DESIGNING WITH PRECAST CONCRETE

Curing of High Performance Precast Concrete

TECHNICAL GUIDE

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Curing of High Performance Precast Concrete

Proper curing of concrete is critical to ensuring a product that is strong, watertight, and durable. Curing is the chemical reaction (referred to as hydration) that occurs between the cementitious materials and water, to form a Calcium Silicate Hydrate (CSH) gel, or the "glue" that binds all of the ingredients together. In order to achieve complete hydration, it is imperative that moisture not evaporate from the product, and that the product be in a heated environment. **This paper discusses the curing cycle for precast concrete cured in controlled environments, with special emphasis on: (1) the allowable maximum curing temperature to avoid delayed ettringite formation (DEF) and (2) the duration of curing required for high performance concrete.**

Background

There are essentially three basic curing methods, all of which are designed to keep the concrete product moist:

1. One method is to maintain the presence of mixing water in the product while it hardens. This can be achieved by ponding, fogging or spraying, and wet coverings such as wet burlap.

2. Another method is to minimize moisture loss by utilizing membranes such as forms, canvas or polyweave tarps, or by using curing compounds.

3. One of the most common methods, used at precast plants, is accelerated curing where strength gain is accelerated by the use of live steam, radiant heat or heated beds. The use of commercial accelerating admixtures is also commonly used by some precast manufacturers.

Live low-pressure steam curing, in tandem with tarping or covering (See Figure 1) is a common method because it has the advantage of providing the heat necessary to accelerate the hydration process, while also ensuring the retention of moisture in the product. In order to be effective, it is necessary to follow a proper curing cycle.

Figure 1. Precast concrete cured in controlled environments

A typical accelerated curing cycle consists of four parts:

1. **Preset (or Pre-heating)** – this is the initial set of the concrete. Preset allows the product a period of time to commence hydration, and is an important part of the cycle. Subjecting the product to higher temperatures before the product has begun hydration can result in thermal shock, and cracking.
2. **Ramping** – this is the period during which the product is raised from the preset temperature to the curing target temperature, and must be done at a controlled rate of between 10°C to 20°C per hour. The minimum temperature of 10°C/hour is required to rapidly activate the hydration process, while the maximum temperature of 20°C/hour is necessary to prevent thermally shocking the product.
3. **Holding Period** – the product is held at the target curing temperature (60°C to 70°C) until the desired concrete strength is developed.
4. **Cooling Period** – the product temperature is cooled prior to handling, or placing outdoors. This is usually the time at which the differential in temperature between the concrete and the ambient outside temperature is less than 20°C.

- 1) Pre-steaming
- 2) Ramping
- 3) Holding
- 4) Cooling

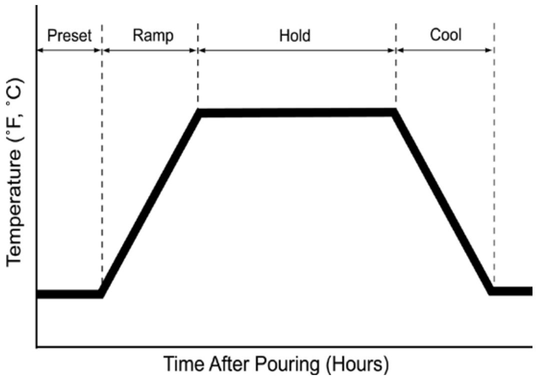


Figure 2. Idealized Accelerated Curing Cycle.

In general, the higher the curing temperature, the faster the desired concrete strength is achieved. Precasters typically achieve 28 day strengths at stripping times of 16 hours or less, depending on the concrete mix design. This curing cycle enables them to reuse their forms on a 24 hour cycle.

There is a limit, however, on what the maximum temperature can be, to prevent Delayed Ettringite Formation (DEF), and damage to the product. The maximum curing temperature that is generally acknowledged by most authorities is 70°C, for products that are exposed to damp or continuously wet conditions in their service life.

Curing Temperatures and Delayed Ettringite Formation

During the late 1990s, DEF (a form of internal sulfate attack) was a major concern throughout Europe, especially in relation to the production of structural elements such as girders. Many manufacturers were curing their products at very high temperatures in excess of 70°C, and as high as 90°C, in order to "double pour" their sections within a 24 hour period. At the same time, however, the cements contained a relatively high percentage of sulfates. As a result, products that were exposed to a moist environment experienced deleterious cracking, after only a few years. Upon investigation, this was determined to be a result of DEF.

Although ettringite is a normal product of early hydration of Portland cement, curing at too high a temperature stops the formation of ettringite during the early hydration process. If the concrete product is later exposed to water, or wet conditions at ambient temperature, ettringite slowly forms and grows in the matrix, leading to a deleterious expansion of the concrete and destructive cracking, known as DEF.

In 1996, RILEM (Reunion Internationale des Laboratoires d'Essais et de Recherches sur les Materiaux et les Constructions) established TC-ISA, a technical committee to study field problems, with regards to DEF and cracked concrete[1]. Frequently, RILEM establishes technical committees (TCs) to investigate specific problems with construction materials. Typically, the TCs have a maximum life span of four years, however, this committee continued its work until they were disbanded in 2002.

Consensus was reached that internal sulfate attack had not been an issue until the early 1990s. It was in the 1990s that cement manufacturers increased the sulfate content of clinkers or cements, and increased the fineness of their cements (Blaine surface area) in response to the increased demand for accelerated early strength development. Committee members believed that this, combined with excessively high curing temperatures, was the principal cause of DEF. While some of the researchers believed a maximum curing temperature of 65°C should be recommended, others acknowledged a maximum of 70°C[2].

Today, a maximum curing temperature of 70°C is commonly accepted around the world[3,4,5,6,7,8] while some authorities permit up to 77°C if Supplemental Cementitious Materials, such as Fly Ash, Ground Granulated Blast Furnace Slag, or Silica Fume are added to the concrete or blended into the cement.

The American Concrete Institute (ACI)[9] defines DEF as a *form of sulfate attack by which mature hardened concrete is damaged by internal expansion during exposure to cyclic wetting and drying in service and caused by the late formation of ettringite, not because of excessive sulfate; not likely to occur unless the concrete has been exposed to temperatures during curing of 158°F (70°C) or greater and less likely to occur in concrete made with pozzolan or slag cement.*

For concrete products exposed to infrequent wetting, and those that are continually dry for their service lives, a maximum curing temperature of 82°C has been shown to be effective in ensuring long-term durability.

Effect of Curing Conditions on the Performance of Precast Concrete

Although low-pressure live steam curing has been accepted as a standard method of accelerated curing, throughout the world, some specifying agencies require girder manufacturers to "secondary cure" ("wet cure") for a period of three, five or seven days after having completed steam curing. Recent research conducted by the National Research Council of Canada (NRCC) on behalf of CPCI (2014)[10] describes the results and analysis of a CPCI/ NRCC project to determine the appropriate length of accelerated curing for precast concrete. The results of a round-robin test at nine different permanent precast concrete plants on the effects of curing time on standard concrete performance tests are presented in this state of the art report.

