Designing Concrete for Durability: From Materials Selection to Long-Term Performance

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Poor Durability Results from:

- Lack of appreciation of the environmental exposure.
- Inadequate specifications to obtain durability in that exposure.
- Lack of understanding by all parties of the methods and practices required to attain durability.
- Lack of inspection to ensure that specifications are being met.

Modified from Bryant Mather

Durability in Severe Environments

ACI 318: The LDP must Identify the Expected Service Exposures

- In some cases, there is a single aggressive exposure, but in other cases, some elements are exposed to multiple aggressive exposures.
- **ACI 318 requires the severity of each exposure category to be identified**.
- e.g. F= freezing, C = corrosion, S = sulfates, P =water.
  - And the severity (Exposure class) need to be called out
  - E.g. C2 for chloride corrosion exposures
  - If there is no exposure, for example to sulfates, then it is still required to be called out as C0.

Specifying Durable Concrete

- **Durability design includes more than the selection of concrete materials and mix proportions.**
- The owner's designer needs to define the exposure conditions for each element in the structure.
- Adequate compaction, protection of fresh concrete, curing and temperature control need to be **detailed in the specifications**
- **Sufficient inspection and testing** be carried out to ensure that the specifications are being followed.
- Performance & objective-based specifications can improve the chances of obtaining of durability and allow for more sustainable options.

Design of Durable Concrete Mixtures

(the usual suspects selected for aggressive exposures)

Objective # 1: **Keep the aggressive fluids from penetrating into the concrete** & to the reinforcing steel.

a) **Lower the Unit Water Content**: to minimize the paste fraction (by optimizing total aggregate grading & using water-reducing admixtures to obtain required workability)

b) **Use low W/CM** $\le$ 0.40 to reduce porosity of paste fraction.

c) **Use SCMs or blended cements** to reduce connectivity of the capillary pore network and to help reduce thermal gradients

But how are these objectives specified?---often by prescriptive limits, and performance is not often directly measured.

Common Causes of Deterioration

Chemical

- Corrosion of steel
- Alkali-aggregate reaction
- Sulfate attack
- Acid attack

Physical

- Freeze/thaw (+scaling)
- Physical sulfate (salt crystallization)

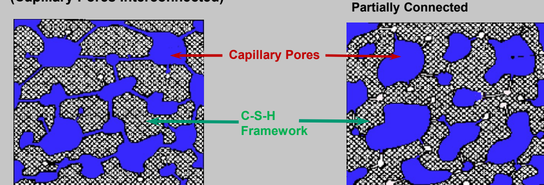
All of these mechanisms involve water . . . and the rate at which they proceed is dependent on the ease with which water (and any dissolved salts) can move into or through the concrete pore structure.
So, reducing the rate of fluid ingress is common to all exposures

Porosity ≠ Permeability

Schematic of 2 concrete matrices with the same porosity (and same strength) but different permeability

High Permeability (Capillary Pores Interconnected)

Low Permeability Capillary Pores Segmented and Only Partially Connected



Strength is affected by porosity (i.e. w/c)
Permeability is affected by porosity (w/c)& connectivity of pores (SCMs)

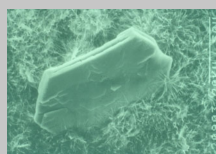
Neville and Brooks 1987

SCM's Improve Durability of Concrete

The advantages of properly designed and cured concretes containing SCM's are lower permeability and chloride diffusion:

1. There is more C-S-H matrix formed

2. The reactions happen later, so that the new C-S-H subdivides and blocks the initial capillary pore system.



Some calcium hydroxide, $Ca(OH)_2$ reacts to form more C-S-H

3. The porous aggregate transition zones (ITZ) become filled with C-S-H, reducing their influence.

e.g. Effect of Slag on Concrete Permeability (at equal [W] and w/cm)

Slag %	Water Content (L/m3)	W/CM	91-day Strength (MPa)	RCPT (coulombs)	Permeability H_2O 10^{-13} m/s
0	200	0.45	35.8	5200	10.1
25	200	0.45	42.7	2450 5.1x	5.4 4.4x
50	200	0.45	42.8	1020	2.3

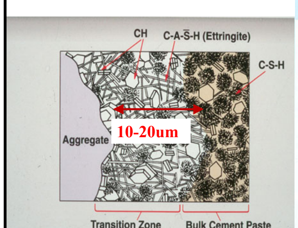
Lower permeability is in part due to improvement of the ITZ

