Carbon Dioxide Sequestration in Concrete for Performance Enhancement and Emissions Reduction

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Carbonation curing at early age: A CO_2 consuming process

- Early carbonation mechanism (Young, 1974)
  - $C_nS+(n-x)CO_2+yH_2O \rightarrow C_xSH_y+(n-x)CaCO_3$
- CO_2 uptake (Steinour, 1956)
  - $\%CO_2 = 0.78\ CaO + 1.1\ MgO + 1.4\ Na_2O + 0.9\ K_2O$
- Technical advantages:
  - Accelerated hydration and early age strength
  - Eliminated $[Ca(OH)_2]$
  - Reduced atmospheric carbonation in service
  - Reduced efflorescence in service
  - Decreased permeability

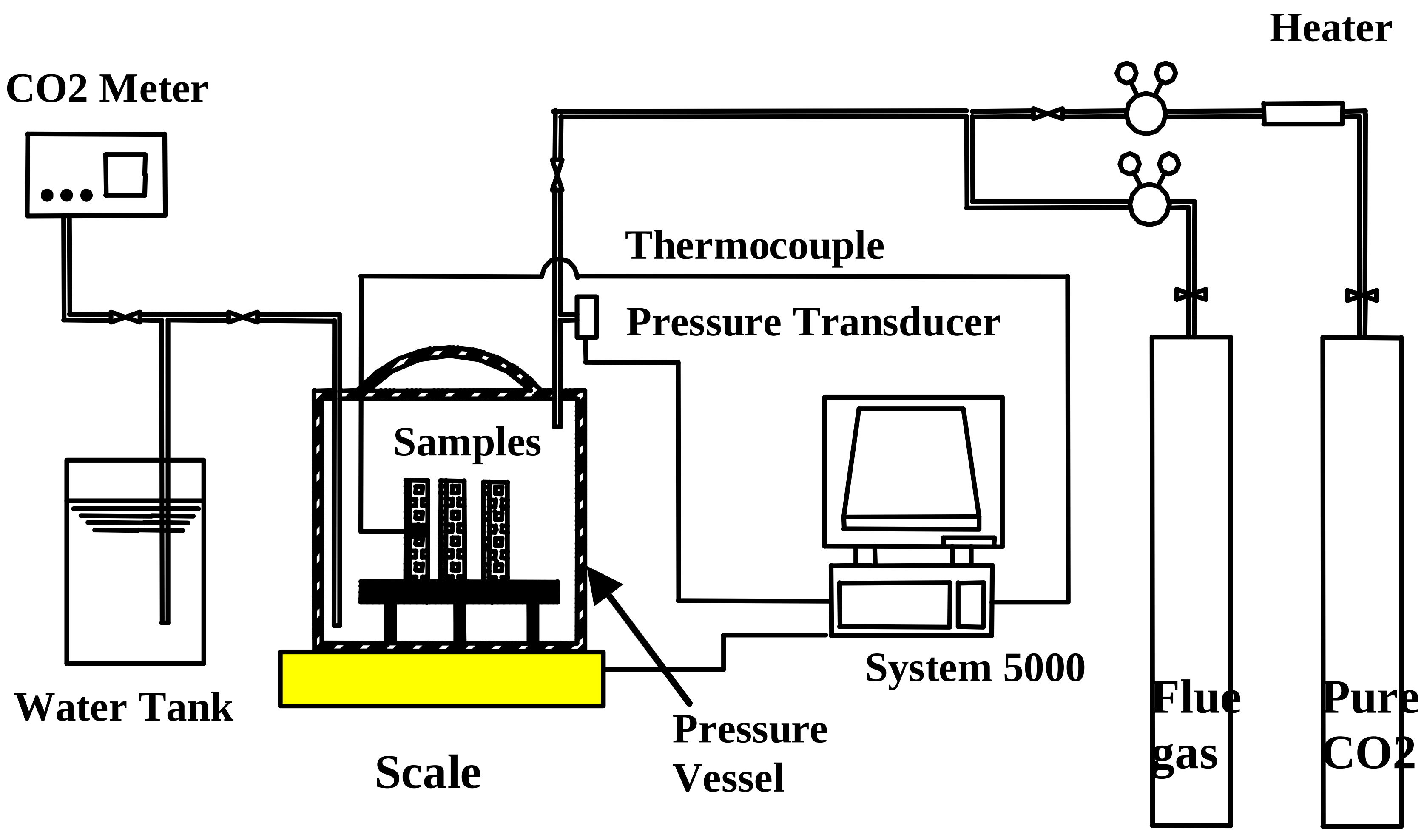
Objectives

- To quantify carbon uptake by precast concrete products (blocks, pavers, cement boards and fiber boards)
- To evaluate performance of carbonated products at different ages
- To determine the potential for emissions reduction