The round-robin testing compared the effects of three different curing regimes (air curing after 16 hour accelerated curing, air curing after 72 hours moist curing, and air curing after 168 hours moist curing) on the compressive strength and rapid chloride penetration properties of precast concrete of samples produced by nine permanent precast concrete plants. The project's goal was to investigate the effects of the accelerated curing regimes on a variety of different concrete mixes particular to the plants, rather than using one standard mix for all of the plants. Each of the nine permanent precast concrete plants participating in the round-robin therefore used a mix design that was commonly used in their daily production for its clients. NRCC reviewed the historical performance data for each plant and verified that the compressive strength values measured in the test program were consistent with those typically measured at each plant, indicating that the mixes used in the research project were typical of those produced by the companies.

Compressive strength and rapid chloride penetration (RCP) tests were carried out on specific CSA A23.1 C-1 and C-XL samples produced in the controlled environments of the plants. Two plants produced C-1 samples while 7 produced C-XL samples, all based on their own standard mixes. Samples were tested at 28 and/or 56 days of age according to the requirements of CSA A23.1-09 (See Table 1).

Table 1. Performance Requirements for High Performance C-1 and C-XL Concrete According to CSA A23.1-09

CSA A23.1 Mix	Plants	Compressive strength	RCP*
C-1	A, B	>35 MPa at 28 days age	<1500 Coulombs at 56 days age
C-XL	C, D, E, F, G, H, I	>50 MPa at 56 days age	<1000 Coulombs at 56 days age

**At the time of this study the age of testing for RCP was 56 days. CSA A23.1-14 now permits RCP to be achieved within 91days.*

All of the plants produced samples that met the criteria of CSA A23.1 in terms of compressive strength and RCP for all curing regimes. More importantly, the samples that were air cured after 16 hour accelerated curing were statistically the same as the 168 hour moist cured samples at a 0.957 statistical significance for compressive strength and 0.95 for RCP.

Typical Plant Testing

All samples were produced during the spring and summer of 2013 using standard, proprietary company mix designs according to standard company practices. C-XL mixes had either silica fume content of between 5-8%, 25% blast furnace slag content and/or fly ash contents of 8-19%. All plants followed CPCI's comprehensive quality control procedures and used PCI Level I/II Quality Personnel.

A minimum of twenty-two compression testing and two air void samples were cast in standard 100 mm x 200 mm cylindrical moulds at most plants. Three 650 mm x 500 mm x 150 mm slabs were cast at each plant for use in coring samples for rapid chloride tests. The samples reached maximum internal temperatures between 46 and 56°C during the casting process, meeting the CSA A23.4-09 maximum temperature requirement of 60°C for damp conditions. A maximum temperature of 70°C is proposed for CSA A23.4-15.

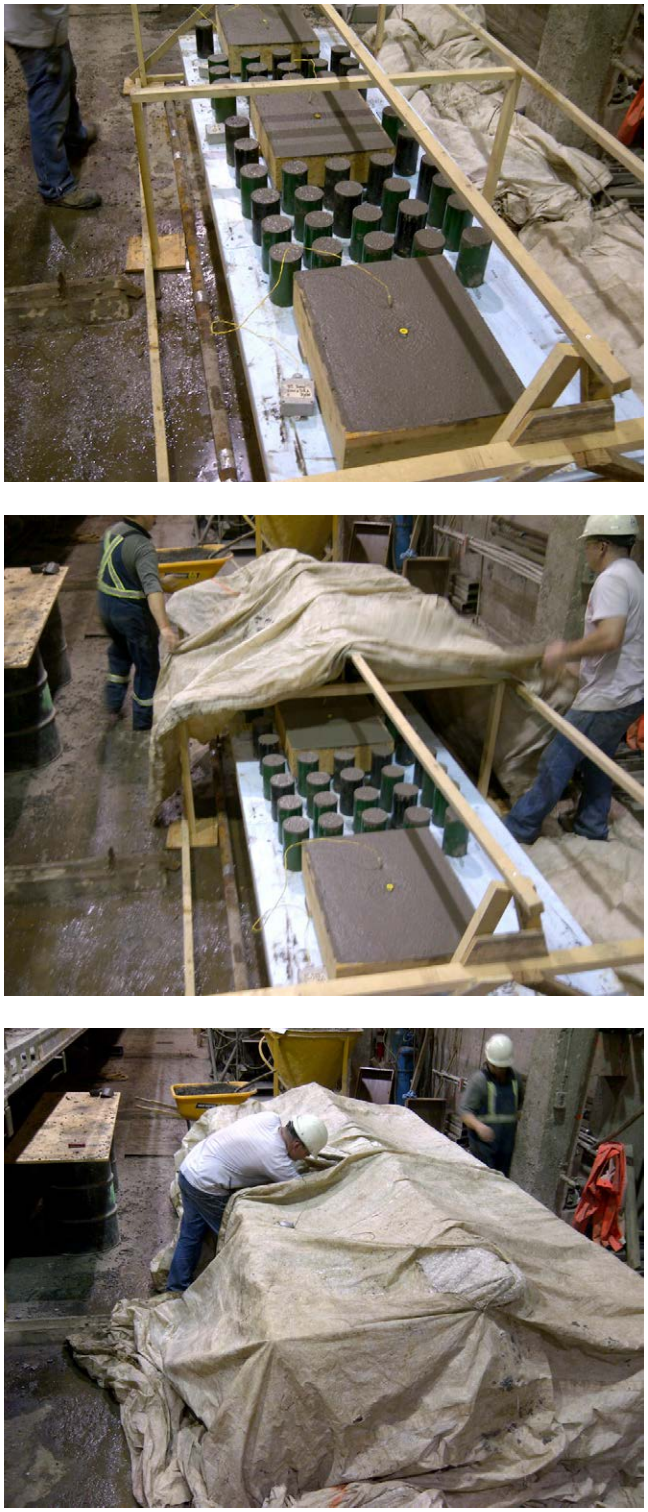


Figure 3. Typical curing chamber used at each plant for the NRCC test program

Compressive Strength Test Results

Figure 4 shows the 28 day and 56 day strength results for Plants A and B for the various curing regimes. The requirements of CSA A23.1-09 for C-1 concrete is 35 MPa at 28 days of aging (See Table 1). Since the age of testing for C-1 samples has changed to to 35 MPa at 56 days for the 2014 edition of CSA, this is also shown. The air cured after heating results for plant B at 56 days of age are within one standard deviation of the average value for the samples moist cured for 168 days, while for Plant A the air cured heating results are within two standard deviations of the average value for the samples moist cured for 168 hours (See Table 2). **Since typical concrete quality programs target control within two standard deviations, the results confirm that reducing the required curing for C-1 accelerated cured concrete to 16 hours will achieve the required compressive strength performance requirements.**

Figure 5 shows the compressive strength results for the C-XL concretes produced at plants C through I for the various curing regimes. The requirement for C-XL concretes according to CSA A23.1-09 is 50 MPa at 56 days of aging (Table 1). Due to the greater number of plants producing the C-XL mixes it was possible to perform a statistical analysis by using small sample matched pair analysis based on Student's t test[11]. This statistical approach analyzes the differences between the matched pairs under the hypothesis that the average of the test data (i.e. the air cured after heating, or the 72 hour moist cure results) is the same as the average of the control data (i.e. the 168 hour moist cure results). Using this statistical analysis tool, a value *T* is calculated for each comparison and compared to a standard t-test distribution table. Using a typical 0.95 acceptance value, the corresponding acceptance test value is 1.943. If the calculated *T* value is less than that value, then the data set being tested is considered to have no differences from the control data set.