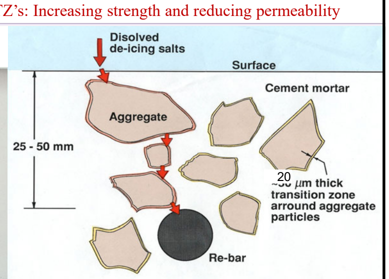
R. Bin Ahmad and Hooton, 1991

Interfacial Transition Zones (ITZ) around aggregate particles are more porous and permeable than the bulk cement paste

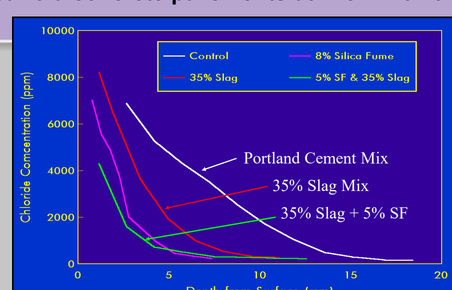
Secondary hydration of SCMs densify ITZ's: Increasing strength and reducing permeability

25-35% of Paste Volume is in ITZ





40-day Chloride Diffusion test results on cores from 2-year old concrete pavements at w/cm = 0.40



Bleszynski, Hooton, Thomas, 2001

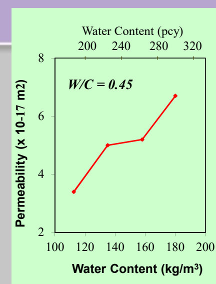
Cement Paste is not Concrete

For a given W/CM, reducing the unit water content [W] of concrete reduces the volume of paste, thus reducing total porosity before hydration starts.

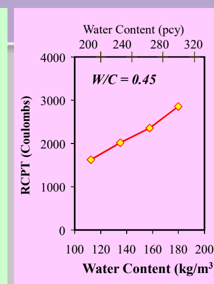
Thanks to chemical admixtures, [W] can be controlled independent of W/CM for a given workability

Reducing paste volume increases sustainability (less use of cementitious materials) for same strength and also results in lower permeability and shrinkage

Permeability:Effect of Water Content at Constant W/C



Gas Permeability



Rapid "Chloride" Permeability

At a fixed W/CM, Reducing water content reduces permeability

Data from M. Thomas

W/C vs. Unit Water Content of Concrete

Cement content (kg/m³)	Water Content (kg/m³) W/C = 0.35	0.45	0.50	0.55
250	-	113	-	138
300	-	135	150	-
350	-	158	-	-
400	140	180	-	-

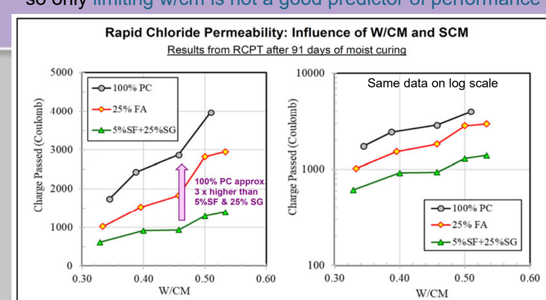
Desired workability at lower water contents obtained using chemical admixtures

W/C has a major impact on strength, but is only one factor in controlling permeability

Decreasing paste content as water content is reduced, at equal w/c = equal strength

M. Thomas

When SCMs are used, permeability is not uniquely related to w/cm so only limiting w/cm is not a good predictor of performance

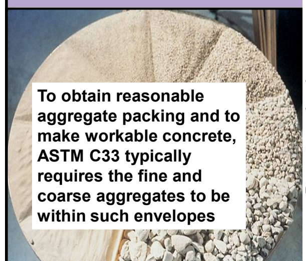


Michael Thomas

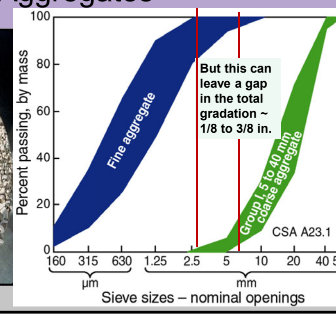
A Common Misconception: More Cement is Not Always Better! (and is less sustainable)

- At a fixed W/CM, adding more cement also raises the unit water content of the mix and **makes the concrete more porous and more permeable** (but does not affect strength).
- High cement contents also lead to higher thermal stresses and increased shrinkage, making the concrete more vulnerable to cracking.
- Chemical admixtures (and optimized total aggregate gradations) can be used to obtain workable concretes at lower cement contents.
- However, prescriptive minimum cement contents in concrete specifications can be a barrier.

