Durability Performance Testing: The Devil is in the Details

R. Douglas Hooton,

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(with acknowledgements to Ken Hover and the late John Bickley)

ACI October 26, 2020
Session honoring Calvin McCall

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For this presentation, I have chosen the Tasmanian Devil from Bugs Bunny

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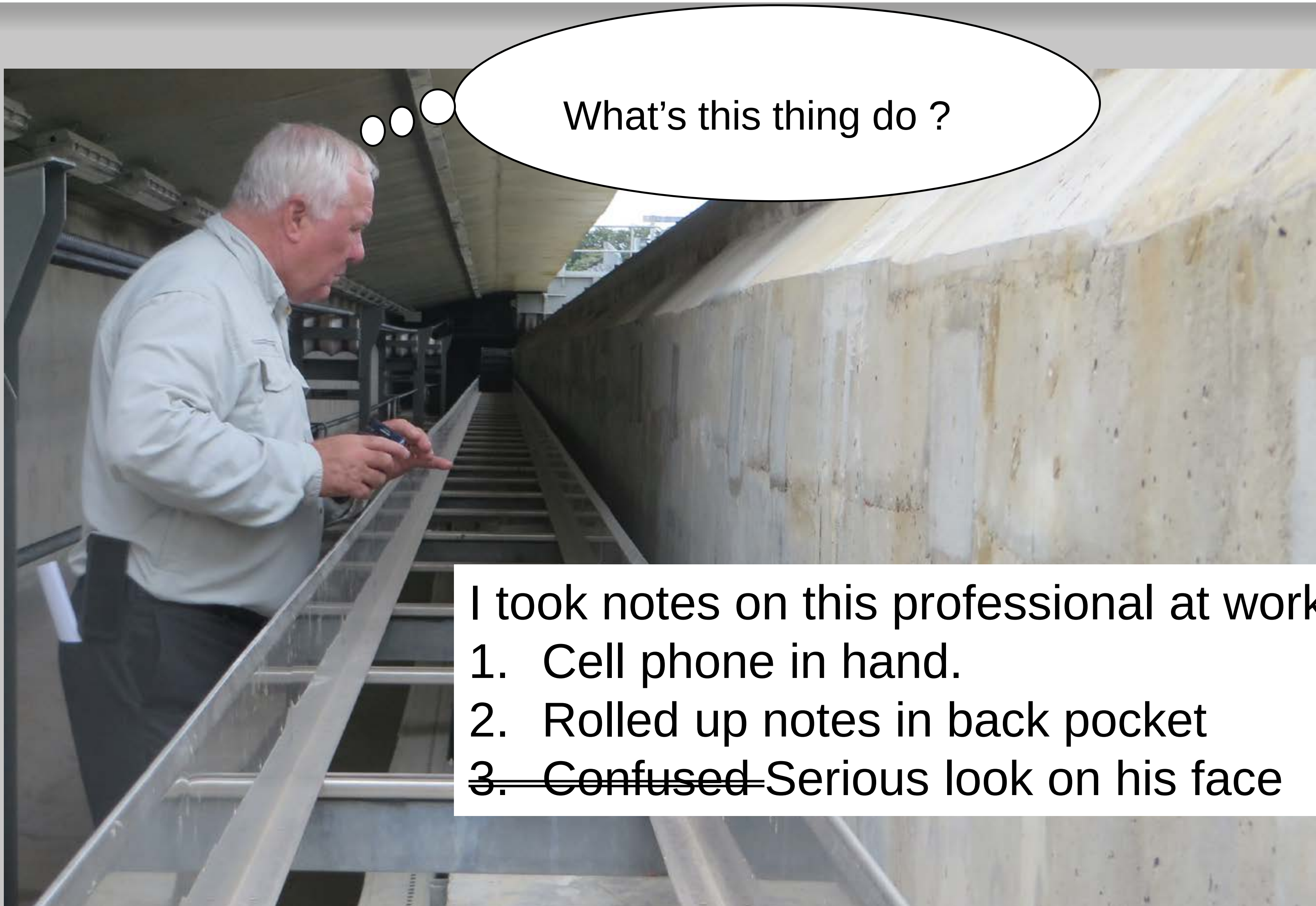
But first, Calvin

Smiling Calvin and his enforcer Ken playing *Devil's advocate* in assessing specification details.

I recently had the pleasure of working with, and learning from, Calvin on a dispute resolution claim on a very large project.



I took notes on this professional at work:

1. Cell phone in hand.
2. Rolled up notes in back pocket

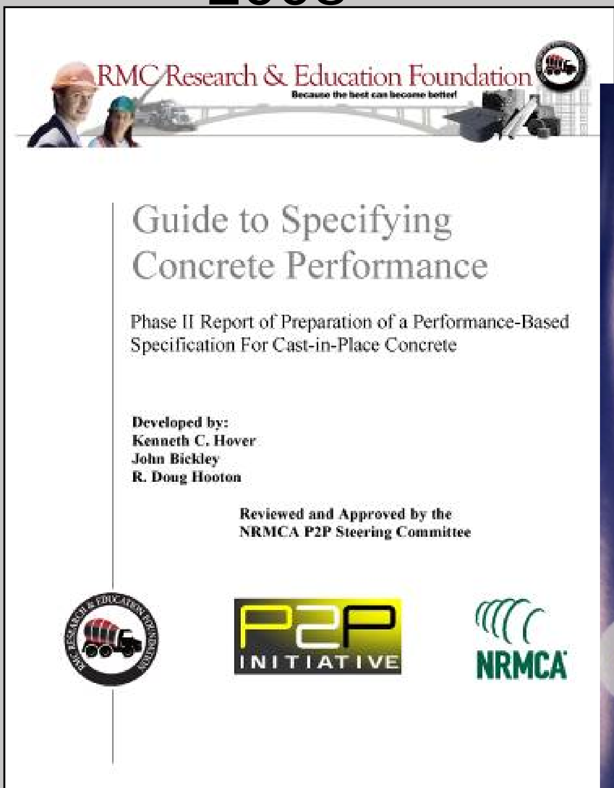
~~3. Confused~~ Serious look on his face

Outline

1. Do we have sufficiently defined exposure categories and sufficient requirements for demonstrating compliance?
2. Do we have adequate performance test methods for assessing compliance regarding durability
3. Types of testing for establishing compliance
4. Inspection issues for achieving durability
5. An example of a performance specification.

There is interest in adopting performance specifications

2008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Guide to Specifying Concrete Performance

Phase II Report of Preparation of a Performance-Based Specification For Cast-in-Place Concrete

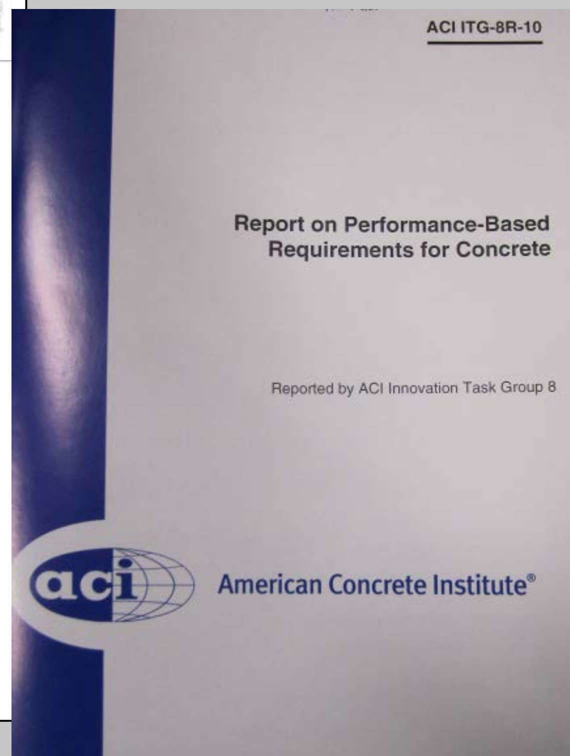
Developed by:
Kenneth C. Hover
John Bickley
R. Doug Hooton