The results of the T-test on the C-XL populations (See Table 10) demonstrated that the 56 day compressive strengths for the air cured after heating were statistically the same as those from the 168 hour moist cured samples at a 0.957 acceptance value. A 0.957 acceptance value corresponds to results within 2.02 standard deviations from the 168 hour moist cured control samples. These results confirm that reducing the required curing for C-XL accelerated cured concrete to 16 hour will achieve the required compressive strength performance requirements.

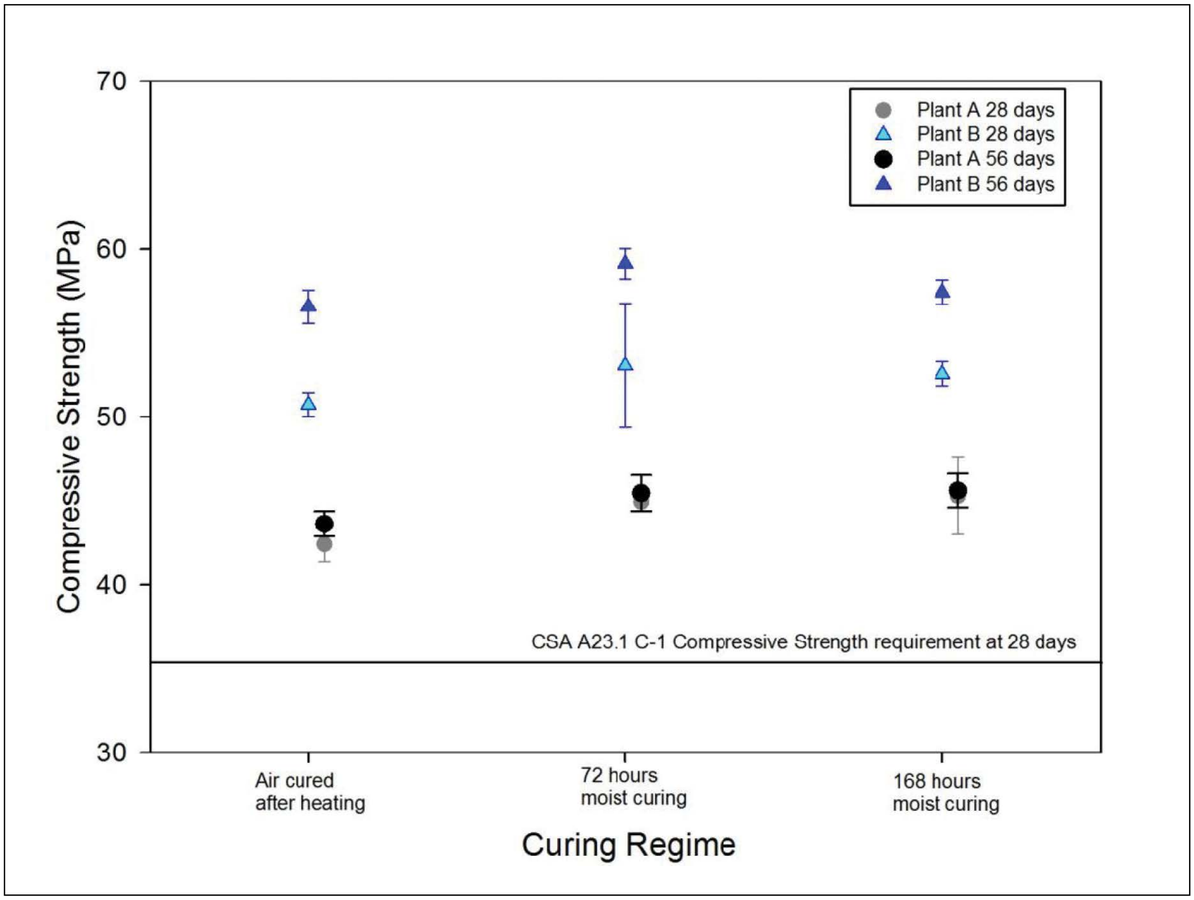


Figure 4. Effects of curing regime on compressive strength for C-1 mixes. (Moving the strength requirement to the same value at 56 days of age was approved for CSA A23.1-14)

Table 2. Average Compressive Strengths for C-1 mixes

Plant	Air cured after heating			Moist cured for 72 hours			Moist cured for 168 hours		
	Average Compressive Strength (MPa)	Standard Deviation (MPa)	COV*	Average Compressive Strength (MPa)	Standard Deviation (MPa)	COV	Average Compressive Strength (MPa)	Standard Deviation (MPa)	COV
A – 28 days	42.6	0.9	0.02	45.3	0.9	0.02	45.5	1.9	0.04
B – 28 days	43.3	0.8	0.02	45.4	0.9	0.02	45.8	0.9	0.02
A – 56 days	50.7	0.6	0.01	53.2	3.0	0.06	52.2	0.9	0.02
B – 56 days	56.9	1.1	0.02	58.8	1.0	0.02	57.8	0.9	0.02

**COV = coefficient of variation*

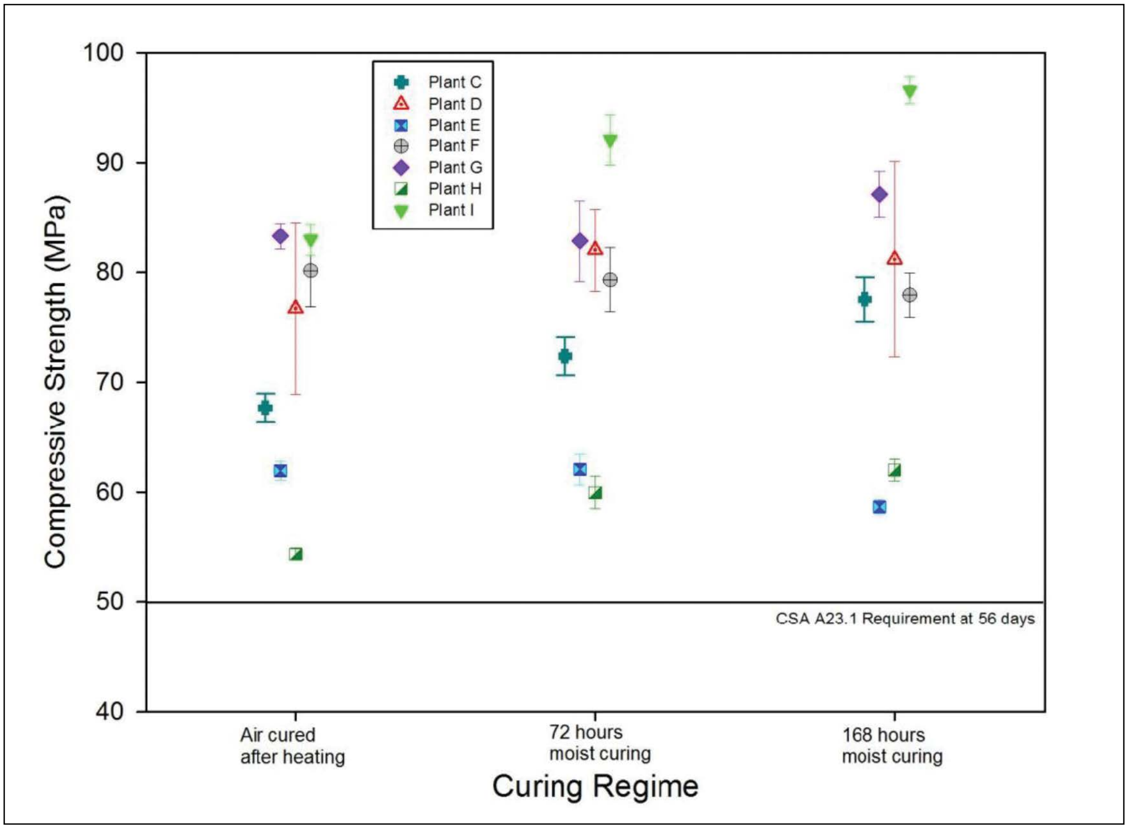


Figure 5. Effects of curing regime on compressive strength at 56 days for C-XL mixes

