WHITE PAPER

CarbonCure Ready Mix Technology – AASHTO Compliance Field Trials

ABSTRACT

Carbon capture, utilization, and storage (CCUS) has been identified as an integral piece of ambitious industrial sustainability targets. Carbon dioxide (CO_2) has been employed as a ready mixed concrete admixture, where an optimum dose of CO_2 is injected into concrete as it is batched. This injection leads to the in-situ formation of mineralized calcium carbonate ($CaCO_3$) and can increase the concrete compressive strength. This benefit can be leveraged in concrete mixture redesigns, where cement is reduced leading to a lower carbon footprint of concrete. As with all new admixtures, it is important to validate the general performance of CO_2 injected concrete. An industrial study was completed to assess the performance impacts of deliberate CO_2 addition. The testing assessed the concrete fresh properties, compressive and flexural strength, freeze-thaw resistance, surface resistivity, shrinkage, permeability, hardened air void characteristics, and chloride diffusion resistance. The in-situ developed $CaCO_3$ resulted in similar concrete fresh properties, improved compressive strength up to 90 days, equivalent flexural strength and equivalent or improved durability performance.

Introduction

The availability, utility and performance of concrete makes it the world's most common building material, with an estimated annual global production of 30 Gt[1]. Due to this scale, rather than the environmental footprint of the material itself, the cement and concrete industry has been estimated to account for about 7% of annual global CO_2 emissions[2], due mainly to the current cement manufacturing process[3]. Leveraging technologies that can reduce the amount of cement used in the concrete material is a good step toward decreasing the carbon footprint of the concrete industry.

Conscious of world sustainable development goals, the construction industry has published roadmaps for lowering the impact of concrete production while meeting increasing material demands[4,5]. The selection of novel strategies that have been identified includes the concept of CO_2 utilization. The use of CO_2 as a feedstock in concrete production has been examined as a new route for emissions reductions[1]. This is an example of CCUS, an integral piece of the roadmap to carbon neutrality by 2050, as outlined by the Global Cement and Concrete Association (GCCA) and the Portland Cement Association (PCA)[4,5]. All stakeholders in the construction industry contribute to this target[5]:

1. Cement producers can reduce cement clinker content, substituting clinker with other cementitious materials such as fly ash, slag, pozzolans, and limestone.
2. Concrete producers can substitute cement content with supplementary cementitious materials (SCMs) to reduce CO_2 emissions from cement manufacturing.
3. Architecture firms, engineering firms and construction companies can focus on efficiency in design and construction.
4. The public sector can award infrastructure projects to companies following net zero guidelines.

As outlined in the Concrete Future roadmap document published by the GCCA, CCUS development has the potential to contribute 1370 Mt CO_2 savings in 2050 or roughly 36% of the CO_2 emissions contributed by the concrete industry[4]. CCUS methods are currently being developed around the world, with CarbonCure Technologies at the forefront of this burgeoning technological landscape.

CarbonCure Ready Mix Technology

CarbonCure Technologies (CCT) has developed a CO_2 utilization approach that injects CO_2 into fresh ready-mix concrete similar to introducing any other chemical admixture. The CO_2 reacts with the calcium silicate phases present in the cement to form calcium carbonate (mainly calcite) nanoparticles that can enhance the compressive strength by improving the cement hydration efficiency of concrete[6]. This allows for the optimization of any concrete mix design by safely reducing cement content and lowering the carbon footprint of concrete. The technology can be applied to a wide range of ready-mix concrete designs.

CO_2 Mineralization in Fresh Concrete

The reaction of environmental CO_2 with hardened concrete (a.k.a. natural or atmospheric carbonation) is conventionally acknowledged to be a durability issue due to such effects as shrinkage, reduced pore solution pH, and carbonation induced corrosion. In contrast, the CO_2 injected in concrete during the mixing process reacts with freshly hydrating cement, rather than the hydration phases present in mature concrete, and does not have the same effects. Consequently, durability is not affected[7]. By virtue of adding CO_2 to freshly mixed concrete, the carbonate reaction products are formed within the concrete mix at the nanoscale and homogeneously distributed.