Reviewed and Approved by the NRMCA P2P Steering Committee

P2P INITIATIVE

NRMCA

2010

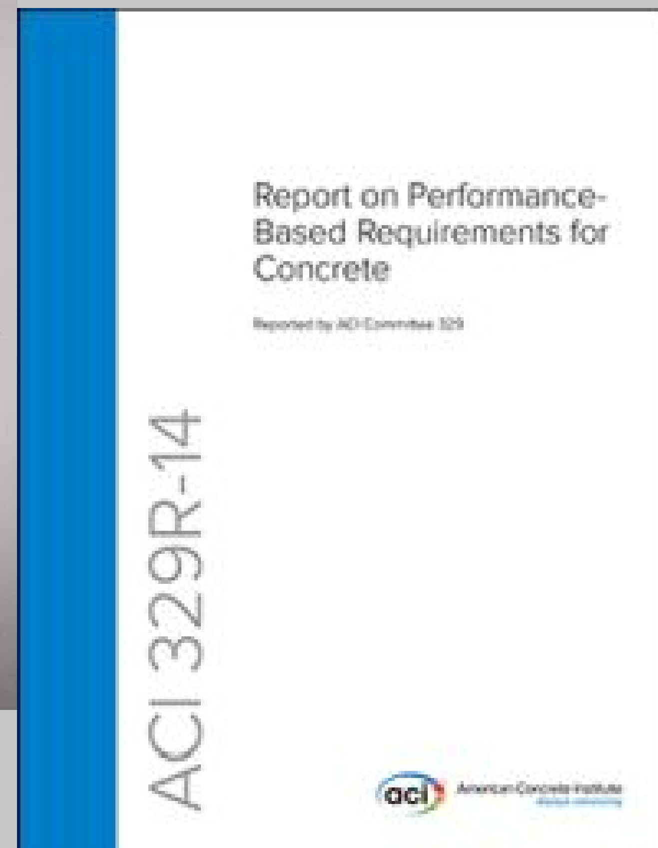

ACI ITG-8R-10

Report on Performance-Based Requirements for Concrete

Reported by ACI Innovation Task Group 8

aci American Concrete Institute®

2014


Report on Performance-Based Requirements for Concrete

Reported by ACI Committee 329

ACI 329R-14

aci American Concrete Institute

ACI Committee 329 is moving things forward

However…

- The scope of C329 is limited to performance of as-delivered concrete and does not extend to as-built performance of concrete structures.
- To help bridge this gap, in 2020 TAC approved formation of **Committee 321 *Durability Design Code*.**
- The intent is to establish both design and construction requirements for obtaining durable structures and in other concrete applications.
- In addition to amalgamating existing exposure classes & defining a wider range of exposure categories that are relevant to all concrete applications, the intent of C321 is to include alternative performance and direct durability requirements in addition to prescriptive/indirect requirements in current standards (w/cm and strength).

All types of deterioration are affected by fluid ingress but I will focus on Chloride Corrosion

Obtaining durability performance in Chloride Exposures

- Even though the fundamental requirement for obtaining durability in severe chloride exposures is to restrict chloride ingress, the current 318 Code only specifies a minimum strength (5,000 psi), maximum w/cm limit (0.40) for C-2 exposure, and internal chloride limits.
- There are no direct requirements that address the obvious durability concerns, such as:
  - limiting rates of chloride penetration,
  - additional curing (for the cover zone),
  - additional cover,
  - limiting cracking due to thermal and drying shrinkage.
  - Inspection of important issues such as cover depths and curing practices during construction.

Exposure Categories for Corrosion: An example of where 318 lags behind other codes w.r.t. durability requirements in chloride & carbonation exposures

1. In ACI 318 all chloride Exposures are C-2, regardless of severity.
2. The C-1 Exposure Class is assumed to be aimed at carbonation (but the word carbonation is not directly mentioned.
3. There are no performance requirements for limiting rates of fluid ingress.
4. Cover Requirements are only for fire and bond (any increased cover requirements in chloride exposures are left to the designer's expertise)
5. Curing Requirements are only for meeting test cylinder strengths and not for assessing the quality of the cover protecting the steel.

USA Unified Forces Guide Spec. UFGS 03-31-30 **Marine Exposure** Requirements (Feb. 2019)

Table 1 - Concrete Design Requirements

Prescriptive requirements	Minimum	Maximum
ASTM C666/C666M Method A Durability Factor at 300 cycles	90	--
Concrete ASTM C157/C157M Drying Shrinkage percent, at 28 days except for high volume fly ash (HVFA) at 56 days.	--	0.05 percent
Initial acid-soluble chloride content in cast-in-place concrete per ASTM C1152/C1152M, percent/cement	--	0.10
Prescriptive requirements	Minimum	Maximum
Initial acid-soluble chloride content in prestressed concrete determined following ASTM C1152/C1152M, percent/cement	--	0.08
Average spacing factor for three specimen following ASTM C457/C457M inch	--	0.008 with no value greater than 0.010
Chloride ion penetrability ASTM C1202 at 56 days, Coulombs	--	1000
Alternatively to ASTM C1202, the concrete surface resistivity AASHTO T 358 at 56 days can be measured, kohm-cm	20	--

ASTM C1202 limit

Alternate resistivity limit

5 exposure categories

Table 2 - Concrete Quality Requirements

Zone	Exposure Condition	Maximum W/CM
Submerged zone, Tidal Splash Zone	(a) Directly exposed to salt water	0.40
	(b) Subject to severe abrasion	0.40
Atmospheric Zone	(a) Directly exposed to marine atmosphere	0.40
	(b) Protected from direct exposure to marine atmosphere	0.45
Buried Zone	(a) Permanently buried in soil	0.40

Table 3 - Supplementary Cementing Material Requirements

SCM	Minimum Content
Class N Pozzolan or Class F Fly Ash SiO_2 plus Al_2O_3 plus Fe_2O_3 > 65 percent or where exposed to sulphates as defined in ACI 318 Table 4.2.1	30 percent
Class N Pozzolan or Class F Fly Ash SiO_2 plus Al_2O_3 plus Fe_2O_3 greater than 70 percent	25 percent
Class N Pozzolan or Class F Fly Ash SiO_2 plus Al_2O_3 plus Fe_2O_3 greater than 80 percent	20 percent
Class N Pozzolan or Class F Fly Ash SiO_2 plus Al_2O_3 plus Fe_2O_3 greater than 90 percent	15 percent
Ultra fine fly ash/Pozzolan	7 percent
Ground granulated blast-furnace slag	40 percent

Minimum SCM reqts.

Chloride Exposure Classes in Different Codes/Standards

Standard	Chloride Exposure Class	Exposure
EN206	**XD1**	moderate humidity
	XD2	wet, rarely dry
	XD3	Cyclic wet and dry
ACI 318	**C2**	All chloride exposures
GB/T50476	**IV-C**	De-icing Spray
(China)	**IV-D**	Chloride groundwater
50 year DL	**IV-E**	Directly exposed to de-icers

Standard	Chloride Exposure Class	Exposure
CSA A23.1	**CXL**	C1 with extended service life
	C1	Structurally reinforced
	C2	Non-structurally reinforced
	C3	Continuously submerged in seawater
	C4	Non-structurally reinforced and no freezing
AS3600	**A2**	Saline soils Conductivity 4-8 deciSiemens/m
	B1	Saline soils Conductivity 8-16 deciSiemens/m
	B2	Saline soils Conductivity >16 deciSiemens/m

Most also have separate categories for addressing Marine and carbonation exposures

In addition to other Marine exposures, four Airborne Marine Chloride Exposures are addressed in Australian CIA Z7/02

Table 5.3. *Exposure Classes for Airborne Salt – Elements Not in Direct Contact with Seawater*

Exposure Class	Precis of class descriptions from AS 2312.1
XS1a	*Low*. Environments in this category include regions remote from the coast (beyond 50 km) but can however extend as close as one kilometre from seas that are relatively sheltered and quiet.
XS1b	*Medium*. The extent varies significantly with factors such as winds, topography and vegetation, around sheltered areas extending beyond about 50 metres from the shoreline, or one kilometre distant from an ocean front with breaking surf.
XS1c	*High*. Around sheltered bays this class extends from the shoreline to about 50 metres inland; from an ocean front with breaking surf, from several hundred metres inland to about a kilometre.
XS1d	*Very High*. Beachfront in regions of rough seas and surf beaches; can extend inland for several hundred metres.

Exposure Class Z7/02	Intensity of exposure	Corresponding class in	
		AS 3600	NZS 3101
XS1a	Low	A2	A2
XS1b	Medium	B1	B1
XS1c	High	B2	B2
XS1d	Very High	†	C

In 318-19, buildings and garages built near the coast are not always recognized as being in C2 exposure.

Condos located in **Pawleys Island, SC**. Balcony soffit corrosion due to wind-borne salt spray.
But that is not considered to be a C2 exposure because indirect wind-borne chlorides are not mentioned in 318.
(P. Emmons)

Multi-level garage ¼ mile from the ocean in **Ventura California**—upper levels of garage are closed due to corrosion.