Typical Standard Grading Limits for Fine & Coarse Aggregates



To obtain reasonable aggregate packing and to make workable concrete, ASTM C33 typically requires the fine and coarse aggregates to be within such envelopes



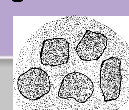
Lower paste contents through optimizing Combined Aggregate Gradations

Combined Aggregate Gradings

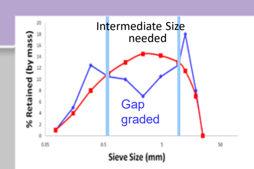
Admixtures

Lower water demand → Reduced Paste Content with Better Performance: less cracking, lower permeability → longer service life

Optimizing Concrete Mixtures

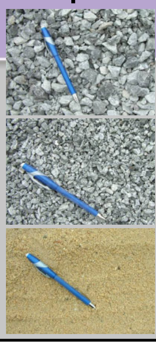


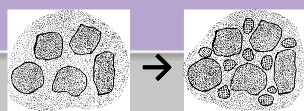
Typical Mix
Gap-graded



- Lack of intermediate aggregate
- ↑ void content of combined aggregate
- ↑ paste fraction required

Optimizing Concrete Mixtures





Typical Mix Gap-graded	**Optimized Mix** Well-graded
• Lack of intermediate aggregate • ↑ void content of combined aggregate • ↑ paste fraction required	• Intermediate size aggregate fill voids • ↓ void content of combined aggregate • ↓ paste fraction required

A predictive approach:
Power Curve Optimization of aggregate Gradations

- The Power curve is an approach based on the work by Fuller and later by Balomey & Talbot, where the mathematical optimum packing of spheres is described by the following gradation:

$$V_{(c)} = (\text{Sieve Size /Max. Size})^n$$

- where V(c) is can be expressed by the cumulative % passing
- The original value of the power exponent, n was 0.5, but in practice, this is too high: n depends on particle shape and the desired slump or slump flow.
- **For low slump mixtures, n = 0.40-0.45**,
- **For high slump and SCC mixtures, n = 0.25-0.30**
- The smallest sizes can also be used to optimize the cementitious materials and mineral filler gradations

The solver function in Excel spreadsheets can be used to simplify optimized aggregate gradations. Most admixture companies also offer this service to customers.

Example 1: Showing Improved Properties of w/cm = 0.40 Concrete by including a Mid-Size 2-8mm (~1/8 to 5/16 inch) Aggregate (added with sand and 20-mm (3/4inch) stone)

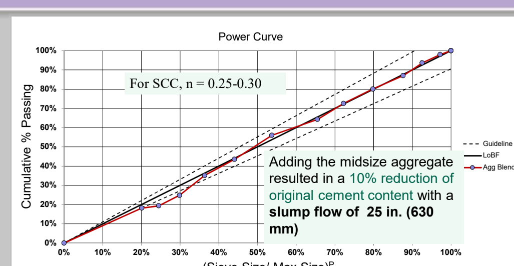
	Standard	Optimized
Total Cementitious Content, pcy (kg/m³)	**600 (360)**	**550 (330)**
Portland Cement Type	**Type I**	**Type I**
Screenings (added as mid-size aggregate)	**No**	**Yes**
MRWR Dose for 80-120 mm slump (mL/100 kg)	935	950
28 day Strength, psi (MPa)	**8,380 (57.8)**	**10,000 (69.2)**
28 day drying shrinkage	**0.033%**	**0.025%**
ASTM C1202 (coulombs @ 56 days)	**900**	**640**

Results of adding the mid-size aggregate:

- **30 kg/m³ (9%) less cement**
- **1620 psi (11.4 MPa) higher strength**
- **Similar admixture dose**
- **24% Lower drying shrinkage**
- **28% Lower permeability**
- The mid-size limestone screenings were from the same quarry as the 20 mm coarse aggregate

M, Anson-Cartwright, PhD, U. Toronto

Example 2: Power Curve Optimization of total Gradation of SCC Mixture using 3 aggregates, with cement and slag cement.



Also, need to Select Aggregates that are Chemically Stable in Concrete (or mitigate ASR with SCMs)

- **Alkali-aggregate reaction** results from use of unstable siliceous aggregates that are chemically attacked in the high pH of concrete → expansive ASR gel
- Such aggregates **need to either be avoided, or use** sufficient cement replacements by appropriate **supplementary cementitious materials** (SCMs).
- All aggregate sources need to have current documented test data to demonstrate that they are not alkali-reactive (or what mitigation is required with their use: See ASTM C1778).

Design for Durable <u>In-place</u> Concrete

<u>Objective # 2</u>: **Prevent cracking and other defects** to keep aggressive fluids from penetrating to the reinforcing steel.

a) Protect the fresh concrete from **plastic shrinkage cracking**
b) Keep the concrete sufficiently moist after set (i.e. **curing**) to make the *covercrete* more impermeable and to lower early-age drying shrinkage
c) Require a **thermal control plan** to minimize thermal cracking due to internal gradients or from external sources (ie. protect from cold or hot temperatures)

To obtain durable structures, these performance requirements also need to be clearly specified and inspected.

