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Innovations in Concrete: 4 Levers to Reduce CO_2 Emissions of Concrete

An expert guide from Dr. Doug Hooton on how to improve the sustainability of concrete while adhering to codes and standards.

Preface

Professor Doug Hooton, PhD is the NSERC/CAC Industrial Research Chair in Concrete Durability and Sustainability at the University of Toronto. His research involves finding ways to reduce the greenhouse gas emissions associated with concrete infrastructure and has informed the specification codes associated with the American Concrete Institute, the Canadian Standards Association, and ASTM standards.

Dr. Hooton joined CarbonCure for a live event to share some of his research findings and observations gleaned throughout his illustrious career.

This report summarizes the discussion.

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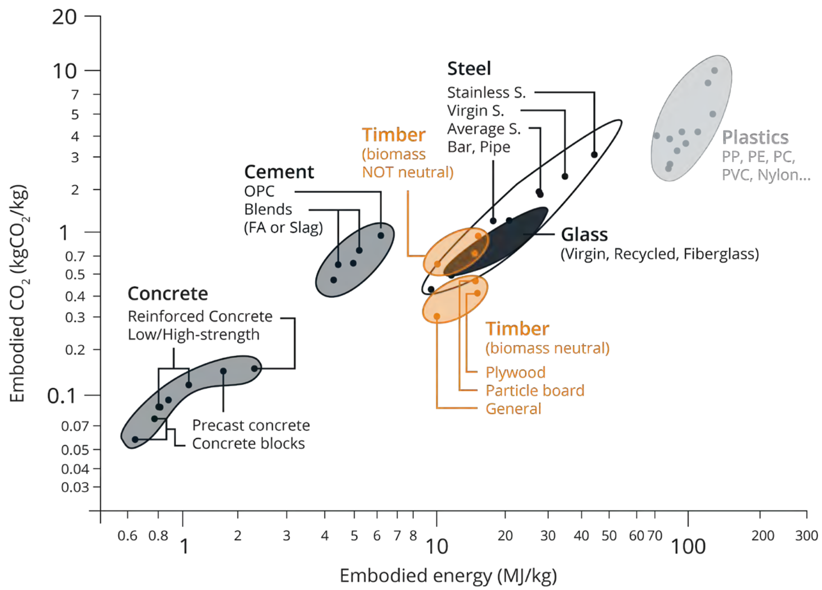
Introduction: Embodied CO_2 in Concrete

In 2014, Barcelo et al. studied the embodied carbon and energy of materials typically used in the construction industry and plotted them on the following graph:



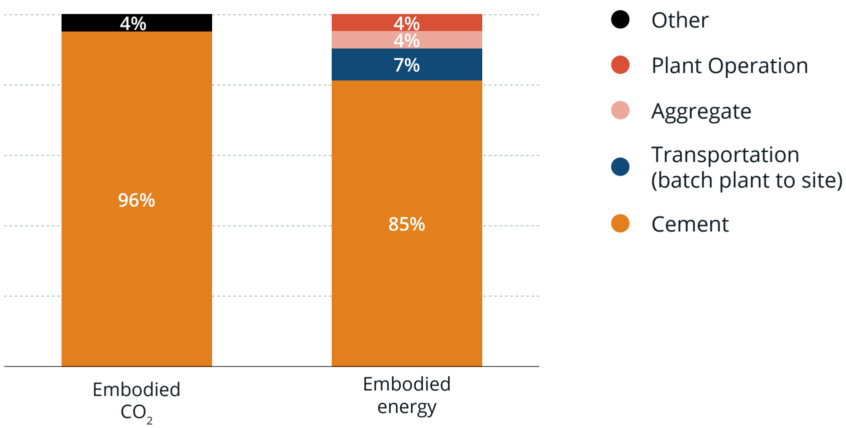
Source: Adapted from Barcelo et al. 2014

Concrete falls at the lower end of the scale in terms of embodied carbon and embodied energy. Concrete is made up of about 10% cement, with the remaining 90% of its components (water, sand, stone) having a low carbon impact due to low extraction and manufacturing impacts. When properly designed, concrete has a long service life and is recyclable. Concrete structures have better lifecycle sustainability due to less maintenance and repair than wood.

So, if concrete is so low on the embodied carbon and energy scale, why is it a problem? Concrete is the most used building material in the world, and is the most consumed resource second only to water. Due to the volume of concrete created globally — particularly in high-growth regions like China and India — concrete is responsible for 7% of all CO_2 emissions and 4% of the energy emissions.

Cement — a key ingredient of concrete — only makes up about 10% of concrete's mass but is responsible for 96% of the embodied carbon emissions of concrete and 85% of the embodied energy.