Hypothetical Division of Corrosion Exposure Categories and Requirement Options (would also include existing chloride limits)

Exposure Class	Exposure Condition	Min. 28 day Strength (psi)	Max. w/cm (unless performance option is met)	Min. Curing Period (days)	Min. cover depth (in.)	Performance Option Select one of RCPT/ Resistivity (max. Coulombs/ min. ohm-m)
C-0 (negligible exposure)	Dry or Permanently Wet	2,500	NA	3	1	NA
Carbonation:						
C1-1	Wet, Rarely Dry	3,500	0.55	3	1.5	NA
C1-2	Moderate Humidity	4,000	0.50	3	1.5	2500/80
C1-3	Cyclic Wet and Dry	4,500	0.45	3	2	2000/100
Deicers:						
C2-D1	Moderate Humidity	4,000	0.50	7	2	2500/80
C2-D2	Wet, Rarely Dry	4,500	0.45	7	2	2000/100
C2-D3	Cyclic Wet and Dry	5,000	0.40	7 (moist cure only)	3	1500/130
Marine & Saline Soils:						
C2-M1	Air-borne Spray	4,000	0.50	7	2	2500/80
C2-M2	Permanently Submerged (or below water table)	4,500	0.45	7	2	2000/100
C2-M3	Tidal, Splash, and Spray (above water table)	5,000	0.40	7 (moist cure only)	3	1500/130

***RCPT (ASTM C1202)/Bulk Resistivity (ASTM C1876). Test method to be specified. Determined on an average of at least two specimens at an age of 56 days unless otherwise specified. Default is for mixture prequalification. If A/E decides to use for acceptance: Running average of 3: <RCPT / >BR Limits For referee testing: Cores – Average of 3: <1.3RCPT / >0.75BR Limits**

While requirements are initially the same for both C2-D and C2-M exposure categories, at least the exposures are more accurately described.

Ok so where are the perfect performance tests?

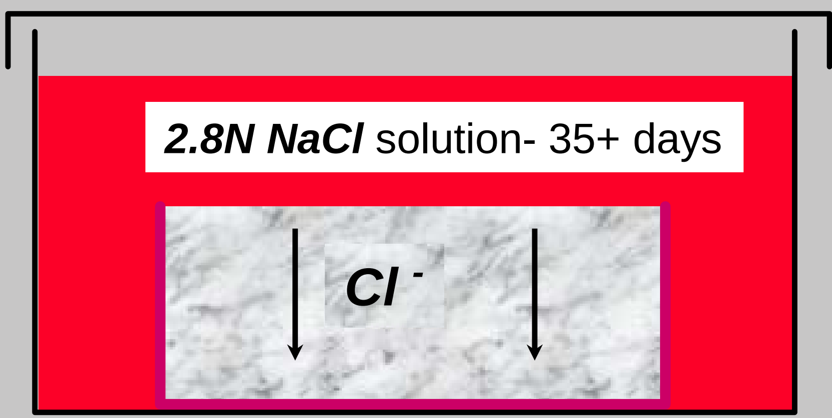
- A perceived barrier to the adoption of performance-based specifications is the lack of an adequate portfolio of reliable and repeatable test procedures.
- This situation is evolving but waiting for the perfect test is a barrier to progress.
- Progress results from action and common sense as well as academic compliance.
- Nearly all the essential properties of concrete can be measured to a practical acceptable level provided the implementation is governed by the appropriate procedures.
- These procedures need to be incorporated in Codes and contract specifications.

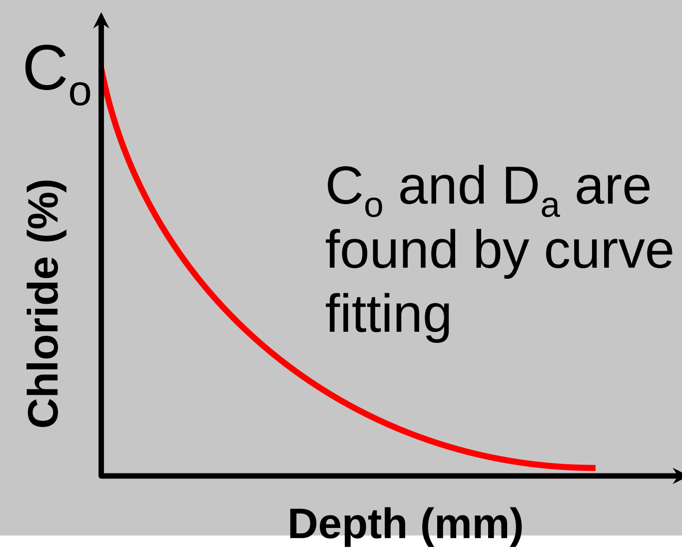
John Bickley, 2011

Performance Specs need Performance Tests

- Durability of concrete depends on preventing penetration of water and aggressive ions.
- Accurate and precise standard tests are needed that are relevant to the fluid penetration resistance of concrete.
- To be used in specifications, these tests also need to be as simple and rapid as possible.
- Appropriate acceptance limits are also needed for different exposure conditions.

Chloride Bulk Diffusion Test (Da)
ASTM C1556 / NT Build 443





C_o and D_a are found by curve fitting

$$\frac{C_x}{C_0} = 1 - erf\left(\frac{x}{2\sqrt{D_a \cdot t}}\right)$$

At 28 days of age, slices are exposed for 35+ days, then profile ground. This test, while it provides an input for many service life models, is labor intensive and only suited for prequalification purposes

Rapid Index Tests

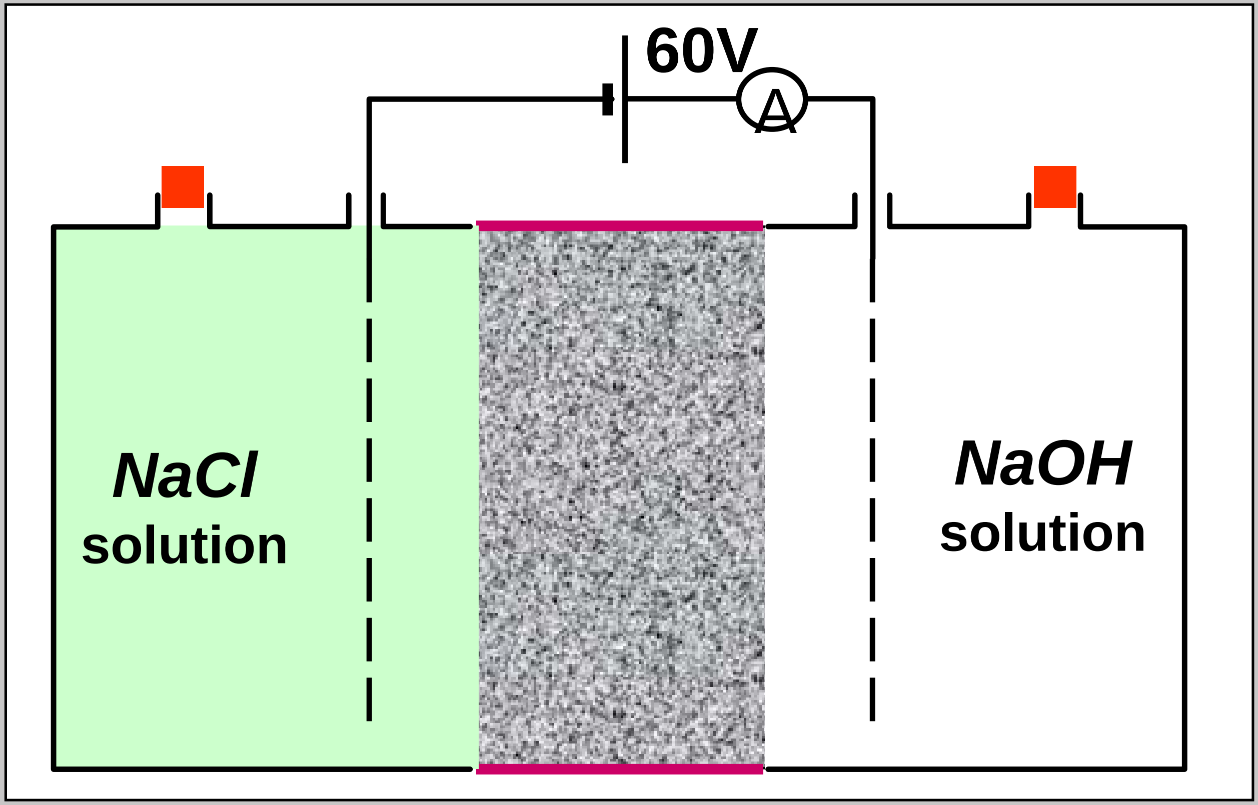
- Chloride diffusion tests can be used for prequalification of mixtures on major projects, but they are impractical (too expensive and slow) for acceptance during construction.
- Rapid index tests that can be related to fluid penetration resistance are more practical for use in QA/QC.

Possible Rapid Index Tests
Which one to pick?

The following methods have been used:

1. ASTM C1202 (AASHTO T277)
2. Rapid Migration Test (Nordtest NT 492)
3. Surface Electrical Resistivity (AASHTO T358)
4. ASTM C1876 Bulk Electrical Resistivity

Rapid Chloride "Permeability" ASTM C1202



Voltage is applied and current passing through concrete is measured and integrated over 6 hours to get charge passed in Coulombs

It is a Rapid Index test for conductivity (connectivity) of the pore system. It does not measure permeability or chloride ingress. But it is a reasonable index test in most cases.