Table 3. Average compressive strengths for C-XL mixes 56 days of curing

Plant	Air cured after heating			Moist cured for 72 hours			Moist cured for 168 hours		
	Average Compressive Strength (MPa)	Standard Deviation (MPa)	COV*	Average Compressive Strength (MPa)	Standard Deviation (MPa)	COV	Average Compressive Strength (MPa)	Standard Deviation (MPa)	COV
C	67.7	1.3	0.02	72.4	1.7	0.02	77.6	2.0	0.03
D	76.7	7.8	0.10	82.0	3.7	0.05	81.2	8.9	0.11
E	61.9	0.9	0.01	62.0	1.4	0.02	58.7	0.7	0.01
F	80.2	3.2	0.04	79.3	2.9	0.04	78.0	2.0	0.03
G	83.3	1.2	0.01	82.9	3.7	0.04	87.1	2.0	0.02
H	54.3	0.5	0.01	60.0	1.5	0.03	62.0	1.0	0.02
I	83.0	1.4	0.02	92.1	2.3	0.02	96.6	1.2	0.01

**COV = coefficient of variation*

Rapid Chloride Permeability Test Results

Chloride ion penetrability was conducted according to ASTM C1202 and CSA S413. In the case of the RCP tests, CSA A23.1-09 required a result of less than 1500 coulombs at or before 56 days of aging for C-1 mixes and of 1000 coulombs at or before 56 days of aging for C-XL mixes. CSA A23.1-14 now permits RCP to be achieved within 91 days for both of these classes of concrete.

The test cores were obtained from the slab samples cast at the plants from at least 50 mm from an edge of the slab using a water cooled diamond core bit and were taken through the full depth of the slab. In the case of the tests according to ASTM C1202, three cores had a 10 mm surface removed from each sample. The next 50 mm of sample was then tested and the results averaged. In the case of the samples for CSA S413, 10 mm was removed from the top and bottom surfaces of two cores and 30 mm from the middle, resulting in 50 mm thick top and bottom samples from each core, for a total of 4 tests per curing condition and age.

Figures 6 and 7 and Tables 7 and 8 summarize the RCP results of the C-1 and C-XL concretes according to ASTM C1202. In all cases, for both types of concrete, the 56 day requirement was met with the samples air cured after heating. The results of the T-test on the C-XL populations demonstrated that the 56 day RCP for the air cured after heating were statistically the same as those from the 168 hour moist cured samples at a 0.95 acceptance value (Table 10). A 0.95 acceptance value corresponds to results within 1.96 standard deviations from the mean of the 168 hour moist cured samples. These results are positive, given that concrete quality programs generally target two standard deviations from the control.

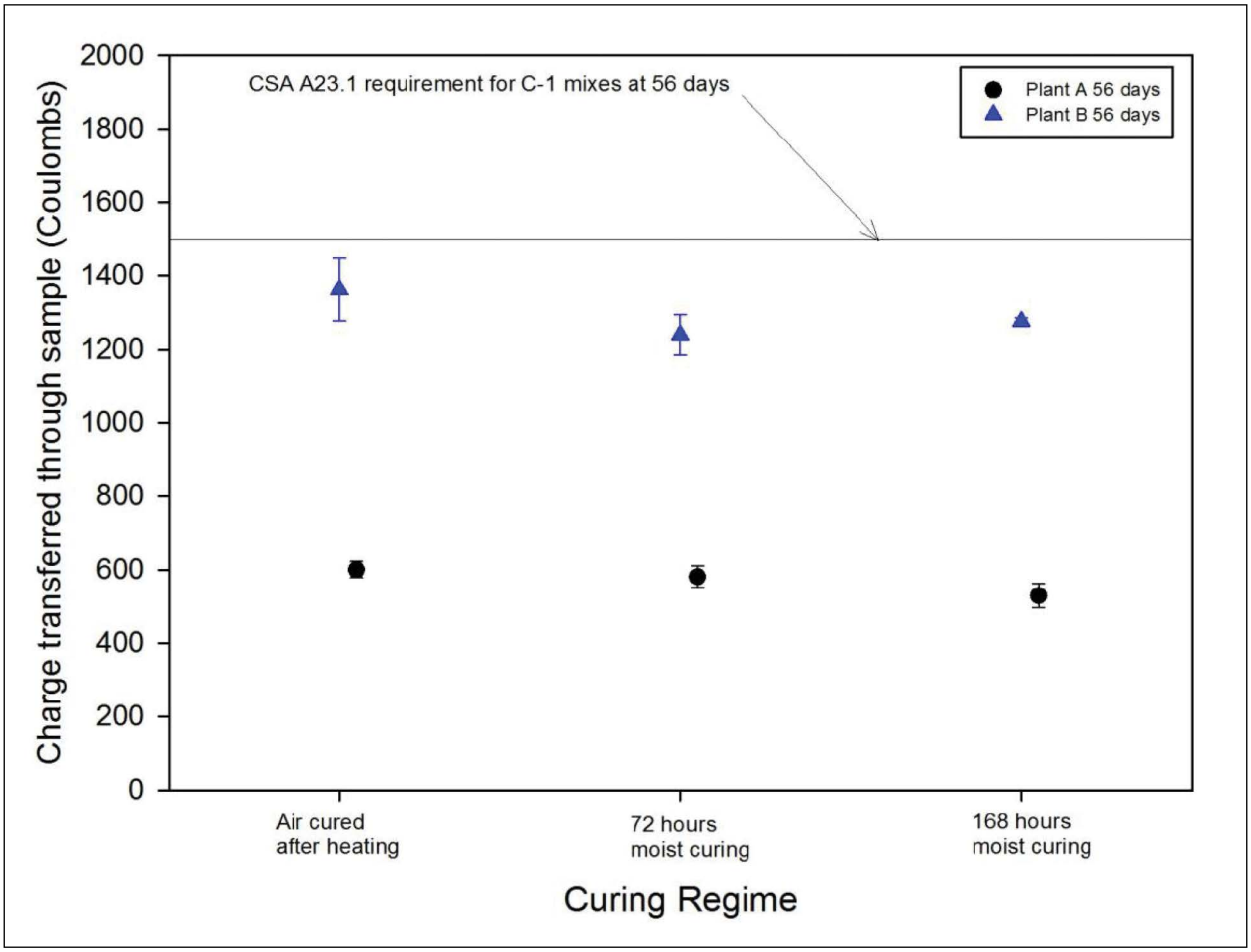


Figure 6 . Effects of curing regime on ASTM C1202 rapid chloride penetration results for C-1 mixes

