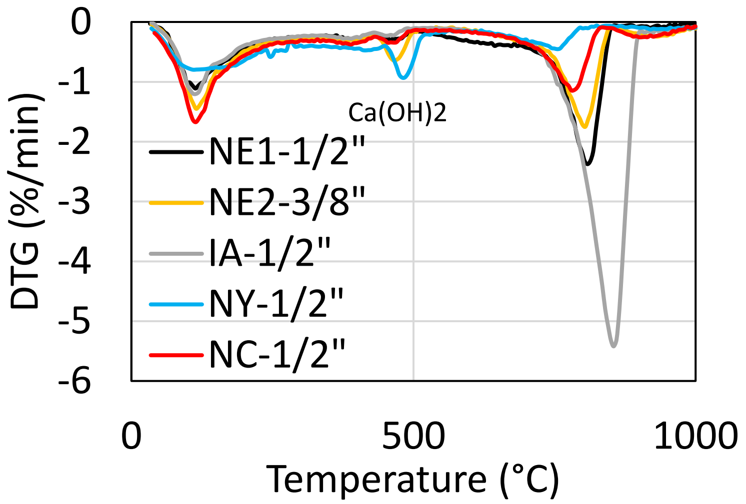


Subtask 2.2: Characterization of RCA

Composition analysis – Thermal gravimetric analysis (TGA)

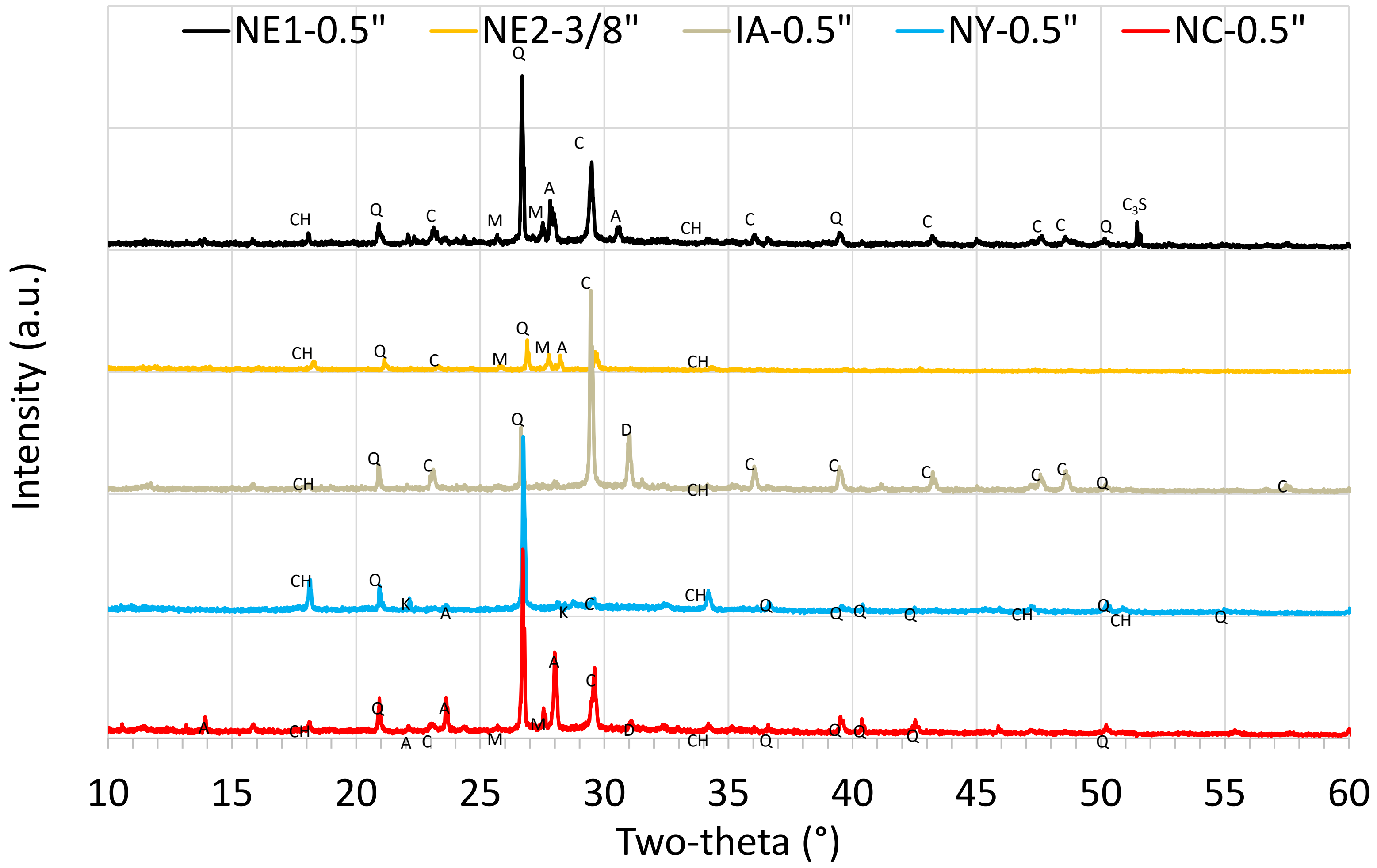
ID	RMC (%)	Final Mass (%)	$Ca(OH)_2$ in mortar (%)	$Ca(OH)_2$ in concrete (%)	$CaCO_3$ in mortar (%)	$CaCO_3$ in concrete (%)
NE1-1/2"	60.88	78.7	6.8	4.1	26.4	16.1
NE2-3/8"	64.4	79.5	9.5	6.1	18.5	11.9
IA-1/2"	53.1	66.8	5.4	2.9	54.3	28.9
NY-1/2"	32.47	82.6	15.1	4.9	7.5	2.4
NC-1/2"	29.31	79.8	8.0	2.3	14.4	4.2