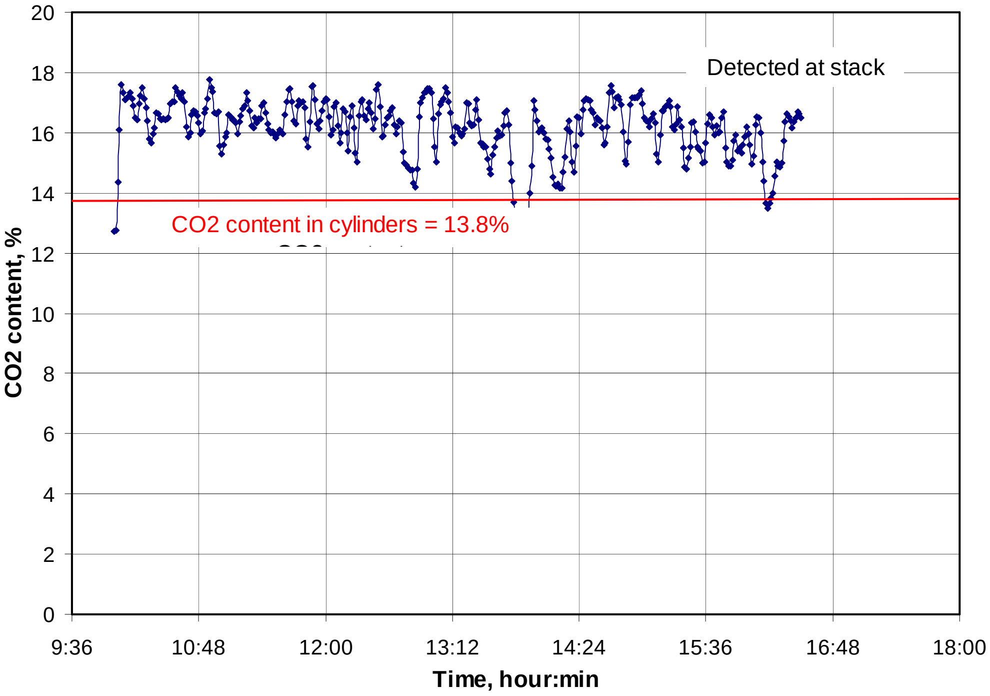
Processing parameters

- Carbonation parameters:
  - For flue gas (14% CO_2), P=5 bar, time=2-8hr
  - For recovered CO_2 (99% CO_2), P=1.5 bar, time=2hr
- Materials (dimension=75x100xt mm):
  - Block: c=10%, w/c=0.26, compact=10 MPa
  - Paver: c=20%, w/c=0.26, compact=10 MPa
  - Mesh bead board: c=60%, w/c=0.3 , cast, dried
  - Fiber board: c=52%, w/c=0.2-0.26, compact=0.7MPa, dried