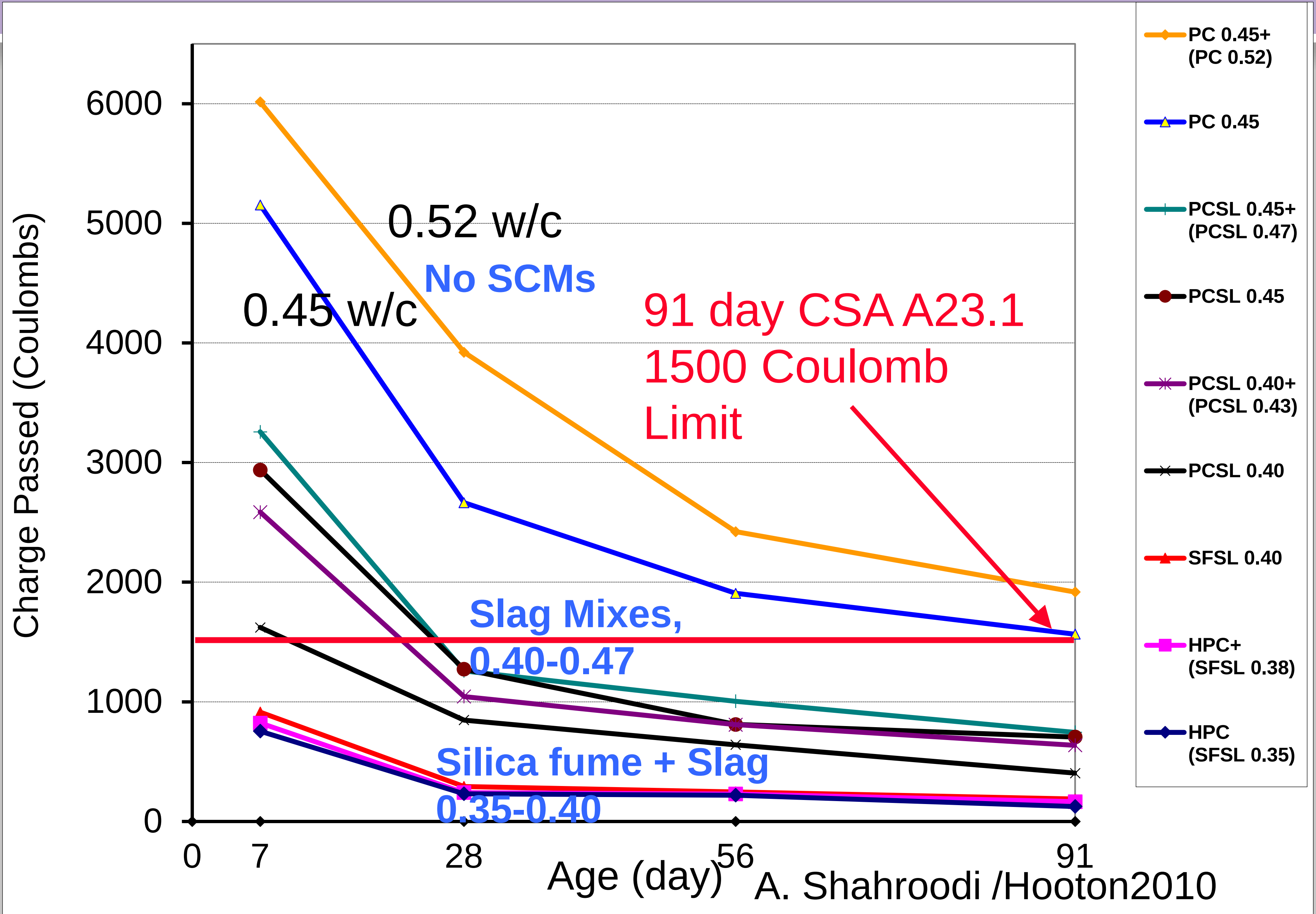
ASTM C1202 with Statistical Performance Limits are used in CSA A23.1

- Example: in C-1 exposure (35 MPa, 0.40, Air-entrained), the Canadian CSA A23.1 Standard requires max. 1500 coulombs @ 91 days for concrete exposed to frost and chlorides.
  - the average of 1500 coulombs for the 3 most recent tests is used for prequalification purposes.
  - For acceptance testing, the running average must be <1500, with all individual test results <1750 coulombs.

It is not helpful to use 28-day limits for assessment of concretes containing SCMs that develop their durability performance at later ages (unless accelerated curing is used)

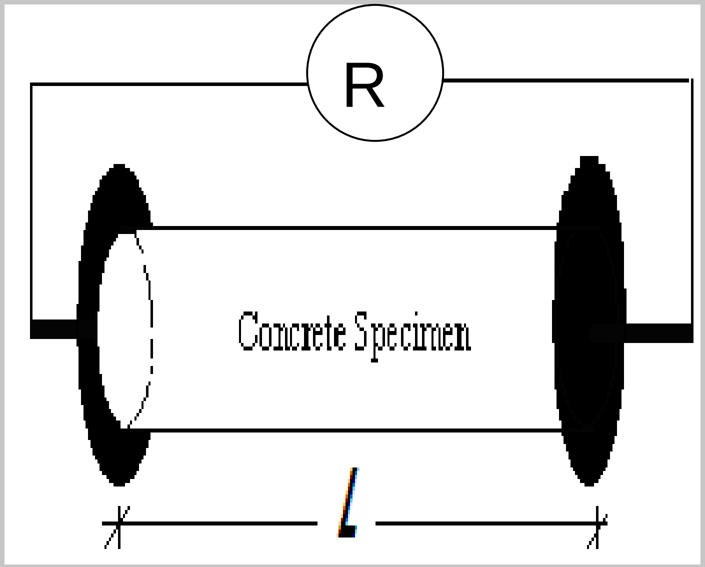
ASTM C1202 vs Age

(28 days is too early to set a limit unless accelerated curing is specified)



Bulk Resistivity Test ASTM C1876

- Simply measure the electric resistance through a wet concrete cylinder or core prior to strength tests

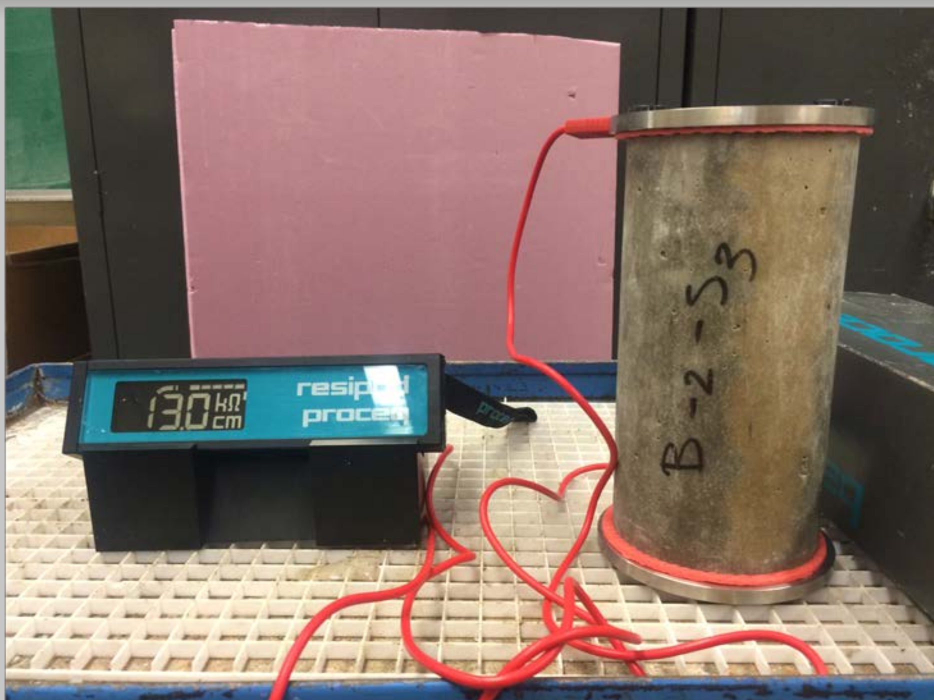


And calculate resistivity accounting for Area and Length of sample

$$\rho = R\ (A/L)$$

Commercial equipment is available

Different Types of Commercial Bulk AC Resistivity Test Equipment meeting ASTM C1876