While it is known that the addition of nano-sized calcite particles can be used to impact the hydration of cement[7], concrete producers attempting to add nanoparticles to a concrete mix often run into technical (e.g. difficulty achieving homogeneous dispersion), operational (e.g. availability and/or quality of supply) and economic (e.g. cost) barriers[2]. The addition of CO_2 injected into the concrete mix enables concrete producers to manufacture calcite nanoparticles within the concrete mixture at the time of production, thus permitting the producer to realize the benefits of calcite nanoparticles while avoiding these common barriers.

AASTHO Field Testing

Even though CO_2 addition into fresh concrete has been proven to be beneficial in strength development, confirming durability compliance is equally as important. The CO_2 used is an industrial byproduct, leading to concerns regarding the consistency and quality of the material, as its quality may affect the consistency and quality of the final concrete produced. Furthermore, there are concerns that the CO_2 itself and any impurities in the CO_2 could potentially adversely react with the concrete components. To alleviate these concerns, CCT engaged with the American Association of State Highway and Transportation Officials (AASHTO) to evaluate the CCT ready-mix technology following the Unique, Patented, Proprietary Products (UP3) testing program. UP3 is a technical service program designed to utilize and exchange information on the evaluation of innovative patented and/or proprietary materials, products, and devices of common interest for use in highway and bridge construction[8]. The ready-mix technology was assessed following the criteria to comply with an AASHTO M194 (ASTM C494) Type S Chemical Admixture. To test the CO_2 addition technology as a Type S admixture, concrete was tested with and without the presence of the additive.

Concrete testing was completed in June 2022, with a concrete producer in Atlanta, GA, USA, to demonstrate the technology for use in infrastructure projects. The testing program was designed by AASHTO. The assessment measured concrete fresh properties, compressive and flexural strength at a variety of ages, and a range of durability properties. The test standards followed, either from AASHTO or ASTM, are listed in **Table 1**.

Table 1: Overview of testing program

	Property	Standard
Included in AASHTO M194 (ASTM C494)	Slump	AASHTO T119 (ASTM C143)
	Air Content	AASHTO T152 (ASTM C231)
	Unit Weight	AASHTO T121 (ASTM C138)
	Time of Setting	AASHTO T197 (ASTM C403)
	Compressive Strength	AASHTO T22 (ASTM C39)
	Flexural Strength	AASHTO T97 (ASTM C78)
	Shrinkage	ASTM C157
	Freeze-Thaw Resistance	AASHTO T161 (ASTM C666)
Additional Durability Testing	Surface Resistivity	AASHTO T358
Additional Durability Testing	Rate of Water Absorption	ASTM C1585
Additional Durability Testing	Hardened Air Void Analysis	ASTM C457
Additional Durability Testing	Chloride Diffusion	ASTM C1556
Additional Durability Testing	Corrosion of Steel Reinforcement (pending)	ASTM G109

Long-term corrosion testing per ASTM G109 (Standard Test Method for Determining Effects of Chemical Admixtures on Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments), is still ongoing and results will not be available until June 2024.

Results and Discussion

The study considered two conditions: 1) reference (Control) concrete mixture, and 2) concrete mixture incorporating CO_2 addition as an admixture (referred two herein as the CCT mix). Three control batches and three CCT batches were prepared for this investigation. The average proportions of the mix variations are presented in **Table 2**, below.

