

Using Carbon Dioxide as a Beneficial Admixture in Ready-Mixed Concrete

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Abstract

Industry awareness of CO₂ emissions from cement production has prompted research into the use of captured carbon dioxide as a feedstock in the production of concrete. Two industrial trials have examined the use of CO₂ in ready-mix production. A CO₂ injection-system delivered carbon dioxide into a ready-mix truck during batching and mixing of concrete. The carbon dioxide was thereby absorbed into the concrete and formed stable, finely distributed nano-scale carbonate reaction products. The impacts of carbon dioxide dose, injection method and time of injection were examined. The concrete slump and temperature was measured. Compressive strength and resistivity were measured at ages from 24 hours to 91 days. Strength improvements up to 14% at 24 hours and 26% at 58 days were observed. The resistivity was not affected by the carbonation treatment. The strength increase is attributable to the reaction of carbon dioxide with the cement very early after hydration started. A combination of isothermal calorimetry and microstructural analysis suggests that the carbonates seed the hydration and contribute to the development of a stronger microstructure. The use of waste carbon dioxide in the process offers a means to upcycle the CO₂ as a beneficial additive to concrete that could be widely employed throughout the built environment.

1 Introduction

Carbon dioxide emissions are recognized as a significant issue relating to cement production and the use of concrete as a building material. It is estimated that 5% of the world's annual CO₂ emissions are attributable to cement production (Damtoft et al. 2008). The industry has previously recognized a number of approaches to reduce the emissions intensity of the cement produced and used (IEA 2009). The most significant improvements in efficiency and cement substitution are likely to be already known and available. Future emissions improvements will likely be incremental. Innovative approaches are sought that can be a part of a portfolio strategy. Thus, a range of further approaches will also have to be pursued.

One potential method is to upcycle captured carbon dioxide into concrete products. The mechanism of the carbonation of freshly hydrating cement was systematically studied in the 1970s at the University of Illinois. The main calcium silicate phases in cement were shown to react with carbon dioxide, in the presence of water, to form calcium carbonate and calcium silicate hydrate gel (Berger et al. 1972) as shown in equations 1 and 2:



Further any calcium hydroxide present in the cement paste will react with carbon dioxide, as show in equation 3:



The carbonation reactions are exothermic. The reaction proceeds in the aqueous state when Ca²⁺ ions from the cementitious phases meet CO₃²⁻ ions from the applied gas. The carbonation heats of reaction for the main calcium silicate phases are 347 kJ/mol for C₃S and 184 kJ/mol for β-C₂S (Goodbrake et al. 1979) and 74 kJ/mol for Ca(OH)₂ (Moorehead 1986).

When the calcium silicates carbonate, the calcium silicate hydrate (C-S-H) gel that forms is understood to be intermixed with CaCO₃ (Berger et al. 1972). C-S-H gel formation occurs even in an ideal case of β-C₂S and C₃S exposed to a 100% CO₂ at 1 atm given the observation that the amount of carbonate that forms does not exactly correspond to the amount of calcium silicate involved in the reaction (Goodbrake et al. 1979).

The reaction of carbon dioxide with a mature concrete microstructure is conventionally acknowledged to be a durability issue due to such effects such as shrinkage, reduced pore solution pH, and carbonation induced corrosion. In contrast, a carbonation reaction integrated into concrete production reacts CO₂ with freshly hydrating cement, rather than the hydration phases present in mature concrete, and does not have the same effects. Rather, by virtue of adding gaseous CO₂ to freshly mixing concrete the carbonate reaction products are anticipated to form in situ, are of nano-scale and homogenously distributed.

Earlier work had pursued reacting carbon dioxide with ready-mixed concrete to maximize the carbon dioxide absorption (Monkman 2014). A limited reaction time and effects on workability were identified as challenges to overcome. Subsequent lab work using isothermal calorimetry identified the potential performance benefit of using an optimized low dose of carbon dioxide to promote the development of finely distributed

carbonate reaction products. It was concluded that a small dose of carbon dioxide could feasibly be used to provide performance benefits in ready-mixed concrete.

2 Experimental

Industrial experiments were conducted where carbon dioxide was delivered to ready-mixed concrete during its production. The trials took place at Metrix Ready Mix in North York, Ontario. A tank of liquid CO₂ was connected to a gas control system and manifold. The liquid was metered for injection into the mixing drum whereupon it converted into a mixture of CO₂ gas and solid carbon dioxide snow. The carbon dioxide was delivered, at a specified flow rate over a fixed injection interval, into the truck whereupon it reacted with the hydrating cement before the concrete mix was completed. The concrete was then subjected to assessment and testing.

2.1 Methods

The fresh concrete was assessed via on-site measurement of slump and temperature. The concrete was further cast into 4" x 8" cylinders for compressive strength testing. A fresh sample was also taken for assessment of the heat evolution via a Calmetrix iCal 8000 isothermal calorimeter set at 22 °C. The fresh samples were approximately 220 g and represented the entire mix; they were not sieved of coarse aggregate.

Concrete performance was assessed through compressive strength testing at 1, 3, 7, 28 days with one trial concluding with a test at 58 days and the other concluding with 56 and 91-day tests. The measurements performed at 1 and 28 days were performed in triplicate, while the measurements at other ages were performed in duplicate. All specimens were subjected to grinding of the bearing faces before testing to ensure planeness. The specimens tested beyond 1 day were subjected to standard moist curing conditions prior to testing. All concrete specimens were prepared and tested in accordance with CSA A23.2. Bulk resistivity was assessed using a Merlin Mark III by Germann Instruments.