The operation was a success but the patient died.

- e.g. For chloride exposures, setting concrete specifications to get low chloride diffusion valueis **not sufficient if** all you end up with is **good concrete between the cracks.**
- Other characteristics of the concrete need to be specified: eg. design to minimize thermal heat rise, autogenous & drying shrinkage to avoid cracking.
- **Attention to adequate site practices** to avoid cracking and defects (protection before set, control of thermal gradients, curing, and possibly internal curing). **This also requires good inspection.**

Unintended In-place Performance

Plastic Shrinkage Cracks on Bridge Deck due to lack of protection prior to final finishing

Tearing of Bridge Deck Surface due to premature loss of workability

Void under rebar due to incomplete compaction of stiff mixture → premature corrosion

Poor Thermal Control Leading to Leaking Cracks

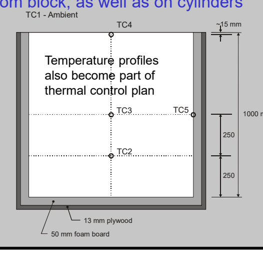
Resulting from prescriptive limits on concrete materials and proportions

Both concretes had w/cm = 0.40, but specs limited % SCMs

Pre-Qualification Tests on 1m^3 Blocks or Larger Mockups for Mass Concrete (results are provided to owner & owner can also take additional cores)

Concrete Suppliers pre-qualify their Proposed Mixes using Monolith or Mockup Tests and perform tests on cores taken from block, as well as on cylinders

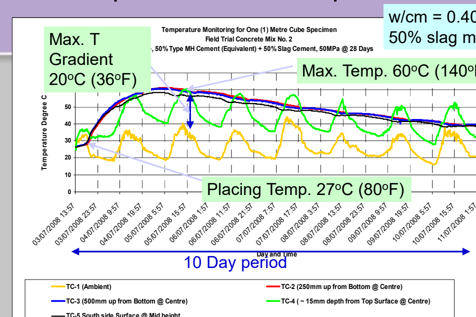
Bickley & Hooton 2012



Thermal Testing using Prequalification Large Block Trials

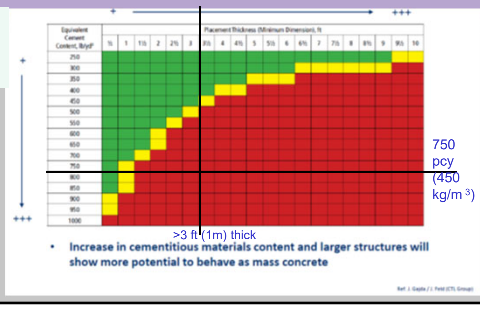
- Performance tests are made on cores taken from the block: results are more realistic than testing lab-cured test cylinders or cubes.
  - *Examples:* Strengths at different ages, hardened air content & distribution, permeability index tests
- Placing, setting and thermal control issues can also be identified in advance.
- This approach has been used on numerous infrastructure & large building projects

Example 1m^3 Trial Temperatures



Also, “Mass Concrete” does not just mean > 1m thick elements

High cement content mixes can lead to thermal cracking



Comparison – for Concrete Mixtures

Prescriptive Specification

- Provides a specific mixture design with limited variation – e.g. cement minimum contents; max. SCM limits.
- Generally enforced by fundamental tests such as strength or slump; the means of mixing and placement are verified.
- Provides specific placement and curing procedures.
- Durability is assumed to occur if the prescription is met (by some magic).

Performance Specification

- Clear, measurable, and enforceable instructions that outline the functional requirements for the concrete.
- Takes into account exposure conditions.
- Does not include provisions for means, methods, concrete mixtures, or materials.
- Allows for, and in many cases, incentivizes, innovation.
- Allows entry and use of new materials

Prescriptive Concrete Specifications

- While traditional prescriptive or recipe-based specifications for concrete have worked well in many applications, they also can inhibit making durable (& lower-carbon concrete) and stifle innovation when the objective is to reduce the GWP of concrete mixtures.
- Common examples:
  - specifications that prescribe **minimum cement contents**
  - limit the types and replacement levels of supplementary cementitious materials (SCMs), (or in blended cements)
  - prevent or limit use of optimized total aggregate gradations.