Table 2: Mix design details for all tested mixes

Component	Unit	Control	CCT
Cement	lb/yd³	606	604
Coarse Aggregate	lb/yd³	1839	1825
Fine Aggregate	lb/yd³	1184	1184
Water	lb/yd³	282	279
Water Reducer	oz/yd³	37.00	36.33
Air Entrainer	oz/yd³	10.67	11.00
Hydration Stabilizer	oz/yd³	16.33	16.67
CO_2	oz/yd³	-	18
w/cm	-	0.465	0.462

**1 lb/yd³ = 0.593 kg/m³, 1 oz/yd³ = 38.681 mL/m³*

Fresh Properties

Table 3 shows the fresh properties results obtained for the Control and CCT mixes. **Table 4** shows the average fresh properties results for the Control and CCT mixes, along with how the data fits within standards specifications (criteria described in AASHTO M194 or ASTM C494 Type S). Concrete slump, air content, density, and setting time values are comparable among the 6 concrete mixes, whilst complying with the standard requirements.

Table 3: Fresh properties results for the Control and CCT batches (numbers in parentheses represent ± one standard deviation from the average of three samples)

Sample ID	Slump (in)	Air Content (%)	Density (lb/yd³)	Initial Setting Time (hr:min)	Final Setting Time (hr:min)
Control 1	3.25	5.5	145.5	4:06	5:20
Control 2	2.75	5.5	143.5	3:33	4:49
Control 3	2.25	4.8	145.5	3:21	4:32
Average	**2.75 (0.5)**	**5.3 (0.4)**	**144.8 (1.2)**	**3:38 (0:21)**	**4:32 (0:24)**
CCT 1	3.00	5.7	144.7	3:35	4:42
CCT 2	3.75	6.0	142.7	3:42	5:00
CCT 3	2.25	5.1	145.1	3:06	4:30
Average	**3.00 (0.75)**	**5.6 (0.5)**	**144.2 (1.3)**	**3:27 (0:19)**	**4:44 (0:15)**

**1 lb/yd³ = 0.593 kg/m³, 1 oz/yd³ = 38.681 mL/m³*

Table 4: Average fresh properties results comparison for the Control and CCT batches, along with the standard requirements (numbers in parentheses represent ± one standard deviation from the average of three samples)

Test Category	Control	CCT	Requirement
Slump (in)	2.75 (0.50)	3.00 (0.75)	Control ± 0.5
Air Content (%)	5.3 (0.4)	5.6 (0.5)	5-7 (Control ± 0.5)
Density (lb/ft³)	144.8 (1.2)	144.2 (1.3)	-
Initial Setting Time (hr:min)	3:38 (0:21)	3:27 (0:19)	Control -1:00 to +3:30
Final Setting Time (hr:min)	4:53 (0:24)	4:44 (0:15)	Control -1:00 to +3:30

**1 in = 25.4 mm, 1 lb/ft³ = 16.018 kg/m³*

Compressive and Flexural Strength

Three concrete batches were prepared for the control and CCT mixes, respectively. Concrete specimens were collected for each batch and test age, and these specimens were demolded after 24 hours of fabrication and stored in a saturated lime-water solution at 73 ±4 °F (23 ±2 °C) until the age of testing. Compressive and flexural strength results in **Figure 1** and **Table 5** show the benefit of adding CO_2 to the concrete mixes.

Figure 1: Early age compressive strength results (error bars represent ± one standard deviation from the average of 3 specimens)

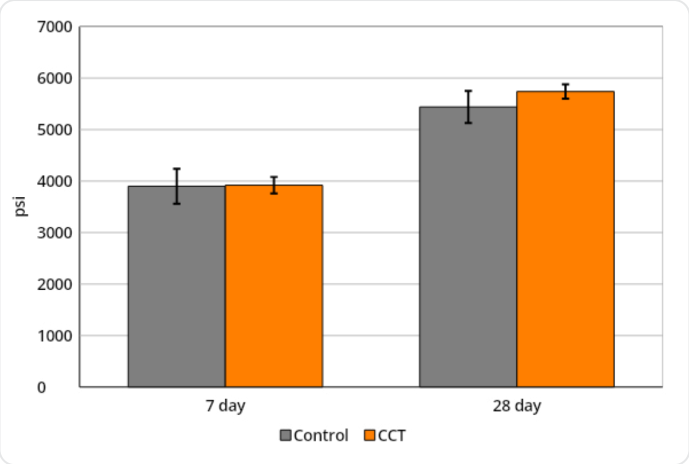


Table 5: Compressive and flexural strength results for the CCT batches (error bars represent ± one standard deviation from the average of 3 specimens)

