CarbonCure Durability Assessment Report
TECHNICAL NOTE

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EXECUTIVE SUMMARY

Concrete was produced using the CarbonCure Ready Mix Concrete Technology whereby carbon dioxide was injected into the concrete during its mixing. The concrete was assessed in the fresh and hardened states and compared to a reference control batch. An extensive durability assessment determined the overall suitability of a class C1 mix produced using the CarbonCure Technology.

The fresh properties of the concrete were unaffected by the carbon dioxide. The compressive strengths were increase 1 to 9% in test ages up to 91 days. The conclusions regarding absorption, drying shrinkage, surface resistivity, bulk resistivity, RCPT, corrosion measurements and pore solution pH were unaltered by the carbon dioxide treatment. Flexural strength increased 6%. Abrasion mass loss improved 7%. The depths of carbonation after accelerated service carbonation were decreased 25 to 54%. Bulk chloride diffusion was unaffected at 180 days of ponding.

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TRIAL OUTLINE

A durability assessment trial of concrete produced using the CarbonCure Technologies ready mix concrete system commenced in October 2014. The testing compared the performance of concrete produced using conventional means and concrete produced after having been subjected to an injection of carbon dioxide in the fresh state. The trial was conducted with the support of Quality Concrete of Dartmouth, Nova Scotia. The analysis was conducted at the CarbonCure laboratory and at the University of New Brunswick Department of Civil Engineering under the supervision of Professor Mike Thomas.

A half size (4 m^3) load of concrete was batched according to the Quality Concrete standard operating procedures. The mix design adhered to the specification for a C1 mix as defined by CSA A23.1. Upon completion of the initial mixing of the concrete the ready mix truck delivered the load to the CarbonCure laboratory. The fresh properties of the concrete were assessed and test samples were created to serve as the reference condition.

A specified dose of carbon dioxide (CO_2) was then delivered into the truck by injecting it directly into the concrete mixing drum. The CO_2 delivery was controlled on-site by the CarbonCure mobile CO_2 injection system. The fresh properties of the carbon dioxide treated concrete were assessed and test samples were created to serve as the carbonated condition.

In addition to the fresh properties (temperature, air and slump), the evolution of heat from the fresh concrete was measured from 0 to 24 hours after mixing by a Calmetrix iCal 8000 isothermal calorimeter. The amount of heat released by the concrete in this range can be used as a proxy for the development of mechanical properties at very early ages.

Concrete from each test load was used to cast 4” x 8” cylinders for compressive strength testing by CarbonCure technical personnel at 1, 3, 9, 28, 56, 91 and 365 days after mixing. Three cylinders from each condition were tested at each test age using reusable end caps. Hardened state analyses further include absorption, RCPT, Resistivity, bulk chloride diffusion, abrasion, flexural strength, freeze-thaw performance, drying shrinkage, service carbonation, salt scaling and corrosion. The test methods followed are listed in Table 1.

Pore solution pH was examined using a dedicated test involving cement paste samples. Paste samples were created with varying levels of carbonation (expressed as CO_2 content by weight of cement) that were achieved through a carbon dioxide injection during mixing. The paste was then cast into cylindrical specimens and moist cured. The pore solution was extracted at 28 days and the pH was measured

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FRESH PROPERTIES

The fresh state properties of the two test batches of concrete are summarized in Table 2.

Neither the concrete temperature nor the air content was changed due to the addition of carbon dioxide. The slump decreased from 3 to 2 inches. However, it should be noted that while the control sample was discharged 20 minutes after mixing started it was an additional 35 minutes before the carbonated sample was discharged. The slump change is likely due to the age of the concrete.

The experimental approach wherein the carbon dioxide batch was created from the same mix of concrete as the control batch resulted in the concrete age contributing to the interpretation of the impact of CO_2 on the fresh properties. Additional trials wherein this experimental limitation was not present have indicated that the workability of the carbon dioxide treated concrete achieve the target workability for the mix.