CO_2 emissions and embodied energy of concrete made with plain Portland cement



Source: PCA, Third Quarter 2006 Survey of Portland Cement by User Group, PCA, November 2006

Cement industry associations around the world, including the European Committee for Concrete, the Portland Cement Association, and the Global Cement and Concrete Association, have developed roadmaps to:

- **Reduce CO_2 emissions by 40-50% by 2030** by making concrete more efficient using currently available innovations
- **Attain carbon neutrality by 2050** by adopting carbon capture and sequestration techniques

These targets are mirrored by the architect, engineer, and contractor (AEC) communities through initiatives like Architecture 2030 and SE 2050.

Due to its volume and potential for decarbonization, concrete is a huge focus area for all industry and climate professionals. This guide covers some of the ways the CO_2 emissions of concrete can be reduced or removed entirely, redefining concrete as being part of the solution.

Ways to Reduce CO_2 Emissions from Concrete Today

There are several, easily implementable levers that concrete producers can use to reduce CO_2 emissions of concrete today:

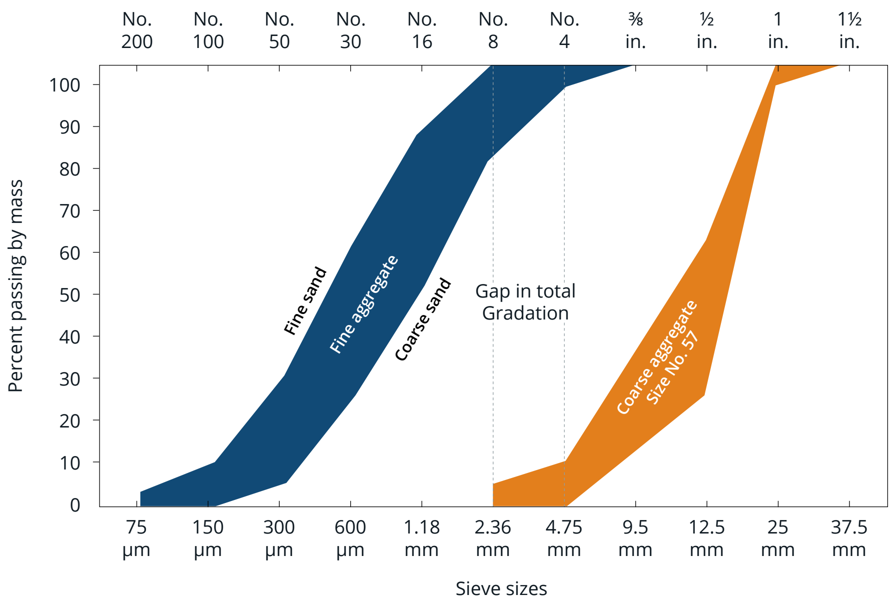
Method	Potential CO_2 Reduction
1. Optimization of total aggregrate gradations	5-15%
2. Use of Type 1L Cement (also known as Potland Limestone Cement or PLC)	10%
3. Increase levels of SCMs	Various
4. Adopt CO_2 mineralization techniques	4-6%

Each of these materials, mixtures, and methods meet current standards and codes and can be implemented easily without any compromise on performance or durability.

1. Optimization of Total Aggregate Gradations

The American Society for Testing and Materials (ASTM) and the Canadian Standards Association (CSA) gradation limits for concrete aggregates have not changed in over 100 years.

In an example shared by Dr. Hooton, we see a typical blend of coarse aggregate and fine sand that leaves a gradation gap — one that would be filled by the paste fraction of the concrete. The paste includes the carbon-intensive cement fraction.



To reduce embodied carbon, however, the gap can be filled by intermediate particles (i.e., the use of a third aggregate). This is known as "well-graded aggregate" and is a common approach in Europe.

By optimizing aggregate gradations, producers can reduce the cement paste fraction and associated CO_2 emissions by 5-15%, while also improving concrete properties, reducing concrete shrinkage, reducing permeability, and increasing strength.

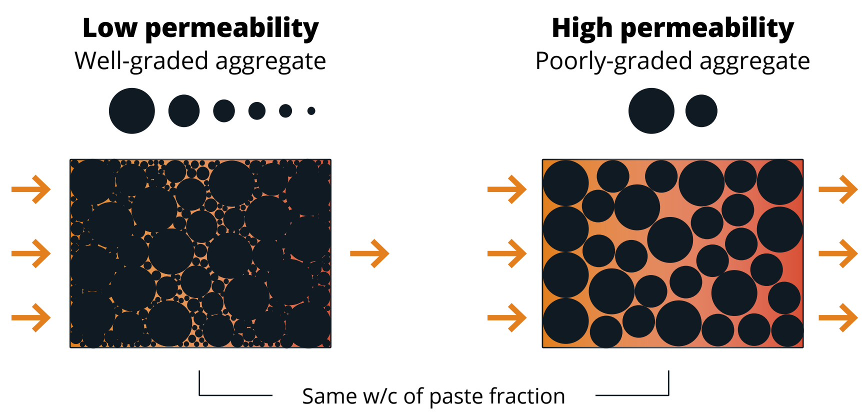
Optimizing Combined Aggregate Gradation

Typical Mix | Gap-graded	**Optimized Mix** | Well-graded
lack of intermediate particles	plenty of intermediate particles
↑ void content	↓ void content
↑ paste fraction required	↓ paste fraction required

Dr. Hooton cited two examples from a **2011 thesis study** on aggregate gradation conducted by Majella Anson Cartwright:

- 16% cement reductions in 7,259 psi bridge deck mixes were obtained (lowered from 784 to 657 lb/yd^3) while meeting a 1,000 coulomb limit at 56 days.
- 8% cement reductions in 5,000 psi mixes were obtained (lowered from 607 to 556 lb/yd^3) while meeting a 1,500 coulomb limit at 56 days.