Test Age	Avg. Control	Avg. CCT	Difference
Compressive Strength (psi) - follow suit			
3 days	2780 (210)	2990 (120)	**+ 7.5 %**
7 days	3900 (340)	3920 (310)	**+ 0.5 %**
28 days	5440 (160)	5740 (140)	**+ 5.5 %**
56 days	6090 (560)	6320 (220)	**+ 3.8 %**
90 days	6210 (650)	6670 (140)	**+ 7.4 %**
6 months	6930 (380)	6730 (420)	**- 2.9 %**
1 year	7320 (480)	7060 (480)	**- 3.5 %**
Flexural Strength (psi)			
3 days	565 (25)	565 (15)	**0.0 %**
7 days	665 (60)	690 (20)	**+ 3.8 %**
28 days	730 (35)	735 (10)	**+ 0.7 %**
56 days	850 (50)	855 (50)	**+ 0.6%**

AASTHO M194 specifies that any Type S admixture must not cause a strength loss greater than 10% at any age. The CCT batches exhibited slight strength gain up to 90 days, with slight strength loss within the AASHTO specifications at the 6 months and 1 year test ages. Design Strength, the compressive strength measurement that concrete structures are classified by, is measured after 28 days. Early strength gain is of the upmost importance to concrete producers, while durability becomes the focus at later ages. Based on the presented data, CO_2 has a positive effect on concrete strength at early ages.

Cement Efficiency

With the available compressive strength data, the performance of the Control and CCT concretes in terms of cement efficiency is outlined in Table 6 below. The cement efficiency is calculated using Equation 1:

$$\text{Cement Efficiency} = \frac{\textit{Compressive Strength (psi)}}{\textit{Cement Weight (lb/yd}^3\textit{)}}$$

Table 6: Cement efficiency values for the Control and CCT batches

Sample ID	7-day Cement Efficiency (psi/ lb•yd^{-3})	Difference (%)	28-day Cement Efficiency (psi/ lb•yd^{-3})	Difference (%)	90-day Cement Efficiency (psi/ lb•yd^{-3})	Difference (%)
Control	6.44	-	8.98	-	10.25	-
CCT	6.49	**0.8%**	9.50	**5.8%**	11.04	**7.7%**

**1 (psi/lb•yd^{-3}) = 0.01163 (MPa/kg•m^{-3})*

The higher cement efficiency numbers obtained for the CCT mix not only evidences the improvement in the cement hydration efficiency that the CarbonCure technology provides, but it also confirms the potential sustainability improvements in terms of obtaining similar performance with a reduced carbon footprint in the concrete.

Durability

Freeze-Thaw Resistance

Freeze-thaw resistance testing was performed on the Control and CCT concrete batches in accordance with AASHTO T161. Three concrete samples were prepared for each batch type, measured for initial relative dynamic modulus of elasticity (RDME), and then subjected to 300 freeze-thaw cycles, respectively. The average RDME after 300 cycles for the Control samples was 87%, while it was 88% for their CCT counterparts. A 13% elasticity decrease was experienced by the Control samples following 32 freeze-thaw cycles, which remained the same following the complete 300 cycle testing set. The CCT samples experienced a 12% elasticity decrease under the same conditions. AASTHO M194 requirements specify that the test mix must not fall below 90% of the control RDME. In this case, the CCT batches had an RDME of 101% in comparison with the Control concrete. This proves that injecting CO_2 caused no additional damage to the concrete's resistance to freeze-thaw damage.

Surface Resistivity

Surface resistivity was measured via a non-destructive test on the same concrete cylinders used to assess the 28-day compressive strength. The specimens were cured in a saturated lime-water solution and, at the age of 28 days, three concrete specimens from each concrete batch type were tested a total of 8 times, each measurement taken after rotating the specimen 90°. The results of the surface resistivity testing are presented in Table 7 below.