The isothermal calorimetry is presented in Figure 1. Two specimens of control concrete are compared to two specimens of the carbon dioxide treated concrete. The data is presented as total energy released (J/g cement) over time. The carbon dioxide treated batch was observed to have a slower heat of hydration release than the control batch. The end of the induction period appeared to occur one hour later in the carbonated concrete. The overall energy release reached 95% of the control after 15 hours of hydration and remained at this relative level for the remainder of the test period.

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HARDENED PROPERTIES

Compressive Strength

The compressive strength data is summarized in Figure 2. The strength of the concrete subjected to the carbon dioxide treatment ranged between 101% and 109% of the control strength across the various test ages through 91 days. It can be concluded that the carbon dioxide had a neutral to small beneficial effect on the concrete strength.

Absorption

The absorption (Table 3, average of two specimens) of the concrete was unaffected by the carbon dioxide treatment. While the control batch had an absorption of 4.2% the carbonated batch was 4.3%.

Abrasion

The abrasion (Table 3, average of two specimens) of the concrete was slightly improved by the carbon dioxide treatment. The abrasion mass loss measured on the CO_2 batch was 7% less than that measured on the control.

Flexural Strength

The flexural strength (Table 3, average of two specimens) of the concrete was slightly improved by the carbon dioxide treatment. The flexural strength increased 6% in the carbon dioxide treated concrete.

Drying Shrinkage

The drying shrinkage of the CO_2 batch through 70 days (presented in Figure 3) was found to be comparable to the control. The average shrinkage of the three CO_2 specimens was slightly larger than the average of the three control specimens at each of the test age. However, the variability of the results, as indicated by the high-low-average presentation of the control series, assures that the difference is minimal. In every case the average shrinkage of the CO_2 specimens was lower than the highest shrinkage of the control specimens.

Service Carbonation

The service carbonation testing showed that the concrete treated with carbon dioxide was more resistant to carbonation in service. The reported carbonation depths (Table 4) are an average of 16 measurements with four taken from each surface of the specimen's square cross section. The carbon-dioxide-treated-concrete subjected to 1 day moist curing before service carbonation showed a 29% reduction in the carbonation depth versus the control. The reductions were 54% for samples moist cured 3 days and 25% for samples moist cured for 7 days.

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Rapid Chloride Permeability Test and Resistivity

The results of the concrete resistivity and RCPT testing are presented in Table 5. The resistivity of the batch treated with CO_2 was slightly lower than that of the control concrete as measured by both the Proceq (surface resistivity) and RCON (bulk resistivity) approaches. However, the interpretation confirms that in both cases the data fell within the same permeability class band. The RCPT charge passed was higher in the carbon dioxide treated batch but still both results were consistent with a Moderate permeability assessment.

Corrosion testing

The corrosion testing has not yet indicated any corrosion occurring in either of the two sample sets. Electrical potential data is presented in Figure 6 and current density is presented in Figure 7. Measurements were conducted with respect to a silver/silver-chloride reference electrode and potentials from 0 to -106 mV are indicative of the reinforcing steel being in a passive state. The electrical potential of rebar in the carbon dioxide treated concrete is lower than in the control case indicating a lower driving force for corrosion. However, since no corrosion is being yet observed the difference is essentially nil. The current densities are essentially the same.

Bulk chloride diffusion

The bulk diffusion of chlorides after 35 days of ponding is presented in Figure 4 while the data after 180 days is presented in Figure 5. The calculated chloride diffusion coefficient at 35 days ponding was 5.8 ´10^{-12} m^2/s for the control sample and 8.8´10^{-12} m^2/s for the carbon dioxide treated sample. The projected surface chloride concentration was 1.03% for the control batch and 1.11% for the CO_2 batch. After 180 days of ponding the calculated chloride diffusion coefficients were 5.4´10^{-12} m^2/s for the control sample and 5.0´10^{-12} m^2/s for the carbon dioxide treated sample indicating there was no difference between the samples. The projected surface chloride concentration was 0.97% for the control batch and 1.12% for the CO_2 batch.

Pore Solution pH

The pore solution pH of the carbonated samples was shown (Figure 8) to be unaffected by the carbon dioxide even at confirmed uptakes well in excess of the amount injected during the durability study. The results suggest that the carbon dioxide injection does not increase the risk of depassivation of ferrous reinforcement and would thereby not lead to increased corrosion risk.