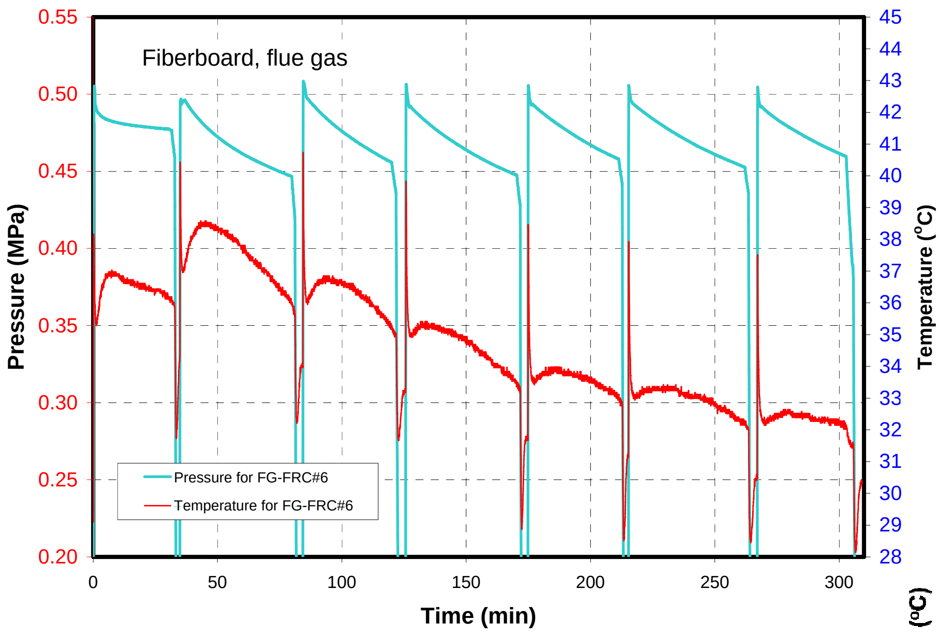
Setup for Carbonation Curing



Collection of cement kiln flue gas

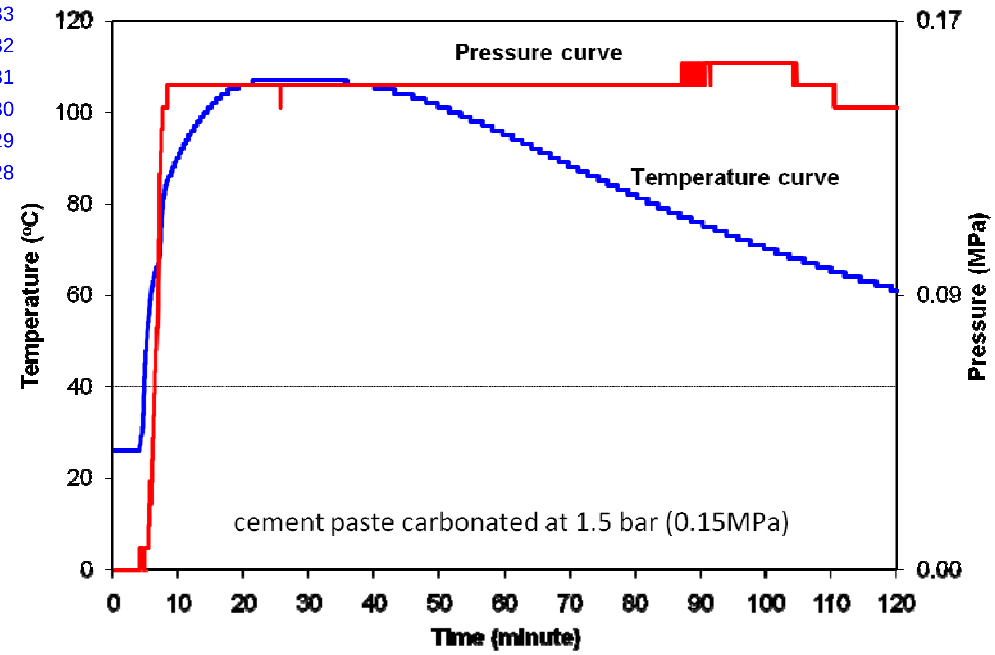


Pressure and temperature curves



Pseudo-dynamic process for flue gas

Statics process for recovered CO_2

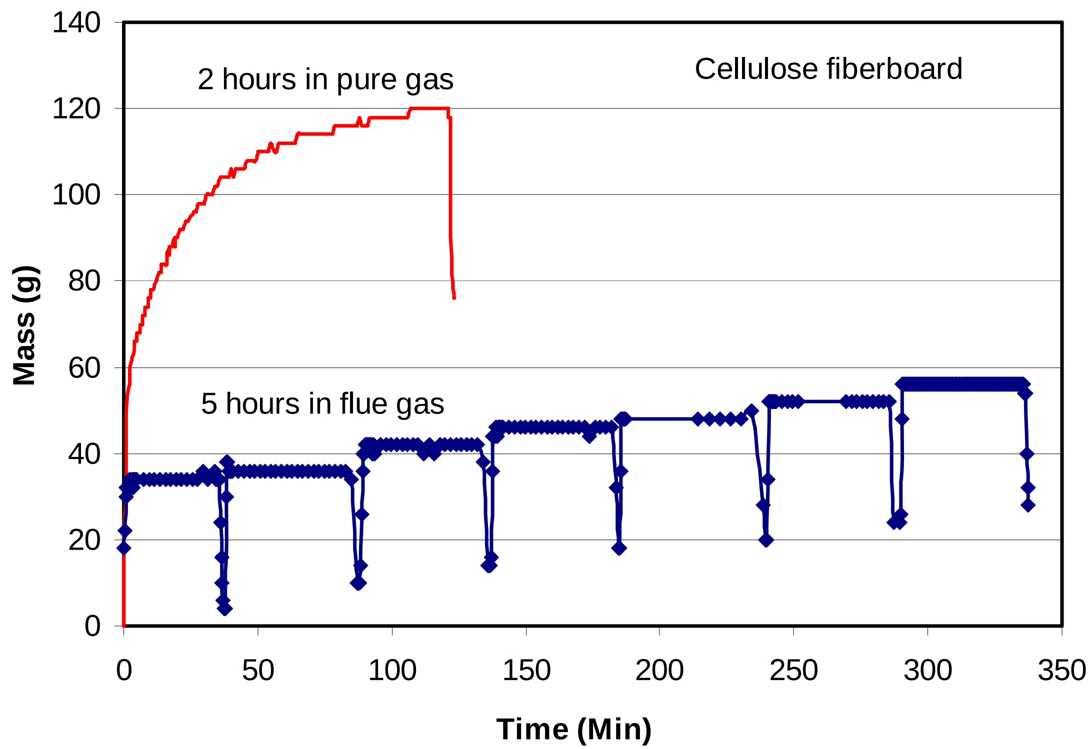


Quantification of CO_2 uptake

- Uptake due to direct mass gain:

$$\%Mass\ gain = \frac{m_{CO2}}{m_{cement}} = \frac{(Mass)_{aft,CO2} - (Mass)_{bef,CO2} + (Mass)_{lost\ water}}{m_{cement}}$$