2.2 Industrial trials

The work was completed in July and September 2014. The trials were conducted on trucks loaded with 4 m³ (half full) concrete using a 25 MPa (3625 psi) mix design summarised in Table 1.

Table 1. Mix Design at Metrix

Component	Type	Quantity	Fraction
Concrete Sand	Fine aggregate	959 kg	42%
20mm Stone	Coarse aggregate	1080 kg	49%
Slag	Binder	53 kg	2%
Cement	Binder	212 kg	9%
Water Reducer	Admixture	190 ml	
Mix Water	Water	155 kg	

The requested load of concrete was first batched into the truck before transport to the wash rack where the batch received final water adjustments by the truck operator. Once the batch adjustments had been completed, a sample of uncarbonated (control) concrete was removed, a slump test was performed, and test specimens were cast. The truck was then subjected to three sequential doses of carbon dioxide with assessment of slump and casting of the treated concrete between each round. The time between the start of mixing and the carbon dioxide application was recorded. All of the test samples came from the same truck to maximize the experimental results from a single batch and to minimize any batch-to-batch variation that may have arisen. The sequential dosing of carbon dioxide was pursued to determine an optimum dose.

The CO₂ delivery was controlled by a mobile gas injection system. The injection proceeded for 30-90 seconds with an additional 90 -180 seconds of high speed mixing after the injection was completed. CO₂ dosages were determined with respect to the content of cement present in the mix and totalled 0.1%, 0.3% and 0.6% by weight of cement (bwc). The truck was set to a slow transit mixing speed at any time other than the pauses for sampling and high speed mixing during the CO₂ injections.

The first trial served as a proof-of-concept effort that a low dose injection could be integrated into a conventional ready-mix operation. While a CO₂ injection delivered to a truck that is stopped at the wash rack is potentially feasible, breaking the delivery into multiple doses represents a possible delay that is preferably avoided and is not universally applicable.

The second trial to increase confidence in the results and to investigate an alternate CO₂ injection mode wherein the gas was added during the initial batching/mixing phase.

3 Results

3.1 First trial

A complete overview of the conditions produced during the first trial day is presented in Table 2. The weather was 19 °C and sunny.

Table 2: First trial production variables, CO₂ settings and fresh results

Sample Code	Condition	Age at injection (min)	CO ₂ Dose (%bwc)	Slump (inches)	Mix Temperature (°C)
1401	Control	-	-	3.5	23.9
1402	CO ₂	42	0.10	3.0	-
1403	CO ₂	56	0.30	3.0	25.6
1404	CO ₂	71	0.60	2.0	26.5

The control concrete was sampled 23 minutes after mixing started. It was observed that with sequential doses of carbon dioxide the temperature of the mix was increasing and the slump of the mixture was decreasing. While a temperature increase would be expected due to the exothermic nature of the carbonation reaction it cannot be concluded whether the observed effects were attributable wholly to the carbonation process, or

further represented normal changes due to the passing of time between measurements, mixing, progress of hydration, increasing ambient temperature, etc.

3.1.1 Isothermal calorimetry

The evolution of heat from the fresh concrete was measured from 0 to 20 hours after mixing. The amount of heat released during early hydration can be used as a proxy for the development of mechanical properties (such as setting or compressive strength) at very early ages (Ge et al. 2009). A summary of the power data for the four batches is presented in Figure 1 and the energy (J/g cement) is presented in Figure 2. The power data is normalized and presented in arbitrary for ease of comparison. Plots exclude any data either acquired during the initial hydration acceleration and deceleration period. Data is plotted starting just after the induction period has ended.

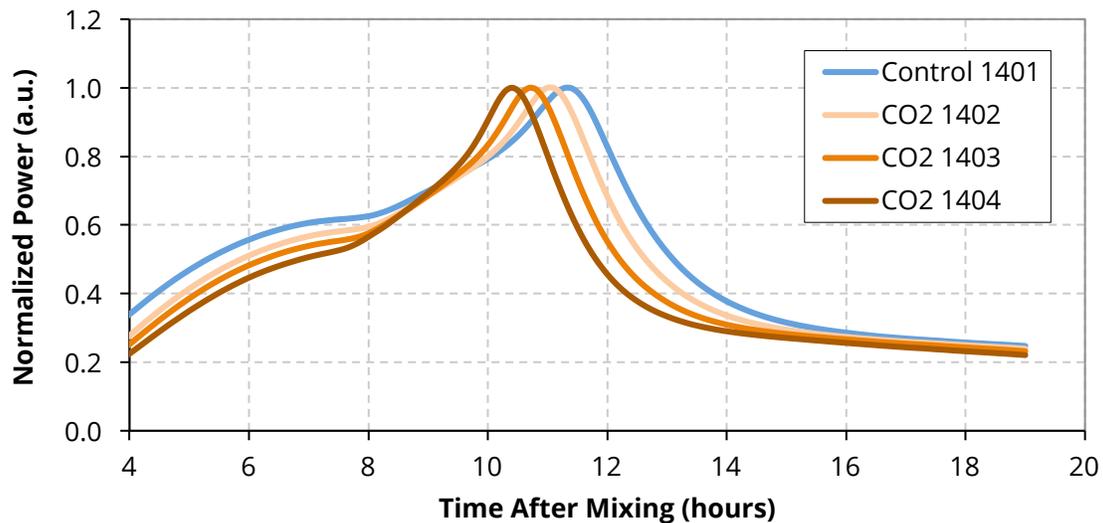


Figure 1: Normalized power during early hydration via isothermal calorimetry of batches produced in first ready-mix concrete trial