Subtask 2.2: Characterization of RCA

Composition analysis – X-ray diffraction (XRD)



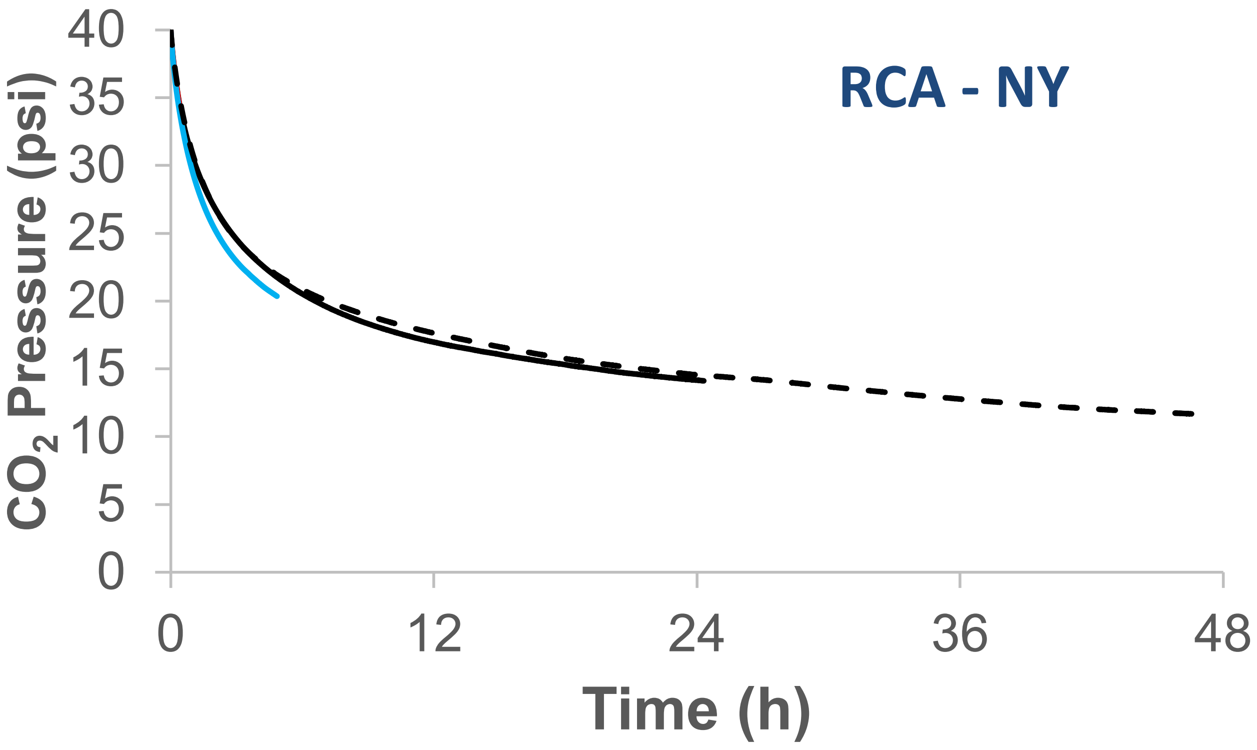
XRD results of the acquired RCA samples from different sources.
Note: Q = quartz, C = calcite, A = albite, CH = portlandite, M = microcline, D = dolomite, and K = kanemite