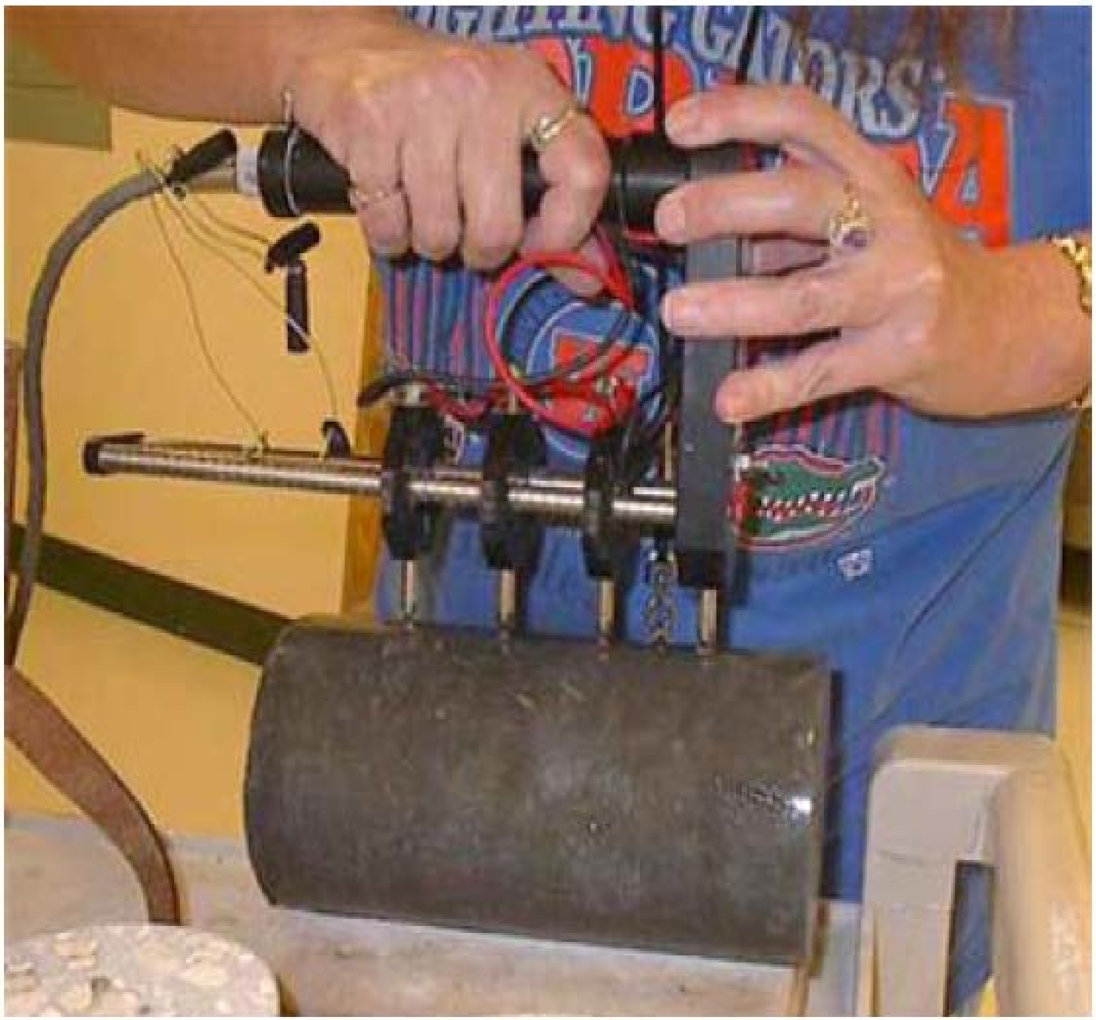


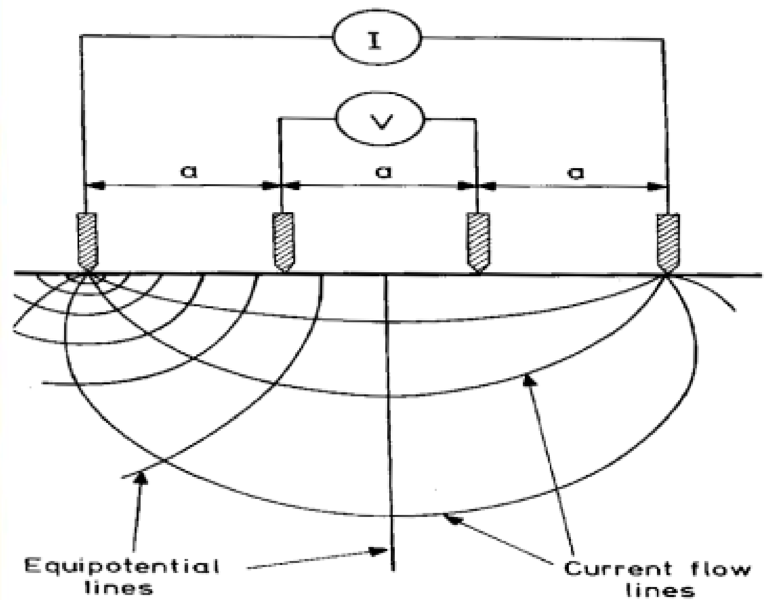
No limits have been specified as yet

Surface Electrical Resistivity

(Wenner probe) AASHTO T358

The Wenner probe applies an alternating current (AC) between the two outer electrodes. The voltage drop is measured between the two inner probes.





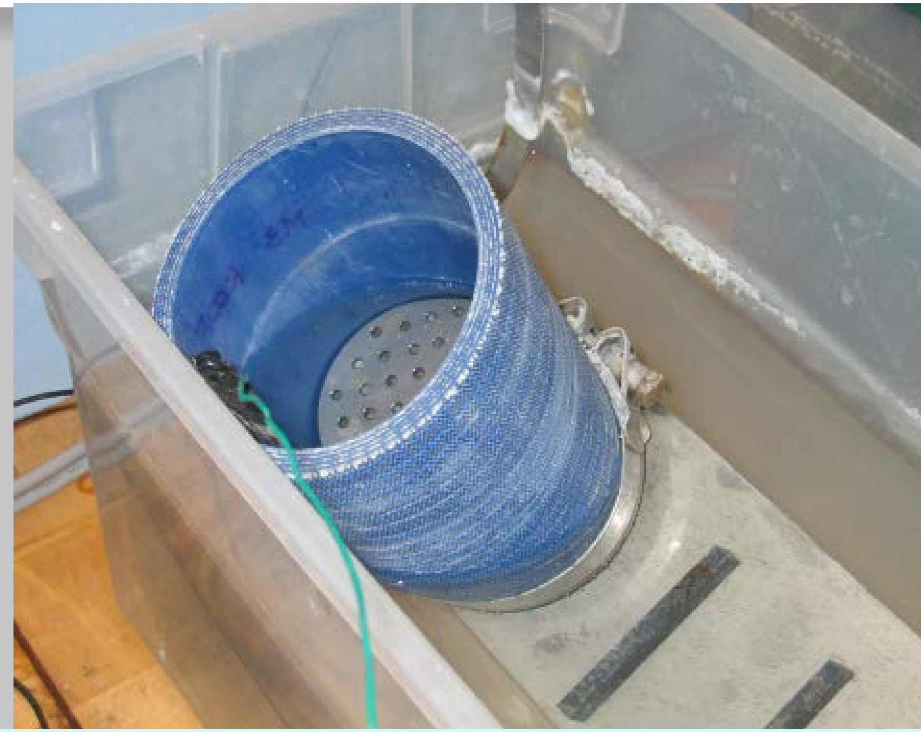
$$\rho = 2\pi a \frac{V}{I}$$

(ohm-m)

Nordtest NT492 Rapid Migration Test

(takes 1-4 days) (adopted by some European designers)

- Concrete disk is sealed and placed over electrode in NaCl sol'n.
- The top surface is covered in NaOH sol'n. with immersed electrode.
- Voltage applied & time of test is based on initial current
- After test, disk is split & sprayed with AgNO3, which turns into white AgCl2 where chlorides have penetrated. Rest turns brown in light.
- Avg. Depth of chloride is measured.
- Diffusion Coefficient is calc'd



$$\mathbf{D_{nssm}} = \frac{\mathbf{0.0239(273+T)L}}{\mathbf{(U-2)t}}\left(\mathbf{x_d} - \mathbf{0.0238}\sqrt{\frac{\mathbf{(273+T)Lx_d}}{\mathbf{U-2}}}\right)$$

$D_{nssm} \equiv \textit{Diffusion Coefficient}, \text{x } 10^{-12} \text{ m}^2/\text{s}$

$U \equiv$ Applied Potential, V

$T \equiv$ Temperature of Solution, ^{o}C

$L \equiv$ Speciment Thickness, mm

$x_d \equiv$ Average Penetration Depth, mm

Coefficients of Variation for Fluid Penetration Tests

(from Hooton CCR V.124, 2019)

Test Method	Average COV (within lab)	Average COV (Between lab)
Electrical charge (coulombs) ASTM C1202; AASHTO T277	12%	18%
Bulk Electrical Conductivity ASTM C1760	9.2%	Not determined
Non-steady State Migration NTBuild 492	15.2%	23.6%
Steady State Migration NTBuild 355	22%	76%
ASTM C1876 Bulk Resistivity	4.3%	13.2%
Bulk Chloride Diffusion	Da 20.1% (apparent diffusion)	Da 28.3%
Nordtest NTBuild 443 ; ASTM C1556	Cs 13.3% [surface]	Cs 18.1%
Wenner Probe, surface Resistivity	6.3%	12.5%
AASHTO T358 Surface Resisitivity	4.3%	10.3%
Air-Permeability Method SIA 262/1-E	3.8%	25.7%
Rate of Water Absorption ASTM C1585	6.0%	Not determined

When setting limits, we need to be aware of the reproducibility of the test methods, and set statistical (single value) limits as well as average limits.