Table 7: 28-day surface resistivity results for the Control and CCT batches

Sample ID	Reading #1 (kΩ.cm)	Reading #2 (kΩ.cm)	Reading #3 (kΩ.cm)	Reading #4 (kΩ.cm)	Avg. Reading (kΩ.cm)	Overall Reading (kΩ.cm)
Control	12.4	12.2	10.2	11.8	11.7	**12.1**
	11.4	10.7	11.9	11.5	11.4	
	11.9	13.2	11.1	11.5	11.9	
	11.7	12.9	11.2	12.4	12.1	
	12.3	13.3	13.1	12.3	12.8	
	13.9	13.3	12.2	12.2	12.9	
CCT	13.6	13.0	13.0	13.2	13.2	**13.0**
	14.4	14.4	14.5	12.7	14.0	
	13.2	12.4	11.7	14.0	12.8	
	13.3	11.0	12.1	12.3	12.2	
	12.7	13.1	12.7	12.3	12.7	
	12.3	13.3	12.3	13.7	12.9	

Both control and CCT mixes exhibited a similar average surface resistivity value that fall within the 'Moderate' chloride ion penetrability category, according to Table 1 in AASHTO T358 (**Table 8** in this report). As such, the durability performance is expected to be equivalent for the two mixes.

Table 8: Chloride ion penetration categories (from AASHTO T358)

Chloride Ion Penetration	RCP Test Charged Passed (coulombs)	100 by 200 mm cylinders (kΩ.cm)
High	>4000	**<12**
Moderate	2000 - 4000	**12 - 21**
Low	1000 - 2000	**21 - 37**
Very Low	100 - 1000	**37 - 254**
Negligible	< 100	**>254**

Shrinkage

Shrinkage was measured through the length change of measured concrete specimens after 14 days of saturated lime-water solution curing, followed by 14 days of air drying. The CCT shrinkage measurement must not exceed a 0.01% increase in comparison with the measured Control shrinkage value to comply with AASHTO M194 Type S admixture standards. The length changes recorded following the shrinkage test are presented in **Table 9** below.

Table 9: Concrete shrinkage results for the Control and CCT batches

Sample ID	Test 1	Test 2	Test 3	Avgerage Shrinkage	Difference
Control	- 0.022%	- 0.022%	- 0.017%	**- 0.020%**	-
CCT	- 0.033%	- 0.027%	- 0.019%	**- 0.026%**	0.006

Both Control and CCT exhibited a similar average shrinkage value, with the CCT samples fitting within the allotted shrinkage increase of 0.01%. As such, the shrinkage resistance is expected to be equivalent for the two mixes.

Rate of Water Absorption

Water absorption analysis was completed on the Control and CCT batches in accordance with ASTM C1585-20. The purpose of this testing was to measure the rate of absorption of water by the Control and CCT batches, to determine whether the addition of CO_2 affects the permeability of the concrete. The results from this testing are presented in **Table 10** below.

Table 10: Rate of absorption of water by the Control and CCT batches

Sample ID	Diameter (in)	Initial Rate of Absorption (in/sec$^{1/2}$)	Secondary Rate of Absorption (in/sec$^{1/2}$)
Control 1	4.004	4.33E-05	1.57E-05
Control 2	4.016	4.33E-05	1.57E-05
Control 3	4.000	3.94E-05	1.57E-05
Average	**4.008**	**4.33E-05**	**1.57E-05**
CCT 1	4.012	3.94E-05	1.57E-05
CCT 2	4.001	3.94E-05	1.57E-05
CCT 3	4.047	3.54E-05	1.57E-05
Average	**4.024**	**3.94E-05**	**1.57E-05**

**1 in = 25.4 mm*

Both Control and CCT exhibited similar average rates of water absorption, indicating that the permeability of the concrete is unaffected by the addition of CO_2.

