CO_2 Utilization in Concrete Production

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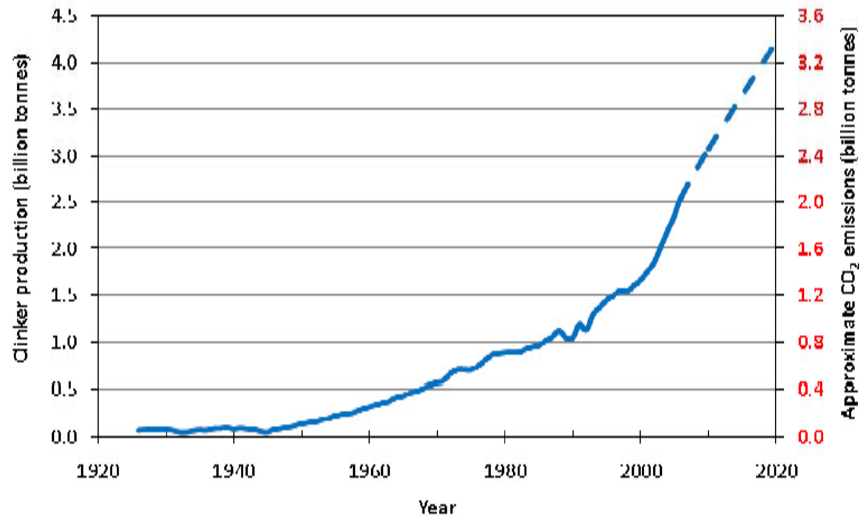
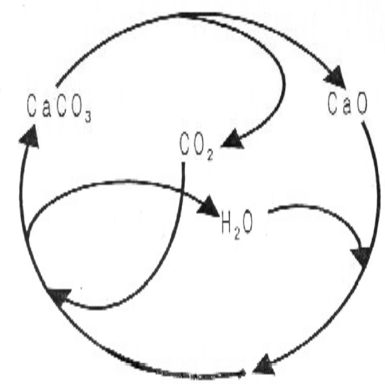
CO_2 Emission and Its Utilization





- Utilization of CO_2 in concrete production to reduce emission and improve performance

Use of CO_2 as Curing Agent

- Weathering carbonation at late age:
  - $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$
  - $3CaO \bullet 2SiO_2 \bullet 3H_2O + 3CO_2 \rightarrow 3CaCO_3 + 2SiO_2 \bullet 3H_2O$
  - CO_2 uptake is difficult to quantify
  - Passive carbonation can be detrimental
- Carbonation curing at early age (Young, 1974):
  - $CO_2 + H_2O \rightarrow H_2CO_3$
  - $C_3S + 1.2H_2CO_3 \rightarrow C_{1.4}SH_{0.6} + 1.2CaCO_3 + 0.6H_2O$
  - CO_2 uptake can be estimated
  - Performance can be improved

Benefits of Early Carbonation

- Technical:
  - Increased early age strength
  - Accelerated production
  - Reduced calcium hydroxide
- Environmental:
  - Permanent storage of CO_2 into a form of stable calcium carbonate
  - Carbon credit in a cap and trade system

How Much CO_2 Can Be taken?

- The theoretical maximum of CO_2 uptake by Portland cement :
  - ***CO_2 (wt%) = 0.785 CaO + 1.09 MgO + 1.42 Na_2O + 0.935 K_2O***
- At 100% carbonation, CaO is totally reacted with CO_2 to form $CaCO_3$ and carbon dioxide uptake can reach 50 wt%.

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO
Portland cement	62.9	20.7	3.7	3.0	4.2

Objectives

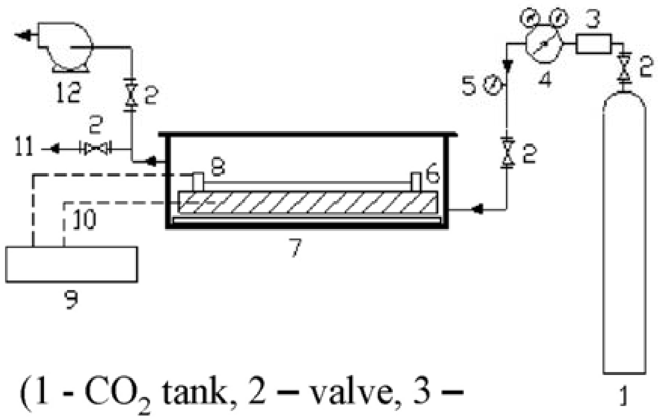
- To quantify carbon uptake capacities in dry mix concretes
  - Products: blocks, pavers, pipes, piles, hollow-core slabs, etc.
- To evaluate performance of carbonated products at different ages
- To perform cost analysis between carbon dioxide curing and steam curing