Table 4. ASTM C1202 rapid chloride penetration results for C-1 mixes at 56 days age

Plant	Air cured after heating			Moist cured for 72 hours			Moist cured for 168 hours		
	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV*	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV
A	601	22	0.04	581	30	0.05	529	34	0.06
B	1362	85	0.06	1240	54	0.04	1276	9	0.01

**COV = coefficient of variation*

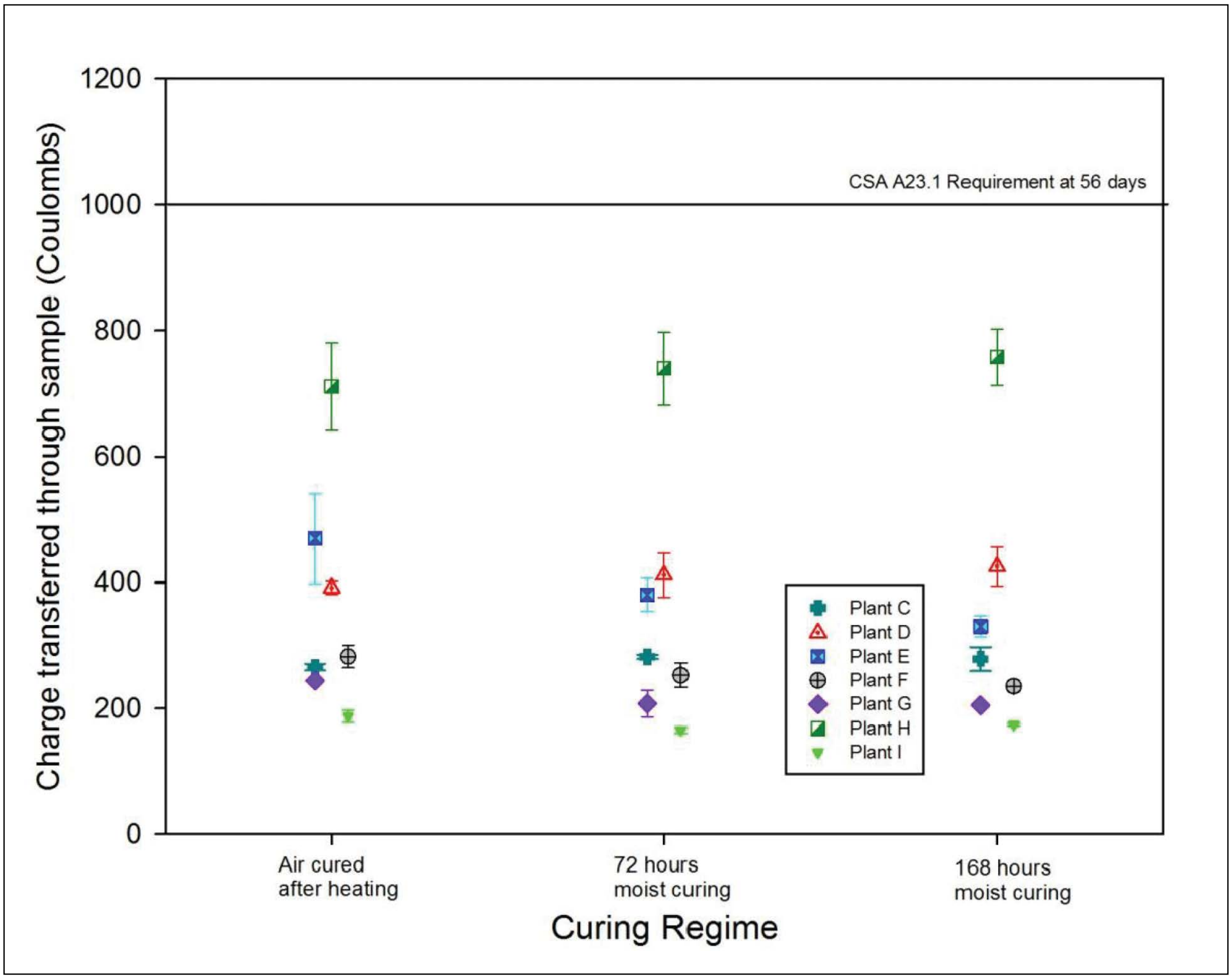


Figure 7. Effects of curing regime on rapid chloride penetration according to ASTM C1202 at 56 days age for C-XL mixes

Table 5. ASTM C1202 rapid chloride penetration results for C-XL mixes at 56 days age

Plant	Air cured after heating			Moist cured for 72 hours			Moist cured for 168 hours		
	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV*	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV
C	265	5	0.02	282	4	0.01	278	19	0.07
D	391	10	0.03	411	35	0.09	425	31	0.07
E	470	72	0.15	380	26	0.07	330	17	0.05
F	282	18	0.06	252	20	0.08	235	9	0.04
G	244	2	0.01	207	21	0.10	205	5	0.02
H	711	69	0.10	740	58	0.08	758	45	0.06
I	187	10	0.05	165	5	0.03	174	3	0.02

**COV = coefficient of variation*

RCP testing was also conducted according to CSA S413. CSA S413 requires separate measurements of top and bottom sections of the slab. The results from these tests are therefore presented in Tables 6 through 9. **In all cases, the RCP results meet the required performance with samples air cured after heating, and in all cases the top and bottom cores for the air cured after heating were statistically the same as the 168 hour moist cured samples, at a 0.95 probability of acceptance.**

Table 6. CSA S413 rapid chloride penetration results for C-1 mixes (top of slab)

Plant	Air cured after heating			Moist cured for 72 hours			Moist cured for 168 hours		
	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV*	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV
A	705	64	0.09	566	29	0.05	498	51	0.10
B	1349	64	0.05	1219	7	0.01	1141	170	0.15

**COV = coefficient of variation*

Note: The CSA A23.1-09 C-1 RCP limit of 1500 coulombs within 56 days was changed to 91 days in the latest edition, CSA A23.1-14.

Table 7. CSA S413 rapid chloride penetration results for C-1 mixes (bottom of slab)

Plant	Air cured after heating			Moist cured for 72 hours			Moist cured for 168 hours		
	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV*	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV
A	643	20	0.03	576	49	0.09	517	6	0.01
B	1123	21	0.02	1136	59	0.05	1091	22	0.02

**COV = coefficient of variation*

Note: The CSA A23.1-09 C-1 RCP limit of 1500 coulombs within 56 days was changed to 91 days in the latest edition, CSA A23.1-14.

