Creating Sustainable Concrete Through Carbon Sequestration

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Introduction

Background

The construction industry is one of the largest sources of carbon dioxide (CO_2), with **concrete production** accounting for **8% of global emissions** (Rodgers, 2018). In fact, concrete emits 0.8-0.95 tonnes of CO₂ for every tonne produced, totaling **over 1.5 billion tonnes of CO₂ annually** (Massoumi Nejad et al., 2025). The process of **carbonation immobilizes CO2** as stable carbonates via dissolution and recombination with calcium or magnesium (Li et al., 2022). This presents a promising solution for **CO_2 sequestration in concrete** (Laurent, 2023).

Concrete Carbonation

Passive Carbonation: Portland cement (concrete binder) naturally carbonates from atmospheric CO_2 due to moisture content and calcium-bearing phases (portlandite ($Ca(OH)_2$) and Calcium Silicate Hydrate) (Anabela et al., 2020)

Carbonation Curing: Exposing fresh concrete to controlled CO_2 in a pressurized carbonation chamber accelerates the carbon sequestration process (Li et al., 2022)

Mineral Carbonation: Pretreat Ca/Mg rich Supplementary Cementitious Materials (SCM's) with CO_2 and then use in concrete (Pu et al., 2021 and Kazemian & Shafei, 2023)

Passive Carbonation

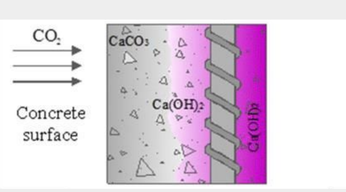

Figure 1: Passive carbonation diagram (Possan et al., 2017)

✅ Stable, long-term CO_2 storage (Anabela et al., 2020)

❌ Long exposure periods (Van Roijen et al., 2024)

Carbonation Curing

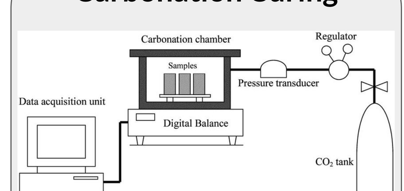

Figure 2: Carbonation curing setup (Shao et al., 2014)

✅ Rapid CO_2 uptake

✅ Increased strength

❌ Process-dependent and inconsistent (Li et al., 2022)

Mineral Carbonation

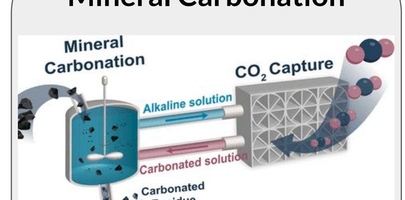

Figure 3: Mineral carbonation flowchart (Ragipani et al., 2022)

✅ Stable carbonates

✅ Sustainable SCM's

❌ Material-dependent

❌ Strength tradeoffs (Kazemian & Shafei, 2023)

Problem

Existing CO₂ sequestration methods each provide benefits, but **none solve** all major challenges of **speed, process consistency,** and **consistent material performance.**

Engineering Goal

Create and optimize a **structurally sound concrete mix** from **recycled materials** that **quickly and consistently sequesters CO_2** when carbonation-cured, helping mitigate carbon emissions and assist in the future of sustainable construction.

Experimental Setup

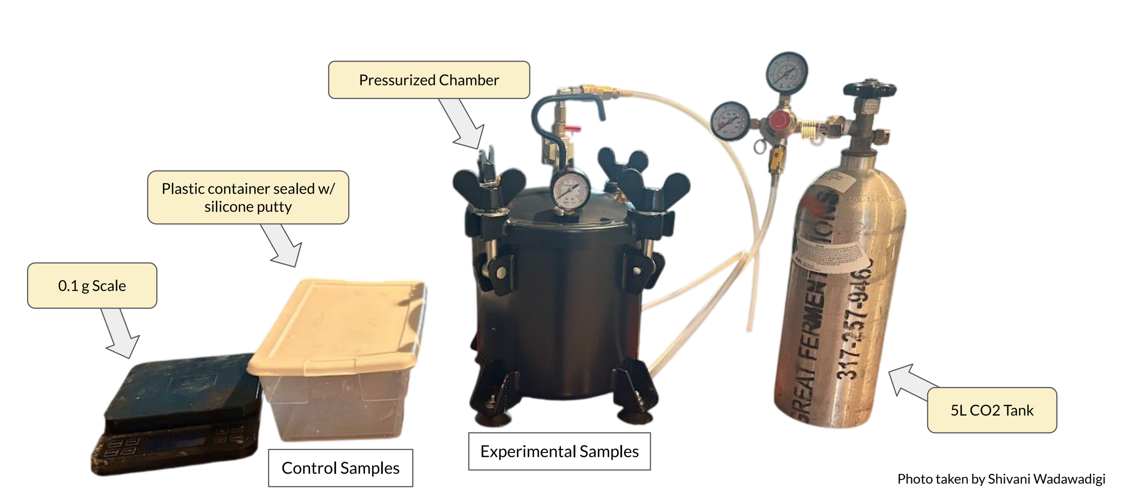

Photo taken by Shivani Wadawadigi

Materials & Methodology

Carbonation Testing

Three trials; Trials 1 and 2 tested the original 8 mixes while Trial 3 tested the optimized 9th mix.