Mixture Proportion

		C	W/C	S/C	CA/C	Preset, hr	Carbonation time, hr
B1	Cement paste	1	0.15	0	0	0	2
B2	Cement paste	1	0.15	0	0	17	2
B3	Cement paste	1	0.15	0	0	0	18
B4	Cement paste	1	0.15	0	0	17	18
B5	Concrete	1	0.26	1.3	2.6	0	2
B6	Concrete	1	0.26	1.3	2.6	17	2
B7	Concrete	1	0.26	1.3	2.6	0	18
B8	Concrete	1	0.26	1.3	2.6	17	18

- Early carbonation parameters:
  - Recovered CO_2 (99%) at gas pressure of 1.5 bar.
  - Sample size: 76x127x30 mm & 25x25x254 mm

Carbon Uptake by Cement Binder



(1 - CO_2 tank, 2 – valve, 3 – heater, 4 – regulator, 5 - pressure gauge, 6 - bar sample, 7 - pressure vessel, 8 - LVDT assembly, 9 - data acquisition system, 10 – thermocouple, 11 – discharge, 12 - vacuum pump.)

1) Infrared (IR) based carbon analyzer method

$$CO_2\ uptake(\%) = \frac{(Mass)_{CO2@800C}}{(Mass)_{dry\ binder}}$$

2) Mass gain method

$$CO_2\ uptake(\%) = \frac{(Mass)_{aft,CO2} - (Mass)_{bef,CO2}}{(Mass)_{dry\ binder}}$$

Carbon Uptake

Cement paste:

	T, °C (bar)	WL,% (bar)	Uptake %, (bar)	T, °C (slab)	WL,% (slab)	Uptake, %, (slab)	CO_2 content, % (slab)		
							surface	core	Ave.
B1	51.6	13.99	10.65	89.4	20.76	10.83	10.21	8.83	9.52
B2	46.6	5.71	9.58	77.0	11.87	10.85	9.52	8.95	9.24
B3	47.9	14.41	13.78	97.3	22.41	12.68	11.70	10.08	10.89
B4	41.4	3.19	13.29	86.2	13.73	13.22	13.46	12.04	12.75

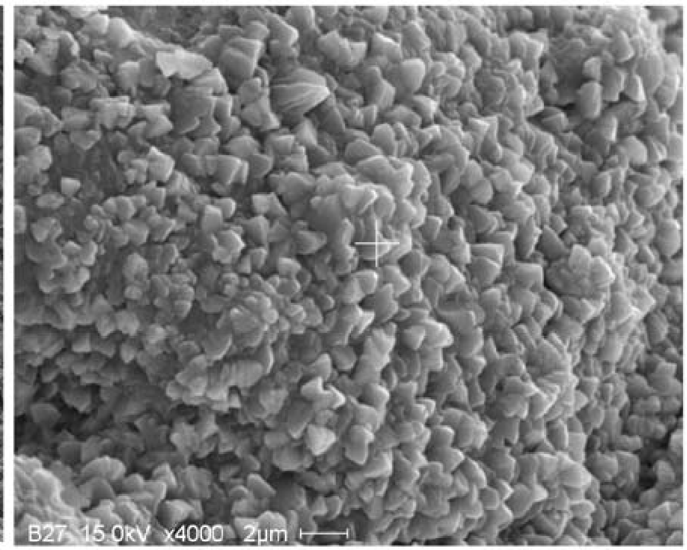
Note: T: peak temperature; WL: water loss; Uptake: CO_2 uptake based on Eq 1; CO_2 content: measured by CO_2 analyzer; Bar: measured from bar sample; Slab: measured from slab samples.

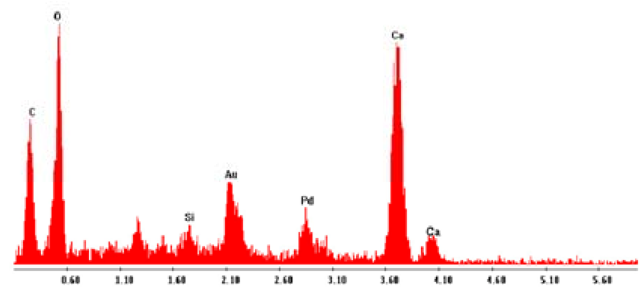
Concrete

	T, °C (bar)	WL,% (bar)	Uptake, % (bar)	T, °C (slab)	WL, % (slab)	Uptake, % (slab)	CO_2 content, % (slab)		
							Carb.	Hyd.	Diff.
B5	40.2	7.88	9.70	59.9	16.49	10.15	15.22	7.22	8.0
B6	41.0	0.65	7.38	43.1	6.67	8.37	16.10	8.36	7.74
B7	41.4	6.31	12.98	56.9	17.99	15.02	20.39	7.52	12.87
B8	37.6	0.60	11.75	41.7	5.93	10.46	20.11	9.25	10.86