Table 8. CSA S413 rapid chloride penetration results for C-XL mixes at 56 days of age (top of slab)

Plant	Air cured after heating			Moist cured for 72 hours			Moist cured for 168 hours		
	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV*	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV
C	429	36	0.08	422	19	0.05	384	7	0.02
D	392	12	0.03	419	21	0.05	397	72	0.18
E	352	76	0.22	335	17	0.05	327	10	0.03
F	285	10	0.04	270	4	0.01	250	25	0.10
G	230	14	0.06	248	10	0.04	215	29	0.13
H	758	54	0.07	726	28	0.04	688	106	0.15
I	239	33	0.14	206	5	0.02	207	6	0.03

**COV = coefficient of variation*

Note: The CSA A23.1-09 C-XL RCP limit of 1000 coulombs within 56 days was changed to 91 days in the latest edition, CSA A23.1-14

Table 9. CSA S413 rapid chloride penetration results for C-XL mixes at 56 days age (bottom of slab)

Plant	Air cured after heating			Moist cured for 72 hours			Moist cured for 168 hours		
	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV*	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV	Average Charge transfer (coulombs)	Standard Deviation (coulombs)	COV
C	473	17	0.04	482	42	0.09	424	10	0.02
D	396	16	0.04	420	51	0.12	380	13	0.03
E	312	9	0.03	308	26	0.08	313	6	0.02
F	276	1	0.00	269	20	0.07	272	11	0.04
G	225	6	0.03	245	20	0.08	225	16	0.07
H	666	24	0.04	697	38	0.05	700	43	0.06
I	217	0	0.00	194	5	0.03	195	25	0.13

**COV = coefficient of variation*

Note: The CSA A23.1-09 C-XL RCP limit of 1000 coulombs within 56 days was changed to 91 days in the latest edition, CSA A23.1-14

Table 10. Matched pair T-test results for 56 day old C-XL samples

	Compressive Strength		RCP by ASTM C1202		RCP by CSA S413 – Top		RCP by CSA S413 – Bottom	
	Air Cured after Heating	72 hours moist cure	Air Cured after Heating	72 hours moist cure	Air Cured after Heating	72 hours moist cure	Air Cured after Heating	72 hours moist cure
$\overline{\mu_s}$	4.86	1.49	16.1	4.73	32.1	26.3	5.1	16.5
σ_s	6.16	3.38	41.6	23.4	51.0	22.5	33.2	25.8
T	2.09	1.17	1.03	0.53	1.67	3.09	0.40	1.70
Hypothesis accepted?	No*	Yes	Yes	Yes	Yes	No	Yes	Yes

**Note: All T-test values in the above table compare the air cured after heating and the 72 hour moist cure samples to the 168 hour moist cured samples. If the calculated T value is less than 1.943, then the data set being tested is considered to have no differences from the control data set at a 0.95 probability of acceptance. The T value of 2.09 corresponds to a probability of acceptance of 0.957 (ie. +/-2.02 standard deviations from the norm) which is the typical standard of control for concrete testing.*

Durability of Accelerated Cured Precast Concrete

In 2015, CPCI commissioned research by the University of Toronto[12] to further investigate the durability of accelerated cured high performance concretes, specifically the effect on the surface absorption of chlorides. Of particular interest was the examination of the outer 10 to 20 mm of concrete cover, and its resistance to chloride penetration by de-icing salts.

Five precast concrete slabs (275mm x 375mm x 100mm in size) were cast at a precast plant and the mix used was a 60 MPa C-XL concrete mixture, which was then subjected to varying curing regimes. ASTM C1585 rate of absorption tests were conducted on the formed face, and surfaces 10 and 20mm from the formed face (see Figure 8). Instead of using water for this test, a 2.8M NaCl solution was used. The purpose was to determine whether the differences in curing regimes affected the surface absorption relative to absorption of the interior of each concrete slab, and also to see if the depth of near surface chloride penetration was affected. The test specimens were exposed to salt water absorption for a total of 8 days and the depth of chloride penetration was determined on split surfaces using silver nitrate spray.

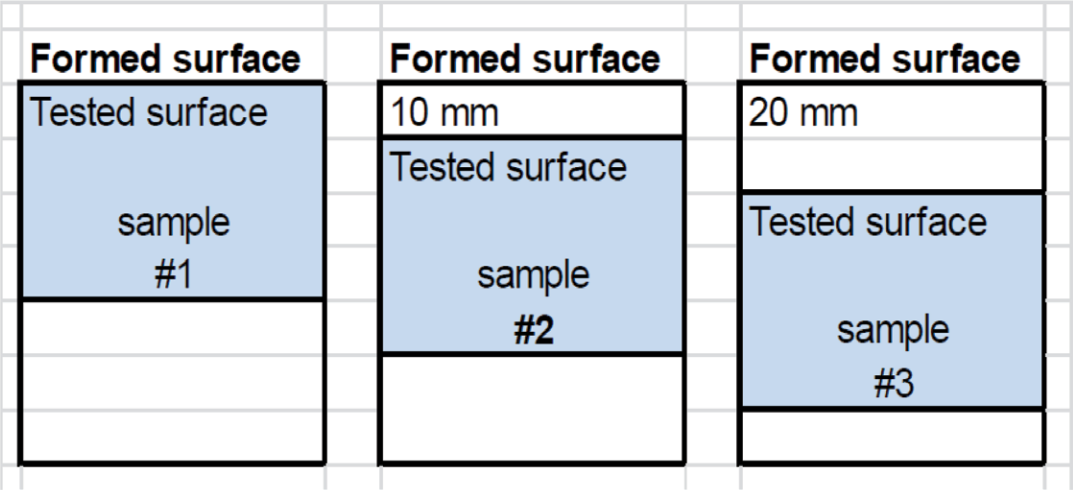
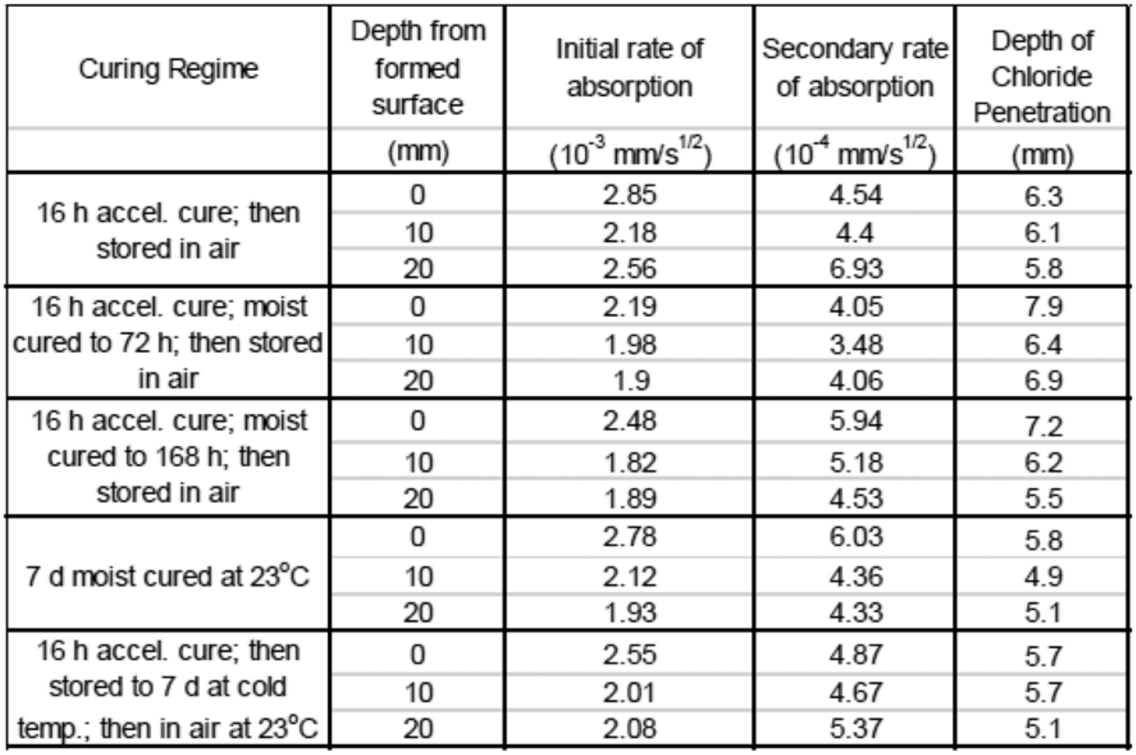