In both examples, the reduced cement mixes included intermediate-sized aggregate produced from excess smaller fractions of the coarse aggregate, taken from the same quarry.



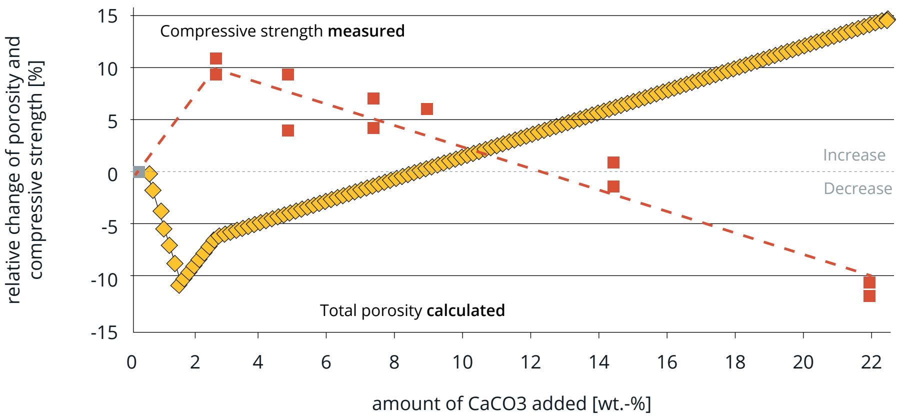
Optimized Total Gradation of Aggregates can save up to 15% of cement (Anson-Cartwright & Hooton 2011)
Results in lower permiability and lower shrinkage

2. Use of Type 1L Cement (PLC)

By using Type 1L cement (also known as PLC), concrete producers can reduce CO_2 emissions by **up to 10%** compared to regular Portland cement — with no change in performance.

Type 1L cement (CSA Type GUL) is permitted in ASTM C595 or AASHTO M240. ASTM C595 requires that Type 1L has the same setting times, strength development, and heat of hydration limits as C150 (i.e., equal performance to regular Portland cement). The only chemical difference between Type 1L and regular Portland cement is the loss on ignition (LOI) limit which is higher for Type 1L, given the higher limestone content. The Blaine fineness of Type IL is also higher to improve the strength development.

Correlation: Porosity — Compressive Strength



exp. Data by D. Hertford, Aalborg cement, T. Matschel

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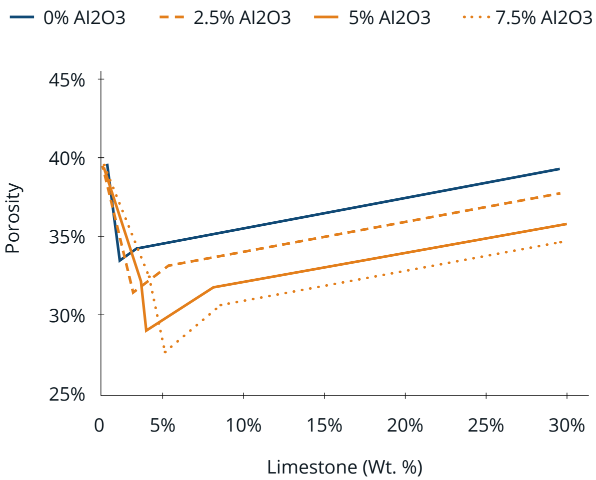
3. Increase Levels of SCMs

When concrete producers use SCMs like fly ash, silica fume, and slag along with Type 1L cement, additional synergies can be gained.

In fact, Type 1L cement with SCMs can perform better at an early age than Type 1 with SCMs. This is due to the nucleation effects of the finer limestone particles on calcium-silicate reactions and formation of additional carbo-aluminates (Al_2O_3) which fills in pores and increases the strength.



Since CO_2 reduction is directly proportional to the percentage replacement of cement, increasing levels of SCMs can reduce CO_2 emissions greatly. SCMs can also result in better durability, resistance from chloride ingress, and reduced sulfate attack, ASR, and thermal cracking.