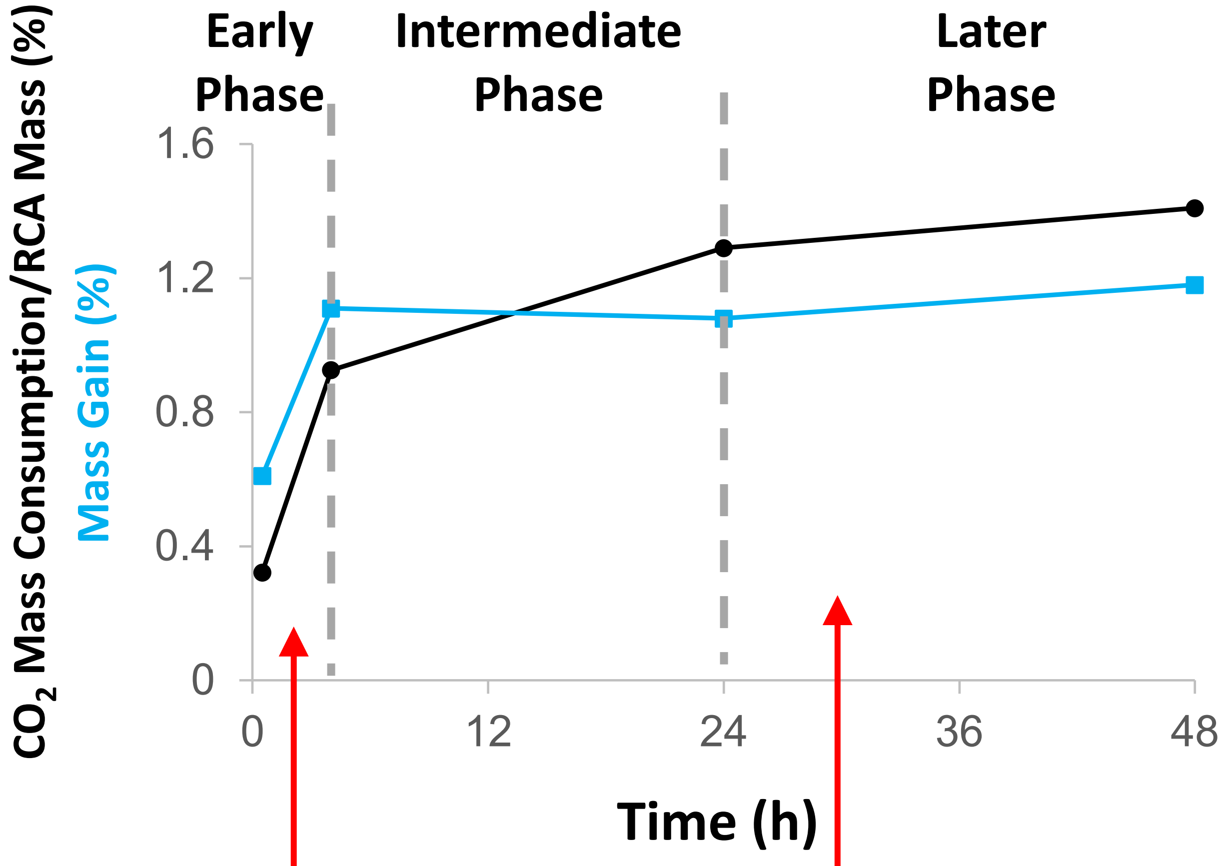
Subtask 2.2: Characterization of RCA

So far, important factors for the carbonation reaction

Source	RMC (%)	Paste Content in Concrete (%)	Water Absorption (%)	$Ca(OH)_2$ in Concrete (%)	Normalized CO_2 Sequestration Capacity (%)	ACV (%)	F/T (%)
NE-1 ½”	60.8	19.21	5.18	4.1	1.48	19.06	30.84
IA ½”	53.1	17.89	9.54	2.9	1.32	19.37	27.13
NY ½”	32.4	18.48	5.61	4.9	1.26	10.11	23.17
NC ½”	29.3	12.86	3.61	2.3	0.78	8.46	19.23
NE-2 3/8”	64.4	29.25	7.38	6.1	2.51	19.97	29.52

Subtask 3.1: Measurement of reaction kinetics at small-scale reaction chamber





$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

$C\text{-}S\text{-}H + CO_2 \rightarrow CaCO_3 + SiO_2 + nH_2O$

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

$C\text{-}S\text{-}H + CO_2 \rightarrow CaCO_3 + SiO_2 + nH_2O$