ASTM is currently conducting new interlab tests for C1202, C1876, and C1556. (with a Covid19 delay)

After selecting a test, where to measure the Point of Performance?

K. Hover

Prequalification (model input tests)	Identity Testing		
	Acceptance at Chute		
		Accept at Point of Placement	
			Accept in-place

If performance specifications are adopted, different types of testing are needed

1. **Pre-qualification:** To provide a mixture that when placed under defined conditions can meet the spec.
2. **On-site QA/QC:** To document that:

   a) materials supplied meet the spec.

   b) the concrete supplied is equivalent to that which was pre-qualified (Identity Testing),

   c) pre-qualified placing /curing practices are being followed **(ie. test after change of ownership)**
3. **In-place:** Using in-place, core or NDT tests on the structure to ensure that on a statistical basis, the concrete + placement/curing methods meet owner-defined performance levels.

Should the same limits be applied in all cases?

Specified values <u>should</u> vary with point of evaluation (and test age should be considered): e.g. ASTM C1202,

Producer Target ~1150 Coulombs

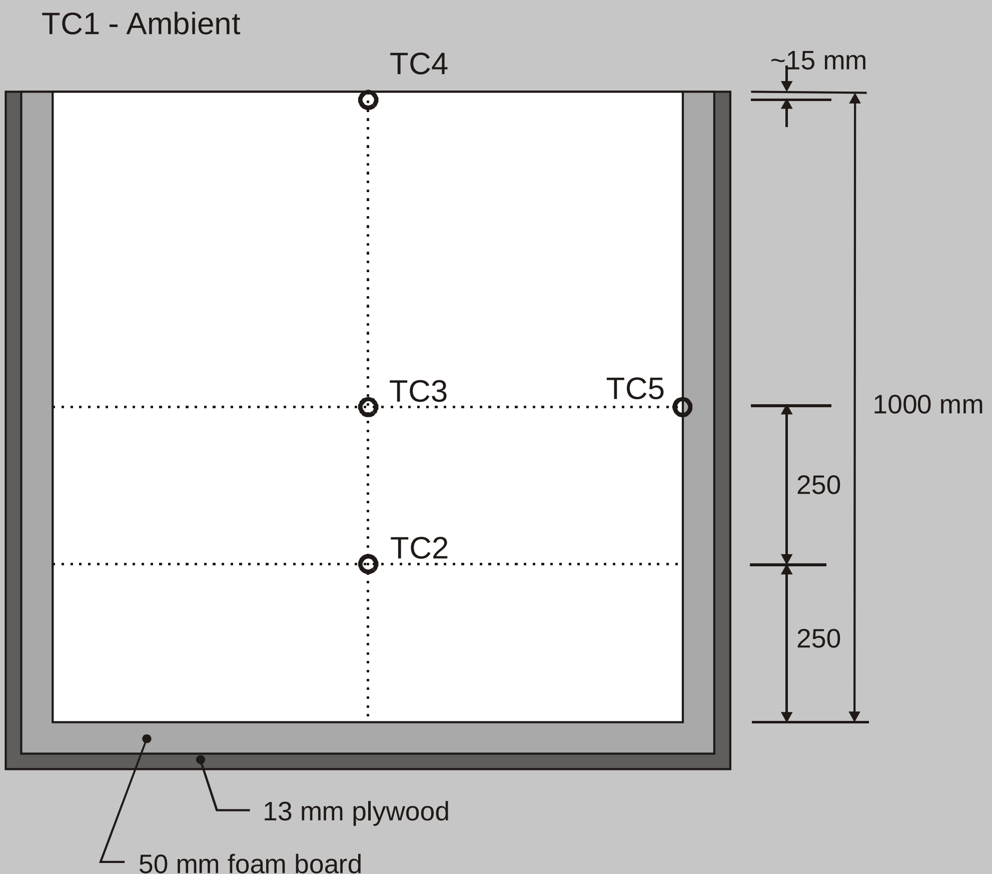
Specified 1500 Coulombs

In-place Average <1500 and no single value >1850 Coulombs

(values from 2008 paper by Lobo & Obla in Concrete in Focus) Different values than in CSA A23.1

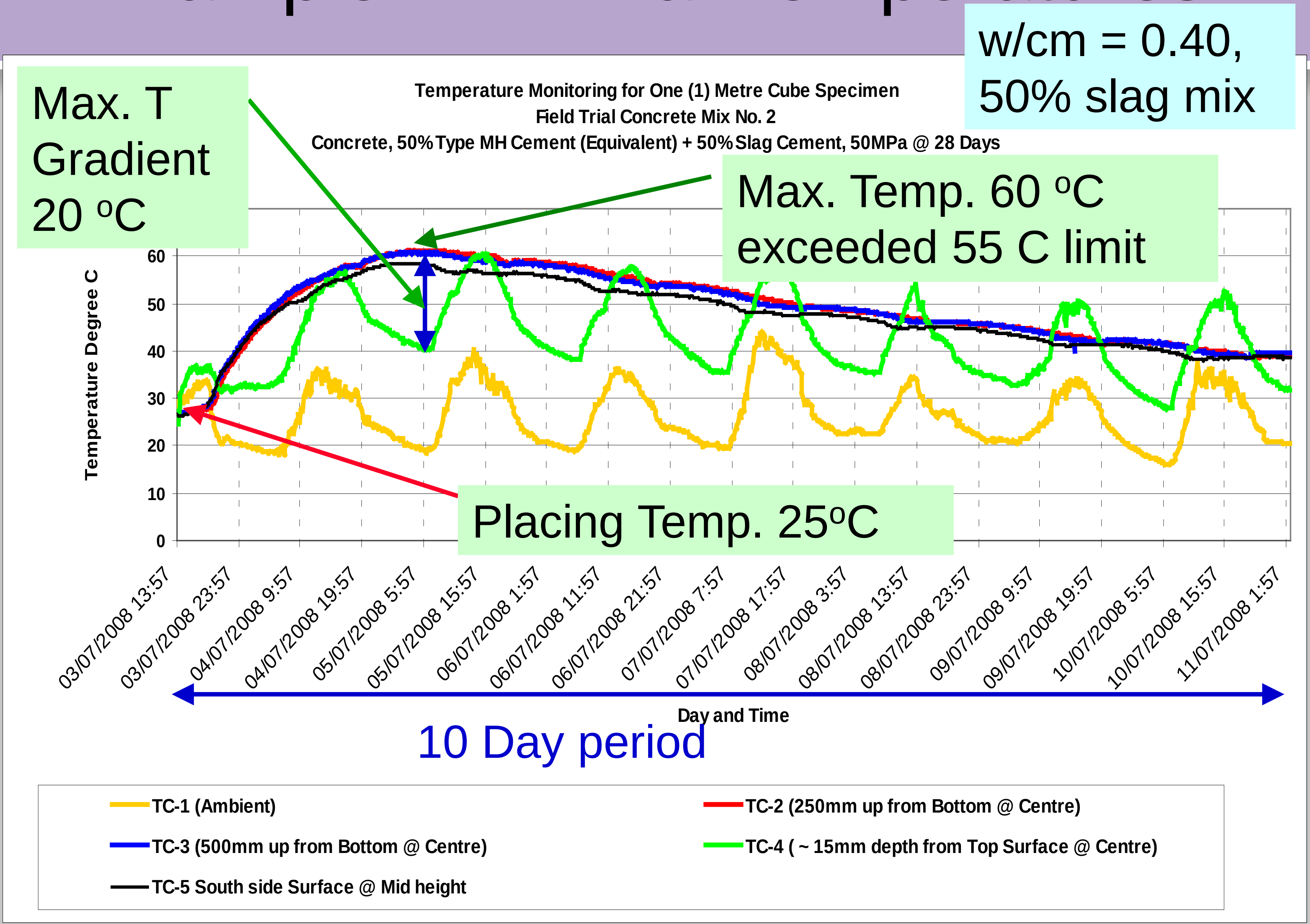
Pre-Qualification Tests on 1 m^3 Monolith for Mass Concrete (results provided to owner & owner can also take cores)

Concrete Suppliers must pre-qualify their Proposed Mixes using Monolith Tests and perform tests on cores from block