Strengths of air-entrained concrete cured at 73 °F with Type 1L cement and SCMs

Mix Identification 400 kg/m3 (666 lb/yd3) mixtures	% clinker in binder	w/cm	Compressive strength (psi)			
			7 day	28 day	56 day	182 day
Type I Cement Control	89*	0.40	5700	6600	7350	7630
Type I + 40% Slag	53	0.40	4760	6700	7130	7420
Type IL (15) + 40% Slag	46	0.40	5380	7580	8340	8580
Type IL (15) + 50% Slag	38	0.40	5260	8020	8710	9510
Type IL (15) + 6% Silica Fume * 25% Slag	53	0.40	6670	9420	10,160	11,020

**3.5% limestone and 8$ gypsum*
Source: U. of Toronto Field site Data

Rapid chloride permeability testing of air-entrained concrete cured at 73 °F with Type 1L cement and SCMs

Mix Identification 400 kg/m3 (666 lb/yd3) mixtures	% clinker in binder	w/cm	Chloride penetrability (coulombs)		
			28 day	56 day	182 day
Type I Cement Control	89*	0.40	2384	2042	1192
Type I + 40% Slag	53	0.40	800	766	510
Type IL (15) + 40% Slag	46	0.40	749	581	441
Type IL (15) + 50% Slag	38	0.40	525	428	347
Type IL (15) + 6% Silica Fume * 25% Slag	53	0.40	357	296	300

4. Adopt CO_2 Mineralization Technologies

CarbonCure's **CO_2 mineralization technologies** introduce a precise dose of captured CO_2 into concrete during mixing, similarly to an admixture. Upon injection, the CO_2 **mineralizes**, resulting in a compressive strength improvement that enables mix optimization without impacting fresh or hardened properties.

By introducing the CO_2, **concrete producers** can optimize their mix designs to use cement more efficiently and reduce CO_2 emissions by 4-6% on average, though every case is different depending on mix designs.

The CO_2 reacts to form nano-carbonate minerals that act as nucleation sites to accelerate hydration. This leads to strength gains that allow the reduction of cement content in mix designs while maintaining strength performance.

The following table compares the baseline concrete mixes of three ready mix producers across the United States with an optimized mix using CarbonCure. Every producer in this example reduces cement by an average of 4%, while showing a neutral impact on fresh and hardened concrete properties.

Mix		Date Range	% Cement Reduction	w/cm	% Air Content	Slump (in)	7D Strength (psi)	28D Strength (psi)
1	Baseline	1/31/2019 - 4/17/2020		0.52	4.4	4.9	2,684	3,741
	Optimized	6/5/2019 - 10/8/2020	5	0.54	4.5	5.6	2,629	3,676
2	Baseline	10/15/2020 - 1/2/2021		0.53	1.9	5.0	2,803	3,998
	Optimized	10/19/2020 - 1/27/2021	5	0.54	1.9	6.2	2,777	3,848
3	Baseline	11/30/2018 - 6/20/2020		0.41	4.7	4.8	4,120	5,318
	Optimized	2/16/2017 - 1/22/2021	3.8	0.42	4.2	5.6	4,150	5,568
4	Baseline	8/23/2019 - 11/13/2020		0.54	1.5	5.1	2,624	4,453
	Optimized	6/11/2019 - 9/21/2020	3.85	0.57	1.5	4.7	2,681	4,520
5	Baseline	8/3/2019 - 11/12/2020		0.42	4.1	6.0	3,889	5,627
	Optimized	7/7/2020 - 1/15/2021	3	0.46	3.8	6.4	3,618	5,786
6	Baseline	11/1/2019 - 10/24/2020		0.44	1.8	5.8	3,856	5,276
	Optimized	5/17/2019 - 12/14/2020	4	0.46	1.8	1.8	3,912	5,139

Durability of Concrete Innovations

When implementing any of the innovations described above, concrete producers typically want to test the performance of the mix designs to ensure that durability is not compromised. The following sections compare concrete with varying innovations with traditional concrete mix designs for shrinkage, alkali-silica reaction, freeze-thaw, chloride penetration resistance, carbonation, and sulfate resistance.

Shrinkage

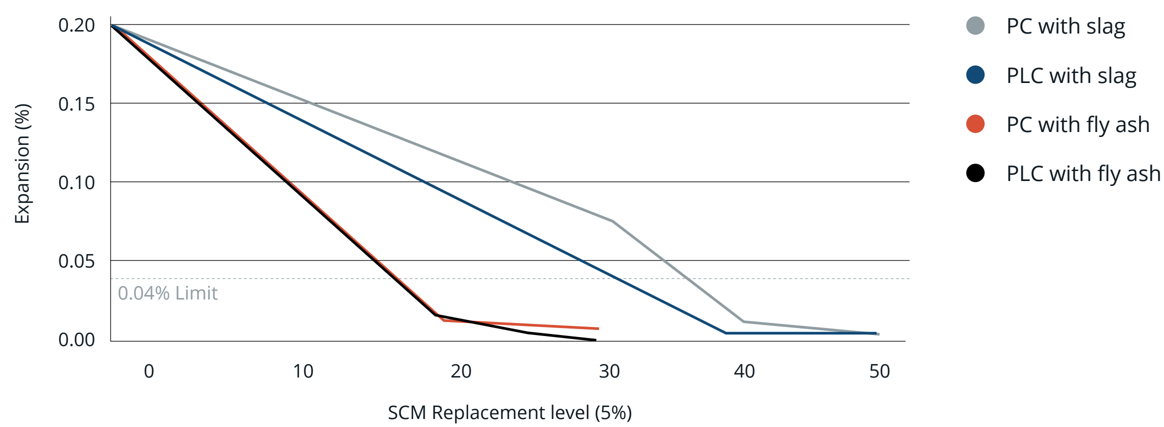
Drying Shrinkage % after 7d wet cure
CSA A23.1 (ASTM C157) w/cm = 0.40 mixtures