- Mixes designed using an L9 Taguchi Array (4 Factors, 3 Levels) (see Table 2)
- CO2 sequestration was measured via **weight gain**
- 8 mixes (see Table 1) tested in CO2 pressure chamber
- RH controlled using a supersaturated NaCl solution to target an RH of 74-76% (Saturated Salt Solutions and Air Humidity, 2014)
- Temperature was maintained at ambient conditions
- Samples sealed to prevent dilution/contamination

Mix	SCM	Aggregate	Additive	Water-Binder
Mix 1	**Fly Ash**	**Recycled**	None	0.4
Mix 2	Slag	Natural	Biochar	0.4
Mix 3	Hydrated Lime	Steel Slag	Accelerator	0.35
Mix 4	Fly ash	Steel Slag	Biochar	0.4
Mix 5	Slag	Recycled	None	0.4
Mix 6	Hydrated Lime	Natural	Accelerator	0.35
Mix 7	Fly Ash	Natural	Biochar	0.35
Mix 8	Slag	Steel Slag	Accelerator	0.45

Table 1. Initial Eight Concrete Mixes

Factors	Level 1	Level 2	Level 3
SCM	Fly ash	Slag	Hydrated Lime
Aggregates	Recycled	Natural	Steel Slag
Additives	None	Biochar	Accelerator
Water-Binder	0.35	0.4	0.45

Table 2. L9 Taguchi Array showing factors and levels used

Carbonation Experiment Workflow

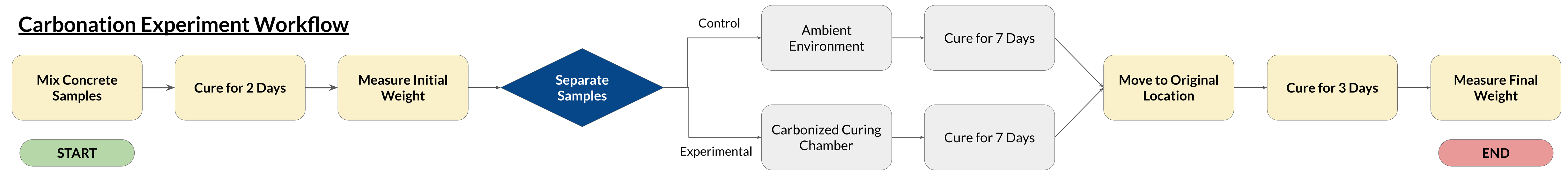

Figure 3: Flowchart detailing Carbonation Trials

Structural Testing

Measured through compression testing

- 32 samples; 4 samples per mix (2 control, 2 experimental)
- Tested *MTS Insight Electromechanical Testing System* until failure
- Peak load recorded

Optimization

Goal: maximize CO2 Sequestration

Used a regression using *JMP Student Version*, shown in Figure 5.

Optimal Mix:

- Hydrated lime
- Steel Slag
- Water/Binder = 0.3

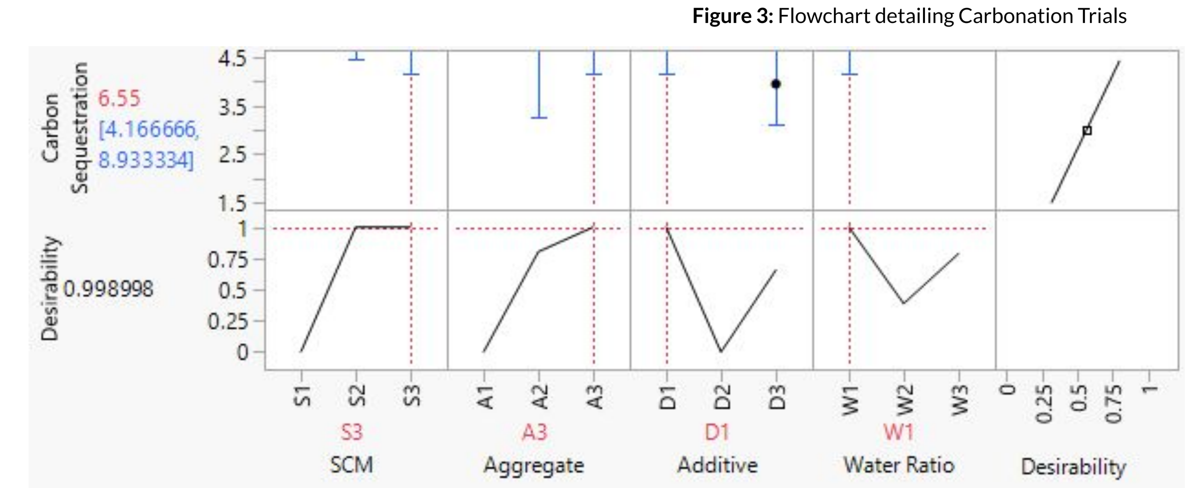

Figure 4. *JMP* Optimization of Concrete Mixes

Results and Discussion

Mix	Trial 1 Avg. CO2 (%)	Trial 1 Avg. CO2 (g)	Trial 2 Avg. CO2 (%)	Trial 2 Avg. CO2 (g)	Average CO2 (%)	Average CO2 (g)
Mix 1	4.53%	2.90	5.89%	4.15	5.21%	3.52
Mix 2	3.39%	2.35	4.10%	2.95	3.74%	2.65
Mix 3	3.78%	3.55	4.46%	4.35	4.12%	3.95
Mix 4	2.19%	2.00	3.48%	3.25	2.84%	2.62
Mix 5	4.69%	3.15	5.12%	3.75	4.91%	3.45
Mix 6	2.38%	1.70	4.23%	2.80	3.30%	2.25
Mix 7	3.96%	2.75	4.82%	3.45	4.39%	3.10
Mix 8	3.57%	3.80	3.95%	3.95	3.76%	3.88

Table 3. Carbon Sequestration of Original Eight Mixes

Mix	Trial 3 Avg. CO2 (%)	Trial 3 Avg. CO2 (g)
Mix Optimal	6.60%	6.40

Table 4. Carbon Sequestration of Optimized Mix

Compression Test Results

- 32 compression tests (2 experimental, 2 control per mix)
- One experimental sample of mix 1 invalidated due to test failure (31 total results)

7 of the 8 mixes performed **better** than their control counterparts.

3 out of 8 mixes met industry standards of 4000 psi for commercial usage (National Ready Mixed Concrete Association, 2021)

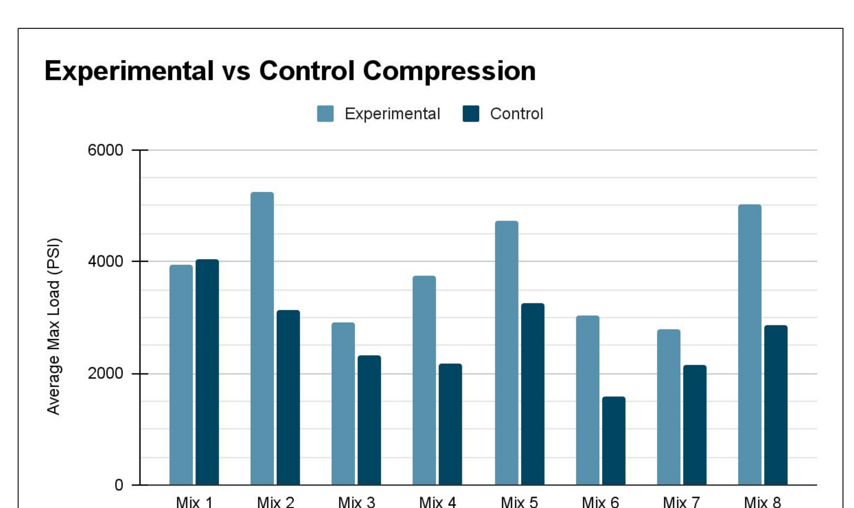

Figure 5. Experimental vs Control Compression Testing

Each bar shows the max load (PSI) sustained by each sample in a compression test until failure

Carbon Sequestration Results

- 57 samples tested in the first two trials (32 experimental, 25 control)