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CONCLUSIONS

The concrete treated with carbon dioxide had fresh state properties consistent with the desired performance. The required workability and air content was achieved.

The compressive strength of the carbonated concrete was found to be equivalent to 9% better than the control in test ages up to 91 days. Absorption was not changed due to the carbon dioxide. Drying shrinkage between the CO_2 and control batches were comparable. The surface resistivity, bulk resistivity and RCPT indicated that the two batches had comparable permeability. Corrosion measurements indicated that corrosion had not started in either sample and pore solution pH was unaltered by the carbon dioxide treatment. Flexural strength increased 6%. Abrasion mass loss improved 7%. The depths of carbonation after accelerated service carbonation were decreased 25 to 54%. Bulk chloride diffusion was unaffected at 180 days of ponding.

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TABLES

Table 1: Overview of testing performed during the durability trial.

Test	Reference
Compressive Strength	ASTM C39
Absorption	ASTM C642
Rapid Chloride Permeability Test (RCPT)	ASTM C1202
Bulk Resistivity	RCON2
Bulk Diffusion of Chlorides	ASTM C1556
Abrasion	ASTM C944
Flexural Strength	ASTM C78
Freeze-thaw performance	ASTM C666
Drying shrinkage	ASTM C426
Service carbonation	RILEM CPC-18
Salt Scaling	BNQ NQ 2621-900
Corrosion	ASTM G109, C876

Table 2: Overview of the fresh properties of the two test batches.

Batch	Temperature, °C (°F)	Slump, mm (inches)	Air Content
Control	19.8 (67.6)	76 (3.0)	5.4%
CO2	19.4 (66.9)	51 (2.0)	5.6%

Table 3: Absorption, abrasion and flexural strength

Batch	Absorption	Abrasion (g mass loss)	Flexural Strength (MPa)
Control	4.2%	5.35	6.51
CO2	4.3%	4.95	6.90

Table 4: Carbonation depth in mm at 91 days exposure for control and carbon dioxide-treated concrete after three different curing approaches.

Batch	1 day cure	3 day cure	7 day cure
Control	1.7	2.4	2.4
CO2	1.2	1.1	1.8

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Table 5: Resistivity and RCPT data for control and carbon dioxide-treated concrete

Batch	Proceq (kΩ.cm)	RCON (kΩ.cm)	RCPT @ 56d, coulombs	RCPT rating
Control	11.43	6.48	2403	Moderate
CO2	11.00	6.28	2785	Moderate