Age	GU 100%	PLC 10 100%	PLC 15 (100%)	GU 70% SLAG 30%	PLC 10 70% SLAG 30%	PLC 15 70% SLAG 30%
28 days	0.036	0.037	0.037	0.026	0.027	0.025
1 year	0.069	0.061	0.062	0.058	0.052	0.053
2 years	0.067	0.068	0.065	0.062	0.06	0.067

Shrinkage was unaffected by the PLC (Type IL)
Reduced 28-day shrinkage with 30% slag mixes

Alkali-Silica Reaction

2-year ASTM C1293 Concrete Prism Expansions



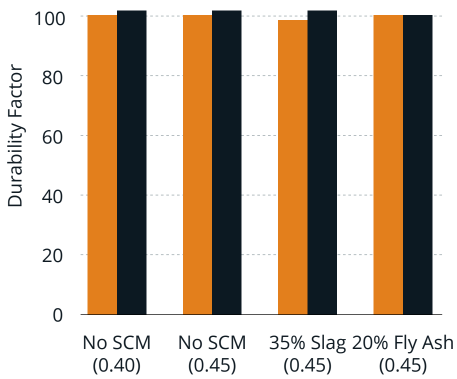
Source: Thomas et al 2013.

Freeze-Thaw and De-Icer Scaling Resistance

Results of free-thaw and de-icer salt scaling tests for PC and PLC concrete with and without SCM

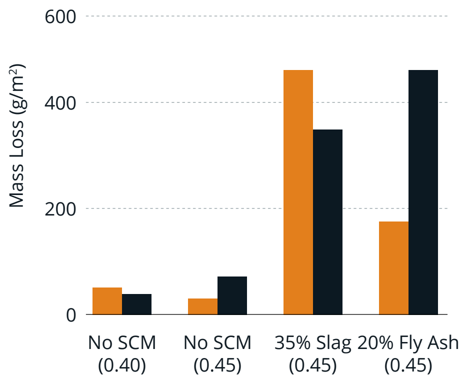
Freeze-Thaw Resistance (ASTM C666)

Supplementary Cementing Materials (w/cm)



Scaling Resistance (ASTM C 672)

Supplementary Cementing Materials (w/cm)

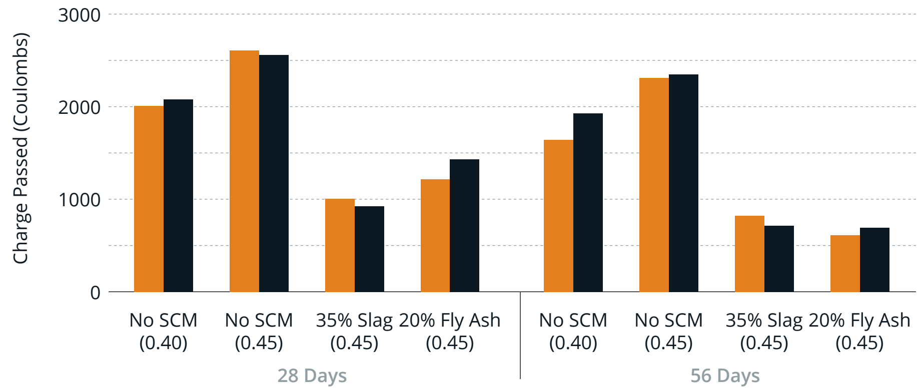


PC PLC

Chloride Penetration Resistance

ASTM C1202 Coulombs

Supplementary Cementing Materials (w/cm)