Types of Concrete Specifications

- **The majority of concrete specifications are either prescriptive, or contain a hybrid of prescriptive and performance limits.**
- **Prescriptive limits in concrete specifications are historical** and are based on assuming the paste fraction of concrete is only portland cement and water
- They often include **restrictions on materials** and **limits on proportions** that prevent use of reduced carbon concretes.
- Prescriptive specifications do not allow for adoption of rapid advances that have occurred in concrete technology, such as new chemical admixtures, SCMs, and new types of cementitious materials, **so they often act to restrict adoption of more durable & lower-carbon concretes**.

Why this is important?

- **A mixture of prescriptive and performance requirements confuses the roles and responsibilities** of the designer, concrete supplier and contractor, and leads to litigation when problems occur.
- With performance specifications,
  - **the designer needs to state the required concrete properties in quantifiable terms,**
  - **the concrete producer is responsible for delivering the specified concrete, and**
  - **the contractor is responsible for the in-place concrete.**
- While there is global interest in transitioning to performance specifications, due to perceived risks associated with change, adoption has been slow.
- Performance Specifications also provide flexibility to use alternative concretes if they meet required performance objectives.

Specifying Durability Performance

- Additional performance tests may be needed to address specific durability exposures, but for almost all aggressive exposures, **the most important property for resisting concrete deterioration is to limit the penetration of aggressive fluids.**
- Unfortunately, many specifications and codes only indirectly address durability by requiring minimum **28-day strengths and lower water to binder ratios**, and **those limits are inadequate** for demonstrating the improved permeability provided by blended cements or SCMs.

Set performance test limits in specs.

- To be durable in aggressive exposures, the primary goal is to reduce ingress of fluids.
- Therefore, use relevant performance index tests for fluid ingress for qualification of concrete mixtures.
- ASTM C1202 Coulombs or ASTM C1897 Bulk Resistivity with limits set at an age relevant to the concrete mixtures
  - Such limits can replace prescriptive minimum cement contents and w/cm limits

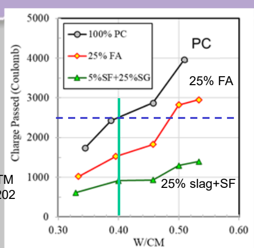
Prescription vs Performance in Codes

- Current prescriptive requirements in Codes, Specs and Standards make it difficult to adopt materials & mix proportions that can provide lower GWP concretes.

For example:

- **For durability exposures, the ACI 318 Code only requires meeting max. w/cm limits and minimum 28-day *strength*.**
  - e.g **for ACI C-2 Chloride exposure**: **0.40 w/cm and 5000 psi (35 MPa)**
  - But **these requirements are not directly linked to the durability issue**; i.e. resistance to ingress of aggressive chlorides.
  - These current requirements result in allowing concretes with different levels of durability
  - **5000 psi (35 MPa) is not needed for durability**, but that the only property being measured on the delivered concrete.

Example of why w/cm limits in ACI 318 for chloride exposures do not provide concrete of equal durability (as indicated by permeability)



ASTM C1202

M. Thomas

1. w/cm limits do not consider the impact of SCMs on permeability
2. A SCM mixture at 0.5 w/cm may provide equivalent durability to a 0.4 w/c portland cement mixture.
3. **Also, the permeability benefits of some SCMs are not attained at 28 days. Later-age limits (or accelerated curing) are more appropriate.**

Draft **ACI 321 Durability Code** under development

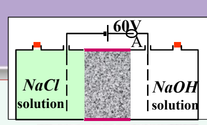
- This draft code will have more exposure categories, each with a performance option. For proposed CD2 deicer exposures

Option 1	Option 2
Maximum charge passed [b] (ASTM C1202), coulombs (for 28 d accelerated curing or 90 d lab curing)	Minimum Resistivity [b] (ASTM C1876), ohm-m (for 28 d accelerated curing or 90 d lab curing)
1500	**120**

ASTM Accelerated Curing = 7d @ 23C then 21d @ 38C

The CSA A23.1 Specification requires < 1500 Coulombs at 90d (or allows an equivalent bulk resistivity limit if approved by the owner

Rapid Index Tests are needed for mix qualification & QA/QC



- ASTM C1202 (coulombs):

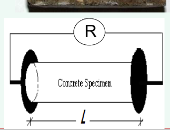
2 days to complete

- NT Build 492:

- ASTM C1897 Bulk Resistivity:

One minute to complete

ρ = R (A/L)