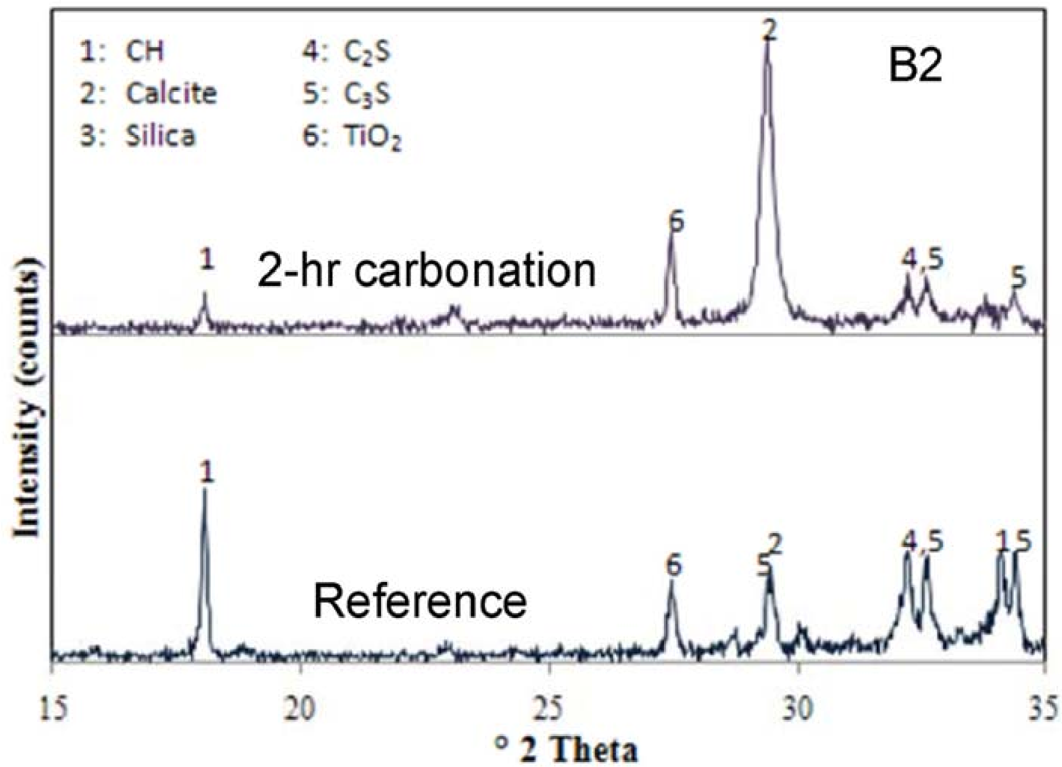
Note: T: peak temperature; WL: water loss; Uptake: CO_2 uptake based on Eq 1; CO_2 content: measured by CO_2 analyzer; Bar: measured from bar sample; Slab: measured from slab samples; Carb: carbonated; Hyd: hydrated; Diff: difference (CO_2 content due to carbonation).

SEM of Carbonated Concrete





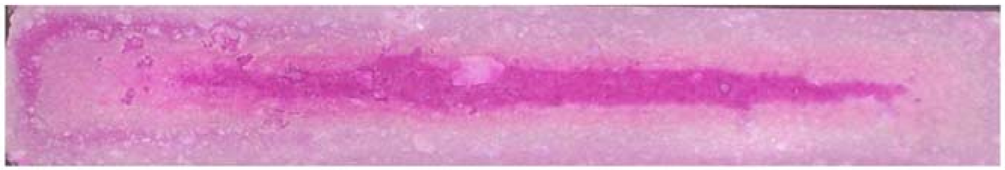
XRD Patterns



After 7-day subsequent hydration

Effect of Subsequent Hydration

Phenolphthalein tests of carbonated cement:

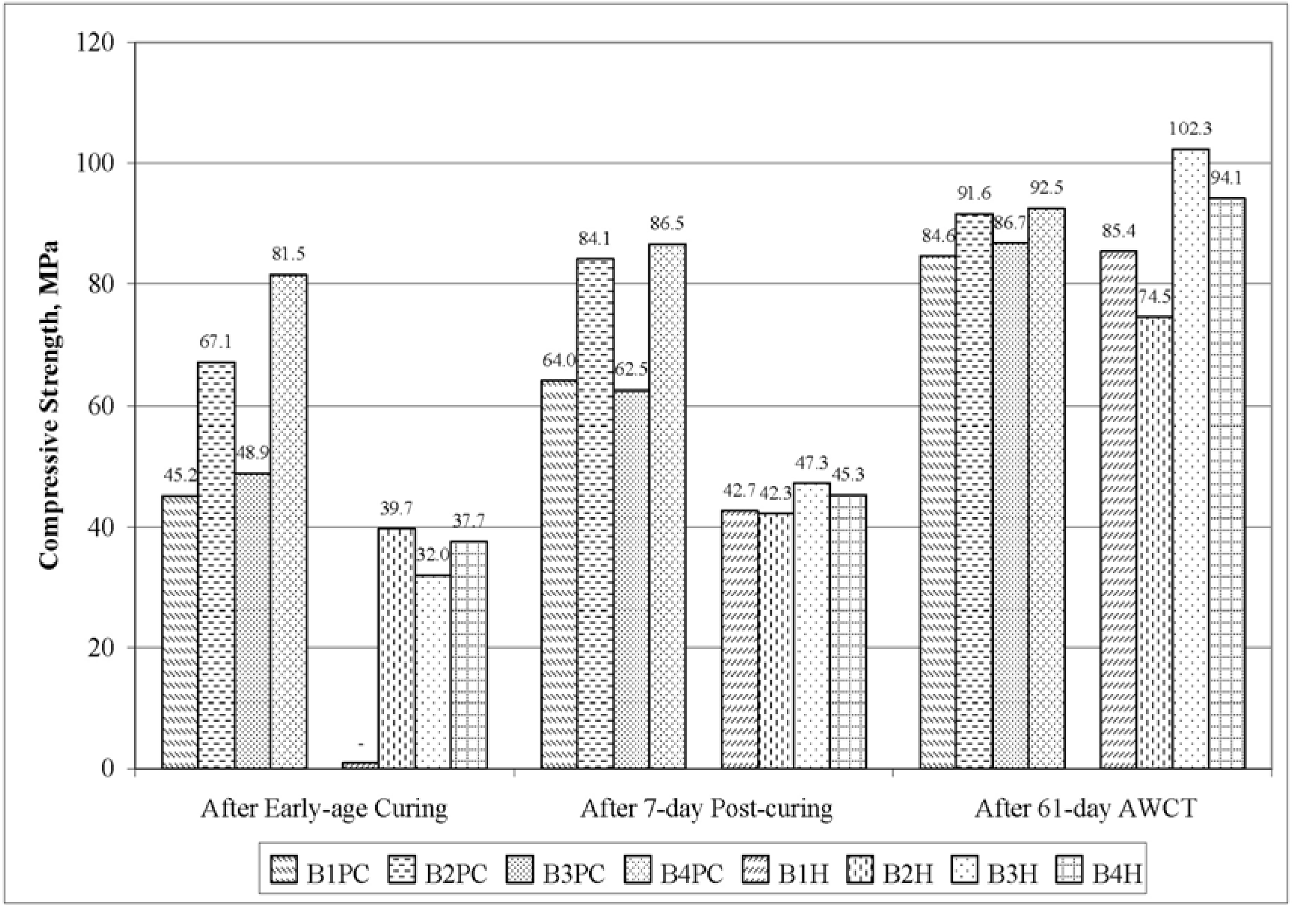


After 2 hours, uptake=13%

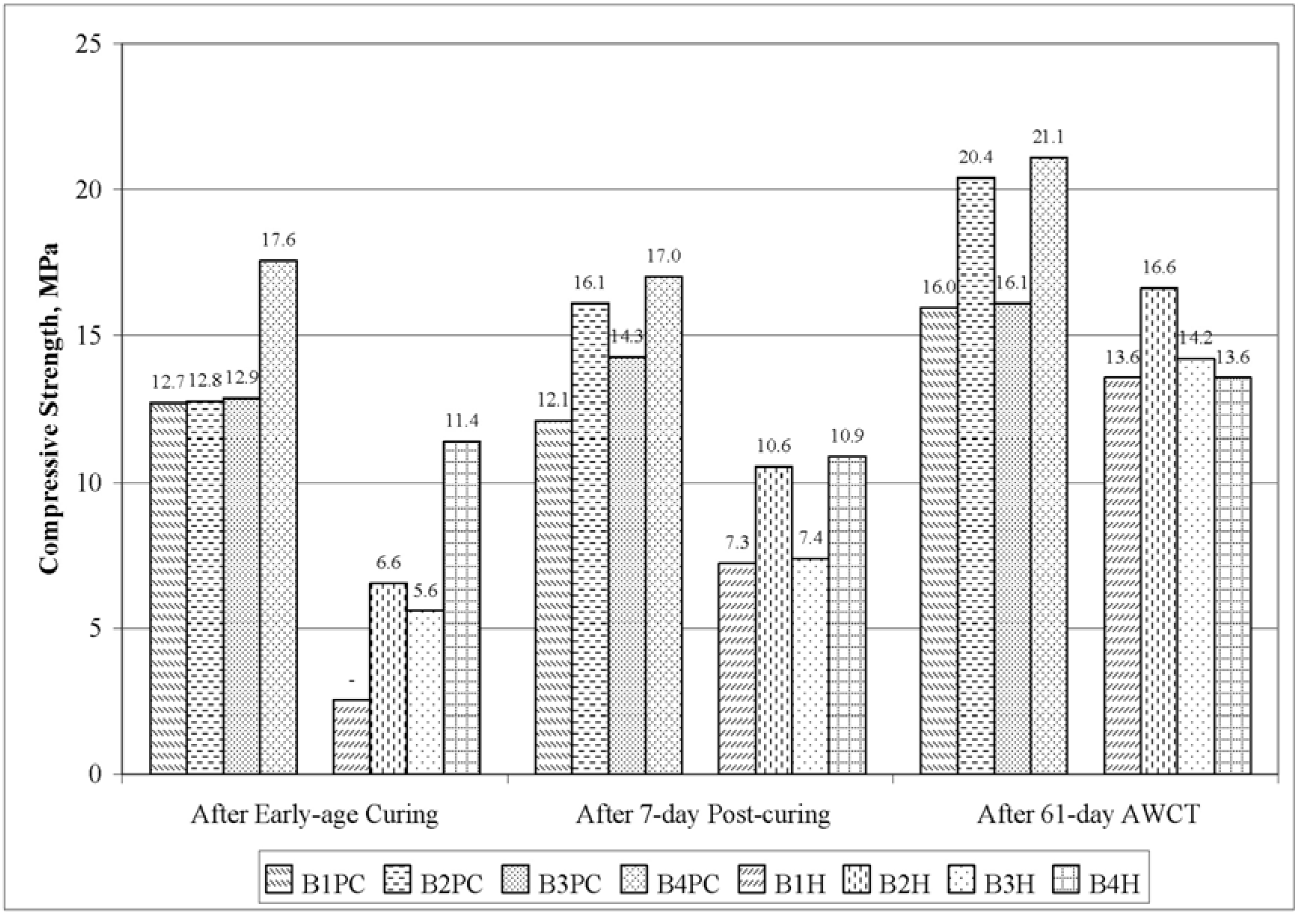