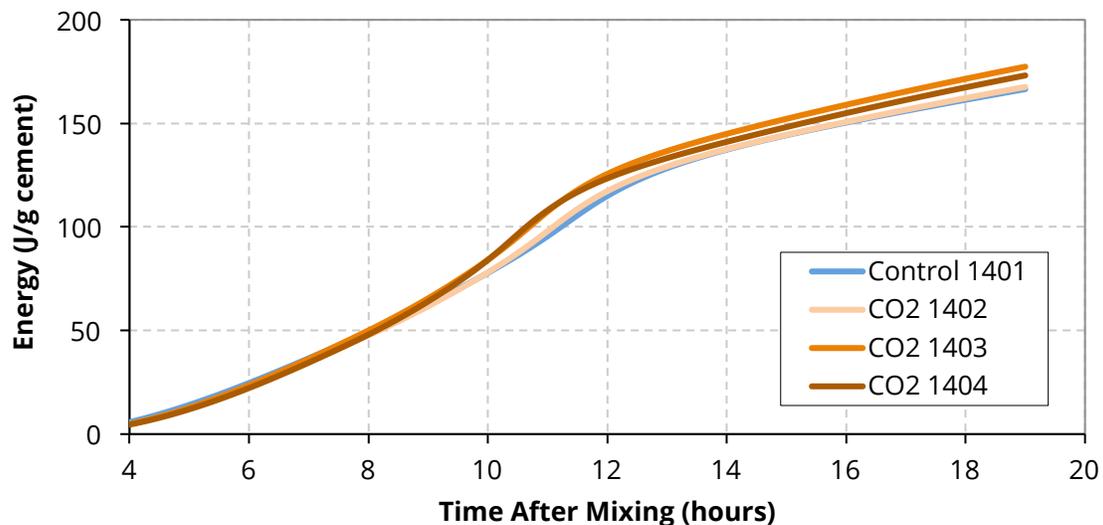


Figure 2: Energy during early hydration via isothermal calorimetry of batches produced in first ready-mix concrete trial

The carbon dioxide injection did not appear to have any effect on the induction period. The acceleratory stage of hydration for each sample was underway by 4 hours. By 7 hours the heat evolution of the carbonated samples occurred at an increased rate (as noted in a shift to the left of the shape of the curves) where the effect was greater with the greater dose of carbon dioxide. Further, the heat release at the peak of the early hydration was found to increase in magnitude and be shifted to earlier times as the carbon dioxide dose increased.

An alternate interpretation of the data considers the total energy released with time. The energy release relative to the control can be quantified at various ages and used as a metric of hydration progress. It is shown that at 6 hours the carbonated batches had released about 10% less energy than the control. The low dose had matched the control by 11 hours and remained equivalent thereafter. The second dose of CO₂ reached 101% of the control at 9 hours before improving to 12% better at 12 hours and finishing at 6% more energy released through 20 hours. The highest dose reached 102% of the control at 10 hours, 13% at 12 hours and 4% increase through 20 hours. It is observed that the carbon dioxide may have slightly slowed the hydration in the first 8 hours but in the 10 to 14 hour range an accelerating effect could be realized in the two higher doses. This potentially corresponds to a performance benefit such as a higher strength at these times.

3.1.2 Hardened properties

The average compressive strength measured for each carbonated condition across the five test ages for the first trial is given in Figure 3. Each data point represents the average measured compressive strength in MPa with the relative comparison to the corresponding control value displayed as a percentage.