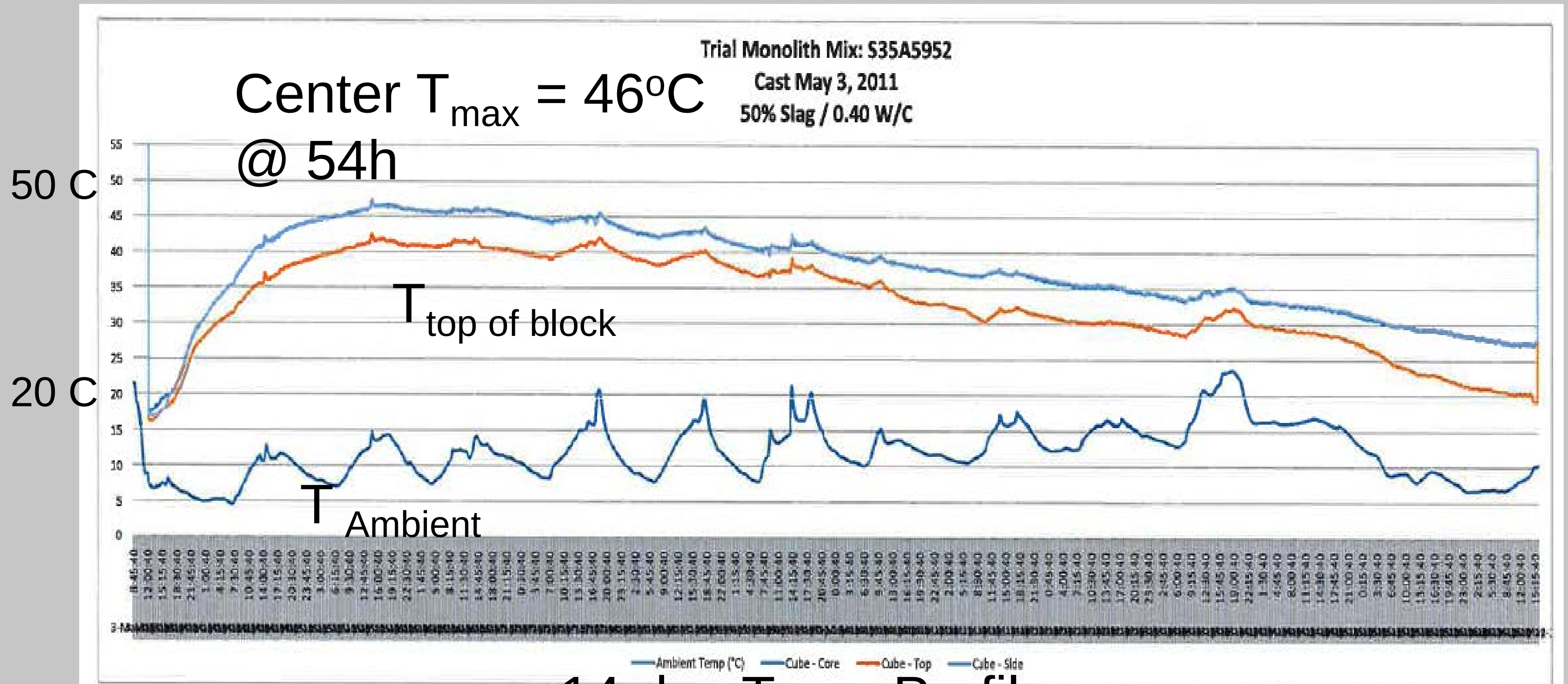


Bickley & Hooton

Example 1m³ Trial Temperatures



50% Slag. w/cm = 0.40, 6% Air with larger aggregate and cooler weather



14 day Temp Profile.

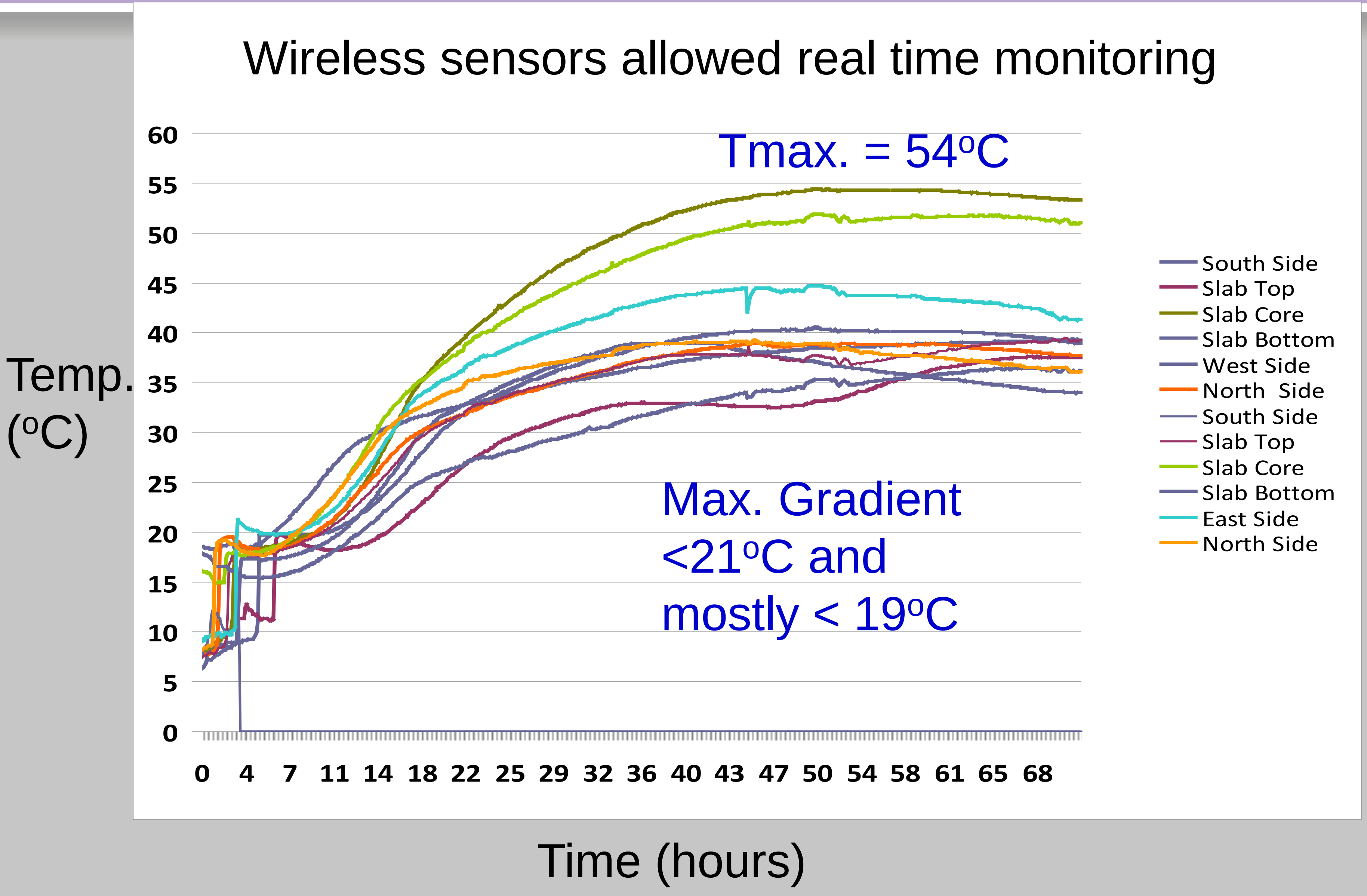
$T_{batched}$ = 17C, $T_{delivered}$ = 22C, Time to form removal = 242h

2.2 m thick, 1200 m^3 Initial Mass Slab Placement

CSA C-1 mix (35 MPa, w/cm < 0.40, permeability index <1500 coulombs @ 56d) with 125-160mm slump and 5-7% air.

- 50% slag
- 40mm aggregate to help reduce heat (Top re-bars at 150 mm spacing).
- T.max. = 55^{o}C with
  max. gradient = 20^{o}C.

In place tests: 2.2m thick Slab Temperature Rise over 1st 72h (concrete placed at <20ºC in 10ºC weather)



Available Pre-placement Identity Tests

To check concrete quality before placement

The current tool kit is pretty slim

Measuring the water content of fresh concrete on site

- Control/uniformity of w/cm.
  - The cementitious materials content in a mixture is well controlled, as is mix water.
  - **But there are other sources of water** (in the drum, in aggregates, trim water, keeping the contractor happy water, etc.)
  - So an estimate of total water content is useful to at least to assess uniformity of concrete as delivered.

The microwave test takes about 15 minutes to complete

Obtaining uniformity of water content will result in better control of strength and permeability

Oh, I forgot finishing water

The typical testing situation

Section 3—Alternative meth... g concrete performance requi...

Spec Req.

1.

2.

3.

4.

5.