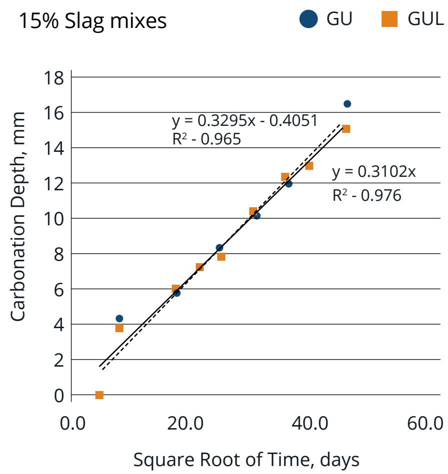


Carbonation

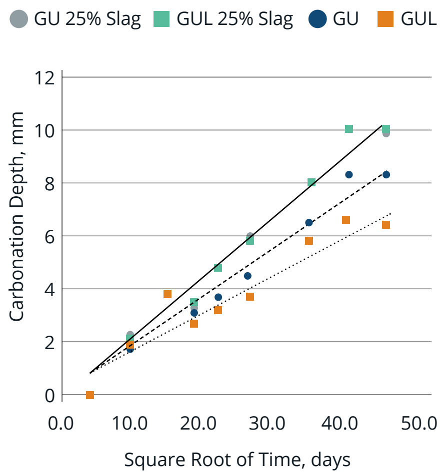
Two carbonation studies (University of Toronto): 7-day moist cured concrete prisms (w/cm = 0.40) stored at 50% rh and 23°C

MTO Gul Trial 2009

15% Slag mixes



MTO Gul Trial 2009



Note: SQRT of 50 days = 6.8 years

No difference in carbonation between Type I & Type IL concretes with 15% Slag

- Type IL mix carbonated less thank Type I mix.
- Both 24% slag mixes carbonated at the same rate, but higher than both the plain Types I & IL mixes

Sulfate Resistance

Long-term tests on concrete have shown that concrete made with Type 1L cement and slag combinations are as resistant to sulfate attack, as Type 1 cement and slag and more resistant than concretes made with Type 5 cement at an equivalent water to cement ratio..

Studies at the University of Toronto and the University of New Brunswick on low-temperature sulfate resistance tests on concrete found concrete with Type 1 and Type 1L cement with the same SCM contents showed similar performance.

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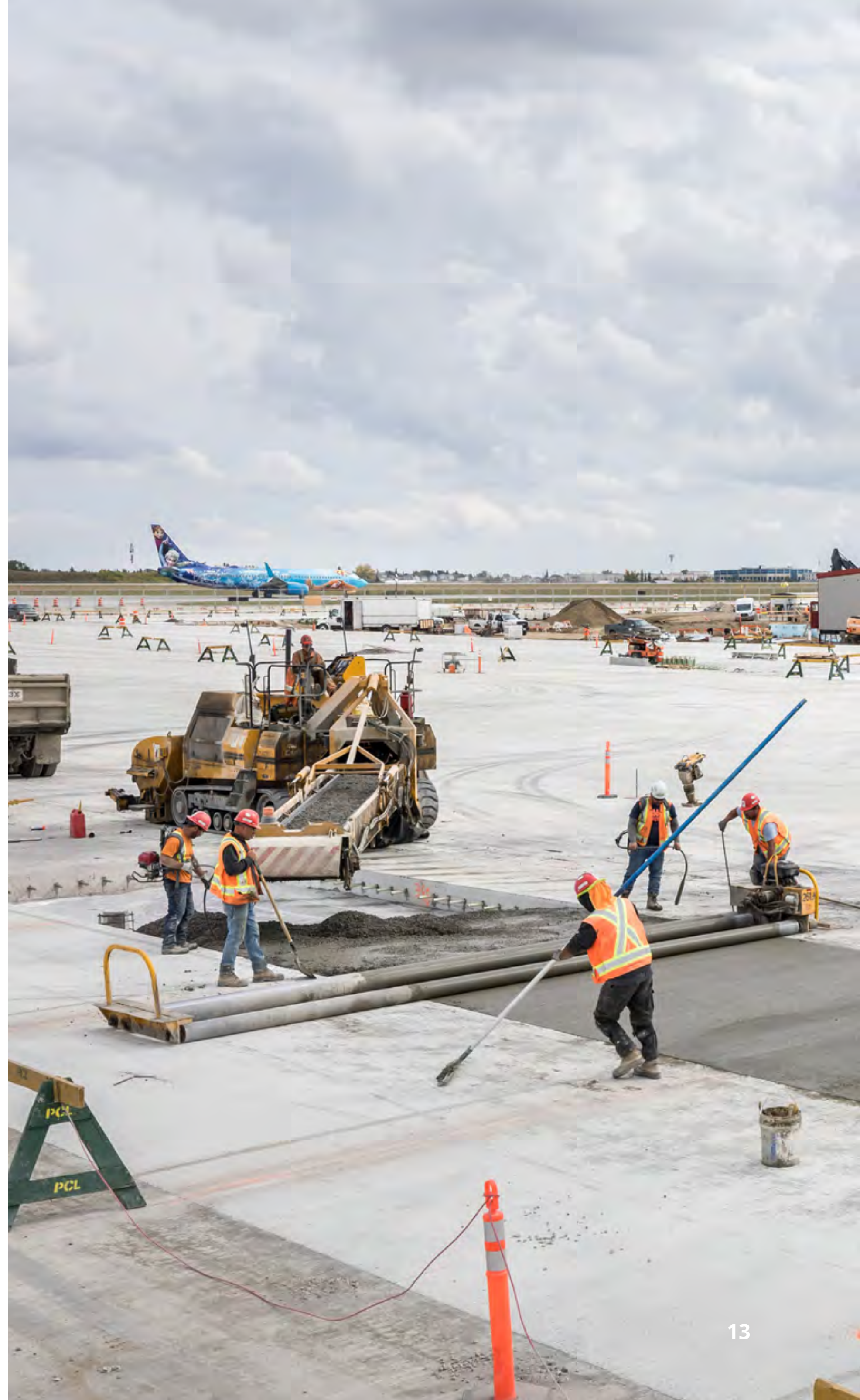