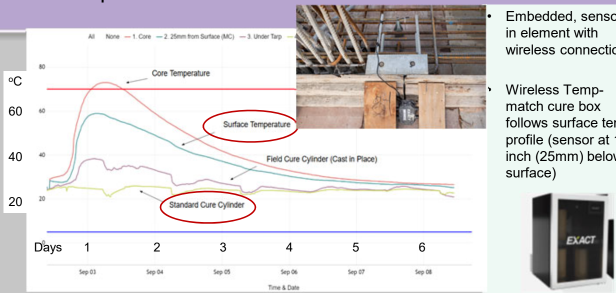


Note that saturation, conditioning fluid & temperature affect test results

Age of Concrete Performance Tests

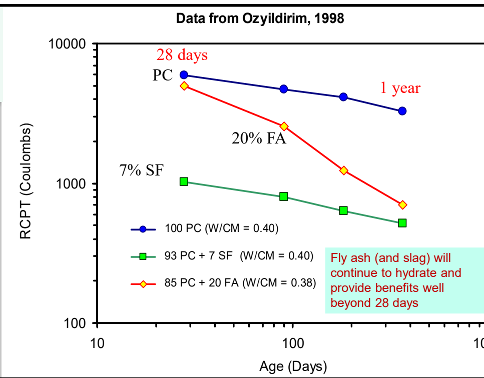
- Typically concrete is qualified and accepted based on fresh properties such as slump/ slump flow and air, and most commonly **28-day strength**
- **But 28-day lab-cured strength alone is not an adequate performance metric:**
  - Construction schedules are controlled by early-age strength development.
  - Concretes with high-SCM levels develop their ultimate properties at later ages (e.g. 56 or 91 days)
  - **Also, early strengths of SCM-mixtures are often underestimated by concrete cylinder tests stored at lab temperatures**

Temperature-Matched Curing better predicts early-age strength development and can be used to accelerate construction



- Embedded, sensors in element with wireless connection
- Wireless Temp-match cure box follows surface temp profile (sensor at 1 inch (25mm) below surface)

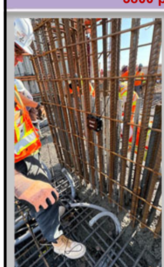
Specifying permeability at 28 days does not predict long-term potential of many SCM mixtures

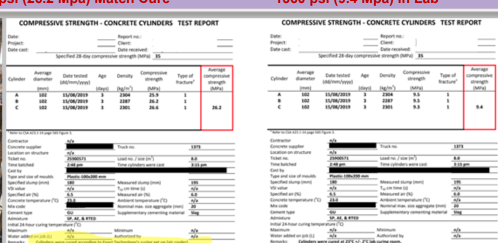


Fly ash (and slag) will continue to hydrate and provide benefits well beyond 28 days

Example Difference in 3-day strength of temp-match & standard lab-cured cylinders: enables faster construction

3800 psi (26.2 Mpa) Match Cure | **1360 psi (9.4 Mpa) in Lab**





Match Curing is being used on many major vertical construction projects across Canada and USA

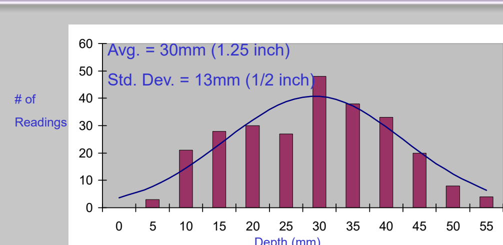
Improving Durability by Minimizing Variability in Cover Depths

- The typical cover tolerance of ± ½ inch allowed in Codes is not adequate for concretes exposed to chloride ingress.
- A local cover reduction of ½ inch on a 2 inch design cover could reduce the time to corrosion by approximately one third.

Proper inspection needs to include correcting shallow cover depths prior to concrete placement.

Lack of Control of Cover Depth & Cover Reducing Features

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

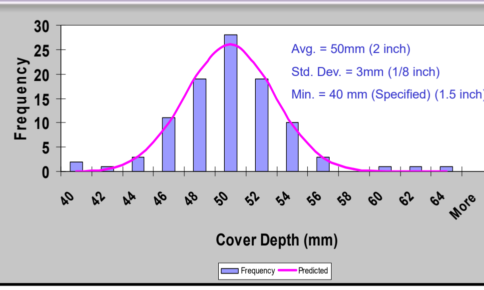


Many building codes allow rebar placement to vary by 12 mm (1/2 inch)

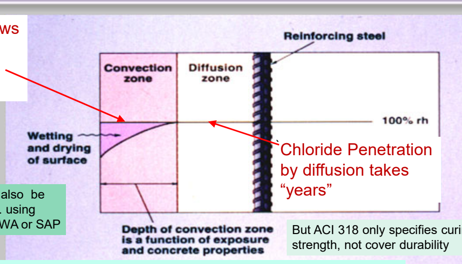
Displaced rebar cage in column base

60mm cover on one side **5mm on the other side**

Concrete Cover: Parking Deck with Inspection and corrections made prior to Placement (Toronto 2001)