Status of Project Objectives and Tasks

Subtask 3.1: Measurement of reaction kinetics at small-scale reaction chamber

Three stages of carbonation reaction

Leaching of Metal Ions from Solid

Dissolution of CO_2

Precipitation of Carbonates

Pseudo-first-order reaction model

Rate of Carbonate Precipitation: $k[Ca^{2+}][CO_3^{2-}]$

$\simeq k'[Ca^{2+}]$

In high pH conditions (typical for RCA leachate)

- Concentration of the limiting reactant $[Ca^{2+}]$: $[Ca^{2+}] = [Ca^{2+}]_0\, e^{-k't}$
- Then, $\Delta[Ca^{2+}] = [Ca^{2+}]_0(1-e^{-k't})$
- Since the consumed CO_2 is directly related to the amount of Ca^{2+} reacted, the total amount of CO_2 consumption (in moles) can be modeled as:

$$CO_2(mol) = a\left(1 - e^{-k't}\right)$$

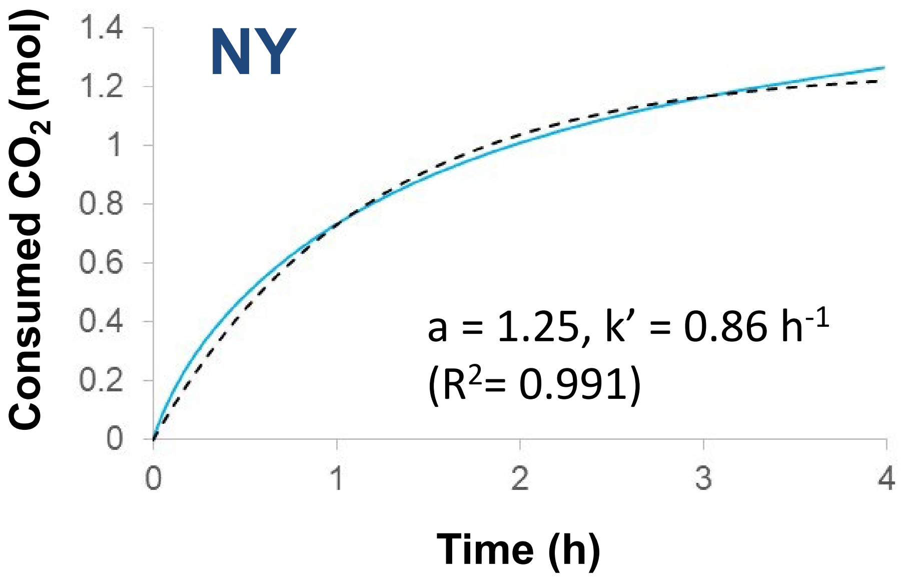
where, a = maximum amount of CO_2 that can be consumed,