After 24 hours in sealed bag

After 28 days in sealed bag

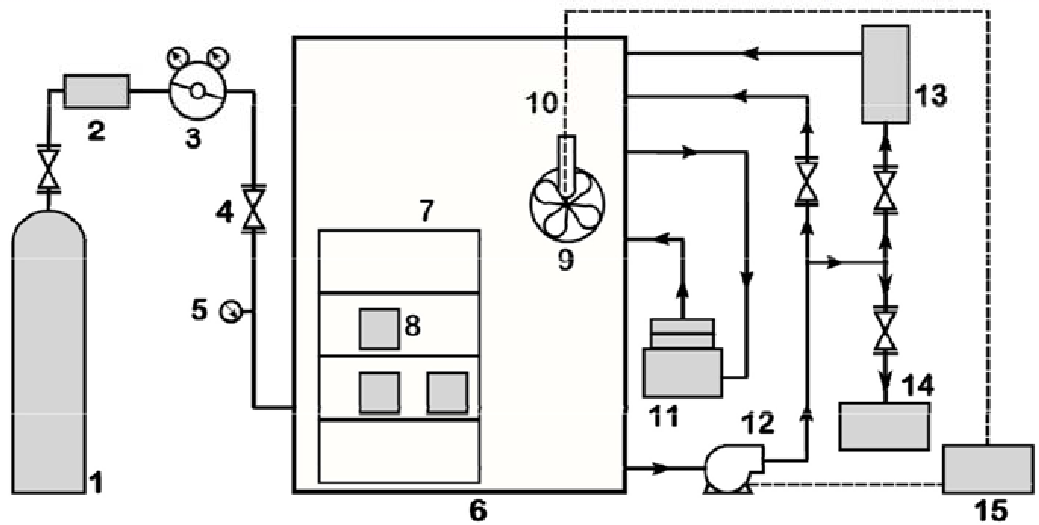
Strength in Cement Paste