Air Void Analysis

Air void analysis was completed on the Control and CCT batches in accordance with ASTM C457, using Procedure B – Modified Point Count Method. The purpose of this testing was to determine if the presence of CO_2 affected the entrained air void structure of the CCT batches. An approximately 4-inch (102-mm) wide by 5-inch (127-mm) tall, polished sample was prepared from each batch type. The air void analyses were performed on these samples using a digital microscope at a magnification of 150x, and the results are presented in **Table 11** below.

Table 11: Microscopical determination of air-void system results for the Control and CCT batches (as per ASTM C457)

Sample ID	Agg (%)	Paste (%)	Air (%)	Total Points	Void Count	Void Frequency (voids/in)	Specific Surface (in^2/in^3)	Chord Length (in)	Spacing Factor (in)	Paste-Air Ratio
Control	65.3	26.5	8.1	1500	1857	12.4	609	0.0066	0.005	3.3
CCT	70.0	22.5	7.5	1501	1861	12.4	659	0.0061	0.005	3.0
Tolerance (per ACI 201.2R and ACI 211.1)							600-1100	0.0036-0.0067	0.004-0.008	4-10

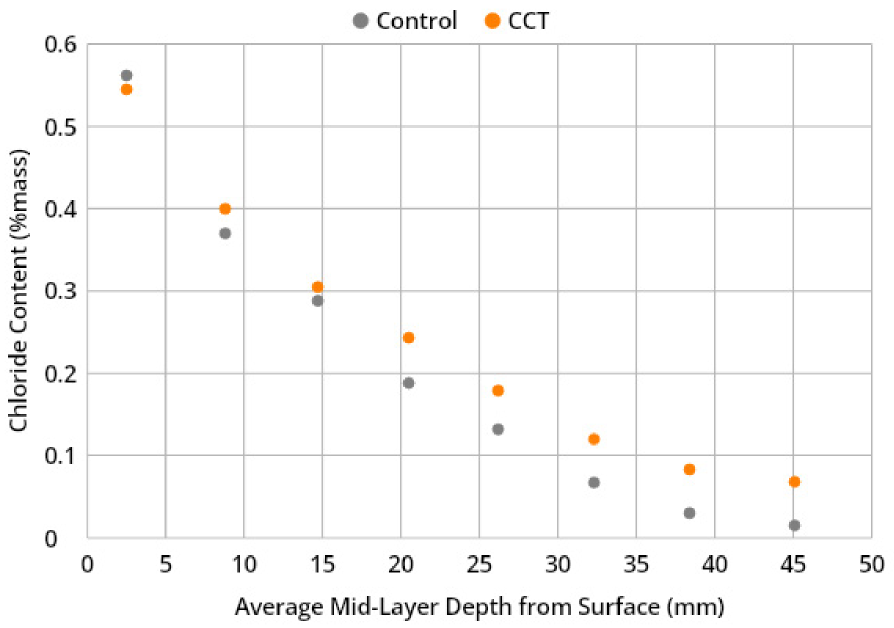
**1 in = 25.4 mm*

According to the tolerance for good air-entrained concrete per ACI 201.2R and ACI 211.1, the Control and CCT batches comply. The Control and CCT batches were slightly below the recommended Paste-Air Ratio range of 4 to 10.

Chloride Diffusion

Chloride diffusion analysis was completed on the Control and CCT batches in accordance with ASTM C1556. Two 4-inch (102-mm) diameter by 8-inch (204-mm) tall cylinders were made from each batch type, and chloride testing was performed on each cylinder at the appropriate depth. Following a 36-day moist curing process, the concrete cylinders were introduced to a NaCl solution for 365 days at 73 °F (23 C°). A summary of the average chloride content results for the Control and CCT batches is presented in **Figure 2** below.