- Uptake from mass curve

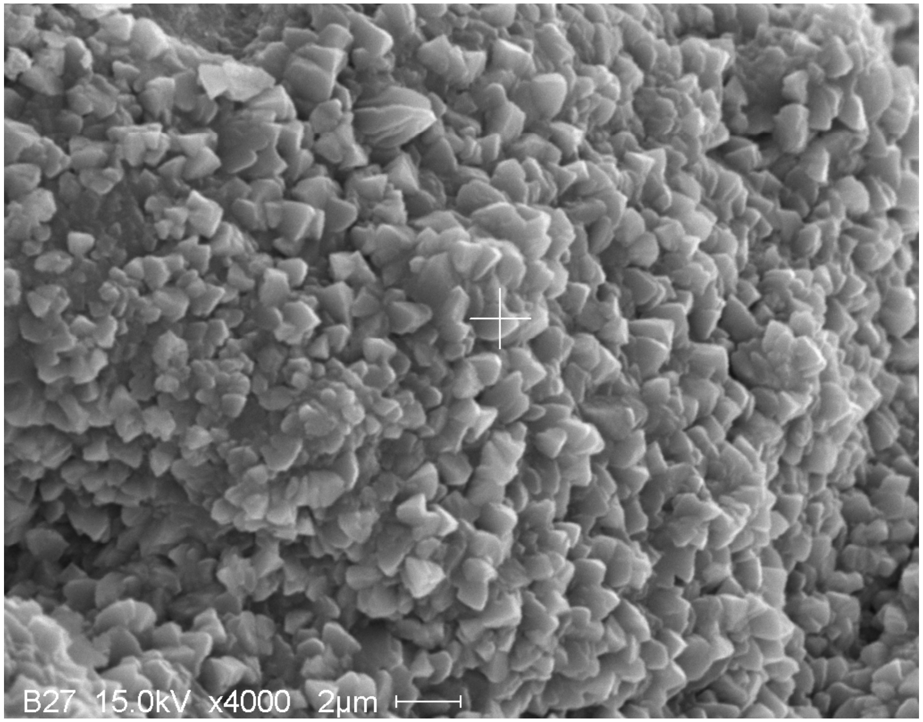


Carbonated concrete block

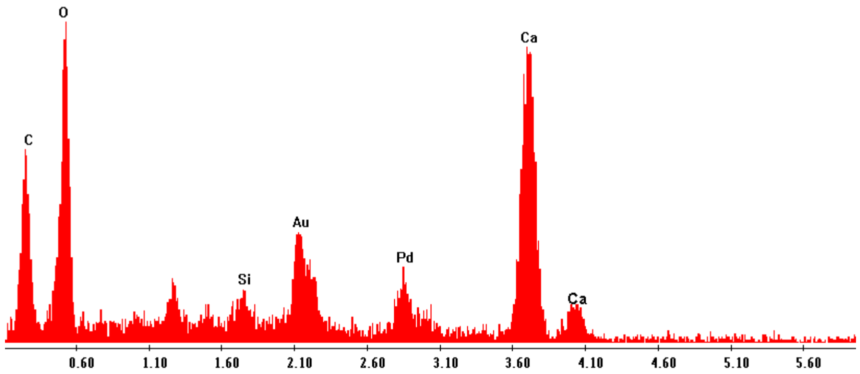
CO2 uptake (%) & compressive strength (MPa):

Case (with recovered CO2)	Uptake, %	2/4/6/8 hr fc	24 hr fc	28 days in plastic bag, fc	28 days in water, fc
1, Permacon product			14.2		
2, hydration reference	0	2.1 (2hr)	12.8	16.1	23.5
3, 2hr CO2	7.7	7.4 (2hr)	10.4	22.8	25.5
4, 2hr CO2+4 hr steam	8.8	8.4 (8hr)	14.6	21.4	23.7
5, 4hr steam	0	5.2 (6hr)	14.6	22.4	24.0
6, 4hr steam+2hr CO2	13.7	10.8 (8hr)	15.2		
7, 4hr CO2	11.0	7.6 (4hr)	10.3	23.3 w/spray	23.2

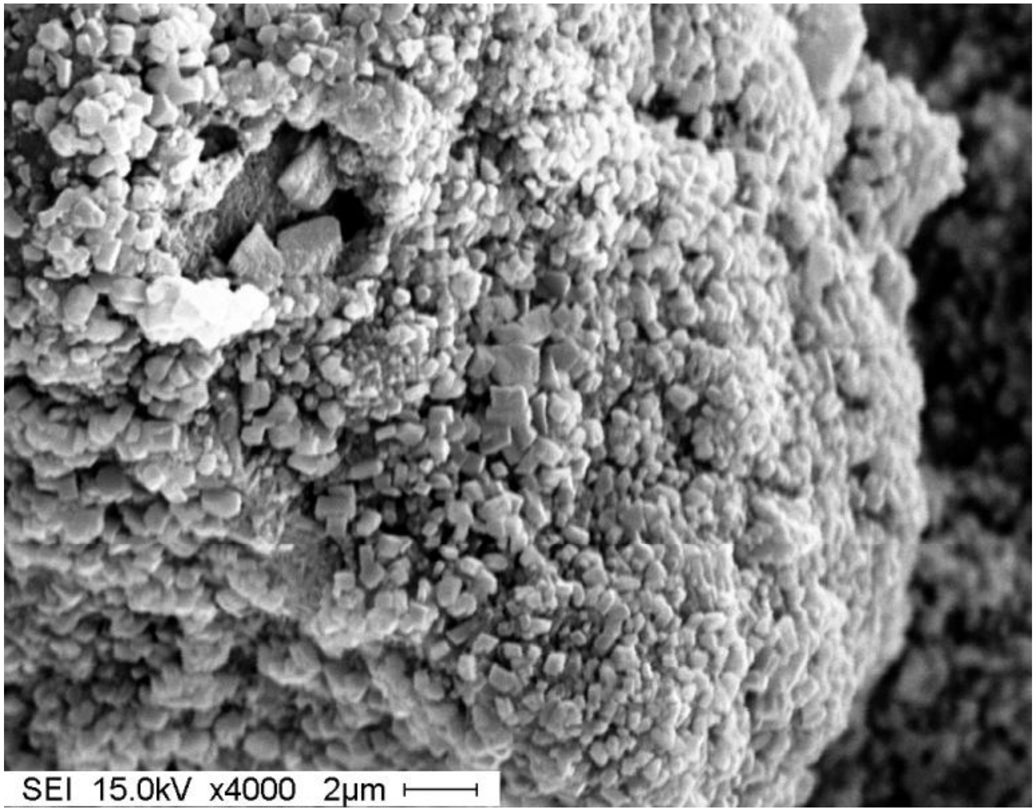
SEM of carbonated block (99%CO_2)