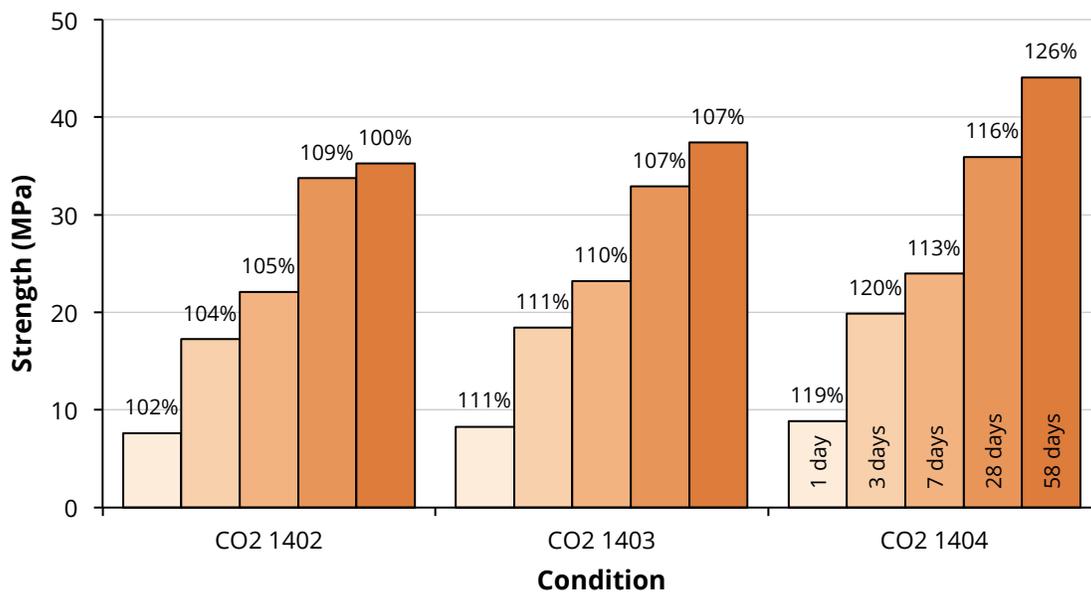


Figure 3: Average compressive strengths of all CO₂-treated specimens from trial 1 further expressed as a percentage of the control value

The results showed an increase in the compressive strength upon carbonation of the concrete mix for the higher two doses. This agrees with the improvement observed

through the calorimetry. The lowest dose of CO₂ had little impact on the compressive strength ranging between being 9% better than the control at 28 days but between 0 and 5% better at the other test ages. Batch 1403, with the middle dose of CO₂, was 11% stronger than the control at the two earlier ages, 10% at 7 days and 7% thereafter. The greatest benefit was seen in the final carbonated batch. A 19% increase in strength was observed at 1 day, 16% increase at 28 days and 26% increase at 58 days.

The bulk resistivity data is presented in Table 3. Higher resistivity values are indicative of lower permeability. The readings showed that the carbonated batches matched the control at all ages.

Table 3: Bulk Resistivity ($\Omega \cdot m$) for first trial test specimens at five different ages

Sample Code	Condition	Test Age				
		1 day	3 days	7 days	28 days	58 days
1401	Control	8.9	19.3	33.6	78.7	106.5
1402	CO ₂	8.8	18.9	25.5	74.1	112.0
1403	CO ₂	8.7	18.8	24.7	67.1	97.7
1404	CO ₂	8.9	20.3	24.1	70.2	101.8

Resistivity ranges that are relatable to the chloride ion penetrability levels described in ASTM C1202 were used to assess the chloride penetrability risk for all samples. The risk was determined to be moderate at 28 days and low at 58 days. The resistivity data reassures that the carbon dioxide injected concrete is equivalent to the control concrete.

3.2 Second trial

An overview of the conditions produced during the second trial day is presented in Table 4. The weather was again 19 °C and sunny. The trial repeated the sequential carbon dioxide dosing at the wash rack that had been explored in the first trial. The control truck was sampled 21 minutes after mixing started. A second truck was tested wherein the carbon dioxide was injected during the batching stage (batch 805).

Table 4: Second trial production variables, CO₂ settings and fresh results

Sample Code	Condition	Age at injection (min)	CO ₂ Dose (%bwc)	Slump (inches)	Mix Temperature (°C)
801	Control		-	3.5	22.4
802	CO ₂	27	0.10	3.0	24.0
803	CO ₂	43	0.30	2.5	24.7
804	CO ₂	52	0.60	1.5	27.3
805	CO ₂	0	0.30	3.0	23.3

Testing of the first truck showed, again, that the temperature of the mix was increasing and the slump of the mixture was decreasing with increasing doses of CO₂. Testing on the second truck showed that the slump was essentially equivalent to that of the control with a slightly increased temperature. The small temperature rise could be associated with the exothermic carbonation reaction but the second truck was batched/mixed 90 minutes after the first and thus the weather could have warmed the input materials.

3.2.1 Isothermal Calorimetry

A summary of the power data for the four batches sourced from the first truck is presented in Figure 4 and the energy is presented in Figure 5. The calorimetry of the concrete from first truck in the second trial was consistent with that of the first. The carbon dioxide was found to offer an accelerating effect.

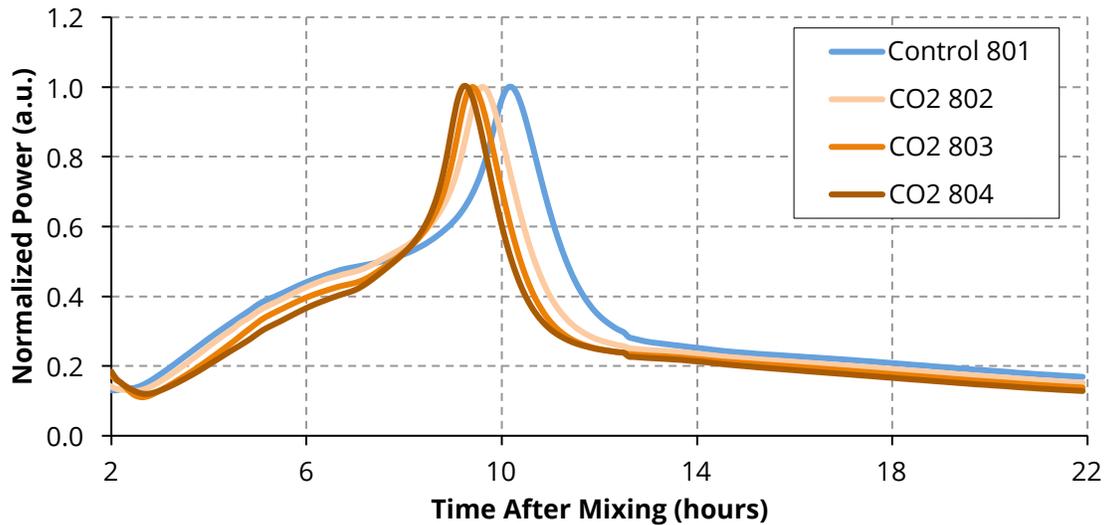


Figure 4: Normalized power during early hydration via isothermal calorimetry of batches from first truck in second ready-mix trial