Codes, Standards, Specifications That Permit Innovation

ASTM, AASHTO, ACI, and CSA specifications allow Type 1L cement in all sulfate exposures:

- In 2012, cements with limestone contents up to 15% were included in ASTM C595 and AASHTO M240 as Type 1L.
- In 2016, ASTM and AASHTO allowed Type 1L and SCM combinations in all sulfate exposures. The only requirement is that ASTM C1012 expansion limits be met using the same limits for blended cements without limestone.
- ACI 318-19 removed previous restrictions on the use of Type 1L cement in sulfate exposures.
- CSA A3001 (2018) and A23.1 (2019) allow Type GUL and SCMs in all sulfate exposures, provided they pass the expansion limit using the CSA equivalent of ASTM C1012.

As of May 2022, Type 1L cement has now been accepted by 38 U.S. and 8 Canadian Department of Transportations.

Specification for Ready Mix Concrete

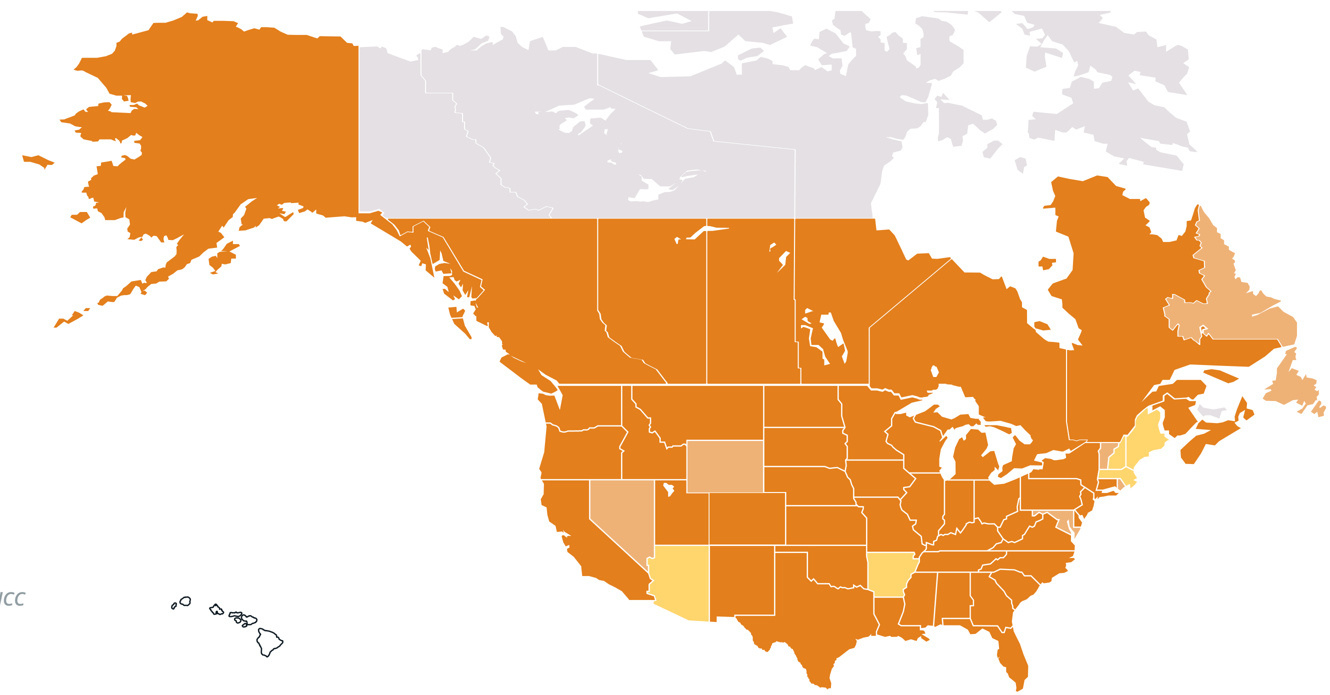
ASTM C94 specification for ready mix concrete specifies that:

- Type 1L cement is allowed in all applications
- SCMs are allowed with no restrictions
- Combinations of coarse aggregates meeting C33 are allowed
- CO_2 mineralization is permitted as a solid chemical admixture, and is compliant with ASTM C494 Type S standards

DOT Acceptance of Portland-Limestone Cement

Tentative data: October 2021

- Accepting
- Planning to accept
- Considering
- Not accepting at this time
- No information



Note: FAA P-501, AIA Masterspec, UFGS 03 30 00, and ACI and ICC building codes permit use of PLC

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Building Codes

Type 1L cement and other ASTM C595 blended cements are permitted in ACI 318-19 building codes. SCMs are permitted in 318 with a limitation on replacement levels for F3 exposure (i.e., exterior flatwork that may be exposed to water and de-icing chemicals). ASTM C1866 ground glass pozzolans have been accepted for the next edition of ACI 318.