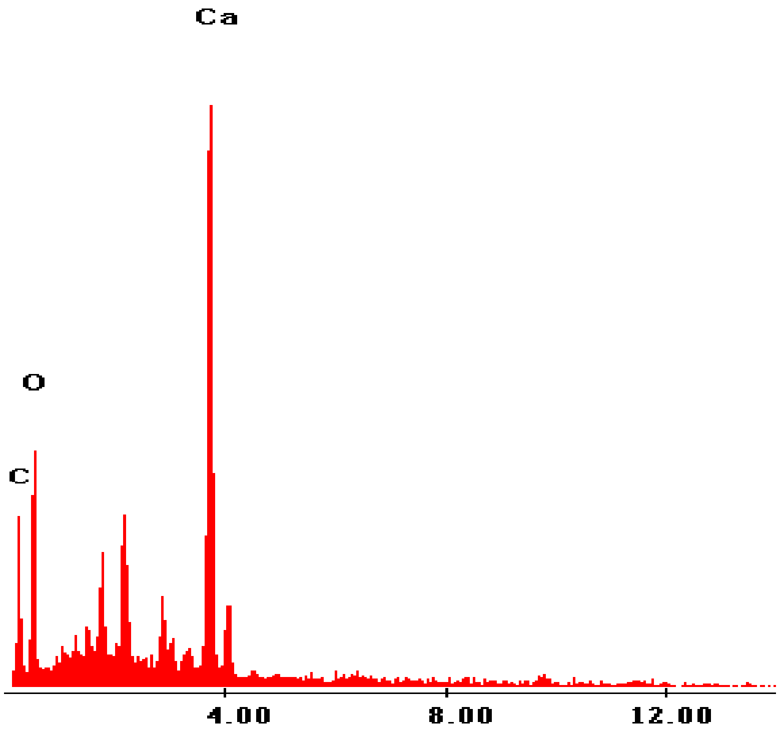


Average CO2 uptake=9.8%



SEM of carbonated block (14%CO_2)