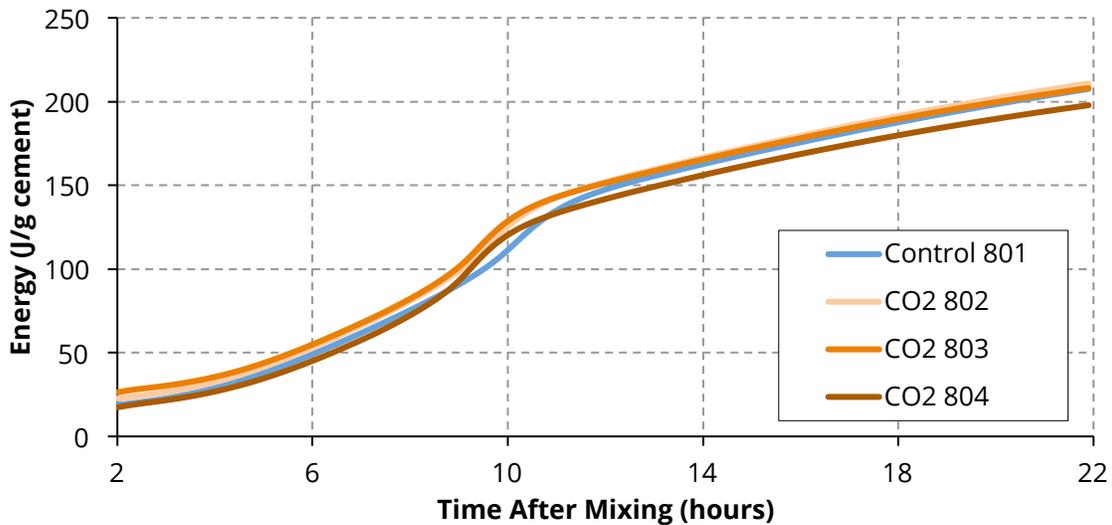


Figure 5: Energy during early hydration via isothermal calorimetry of batches from first truck second ready-mix trial

The data considered as energy shows the magnitude of the effect from the carbon dioxide. The lowest dose released 20% more energy than the control through 2 hours. The benefit declined to 7% at 7 hours before increasing to 13% at 10 hours and thereafter the declining to be equivalent to the control. The middle dose of CO₂ was 41% higher than the control at 2 hours with the benefit declining to 9% at 8 hours. The energy release jumped to 16% ahead of the control at 10 hours before declining to be equivalent to the control. For the highest dose the energy was between 92% and 99% of the control in the first 9 hours before spiking to be 9% ahead and thereafter declining to be equivalent to the control.

It is evident that the lower doses of CO₂ had an affect on the very early hydration and all doses had an effect notably around the 10 hour mark. The shape of the power curves suggests that this time period is consistent with the end of the acceleration period (Gartner et al. 2002) when the initial silicate hydration starts to slow down.

The batch that was dosed with CO₂ during batching (805) showed a calorimetry response that appeared to show some retardation relative to the control. The normalized power is presented in Figure 6 and the energy is presented in Figure 7

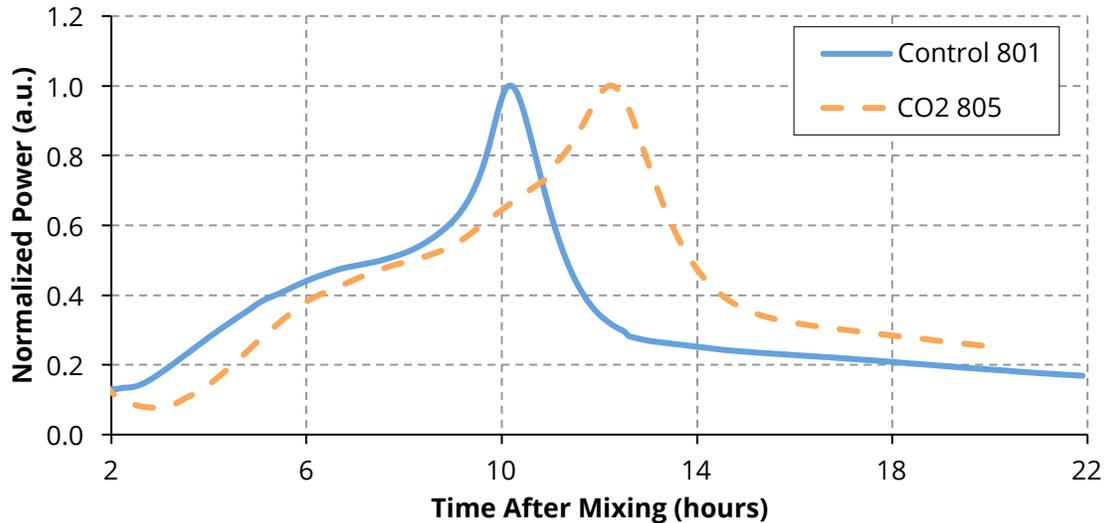


Figure 6: Normalized power during early hydration via isothermal calorimetry of control and batch carbonated during batching from second ready-mix trial