Strength of Concrete



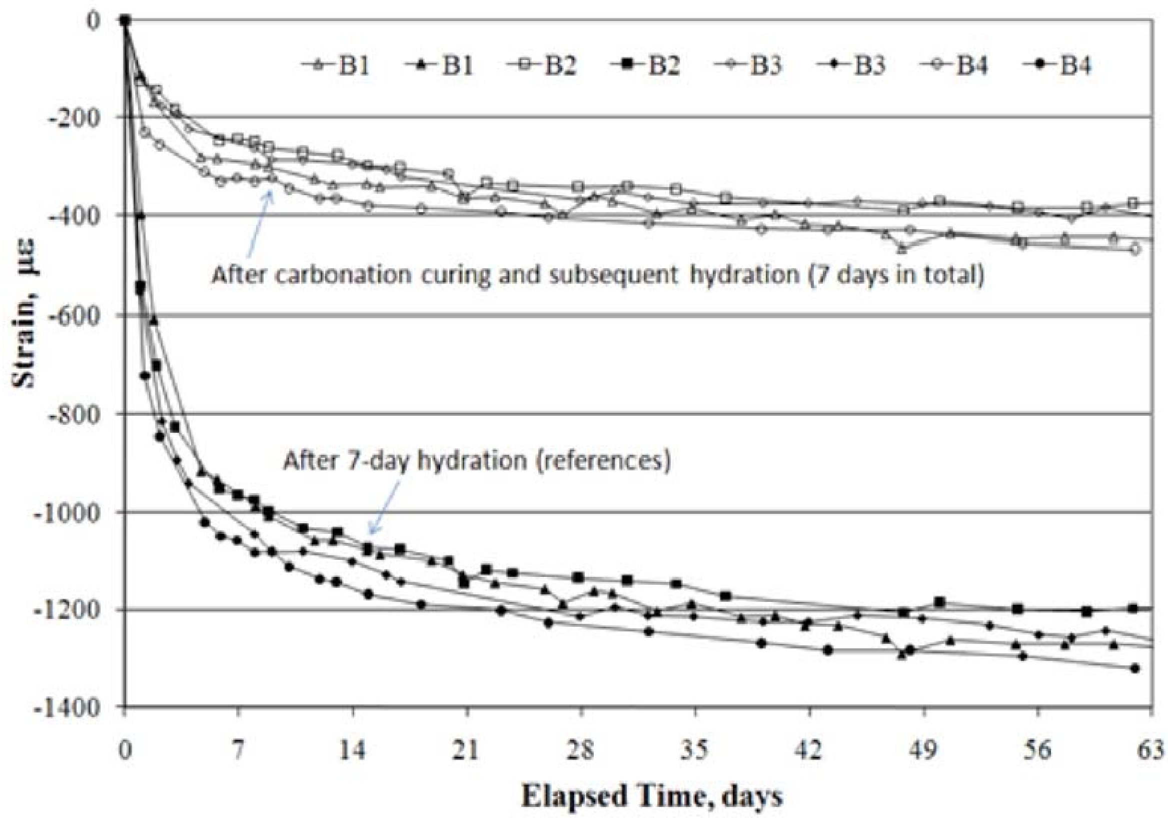
Atmospheric Weathering Carbonation Test (AWCT)