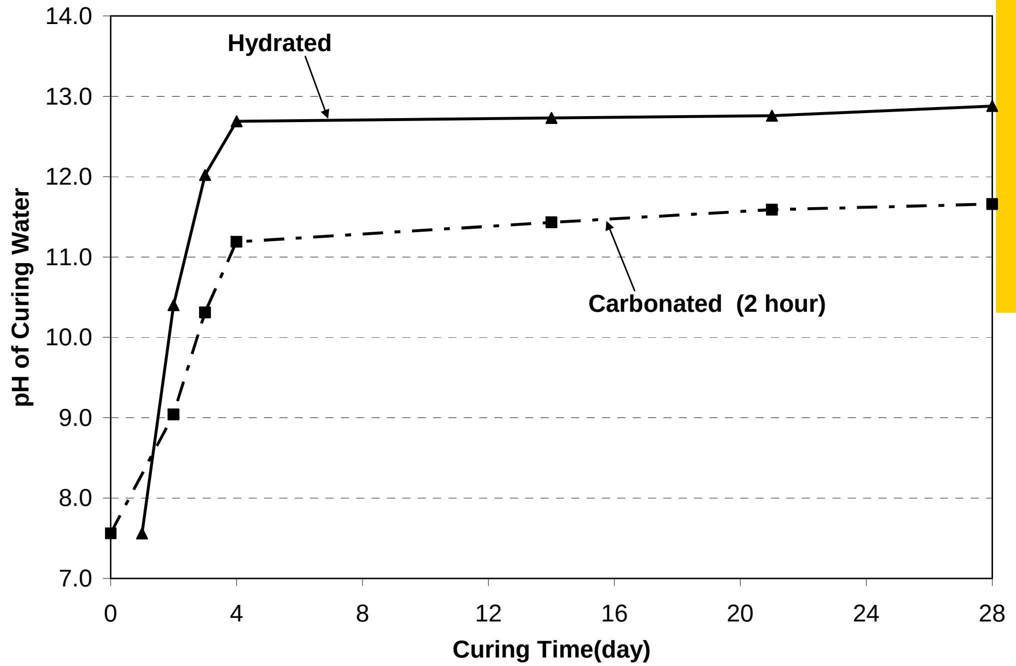


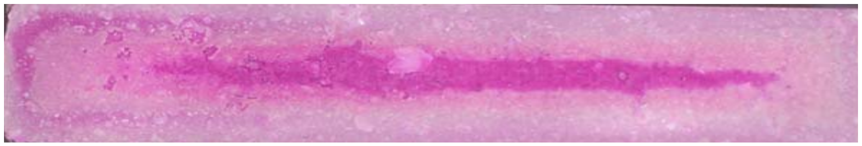


Average 5-hr strength=8.3 MPa

Average CO2 uptake=6.4%

pH of carbonated cement

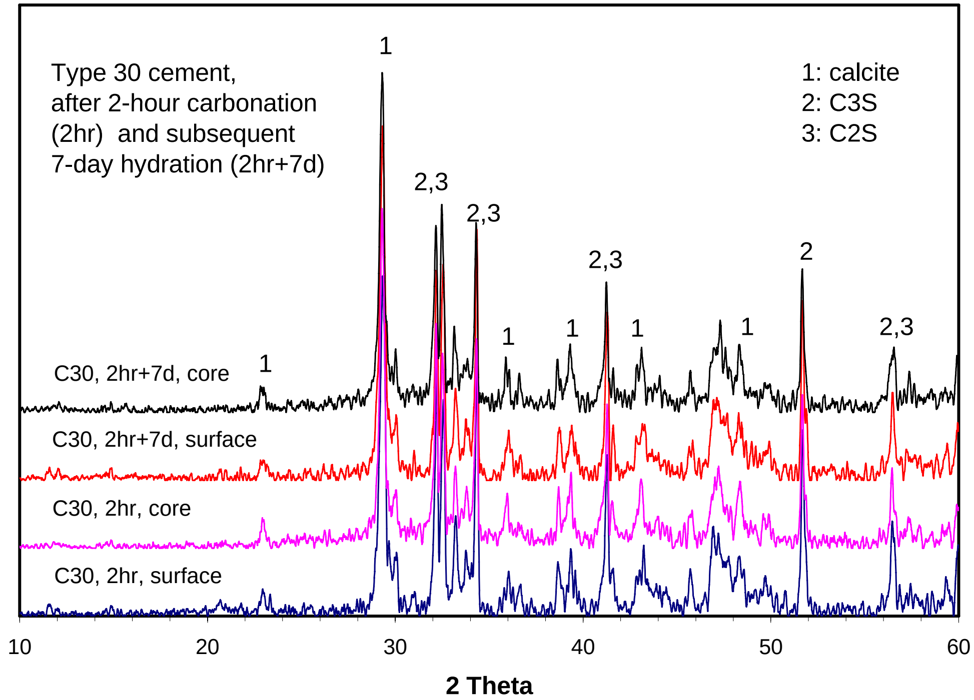




After 2 hours, uptake=13%

After 24 hours in sealed bag

After 28 days in sealed bag



Eliminated $Ca(OH)_2$

Carbonated fiberboard

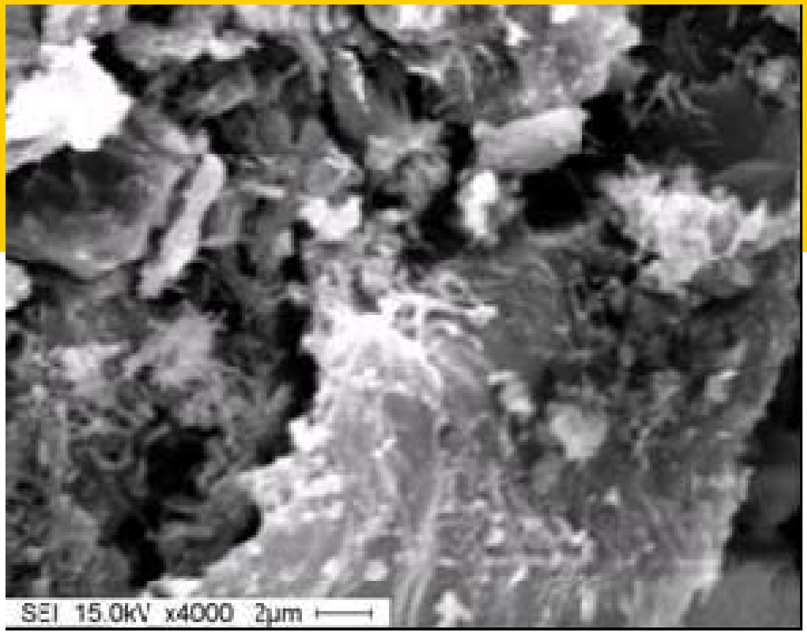
Comparison of uptake and strength by flue gas & pure gas:

				Carbonation Strength (MPa)		Hydration strength (MPa)	
Batch	Product	Mass Gain,%	Water Loss,%	2hr/5hr	28-day	5-hr	28-day
B1	Paste	6.8	13.5	7.4(5h)	11.0	0.4	10.2
B2	CFB	7.0	14.7	10.2(5h)	15.7	3.1	15.6
B3	Paste	13.5	55.5	8.1(2h)	8.4	0.4	10.2
B4	CFB	18.9	59.5	10.5(2h)	12.0	3.1	15.6

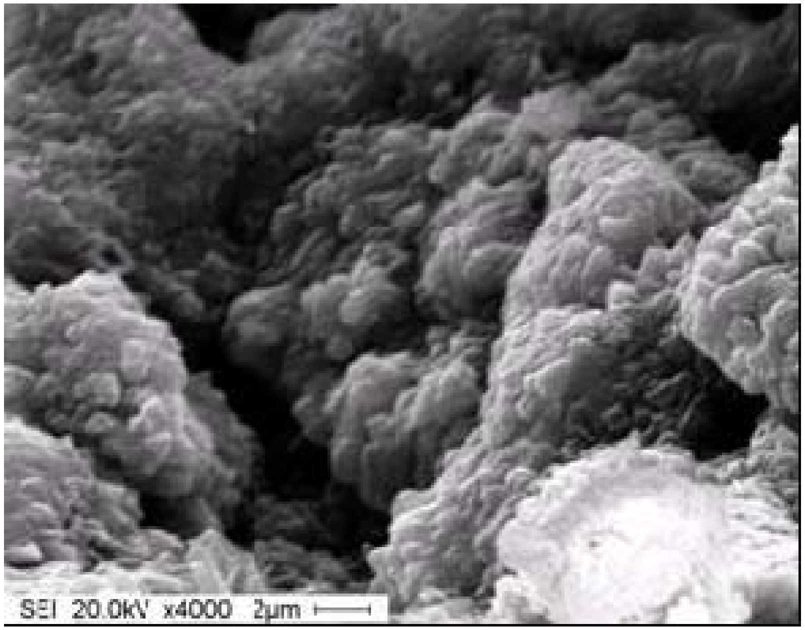
B1 & B2: flue gas carbonation (99% CO_2);

B3 & B4: pure gas carbonation (14% CO_2).