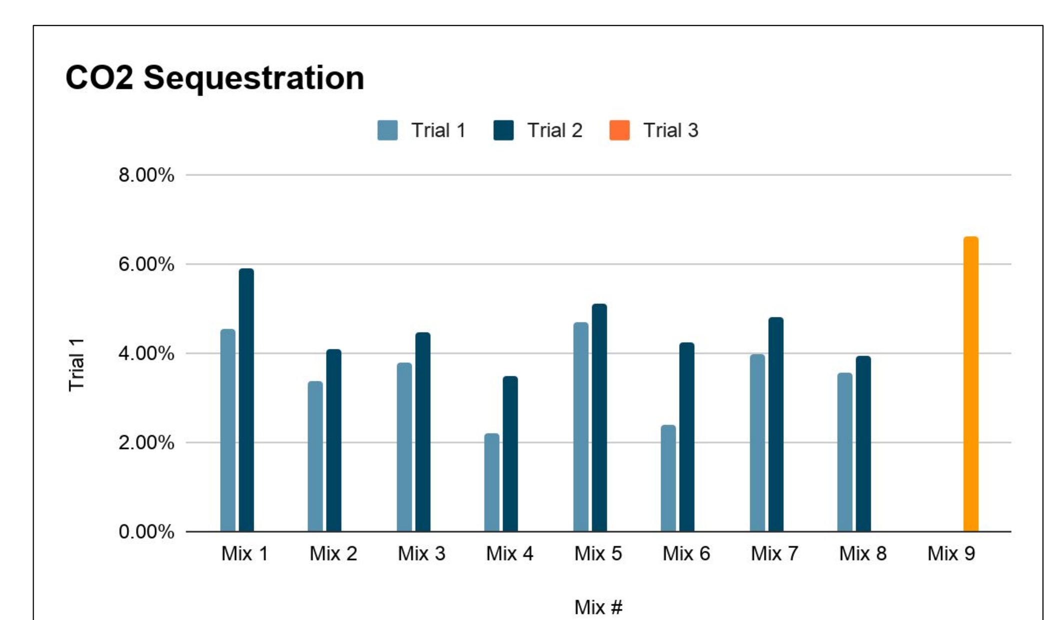

Figure 6. Carbon Sequestration by Mix

Discussion

- Mix optimization is essential for carbonation cured concrete. The optimized mix outperformed the initial eight mixes, suggesting that carbonation-cured concrete is suited to the iterative engineering workflow.
- Unclear pattern between the mixes which sequestered the most carbon and the mixes that gained the most compressive strength relative to their control counterparts.
  - Contradicts the expectation that the most carbonized mixes would increase in strength the most (Kazemian & Shafei, 2023)

Statistical Analysis

Mix	Mean CO %	SD	95% CI (lower, upper)	CI width
1	5.215	0.869	(3.833, 6.597)	2.764
2	3.740	0.732	(2.575, 4.905)	2.330
3	4.123	0.473	(3.371, 4.875)	1.504
4	2.835	0.868	(1.454, 4.216)	2.762
5	4.910	0.376	(4.312, 5.508)	1.196
6	3.305	1.153	(1.470, 5.140)	3.670
7	4.390	0.566	(3.489, 5.291)	1.802
8	3.523	0.485	(2.751, 4.295)	1.544
Optimal	**6.600**	**0.0258**	**(6.559, 6.641)**	**0.082**

Table 5: 95% Confidence Interval (CI) for CO_2 sequestration of each mix

Mix Optimal has **smallest SD** and the **narrowest 95% CI** by ~14.5x, showing **consistent uptake**

	SS	df	MS	F	p-value
Between Mixes	42.37155	8	5.29644	11.09586	**8.661e-07**

Figure 6: ANOVA testing results for CO_2 sequestration of each mix

Small P-value of 8.661e-7 indicates **highly significant differences** in CO₂% uptake **across mixes**

Tukey Post-HOC HSD Results:

Mix Optimal CO_2 sequestration **significantly higher** than all other mixes except Mix 1 (α = 0.05).

Mix 1 CO_2 sequestration not significantly higher than any other mixes (α = 0.05)

Conclusion

✓ **Recycled materials** were incorporated as SCM's in the concrete matrix, including **steel slag** and **recycled aggregate**, supporting sustainable construction and a circular economy

✓ **Rapid CO_2 sequestration** was achieved by the optimized mix, uptaking **6.60% of its mass** in CO_2 in a **7-day curing period**

✓ **Consistent CO_2 sequestration** was demonstrated in **the optimized mix.** Additionally, each sample of each mix **retained the sequestered CO_2** between the end of carbonation and the final measurement.

✓ **Structural Strength** met or exceeded industry standards for **3 of the 8 initial mixes**

✓ **Applications: scalable process** viable for controlled-production settings. Especially applicable for **modular construction**, which is predicted to grow into a trillion-dollar industry by 2040 (Bradley et al., 2024)

Photos taken by Shivani Wadawadigi

Future Work

1. Quantify carbonation depth and improve depth of CO_2 penetration
2. Evaluate long-term performance of carbonated concrete mix (freezing, rain)
3. Qualify relationship between mix composition and strength difference between control and carbonated samples

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