Figure 8. Schematic showing the location of the tested surface of the rate of absorption tests on 100 mm diameter cores in the 100 mm thick slabs

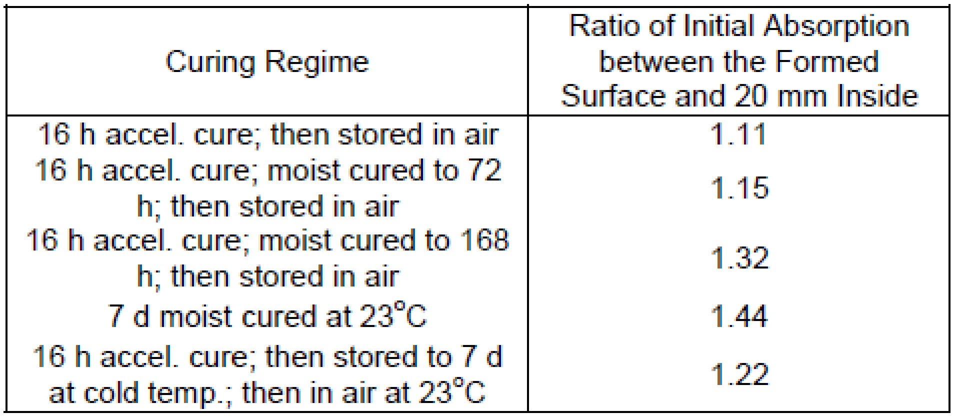
The values given in Table 11 show the rate of absorption results and the average depth of chloride penetration after the 8-day test. The initial rate of absorption is of most interest in terms of relating to chloride ingress from salt splash, with lower initial rates of absorption being better. In all curing regime scenarios, the rate of the absorption of the formed surface (0 mm) is higher than further in (10 and 20 mm). This is likely in large part due to the formed surface having a paste layer, while the 10 and 20 mm depth tests were on saw cut surfaces. The results in all cases are very similar and, from Table 12, it can be seen that the initial rates of absorption at the surface relative to 20 mm inside the slab are no worse for the high-temperature cured slab with no additional moist curing than for the slabs that received additional moist curing. The depth of chloride penetration after absorption from the formed surfaces was only 0.3 to 1.7 mm deeper than from surfaces at 10 or 20 mm depth. Six days of additional moist curing after the accelerated curing regime did not reduce the depth of chloride penetration relative to the accelerated cured slab with no additional moist curing.

Table 11. Initial and secondary rates of absorption and resulting depth of chloride ingress on cores taken from slabs



Curing Regime	Depth from formed surface (mm)	Initial rate of absorption (10^{-3} mm/s$^{1/2}$)	Secondary rate of absorption (10^{-4} mm/s$^{1/2}$)	Depth of Chloride Penetration (mm)
16 h accel. cure; then stored in air	0	2.85	4.54	6.3
	10	2.18	4.4	6.1
	20	2.56	6.93	5.8
16 h accel. cure; moist cured to 72 h; then stored in air	0	2.19	4.05	7.9
	10	1.98	3.48	6.4
	20	1.9	4.06	6.9
16 h accel. cure; moist cured to 168 h; then stored in air	0	2.48	5.94	7.2
	10	1.82	5.18	6.2
	20	1.89	4.53	5.5
7 d moist cured at 23°C	0	2.78	6.03	5.8
	10	2.12	4.36	4.9
	20	1.93	4.33	5.1
16 h accel. cure; then stored to 7 d at cold temp.; then in air at 23°C	0	2.55	4.87	5.7
	10	2.01	4.67	5.7
	20	2.08	5.37	5.1

Table 12. Ratio of Initial Rate of absorption values at the Formed surface to 20 mm below



Curing Regime	Ratio of Initial Absorption between the Formed Surface and 20 mm Inside
16 h accel. cure; then stored in air	1.11
16 h accel. cure; moist cured to 72 h; then stored in air	1.15
16 h accel. cure; moist cured to 168 h; then stored in air	1.32
7 d moist cured at 23°C	1.44
16 h accel. cure; then stored to 7 d at cold temp.; then in air at 23°C	1.22

In addition to the ASTM C1585 tests, the Nordtest NT492 (AASHTO TP64) rapid migration test[13] was conducted on a slice of each concrete slab with the face exposed to sodium chloride in the test being the one perpendicular to the cured face, as shown in Figure 9. This approach was used by Hooton et al[14] and by Ha[15] to demonstrate the impact of curing on the chloride resistance and service life of concrete.

Four 100 x 100 x 50 mm thick slices were cut from the slabs and the slices were vacuum saturated as per ASTM C1202. The face perpendicular to the finished and formed faces was exposed to the Nordtest NT Build 492 test at 56 days of age. After the test, the slices were split open and the split faces were sprayed with 0.1N silver nitrate solution to visually show the depth of chloride penetration (chloride-penetrated portions turn white due to precipitation of silver chloride). The depth of chloride penetration was then measured with a ruler every 2 mm from the top and bottom of each slab for each of the 8 split faces, and then at 10 mm intervals in between.

The average depths of chloride penetration are shown in Figure 10 for each of the five curing regimes. Values of chloride diffusion (D_{nssm}) obtained from the NT492 non-steady state chloride migration test were calculated at each depth. The diffusion coefficients are shown in Figure 11. The results show that chloride diffusion coefficients in the top and bottom outer 10 mm depths of concretes that were accelerated cured with 0 or 2 days of additional moist curing were at least as good as that of the accelerated cured concrete that was then moist cured to 7 days of age.

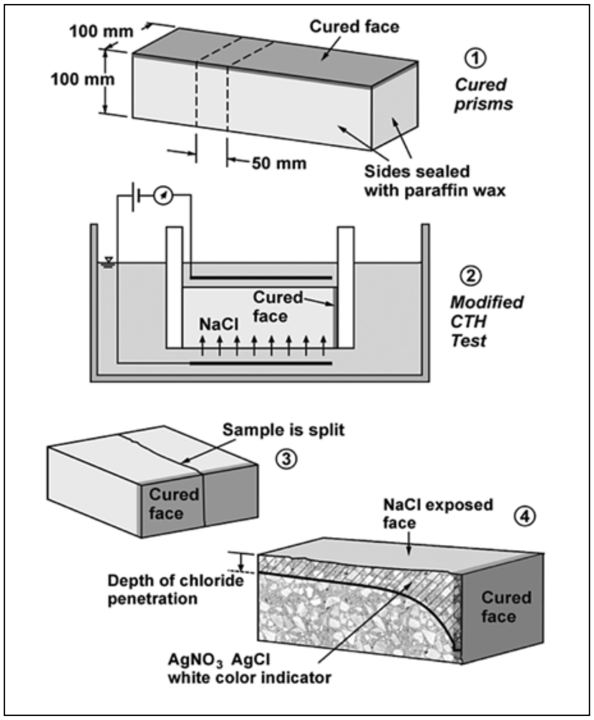


Figure 9. Schematic of Nordtest NT 492 modified as in Hooton et al [14]