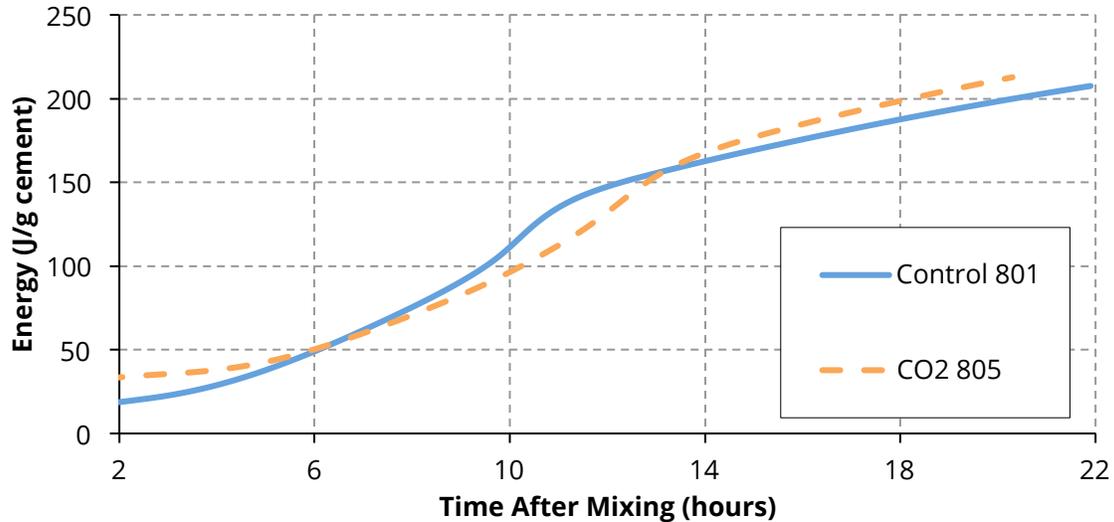


Figure 7: Energy during early hydration via isothermal calorimetry of control and batch carbonated during batching from second ready-mix trial

Theories for the cause of the initial hydration deceleration are varied. Hydration is thought to slow due to early hydration products coating the silicates and retarding dissolution (Gartner et al. 2002) or a change in the dissolution mechanism (Juilland et al. 2010). The subsequent acceleration period begins when the calcium hydroxide concentration in solution is high enough to facilitate a transformation of C-S-H. The extended induction period observed in batch 805 suggests that the initial fast reaction involving CO_2 and formation of the carbonate reaction products resulted in a more resilient coating on the silicates. Heat evolution was slower across the 7 to 13 hour interval and lagged as low as 83% of the control at 11 hours. However, the hydration thereafter accelerated to reach 5% more energy released at 15 hours and 7% more at 20 hours. Once the initial product coating on the silicates has been overcome the hydration accelerates due to increased product surface area providing nucleation sites.

3.2.2 Hardened Properties

The average compressive strength measured for each carbonated condition across the six test ages is summarized for the September trial in Table 5. Both the average strength in MPa and the strength relative to the appropriate control are presented.

Table 5: Compressive strength (MPa) and strength relative to control for concrete produced in second trial

Sample Code	Condition	Test age					
		1 day	3 day	7 day	28 day	56 day	91 day
0801	Control	8.0	14.8	19.2	30.8	32.8	36.8
0802	CO ₂	8.0	15.8	20.4	32.0	27.9	37.8
0803	CO ₂	8.6	16.6	21.4	33.9	37.9	38.9
0804	CO ₂	8.7	16.1	22.1	32.8	36.4	39.6
0805	CO ₂	9.2	18.6	23.2	35.5	38.7	42.4
0801	Control	100%	100%	100%	100%	100%	100%
0802	CO ₂	99%	107%	106%	104%	85%	103%
0803	CO ₂	106%	112%	111%	110%	116%	106%
0804	CO ₂	108%	109%	115%	107%	111%	107%
0805	CO ₂	114%	126%	121%	115%	118%	115%

The results confirmed that an increase in the compressive strength could be realized upon applying a carbon dioxide injection to the concrete mix. Amongst the sequential doses in the first truck it was again seen that the smallest dose had the least effect. Likely the 0.10% bwc dose does not result in sufficient reaction product development to impact the concrete properties. The strengths ranged between 99% and 107% of the control across the test periods excluding an anomalous reading at 56 days showing a decline in compressive strength to 85% of the control value. The 0.3% CO₂ bwc dose offered at least a 6% strength benefit notably reaching 12% at 3 days and 16% at 56 days. The 0.6% dose in the first truck offered a benefit that ranged between 7% and 15%. The results do not offer much to distinguish between the performances of the two higher doses. At three of the ages the strengths increased with increasing CO₂ dose. At the other three ages the strengths associated with the middle dose were higher than that of the highest dose.