Impact of Curing: Proper Moist Curing Reduces the Depth of the Convection Zone in the Cover Layer and can extend Time-to-corrosion of reinforcement by decades



Absorption allows Chloride Penetration in “hours”

Chloride Penetration by diffusion takes “years”

Curing can also be internal: eg. using saturated LWA or SAP

But ACI 318 only specifies curing for strength, not cover durability

Resistance to Chloride ingress can be lost if curing is not adequate

Improve Service Life by Minimizing Variability of in-place Concrete

- If attention to construction details, practices, and compliance inspection is not done in advance, then the variability of each of the important parameters (cover depth and curing) will become larger.
- In such cases, the time to corrosion will be significantly be shortened (or at least there will be less confidence in the prediction).

Curing

“Less than perfect” application of curing compound, by local contractor & part-time graffiti artist

Competent Testing

One of the biggest concrete producer concerns is bad (non-standard) testing.

Concrete not sampled correctly (ASTM C172), or cylinders not properly handled, stored or cured within temperature limits prior to test (ASTM C39), leads to low measured strengths. (especially temperature control)

If test cylinders are abused, then producers worry about similar impacts on cylinders used for RCPT or Resistivity results (so Ontario DOT tests 28-day cores)

This is one of the main reasons producers over-design concrete mixtures

Bad Bad Better?

On-site Freezing of Test Cylinders

- Measured strength will be very low
- Even air-entrained concrete must be protected from freezing before set and until it reaches adequate strength to resist expansive forces

Freeze/Thaw Resistance

Regardless of the cementing materials and admixtures used, concrete will be durable even if saturated when:

1. It is adequately air-entrained.
2. The aggregates are frost-resistant.
3. Adequate strength is developed before exposure to the first freeze (> 5 MPa) and cyclic freezing (> 20 MPa).

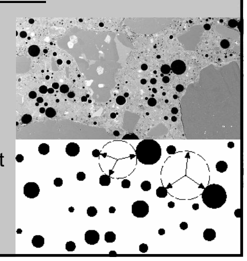
Bryant Mather, 1990

I was also asked to address some specific durability exposures

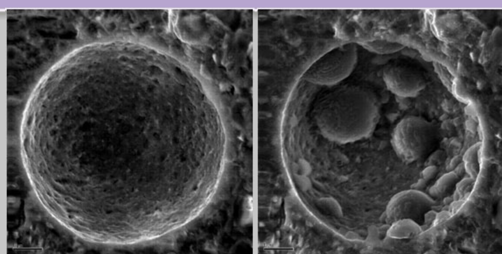
1. Freezing and thawing & scaling resistance
2. Chemical and physical sulfate resistance

Air Entrainment

- Air entrainment greatly <u>increases resistance</u> to freezing and thawing
  - Entrained voids provide pores where water can move to and freeze
  - Need ~5-8% air content for concrete exposed to F/T (for 3/4 or 1 inch aggregate)
  - Size and spacing of air voids are important
  - Spacing factor < 200 µm (0.008 in.)

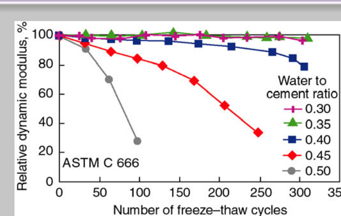


Air void in saturated paste before and after freezing: ice formation



D. Corr

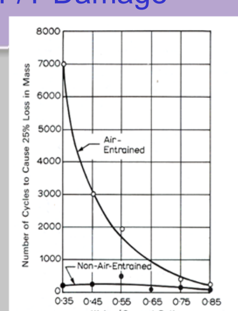
Effect of W/C on Frost Resistance of Non-Air-Entrained Concrete



ACA Design & Control

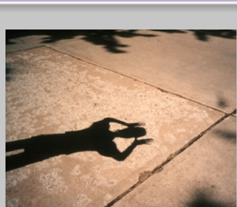
How to Prevent F/T Damage

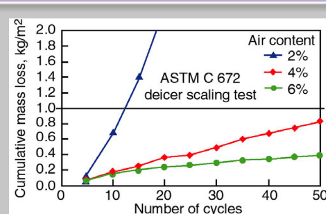
1. **Low w/cm concrete**
   1. Higher tensile strength at early ages and keeps water out
2. **Adequate curing before exposure to freezing**
   - Lower permeability – takes up less water in wet weather
   - Low porosity – reduces amount of "freezable" water in capillary pores
   - Higher tensile strength
3. **Avoid aggregates susceptible to freeze/thaw damage**