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FIGURES

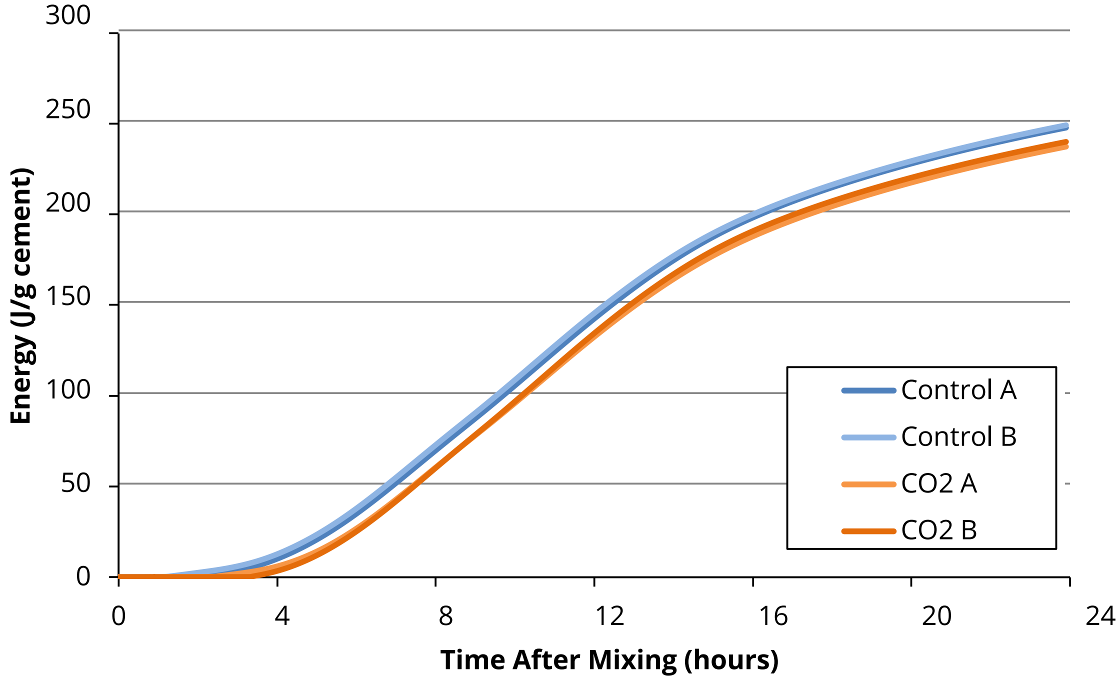

Figure 1: Isothermal calorimetry for control and carbon dioxide-treated batch through 24 hours

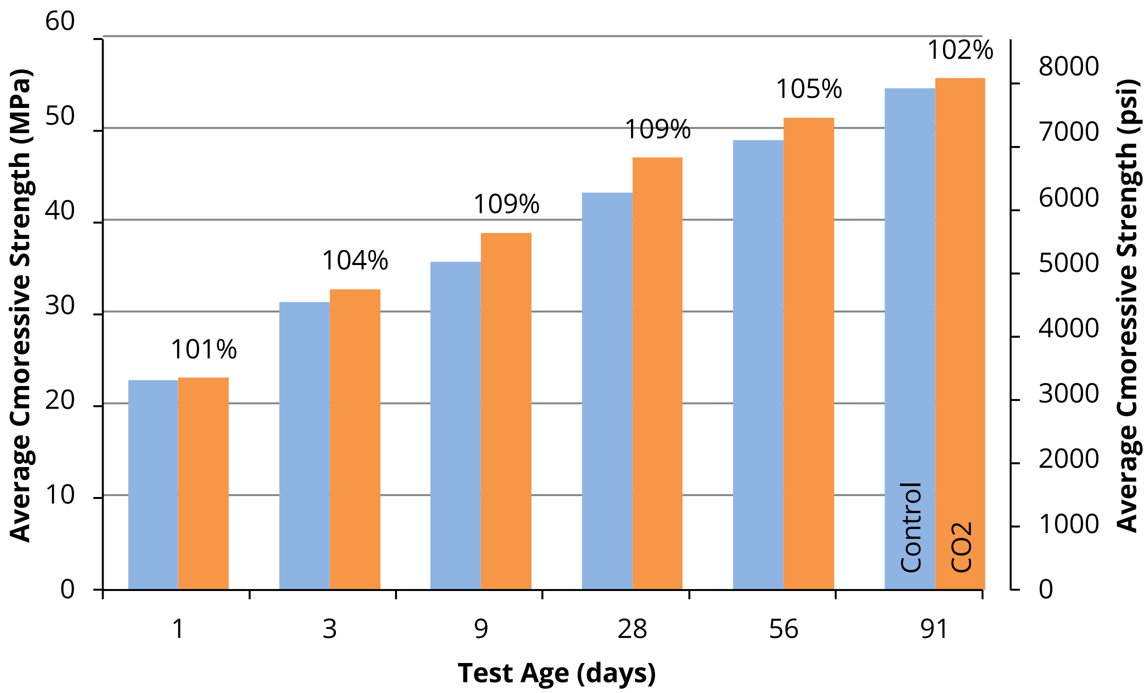

Figure 2: Compressive strength for control and carbon dioxide-treated batch through 91 days