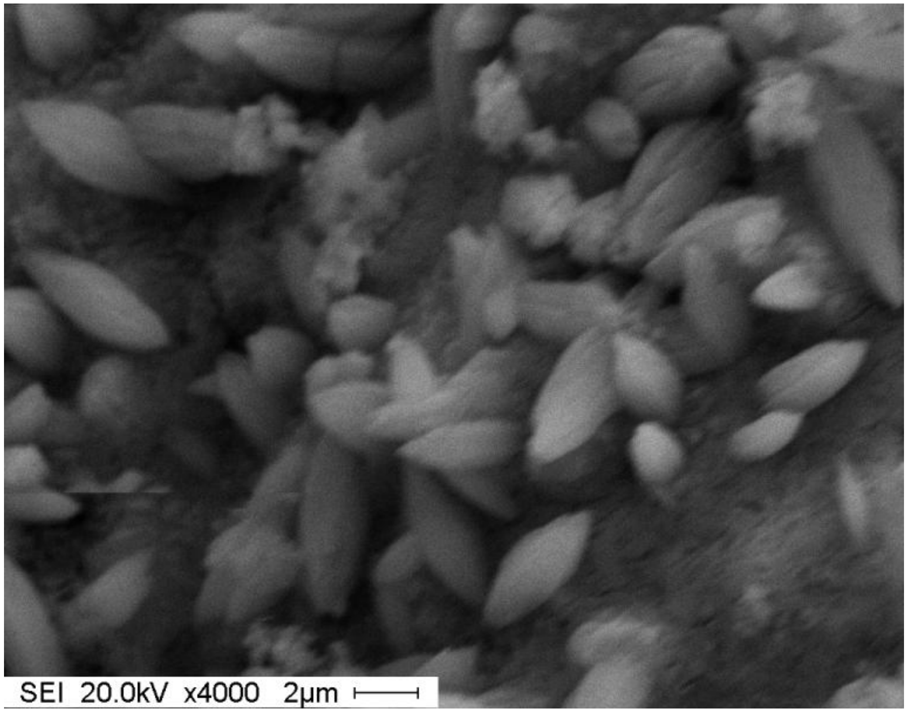
SEM of carbonated cellulose fiberboard



Hydrated

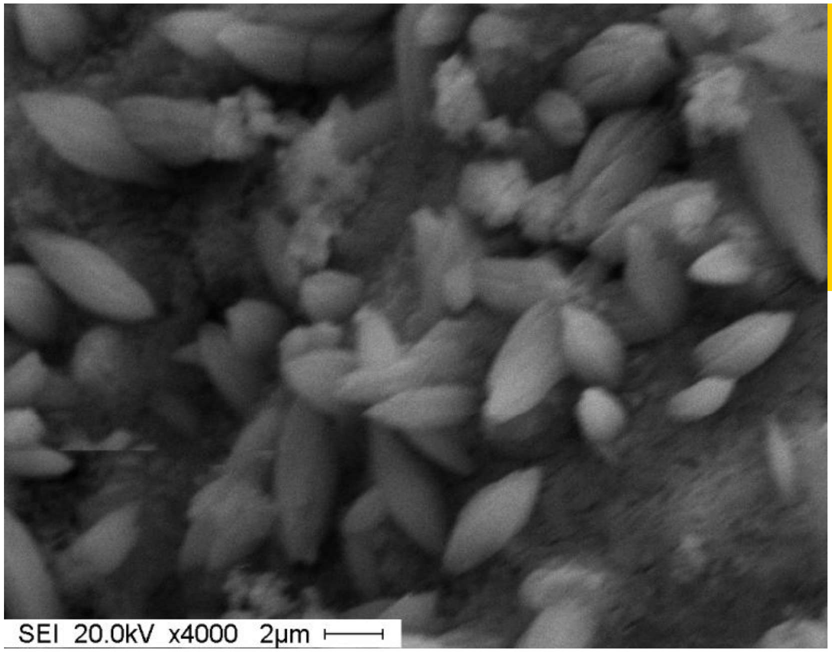


Carbonated in flue gas

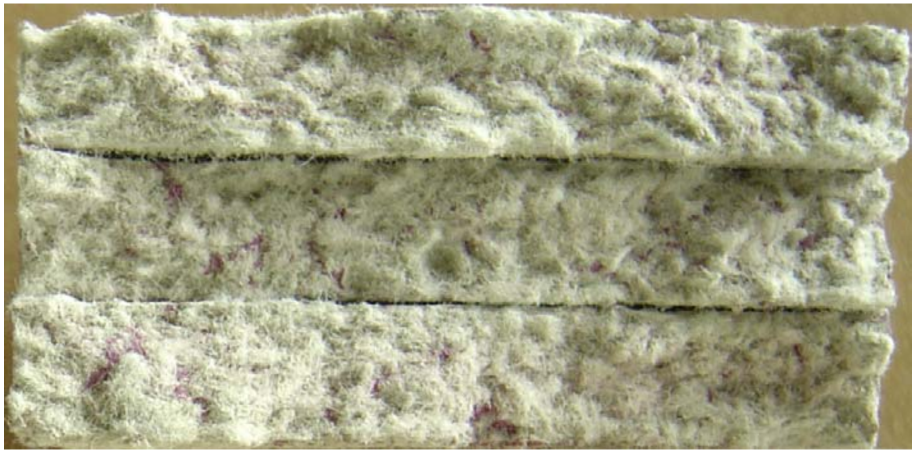


Carbonated in pure gas

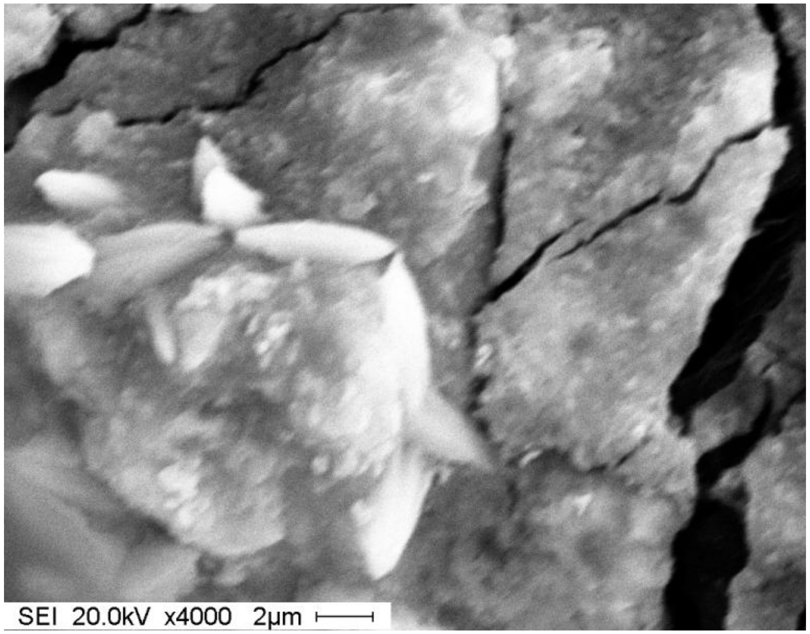
Effect of subsequent hydration on pH



Immediately after 2hr carbonation



Phenolphthalein tests



After 28 days in moisture room

Potential of carbon uptake by precast products in US and Canada

	CMU	Paver	Mesh board	Fiberboard
Annual production in US and Canada	4.3×10^9 units	74×10^6 m^2	75×10^6 m^2	9.1×10^8 m^2
Cement used (Mt)	5.9	2.6	0.595	4.8
%Uptake with 99% CO_2	9.8%	9.8%	12.2%	18.9%
Total uptake from 99% CO_2 (Mt)	0.578	0.255	0.073	0.907
%Uptake with flue gas CO_2	6.3%	6.3%	4.4%	8.1%
Total uptake from flue gas (Mt)	0.372	0.164	0.026	0.389

Energy consumption and CO_2 penalty

			On site		Off site	
Step	**Aspect**	**Unit**	**US**	**CAN**	**US**	**CAN**
Recovery	Energy	(kWh/t)	198	198	198	198
	CO_{2e}	(kg/t)	119.8	43.6	119.8	43.6
Compression	Pressure	(MPa)	2	2	2	2
	Energy Required	(kWh/t)	92.5	92.5	92.5	92.5
	CO_{2e}	(kg/t)	56.0	20.4	56.0	20.4
Transport	distance	(km)	-	-	150	150
	CO_{2e}	(kg/t)	-	-	16.4	16.4
Total	CO_{2e}	(kg/t)	177.4	64.5	193.8	80.9
	Net Efficiency	(%)	82.3	93.5	80.6	91.9

Assuming: 605 gCO2/kWh in the US, 220 gCO2/kWh in Canada.

Energy comparison

	Energy for 1500 concrete blocks (GJ)	Energy per m^3 concrete (GJ)