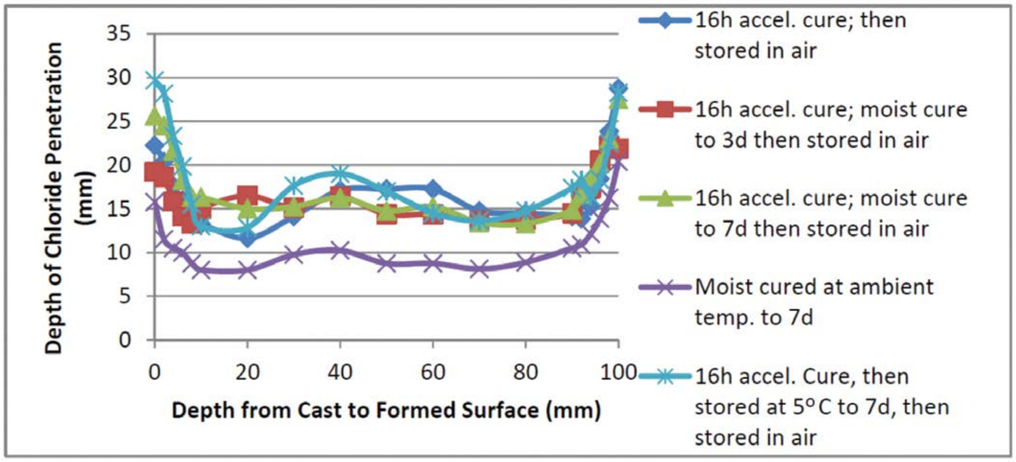


Figure 10. Average depths of chloride penetration from the cast face (left) to the bottom formed face (right) for each curing regime

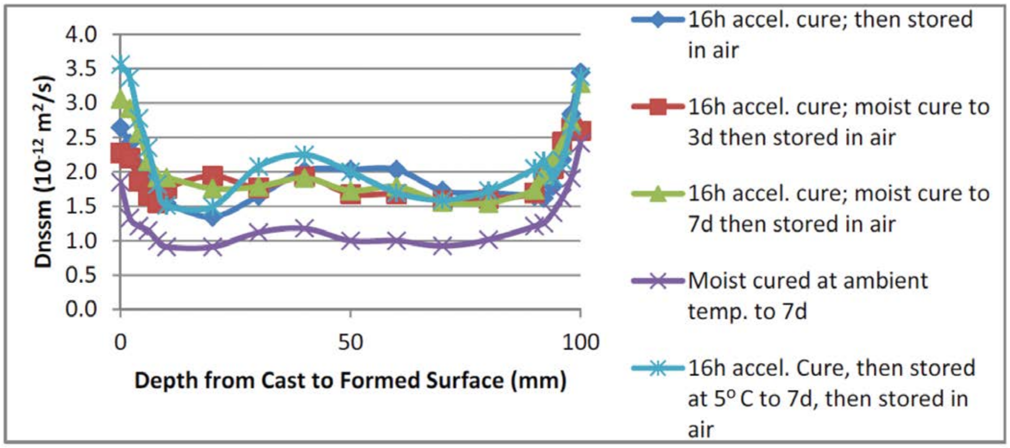


Figure 11. Average NT492 chloride migration coefficients vs slab depths for different curing regimes

Conclusions from University of Toronto Durability Research

(1) Additional moist curing was not required for accelerated-cured concrete prior to the changes made in the 2009 edition of CSA A23.1. The data show that there is no negative impact of omitting additional moist curing for CSA C-XL concrete that has undergone a 16 hour accelerated curing regime. Neither the 56-day rates of surface absorption, chloride penetration resulting from absorption, nor depth dependant chloride diffusion coefficients were adversely affected. Therefore, it appears that similar precast, accelerated-cured CSA C-XL concretes do not require any additional moist curing to provide high chloride resistance in order to have the expected long service life.

(2) The impact of placing one concrete slab immediately after accelerated curing at one day of age to low-temperature (2-4°C) storage (simulating cold outdoor temperatures) had no impact on initial rates of surface absorption and did not have any bigger impact than the depth-dependent chloride diffusion tests on the outer few millimetres below the cast and formed surfaces.

(3) Relative to any of the specimens that were accelerated cured, 7 days of ambient temperature moist curing resulted in a better (lower) average chloride diffusion and better (higher) cylinder strengths. However, for the same relative comparison, 7 days of ambient temperature most curing had no net positive effect on either the rapid chloride permeability when measured in accordance to ASTM C1012, or the initial rate of absorption, when measured in accordance with ASTM C1585, or chloride penetration after 8 days of absorption. Finally, for the same comparison, the bulk resistivity of the ambient temperature moist cured specimens showed significantly lower results than the accelerated cured specimens, but for this test “lower” is a “worse” condition.

Other Significant Durability Research

A 2004 study[16] examined the effectiveness of supplementary cementing materials in reducing the negative effects of accelerated curing on chloride penetration resistance. Testing included rapid chloride permeability according to ASTM C1012, as well as bulk diffusion, and chloride migration, and the study reported that the tests for all three chloride penetration resistance tests show a similar trend. The study also reported that “with the use of the ternary ordinary Portland cement (OPC)–Silica Fume–Ground Granulated Blast Furnace Slag binders, accelerated curing did not have detrimental effects on chloride penetration resistance and provided 18-h strengths in excess of 40 MPa.” In this study, the accelerated curing regime chosen was typical of what is currently used in the precast industry-controlled accelerated curing for 18 hours and no subsequent moist curing thereafter. The study also included controls for non-accelerated mixes and an accelerated mix that was moist cured for the full 7 days.

The accelerated curing scenarios therefore closely mirror what was done in the NRCC research[10] previously described in this report.

The report went on to say that “Concrete mixtures containing 8% Silica Fume and 25% slag appear to have good potential for use in precast operations employing accelerated curing. They combine high early strength with superior chloride penetration resistance and are easier to place and finish than concretes that contain 8% SF alone.” It should also be noted that the NRCC research[10] study in this report utilized C-XL mixes with either silica fume contents of between 5-8%, 25% blast furnace slag content and/or fly ash contents of 8-9%.

Another final interesting outcome of the study[16] was the relation of rapid chloride penetration testing (ASTM C1202) to bulk diffusion. This report found a high correlation between the two, of r^2 equal to 0.973. Chloride migration testing was also conducted and also related well.

Concluding Remarks

The objective of an effective, efficient curing procedure is to enable concrete product manufacturers to produce their products quickly, efficiently and economically. Research shows that accelerated curing for 16 hours followed by air drying produces concretes that meet the performance criteria for high performance concretes according to CSA A23.1. Moreover, it is widely accepted that a maximum curing temperature of 70°C is safe and conservative. Both strategies offer the precaster the ability to develop mix designs and curing cycles that result in savings for the producer and more sustainable products that use less cement. CPCI precasters are committed to manufacturing products that are strong, economical and sustainable.

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