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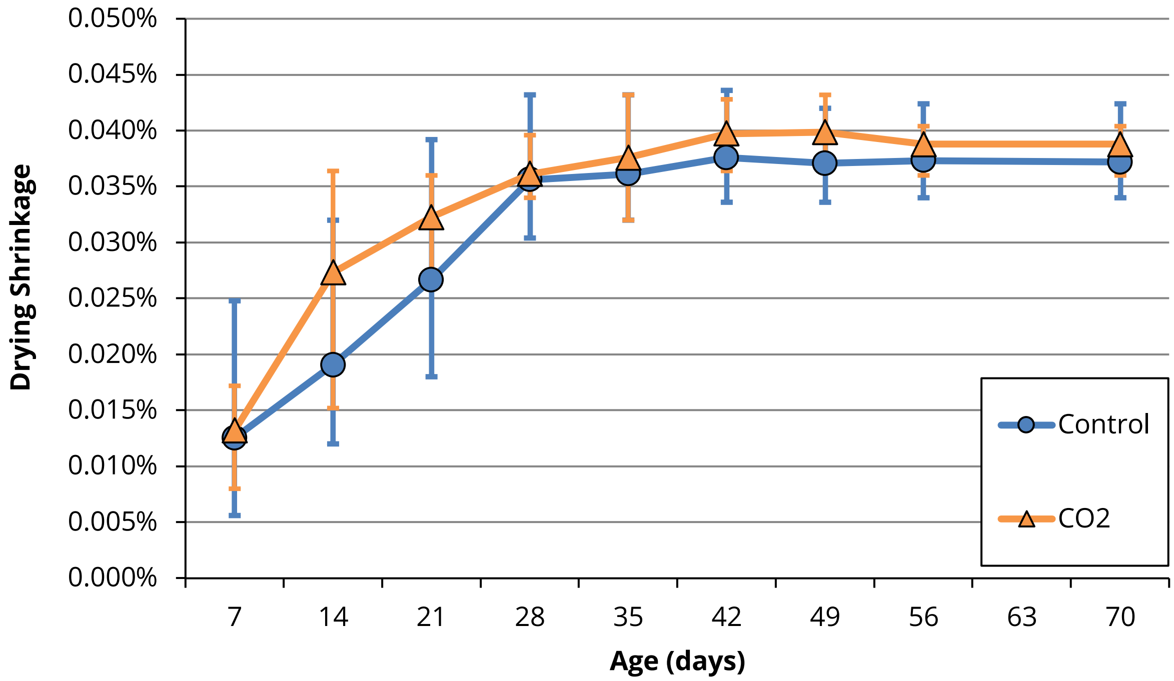

Figure 3: Drying shrinkage for control (high-low-average) and carbon dioxide-treated batches