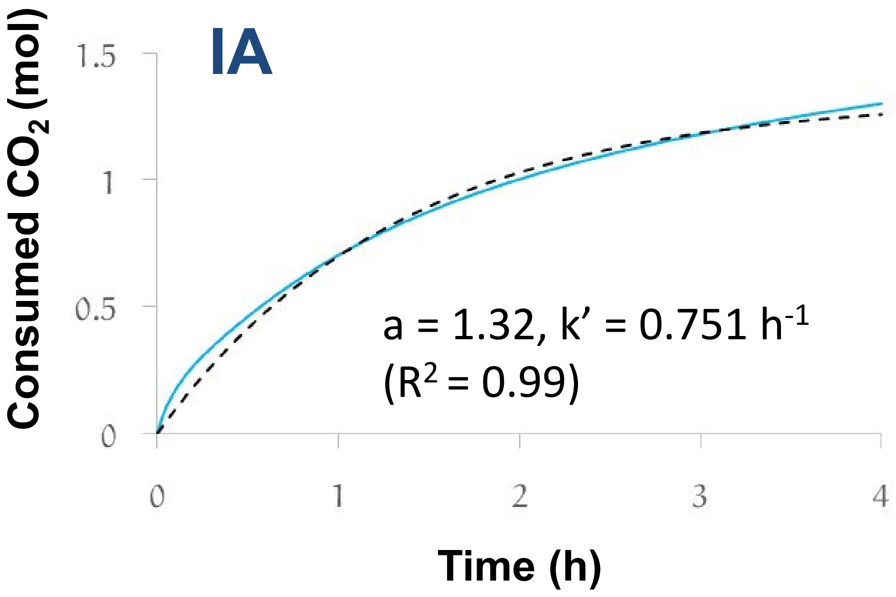
k' = rate constant for the reaction.