Steam curing		
• I: atmospheric steam curing in ordinary kiln	5.242	0.463
• II: high pressure steam curing (autoclaving)	7.976	0.705
• III: atmospheric steam curing in EPS insulation kiln	1.540	0.136
• IV: atmospheric steam curing using autoclave chamber	2.366	0.209
Carbon dioxide curing		
• MEA method (290kWh/tCO2=1.04GJ/tCO2) at 9.8% uptake rate and 10% cement content	0.213	0.019

Conclusions

- The annual CO_2 sequestration in concrete building products can reach 1.8 Mt (1.44 net Mt) with recovered CO_2 and 0.9 Mt (0.72 net Mt) with flue gas in US and Canada .
- Assuming cement production in US and Canada is about 100Mt/y and its CO_2 emissions is 70%, 1.44Mt net CO_2 uptake can reduce emissions by 2.1%.

Conclusions

- Flue gas carbonation can have sufficient early strength and subsequent hydration.
- Early carbonation has no detrimental effect on late hydration strength.
- pH of early carbonated concrete can be maintained above 11.5, while $Ca(OH)_2$ is eliminated.
- Carbonation consumes much less energy than steam process.

The future

- Cement plant could produce two commodities: cement and CO_2.
- A carbon credit system has to be established to provide incentives for producers.
- More researches are needed to help enhance the uptake capacity, identify the limits and introduce more niche products that are in favor of carbonation.

Acknowledgment

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