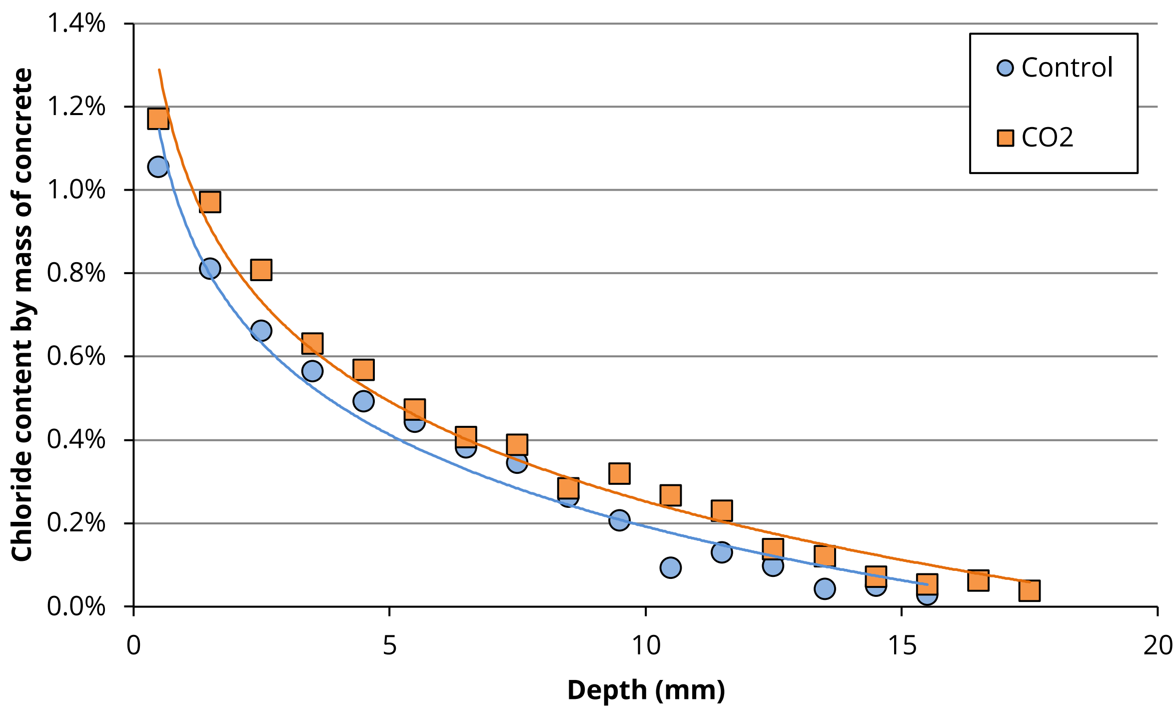

Figure 4: Bulk diffusion analysis of control and carbon dioxide-treated concrete after 35 days of chloride ponding

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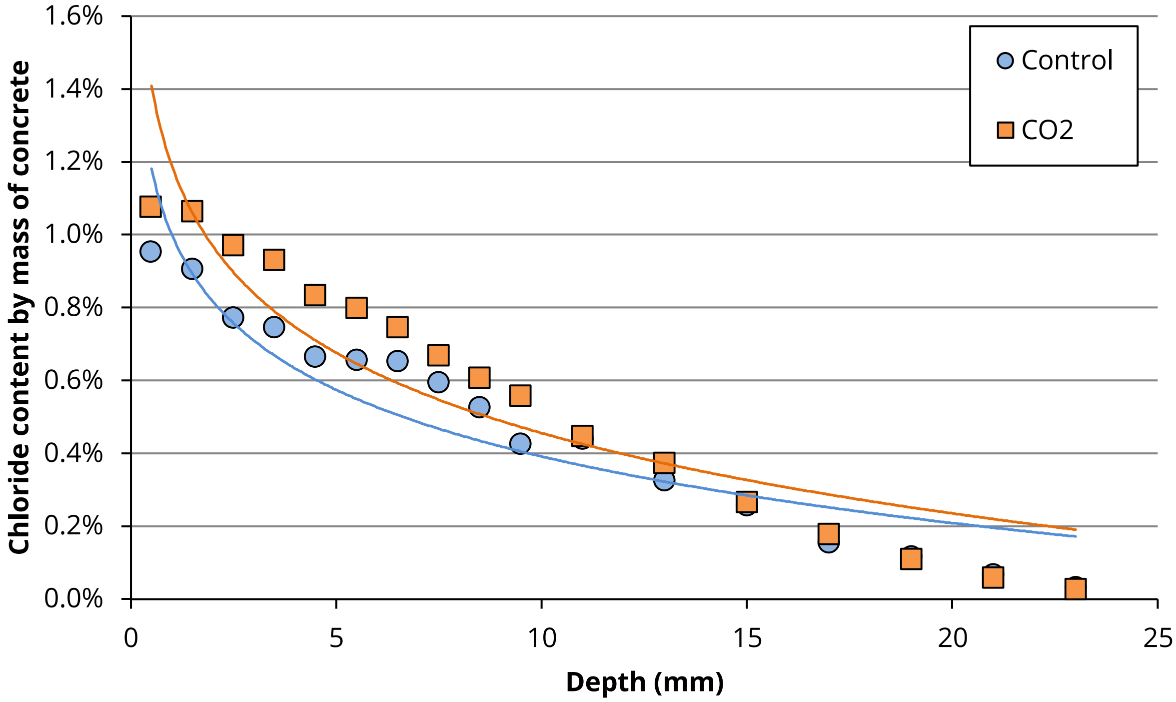