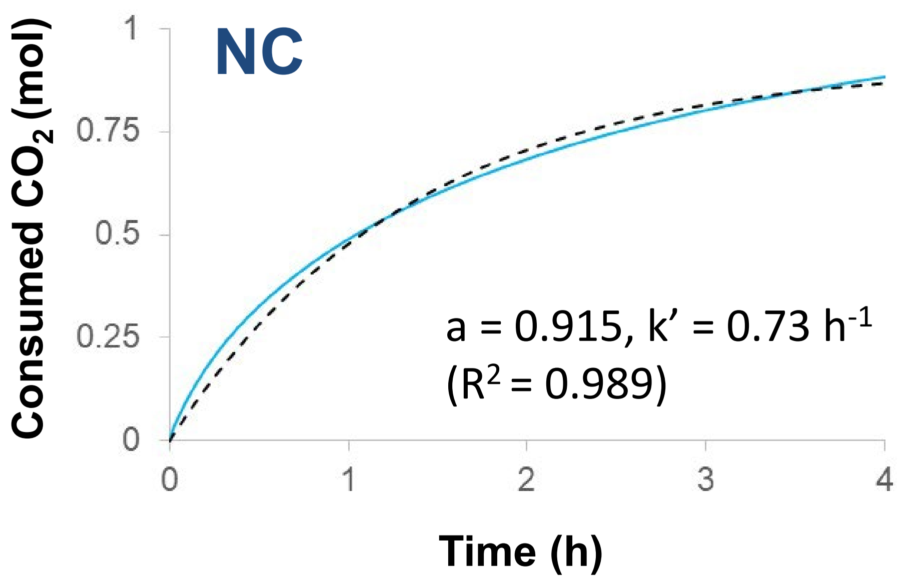
Status of Project Objectives and Tasks

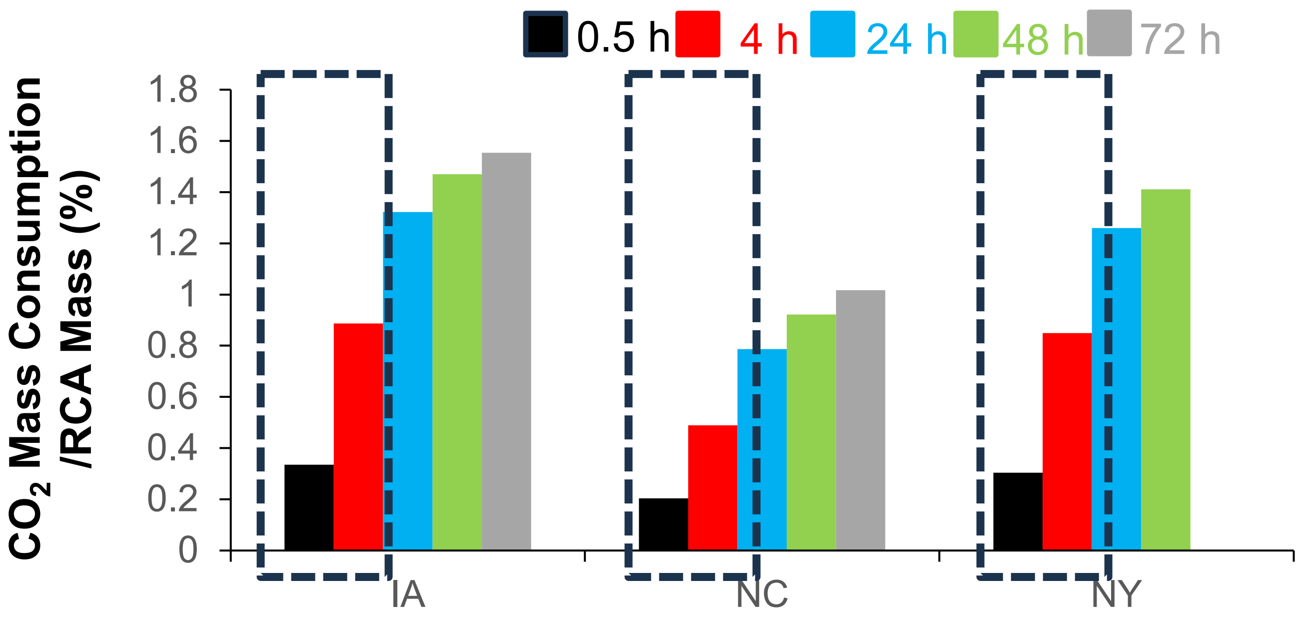
Subtask 3.1: Measurement of reaction kinetics at small-scale reaction chamber

Pseudo first order reaction: Early phase









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Community Benefits Plan

- **Action 1**: Recruit, develop, and graduate a talented and diverse pool of students.
  - 3 undergraduate students at UNL and 2 undergraduate students at UNK were hired from either the Hispanic, African American, or Female student groups.
- **Action 2**: Perform outreach to students in minority or underrepresented groups outside of UNL/UNK.
  - 1 high school teacher from outside of UNL/UNK was invited to participate in the research activities during the summer of 2024.
  - In addition, the project team participated in 2 outreach events that invited local high school students and engaged them in the hands-on activities.
- **Action 3**: Provide meaningful training and learning experiences to all team members to improve their understanding of diversity, equity, and inclusion concepts and enable them to apply these ideas to model behaviors.
  - PI, co-PIs, and graduate students attended 3 workshop events that are relevant to diversity, equity, and inclusion.

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Next Steps

Task 1.0 Project Management and Planning

Subtask 1.1 – Project management plan

Subtask 1.2 – Diversity, Equity, and Inclusion

Task 2.0 Field Sampling

Subtask 2.1 – Acquisition of RCA

From different locations with temp-humidity

Source code for concrete mixture

Origin of infrastructure, size, and gradation

Subtask 2.2 – Characterization of RCA

Physical/mechanical properties of RCA

Residual mortar content (RMC)

Chemical composition (XRD, TGA, etc.)

→ several groups of RCA

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Different RCA groups, CO_2 pressure, temperature

Subtask 3.2 – Measurement of physical and mechanical properties of CO_2-treated RCA

Physical/mechanical/chemical tests

Subtask 3.3 – Measurement of reaction kinetics at large-scale reaction chamber

Subtask 3.4 – Prediction of reaction rates and carbon uptake rates at anticipated field conditions

Solid-gas kinetic models, CO_2 mass consumption

Subtask 3.5 – Development of Protocols for Optimum CO_2 sequestration of RCA

Task 4.0 Resource Assessment

Subtask 4.1 – Resource assessment of RCA: expected resources of each RCA groups

Subtask 4.2 – CO_2 storage potential

Subtask 4.3 – Cost and market analysis: Industrial wastes and mineralization process

Acknowledgment - Funding Supports

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Thank you!
Questions?