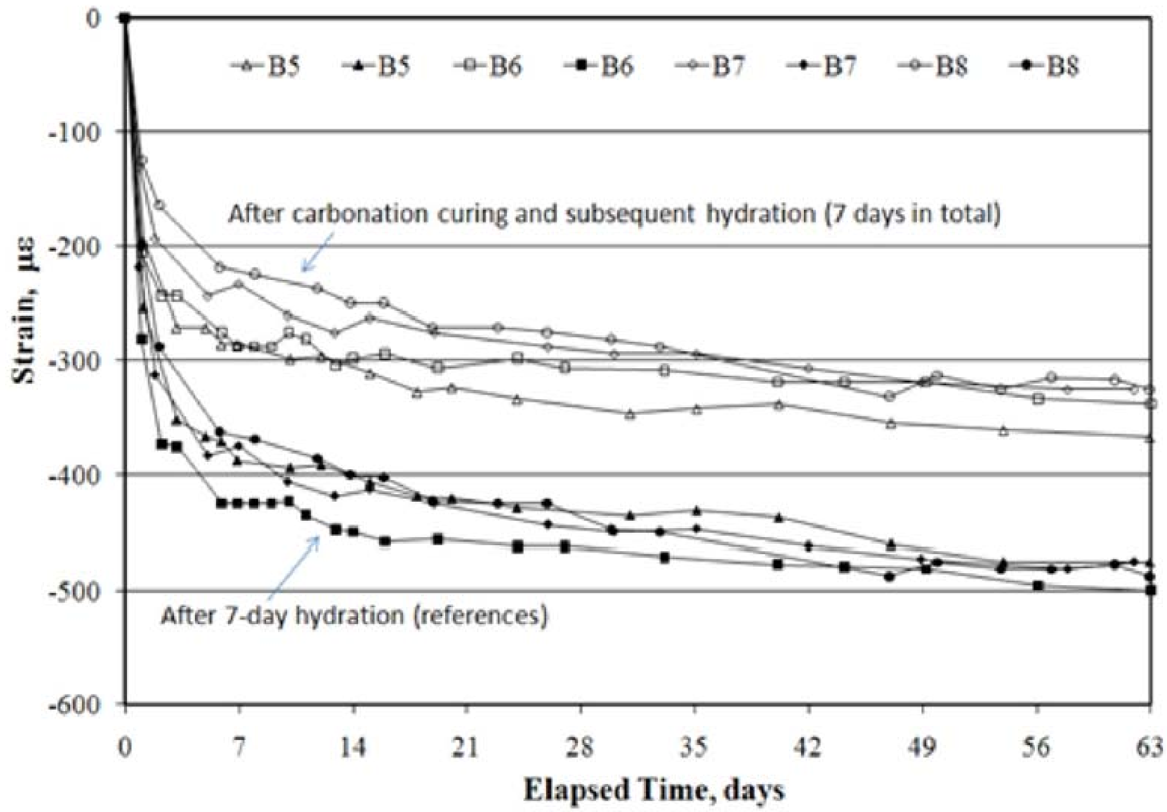
1 - gas tank
2 - heater
3 - regulator
4 - valve
5 - pressure gauge
6 - AWCT chamber
7 - shelves
8 - samples
9 - fan
10 - humidity probe
11 - humidifier
12 - pump
13 - desiccator
14 - CO2 analyzer
15 - humidity controller

Condition: 50%CO2, 60% RH, 25 ^{0}C, 7-day curing.

AWCT Shrinkage of Carbonated and Hydrated Cement



AWCT Shrinkage of Carbonated and Hydrated Concrete



Freeze-Thaw Resistance of Concrete

CSA A231.2-95 for 28-day concrete pavers:

•16-hr freezing at -15 C in 3% sodium chloride solution

•8-hr thawing at 22 C;

•Mass loss is calculated at10, 25 and 50 cycles.

Sample	Carbonation Treatment	Cumulative Mass Loss, g/m^2	
		10 Cycles	25 Cycles
SC	22 h Preset + 22 h CO2	218	1425
SH	Hydration	1762	10601

Carbonated, after 25 cycles

Hydrated, after 25 cycles

Freeze-Thaw Resistance of Concrete Pavers

Sample	Carbonation Treatment	CO_2 uptake, %	24-hr Strength, MPa	Cumulative Mass Loss, g/m^2	
				10 Cycles	25 Cycles
P1C	2 hr Preset + 4 hr	3.4	31	2.7	37.6
P2C	19 hr Preset + 5 hr	7.4	46	2.2	5.4
P3H	Hydration	0	35	26.9	328.0

Carbonated

Hydrated

Cost Analysis

- Steam curing
  - Atmospheric steam curing: 0.59 GJ/m^3=164 kWH/m^3
  - Assuming $0.1/kWH, 1$m^3$ concrete costs $16.4.
- Carbon dioxide curing
  - Assuming density = 2400kg/m^3, cement content = 20%, and carbon uptake = 10% of cement
  - One cubic meter concrete needs 48 kg CO_2
  - If cement producer captures CO_2 at a price of $50/t and sells it to concrete producer at $80/t, 1$m^3$ concrete costs $3.84.

Carbonation of Pervious Concrete

Mix Design	Unit	Unit/m3
Coarse Aggregate	kg	1498.00
Fine Aggregate	kg	104.00
Cement	kg	343.00
Silica Fume		
Water	kg	93.00
Air Entraining Agent	ml	
Super Plasticizer	ml	
W/C		0.2711
Paste/Aggregates		0.2722
Fine/Coarse		0.0694

Average carbon uptake in 2 hr = 8%

- Demoulded in 4hr;
- Dried in air overnight (19hr);
- Carbonated in a chamber for 2 hr at 1.5 bar with pure CO2;
- Tested at 24 hr, 7 days and 28 days