The final batch showed the greatest promise given that the strength benefit exceeded 14% at all ages including a 26% benefit at 3 days and 15% at 91 days. This final batch is of particular interest since the industrial implementation would clearly be the simplest and most scalable of any of the investigated variations.

The bulk resistivity measurements were consistent with what was observed in the first trial insofar as the assessments of the carbonated batches were equivalent to the control. The chloride penetrability risk for all samples was assessed to be moderate at 28 days and low at 91 days.

4 Discussion

The performance improvement observed due to formation of the carbonate reaction products is analogous to growing an in-situ nanoparticle CaCO₃ addition that would act as nucleation sites and impact later hydration product development. The calorimetric evidence is similar to what can be observed by ex-situ additions of nano-CaCO₃ (10% by

mass) to C_3S (Sato and Diallo 2010). Model system work theorized that the nano-carbonates acted on the surface or in close proximity to calcium silicate particles. In one interpretation, the carbonates could affect the stability of the Si-rich reaction product that covers the surface of the hydrating calcium silicates during the induction period. Alternately the products could act as heterogeneous nuclei for C-S-H growth after the induction period.

The batch 805 test showed that adding carbon dioxide during the batching resulted in retardation from 7 to 13 hours before an overall increase in early hydration. The dose of CO_2 was delivered during the earliest exposure of cement to water and the carbonate ions would likely not have found Ca^{2+} ions in the bulk of the aqueous phase. The carbonate reaction products likely formed on the cement particles and impaired the first development of C-S-H during the acceleration phase. The overall increase in hydration suggested that there initially may have been fewer active sites on the cement particles actively fuelling the growth of the hydration products but the presence of carbonate phase nuclei may have contributed to a net hydration increase as time proceeded.

The carbon dioxide that was added to concrete at the wash rack was added 45-70 minutes after mixing started (a limit of the temporary nature of the test facilities rather than through any particular experimental design). After 45 min of hydration the aqueous phase of the concrete mix would likely be saturated in Ca^{2+} ions. It is probable that the carbonation reaction products could be formed in the pore solution where the carbonate anions would first encounter the cations. Acceleration due to reaction product particles acting at a distance from the cement particle surfaces is possible. Work with C-S-H additions (1-4% by weight) to hydrating cement systems suggested increases in early hydration rate and total amount of early hydration were attributable to the creation of new nucleation sites within the pore space away from the particle surfaces (Thomas et al. 2009). Such a mechanism is particularly relevant to the reactions at hand. Reflecting upon the chemical equations 1 and 2 previously presented it is apparent that C-S-H gel formation is expected alongside the calcium carbonate development.

The amounts of carbon dioxide used were 0.6% by weight of cement or lower. This amount of CO_2 would correspond to a maximum 1.4% by weight $CaCO_3$ (in practice the actual amount of absorbed carbon dioxide is likely lower given that not all of the dosed gas is expected to be consumed). The small amount of CO_2 involved attests to the potency of the impact. In addition, in-situ production addresses one of the challenges of incorporating nano- $CaCO_3$ into cement systems, namely, achieving effective dispersion and fine distribution (Kawashima et al. 2014). Conventional approaches to add nano-calcite to concrete require the creation of a nano-suspension through ultrasonication (Wang et al. 2014).

The two dosing approaches used represent three different potential industrial approaches. (1) Dosing the carbon dioxide during batching represents an industrially scalable approach that offers minimal interruption to the conventional batching and mixing process. Gas delivery equipment could be integrated into the standard ready mix production. (2) In cases where the ready-mix concrete trucks are first batched and then pause within the plant, such as at a wash rack, an interval exists wherein carbon dioxide could be supplied concurrent with other normal production operations. In this case the mix will have had 5 to 10 minutes of hydration before the carbonation reaction takes

place. (3) Finally, if an extended hydration time is known to have advantages then the CO₂ could be dosed at the job site immediately prior to placing. It is possible that a small portable carbon dioxide injection system could be installed on trucks or at big projects.

One outcome of using a tool that can unlock a consistent strength benefit could be to sell a given concrete mix for at a price premium. A 15% strength improvement to a 35 MPa mix would allow for the production 40 MPa mix. Alternately, instead of maintaining the mix design and offering a strength-improved 40 MPa mix, the cement content could be reduced in order to deliver the same 35 MPa performance as before. The amounts of carbon dioxide used (and thereby absorbed) in these tests is small and possibly only offers a slight inherent environmental benefit but if carbon dioxide can be used as tool to reduce cement loadings there would be an direct and tangible reduction in the carbon footprint of the concrete so produced.

5 Next Steps

The industrial experiments demonstrated that carbon dioxide could be injected into a ready-mix truck during batching and mixing to bind CO₂ into the paste fraction of the produced concrete. The carbonate reaction products thereby impacted the early hydration and resulted in compressive strength improvements

The industrial trials have inspired further research development. Work is ongoing and has several aims.