Figure 5: Bulk diffusion analysis of control and carbon dioxide-treated concrete after 180 days of chloride ponding

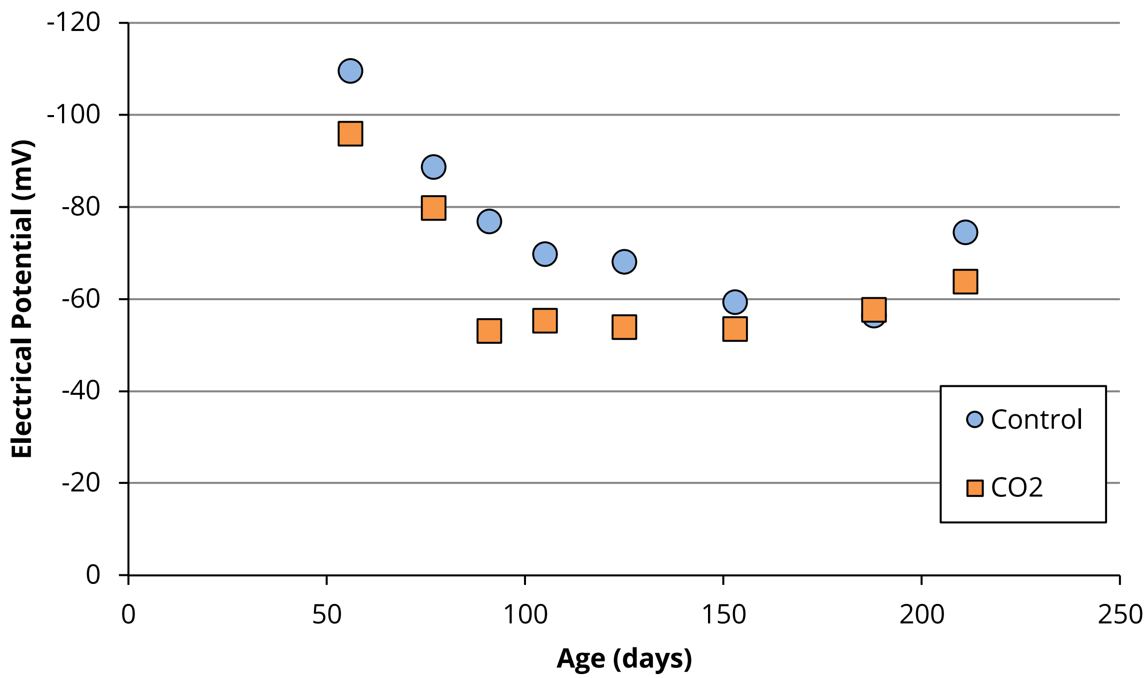

Figure 6: Electrical potential measurements of control and carbon dioxide-treated concrete through 211 days of corrosion monitoring