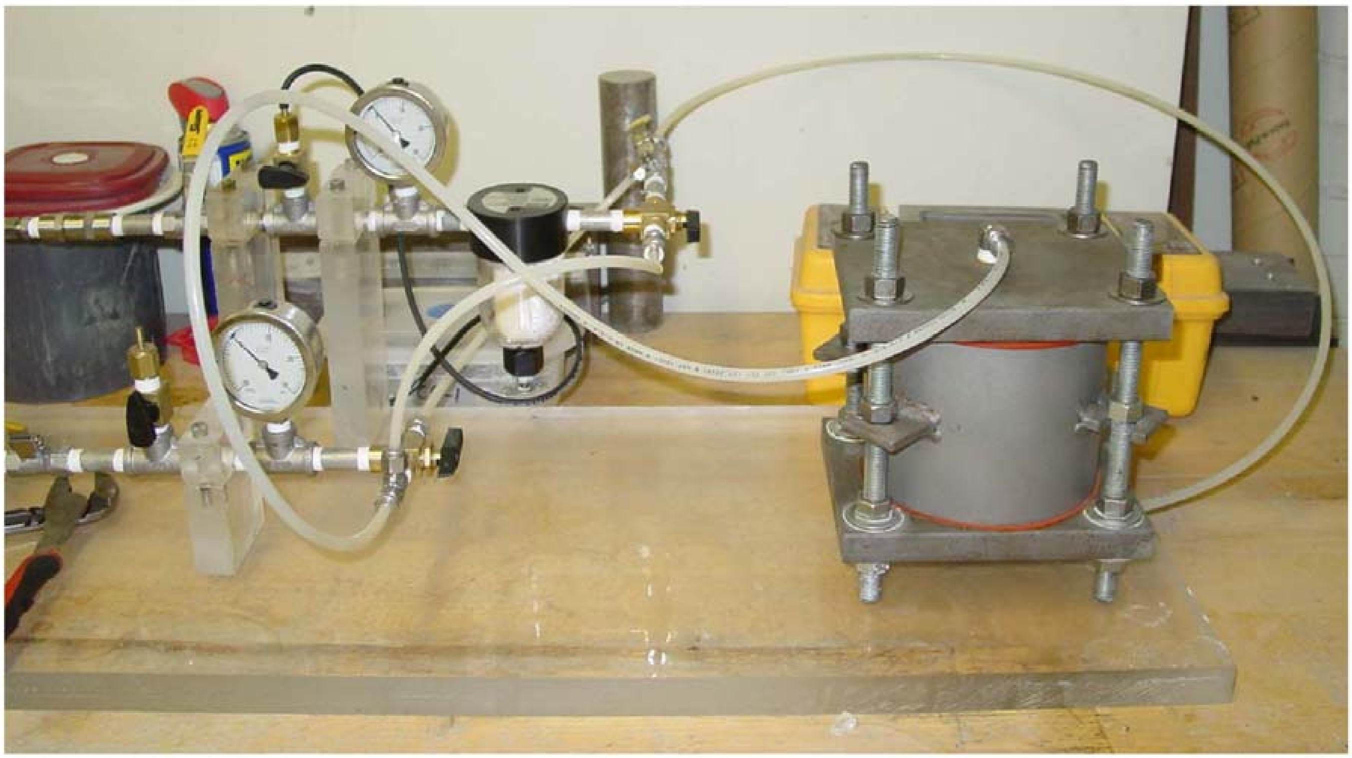
Performance of Carbonated Pervious Concrete

Age (Days)	Reference (Non Carbonated) Compressive strength (Mpa)			Carbonated Samples Compressive strength (Mpa)		
1	8.223	±	0.869	12.251	±	0.646
7	13.047	±	2.259	11.817	±	0.776
14	13.190	±	2.403	11.397	±	1.515
28	16.056	±	1.845	16.115	±	1.614

Age (Days)	Reference (Non Carbonated) k (cm/s)			Carbonated Samples k (cm/s)		
1	0.949	±	0.366	1.272	±	0.100
7	1.105	±	0.242	1.265	±	0.421
14	0.537	±	0.072	0.854	±	0.559
28	0.727	±	0.564	1.001	±	0.236

Age (Days)	Reference (Non Carbonated) Absorption (%)			Carbonated Samples Absorption (%)		
1	4.84%	±	0.11%	4.08%	±	0.04%
7	4.31%	±	0.12%	3.74%	±	0.04%
14	4.24%	±	0.03%	3.73%	±	0.04%

In-Situ Carbonation Simulation



Conclusions

- Carbon dioxide can be beneficially utilized in concrete production.
- Early carbonation has no detrimental effect on late hydration strength.
- High pH value of early carbonated concrete can be maintained, while $Ca(OH)_2$ is eliminated.
- Carbonation curing can cost less than steam curing due to energy reduction.

Challenge

- CO_2 curing is best suited to concrete products that have large specific surface area and use low w/c ratio.
- For thick products, the reaction efficiency will be reduced.
- To promote CO_2 utilization in concrete, an innovative system is needed to provide incentives for both cement and concrete producers.

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