3.1—General

3.1.1 Prequalification and Identity testing

3.1.2 Evaluation at the point of discharge

3.1.3 Evaluation at the point of placement

3.1.4

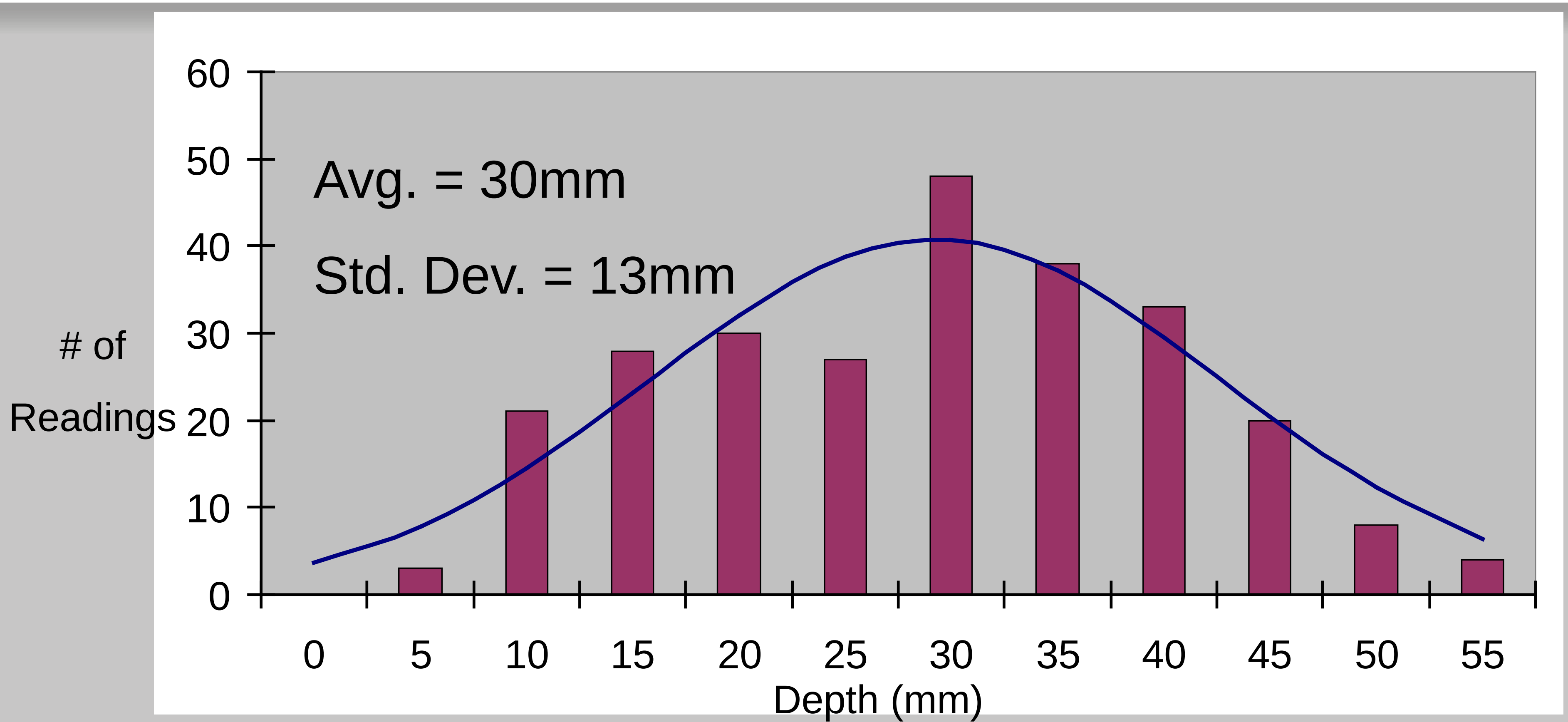
In-place testing

- The owner is interested in the performance of the as-built structure taking into account both the concrete supplied, and the contractor’s means and methods, including the pre-placement inspection of critical items like achieving cover depth.
- A few highway agencies use End Result Specs, taking cores for assessing performance and payments (penalties and bonuses)
- Also, the owner does not only want good concrete between the cracks.
  - So does the contactor have plans to avoid plastic shrinkage & settlement cracks?
  - Is there a thermal control plan?
  - Efforts to minimize of drying shrinkage

Minimizing Variability in Concrete Construction will improve Durability & Impact Service Life

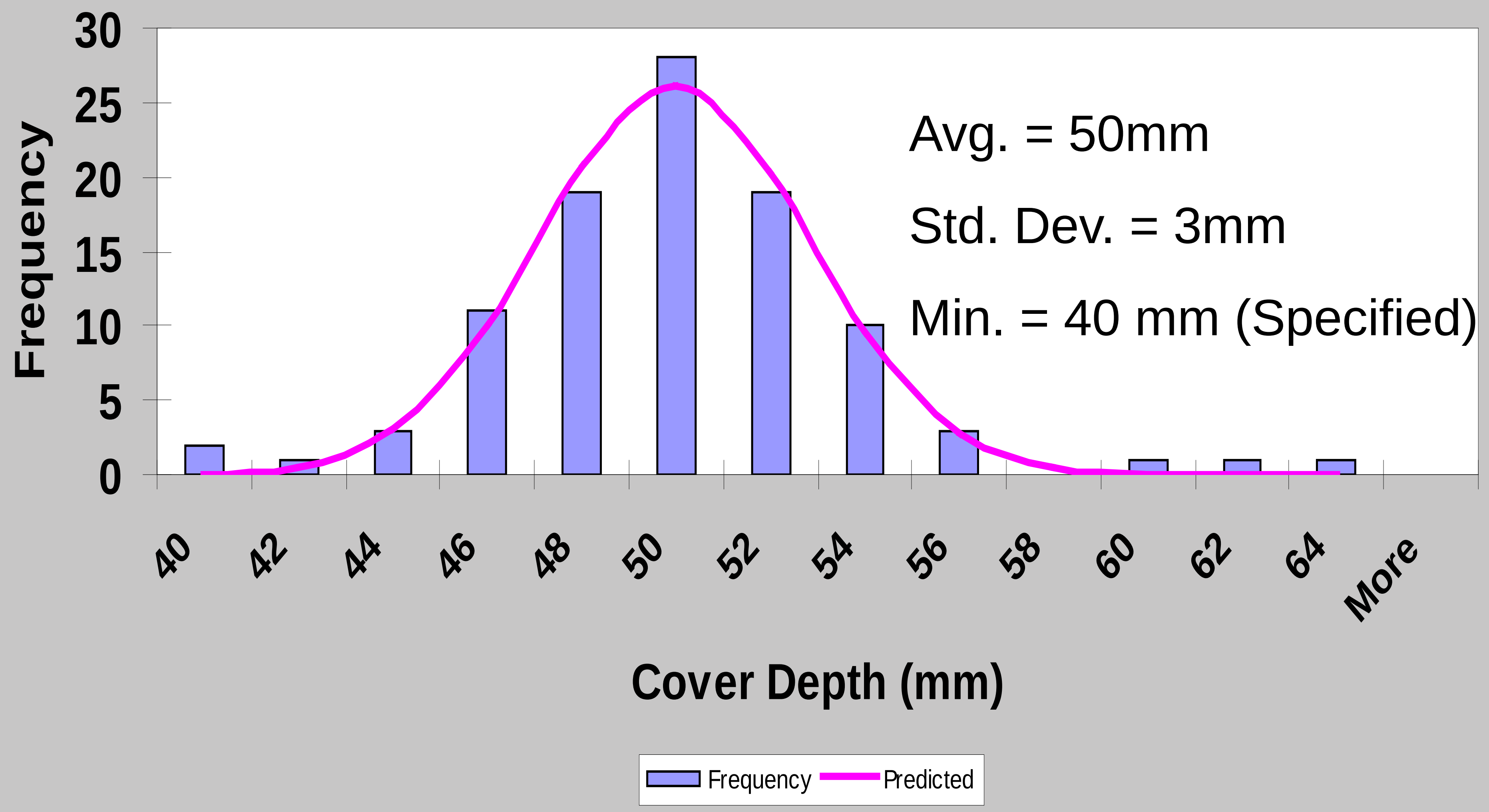
- Attention to construction details, practices, with compliance inspection must be done in advance, to minimize variability of each of the important parameters.
- When minimum cover depth & variability is not checked, the time to corrosion will be significantly be shortened (or at least there will be less confidence in the prediction).

Range of Cover Depth from UK Bridge Piers (260 readings, Frearson, 1985)



Given that many building codes allow rebar placement to vary by ±10 or 12 mm (1/2 inch), this could be considered is typical. And how many times does this get checked before placement?

Concrete Cover: Parking Deck With Good Inspection & Corrections made <u>prior to placement</u>, (Toronto 2001)



Summary

- Measures of durability performance offer improvements over existing strength and w/cm limits
- Performance specifications require reliable standard performance tests and appropriate test limits that address performance concerns.
- Reasonable performance tests exist and have been used in performance specifications. Waiting for perfect performance tests is not good Engineering.
- Tests that better relate to field performance are always needed as well as new tests that address performance issues not covered by existing test methods.
- Need to set statistical limits and appropriate test ages in Specs.
- The only way to move forward is to use the best available methods and good judgment.

Speaking of Judgement…

At the end of a long day, Calvin considers the deep Specification questions:

How something can be defined as both jumbo and shrimp?

Thanks Calvin for your sage advice, good company, and all you do for ACI