1. Examine sensitivity of cementitious materials selection and mix design to the material performance of the carbonated concrete. The action of the carbon dioxide is analogous to that of an admixture. It is anticipated that performance outcomes will depend on the nature of the cementitious system used.
2. Conduct a broad durability study. A carbonated wet mix durability study encompassing compressive strength, flexural strength, drying shrinkage, abrasion, resistivity, service carbonation, salt scaling, pore solution chemistry, bulk diffusion and ASTM G109 corrosion testing is planned to better characterize the performance of the carbon dioxide treated concrete.
3. Characterize the mechanism and morphology of carbonate reaction products. A more fundamental understanding of the physiochemical aspects of the carbonation reaction can help determine the best practices and applications of the technology. It is clear that a carbonation uptake below 0.5% is sufficient to markedly effect the concrete properties.
4. Investigate different dosing times. Any performance difference related to dosing during mixing as opposed to dosing at a wash rack or a job site will impact potential industrial implementations. The approach wherein a single truck was subjected to multiple doses of carbon dioxide simultaneously tested the effects of increasing hydration time prior to carbonation and increasing the total dose. So it was not conclusive from these trials whether the time at dosage was more or less important than the amount of carbon dioxide provided.
5. Assess the reproducibility of the performance benefit. Given that many factors can influence the compressive strength of concrete (air, water to binder ratio, mixing history) it is necessary to pursue a larger industrial test program in order

to gauge the inherent variability of a benefit in the context of the inherent variability of the production.

6 Conclusions

Industrial scale experiments assessed the viability of adding small doses of carbon dioxide to a ready-mix concrete production cycle in order develop performance benefits associated with the in-situ development of carbonate reaction products. Isothermal calorimetry indicated that hydration could be accelerated.

Compressive strength results suggested that a strength benefit of 20% at 3 days, 16% at 28 days and 26% at 58 days was achieved with an optimized dosage of carbon dioxide supplied at the wash rack. In practice this could potentially be a single optimized dose of carbon dioxide provided at the job site. Delivery of carbon dioxide into the concrete during batching resulted in retardation in the 7 to 13 hour timeframe but small acceleration beyond 14 hours. The strength was 26% better than the control at 3 days, 15% better at 28 days and 18% at 56 days. Bulk resistivity, an indicator of permeability, was not changed by the carbonation. The difference in heat evolution between the two dosing approaches hinted at possible differences in the reaction product formation.

The approach potentially can offer strength benefits or allow for cement reductions. Several avenues of investigation are being pursued to further characterize the mechanism of the reaction, understand variations between dosing approaches, and complete a broad durability assessment program.

7 Acknowledgements

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8 References

- Berger, R. L., Young, J. F., and Leung, K. (1972). "Acceleration of Hydration of Calcium Silicates by Carbon-Dioxide Treatment." *Nature: Physical Science*, 240(Dec 8), 16–18.
- Damtoft, J. S., Lukasik, J., Herfort, D., Sorrentino, D., and Gartner, E. M. (2008). "Sustainable development and climate change initiatives." *Special Issue — The 12th International Congress on the Chemistry of Cement. Montreal, Canada, July 8-13 2007*, 38(2), 115–127.
- Gartner, E., Young, J., Damidot, D., and Jawed, I. (2002). "Hydration of Portland Cement." *Structure and Performance of Cements*, J. Bensted and P. Barnes, eds., CRC Press, New York, 584.
- Ge, Z., Wang, K., Sandberg, P. J., and Ruiz, J. M. (2009). "Characterization and Performance Prediction of Cement-Based Materials Using a Simple Isothermal Calorimeter." *Journal of Advanced Concrete Technology*, 7(3), 355–366.

- Goodbrake, C. J., Young, J. F., and Berger, R. L. (1979). "Reaction of Beta-Dicalcium Silicate and Tricalcium Silicate with Carbon Dioxide and Water Vapor." *Journal of the American Ceramic Society*, 62(3-4), 168–171.
- IEA. (2009). *Cement Technology Roadmap: Carbon Emissions Reductions up to 2050*. IEA Technology Roadmaps, OECD Publishing.
- Juilland, P., Gallucci, E., Flatt, R., and Scrivener, K. (2010). "Dissolution theory applied to the induction period in alite hydration." *Cement and Concrete Research*, 40(6), 831–844.
- Kawashima, S., Seo, J.-W. T., Corr, D., Hersam, M. C., and Shah, S. P. (2014). "Dispersion of CaCO₃ nanoparticles by sonication and surfactant treatment for application in fly ash–cement systems." *Materials and Structures*, 47(6), 1011–1023.
- Monkman, S. (2014). "Carbon Dioxide Utilization in Fresh Industrially Produced Ready Mixed Concrete." International Concrete Sustainability Conference, National Ready Mixed Concrete Association, May 12-15 2014 Boston, USA.
- Moorehead, D. R. (1986). "Cementation by the carbonation of hydrated lime." *Cement and Concrete Research*, 16(5), 700–708.
- Sato, T., and Diallo, F. (2010). "Seeding Effect of Nano-CaCO₃ on the Hydration of Tricalcium Silicate." *Transportation Research Record: Journal of the Transportation Research Board*, 2141(1), 61–67.
- Thomas, J. J., Jennings, H. M., and Chen, J. J. (2009). "Influence of Nucleation Seeding on the Hydration Mechanisms of Tricalcium Silicate and Cement." *The Journal of Physical Chemistry C*, 113(11), 4327–4334.
- Wang, X., Wang, K., Tanesi, J., and Ardani, A. (2014). "Effects of Nanomaterials on the Hydration Kinetics and Rheology of Portland Cement Pastes." *Advances in Civil Engineering Materials*, 3(2), 142–159.