Figure 2: Summary of chloride content results for the Control and CCT batches (as per ASTM C1556)



The average chloride diffusion coefficient (Da) results for the Control and CCT batches were calculated in accordance with ASTM C1556. The Da values were determined to be 5.58E-12 and 1.03E-11 m2/s for the Control and CCT batches, respectively. The chloride diffusion coefficient tolerance is not explicitly stated by AASHTO for Type S concrete admixtures. The difference between the Control and CCT's chloride diffusion coefficients is $4.724E^{-11}$, small enough to determine that the addition of CO_2 into the concrete had a miniscule effect on its chloride diffusion resistance.

Corrosion of Steel Reinforcement

Corrosion of steel reinforcement testing was performed on the Control and CCT concrete batches in accordance with AASHTO G109. This test provides a reliable means for predicting the inhibiting or corrosive properties of the CO_2 addition used in CarbonCure concrete. The results for this test will not be available until June 2024, as the corrosion data is to be collected after 2 years.

Concluding Remarks

CarbonCure Technologies has developed a technology that beneficially uses carbon dioxide as an admixture in freshly mixed concrete. The use of this technology across a broad scope of concrete production requires durability testing to confirm no adverse effects are observed on the concrete properties or service life. Under the guidance of AASHTO, a fresh properties, strength and durability study was performed on concrete designed with a water-cement ratio of 0.46 and a design strength of 5000 psi (34 MPa). A comparison between a reference (Control) mix and a test (CCT) mix with a dose of 0.20% CO_2 by weight of cement was performed to confirm unchanged fresh properties, strength benefits and durability compliance.

The concrete fresh properties were not changed by the addition of liquid CO_2. The slump, air content, and density were comparable between the Control and CCT batches. The compressive strength of the concrete was increased by the CO_2 injection, with increases of 8%, 6% and 7% at 3-days, 28-days, and 90-days, respectively. Concrete flexural strength was unaffected.

The concrete durability properties were not affected by the presence of CO_2. The freeze-thaw resistance, surface resistivity, shrinkage, rate of water absorption, hardened air-void analysis, and bulk chloride diffusion depicted similar performance values between the two conditions. The ASTM G109 testing results determining the corrosion of embedded steel potential of the Control and CCT batches will be available in June 2024.

Additional work outside this study measured extracted concrete pore solutions and found that the pH was not impacted in service[9]. The timing of CO_2 addition (immediately after mixing begins), the amount (<1% bwc) and the phases it reacts with (anhydrous cement and the hydration products available in the first minute of hydration) mean that the process is physiochemically distinct from atmospheric carbonation of a mature cement paste microstructure.

CO_2 utilization as a climate strategy for concrete production is a topic that must be considered. Life cycle analyses of the technology have validated that it achieves net carbon reductions, including the generation of Environmental Product Declarations (EPDs) for modified mixtures[10][11][12]. The testing in this study examining the impact of CO_2 on concrete durability was confined to the effect of CO_2. The true value proposition lies in leveraging CO_2 mineralization to support a more efficient use of cement. A durability study examining optimized mixes with a cement reduction will be the next step in this investigation. Nonetheless, this durability study increases confidence that the technology can be used to produce concrete in demanding performance applications, including roads and bridges.

CarbonCure Ready Mix Technology - Opportunities

Building with CO_2 mineralized concrete is an effective way to reduce embodied carbon in the built environment, which is a key tactic for reducing emissions and meeting climate targets. On average, concrete produced with CarbonCure Ready Mix reduces an average 15 to 25 lbs of CO_2 per cubic yard or roughly 5% less CO_2 than conventional concrete. CarbonCure's technologies enable concrete producers to compete and win more bids with low-carbon concrete, catering to the end users in the growing green building market. Concrete producers are also able to generate carbon removal credits when using CarbonCure. Each carbon removal credit represents one tonne of CO_2 removal as an asset, which can be traded, sold, or retired to companies seeking to counterbalance their remaining carbon footprint to reach net zero emissions. Incorporating CarbonCure into daily concrete production is an environmentally conscious solution, reducing costs with a proven technology that enables cement reductions, requiring no upfront capital investment.

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