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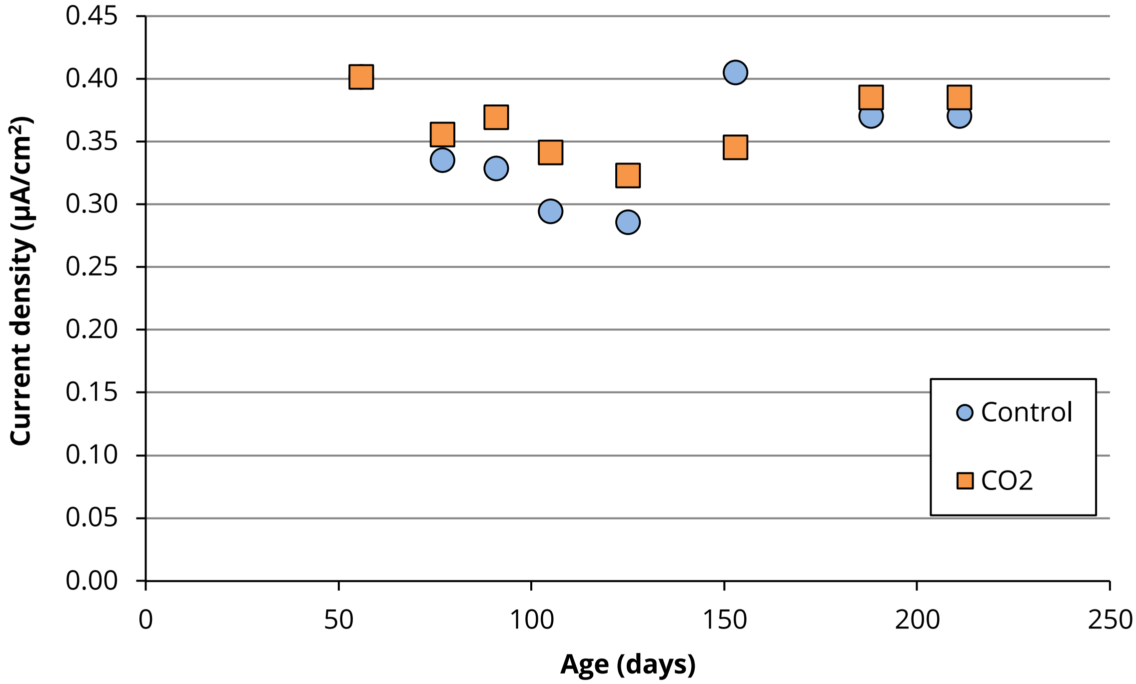

Figure 7: Current density measurements of control and carbon dioxide-treated concrete through 211 days of corrosion monitoring

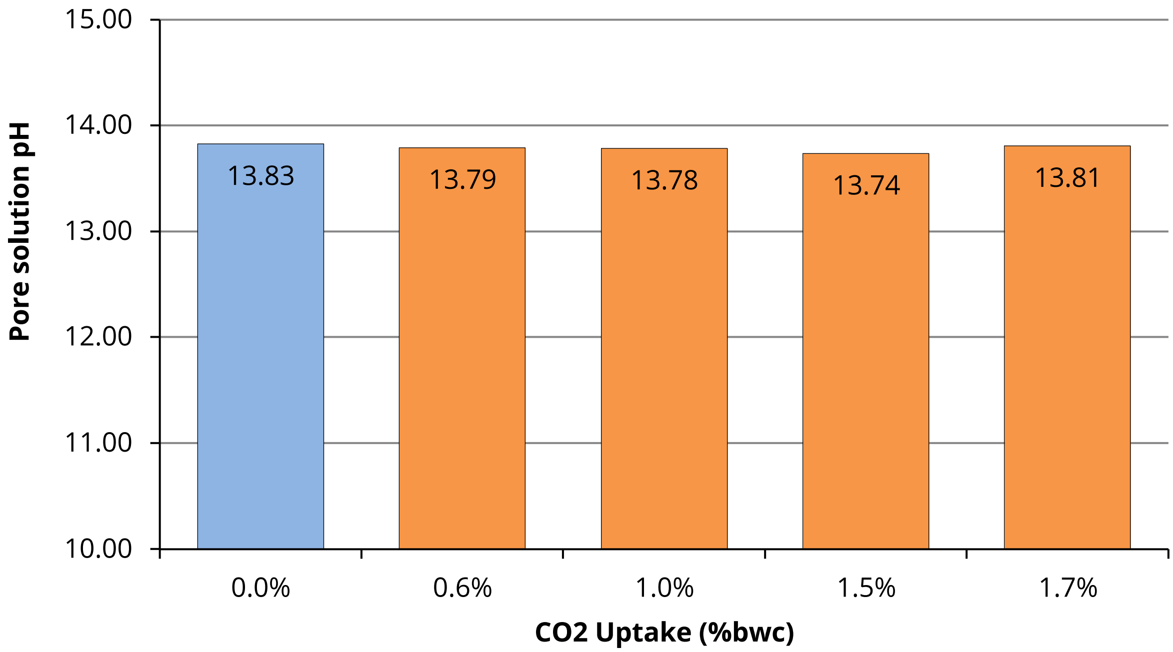

Figure 8: Pore solution pH for control and carbon dioxide-treated pastes

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