CarbonCure has been qualified as an ASTM Type S (specific performance admixture) so can be used in ASTM C595 or ACI 318 (with a review by a licensed design professional).

Specifications for cementitious materials

Cementitious Materials	Specification
Portland cement	ASTM C150
Blended hydraulic cements	ASTM C595, excluding Type IS (≥70) and Type IT (S ≥ 70)
Expansive hydraulic cements	ASTM C845
Hydraulic cement	ASTM C1157
Fly ash and natural pozzolan	ASTM C618
Slag Cement	ASTM C989
Silica Fume	ASTM C1240

Limits on cementitious materials for concrete assigned to Exposure Class F3

Supplementary cementitious materials	Maximum percent of total cementitious materials by mass
Fly ash or natural pozzolans conforming to ASTM C618	25
Slag cement conforming to ASTM C989	50
Silica fume conforming to ASTM C1240	10
Total of fly ash or natural pozzolans and silica fume	35
Total of fly ash or natural pozzolans, slag cement, and silica fume	50

Barriers to Adoption of Sustainability Innovations

1. Legacy Standards, Specifications, and Codes

Progress	CSA	ASTM/ACI
Adoption of Performance Standards for Concrete	2004	-
Adoption of portland-limestone cements	2008	2012
Adoption of Ground Glass Pozzolanos	2018	2020
Allow Use of high SCM replacement levels	Yes	Yes (except for F3 exposure)
Allow use of optimized total aggregate gradations (to minimize cement paste friction)	2014	Allowed but not specifically mentioned
Allow the use of harvested (if processed) landfilled coal ash as SCM	2021	? Balloting ASTM C618 in 2022

Other than strength, there are no performance requirements in ACI 318-19. The durability exposure requirements are mainly just strength and water to cement ratio. ACI 318A is currently balloting a change for C2 (corrosion) exposure that would allow an option to use 1,500 coulombs in lieu of current 0.40 psi and 5,000 psi with a maximum limit of 0.50 psi. If adopted, this would provide concrete with improved resistance to chloride ingress.

The ACI 329R-14 Report on Performance Based Requirements for Concrete covers the performance of concrete and reflects a growing movement to **move from prescriptive to performance specifications**, eliminating minimum cement requirements and allowing more innovation in mix design.

However, some architectural, engineering, and construction companies are still specifying old ASTM or CSA standards and some municipal authorities, states, and provinces are still referencing outdated specifications and codes. Others have their own specifications that are not consistent with current ASTM and CSA specifications. In fact, it is reported that over 2,000 different concrete specifications are in use in the U.S. today. Many still require legacy prescriptive minimum cement contents in concrete in addition to **performance specifications**.

2. Education and Training Gaps

Many design and specification professionals in positions of authority graduated from university 15-30 years ago. At that time, they would not have been trained on sustainability and may still follow best practices formed decades before these sustainability innovations were proven in the market.

There is a requirement to educate these important influencers of the options available to them today and address the benefits, risks, and concerns so they can make better informed decisions.

3. Supply Chain Constraints

It may be difficult to increase the utilization of the most desirable clinker substitutes — e.g. blast furnace slags and suitable fly ashes — since the availability is much less than the total cement production. Further, a very high proportion of these substitutes are already used in cement or concrete. New and reliable sources of good quality materials will be required to support increased cement reductions through replacement by SCMs.

Similarly, many plants have a finite number of bins and limited space for aggregates and cannot easily add additional aggregates that would support the optimization of total aggregate degradation.

Summary

The current standards allow Type 1L cement, SCMs, optimized total aggregate gradations, and proven innovative carbon technologies like CarbonCure. They even permit the use of all four innovations to be used in tandem to achieve the maximum impact on embodied carbon and energy reduction.

However, there is still a need for a broader shift to performance specifications by AEC communities in order to maximize the impact of these innovations and reduce embodied carbon and energy in line with the commitments set out by the industry.

For more information on any of the topics covered in this guide, watch the on-demand webinar with Dr. Doug Hooton hosted by CarbonCure.

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CarbonCure has been used on thousands of projects ranging from healthcare to higher education, residential developments, and corporate campuses.

For more information about building with CarbonCure concrete, visit **carboncure.com**. To get in touch with a CarbonCure representative, send us an email at **info@carboncure.com** or give us a call at **+1 (902) 448-4100** (Worldwide) or +**1 (844) 407-0032** (North America).