Non-air entrained, RR-underpass, retaining wall on Bloor St. West , Toronto ~1920 so > 100 years old

Effect of Air Content on De-Icer Salt Scaling





Cyclic Freezing and Thawing of slabs with 3% NaCl solution ponded on top surface

However, ASTM C672 does not predict field performance of concrete with SCMs---the testing should be delayed until later ages

ASTM C672 does not mimic field conditions

Another classic ASTM Fred Flintstone test

1. does not mimic most field conditions
   - 14d wet cure, followed by 14d in air, ponded with salt solution at 28d and F/T cycles are started---**takes 4 months to complete**
   - Again some SCM concretes do not have adequate maturity at 28d.
   - **Concretes with SCMs often perform poorly in C672, even when they are ok in the field**.
2. **the results are mainly affected by finishing and workmanship**
   - SCM mixtures might have different bleed rates and setting times
   - Premature finishing of slabs can trap bleed water
   - over-finishing can increase surface paste content and knock out air
   - Note: European scaling tests are on formed or saw-cut surfaces

We need better performance tests, especially for freezing & thawing and deicer scaling

A classic Fred Flintstone test

- ASTM C666-A was poor 60 years ago and has not been changed over 60 years and is not well thought out:

1. prisms are stored under water to 14d of age
2. prisms are then submerged in the machine and 300 F/T cycles are started

The procedures do not mimic most field concrete: The concrete never has a chance to dry before F/T cycling and SCM mixes are still developing strength at 14 days

3. The test is labor intensive and takes 4 months to complete

4. But no one is funding serious research to devise a better test or an alternative approach.

ASTM C672 Scaling Slabs

50% OPC + 50% Slag concrete w/cm = 0.45
Prior to scaling test

After only 5 cycles of freezing with salt water on surface

68

The same 50% Slag concrete in test pavements after 10 years field exposure

Premature finishing on the left side segments resulted in some minor scaling & abrasion

69

There are Many Types of Sulfate Attack

I think this sidewalk needs a bit more salt

Effect of w/c on 12% C_3A portland cement concrete in 15,000 mg/L Na_2SO_4 after 5.5 years

Progressive mass loss as [SO4=] ions penetrate and react, forming expansive phases such as Ettringite (AFt)

Testing SCMs and Blended Cements: ASTM C1012 Sulfate Expansion

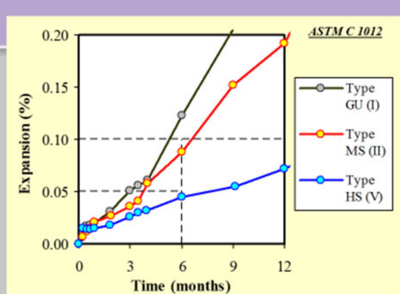
- Used to test Blended-Cements or Cement + SCM
- Mortar bars are exposed to 5% sodium sulfate solution after wet curing for 7 days at 38^{o}C.
- Expansion is measured for 6 or 12 or 18 months.
- Limits are specified in ACI 318 Code and in ASTM C595, C1157, C618, C989 specifications

pH is not controlled, but solutions are changed at each reading

Concretes: After 38 years in 50,000ppm Na_2SO_4, 0.50 w/c portland cement mixes

Alapour & Hooton 2017, ACI Mat. J.

Sulfate Resistance of Portland Cement Mortars



Portland Cements are not required to be tested using ASTM C1012, but this shows relative performance

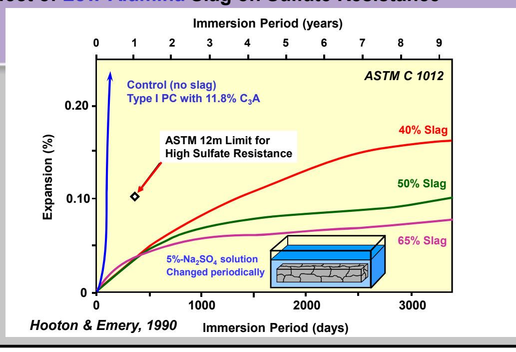
Positive Effects of SCMs & Blended Cements

- Sufficient levels of SCMs can provide sulfate resistance when used with high C_3A Type I cements.
  - Reducing pore connectivity & permeability and limiting sulfate ingress
  - Diluting the Portland cement C_3A*
  - Diluting/reacting to reduce $Ca(OH)_2$ content in the paste fraction, that reacts with sulfate ions to form gypsum and later ettringite

Note: some high CaO (>18%) Class C fly ashes can contain C_3A and reduce sulfate resistance.

- SCMs and Blended cements must meet ASTM C1012 expansion limits

Effect of Low-Alumina Slag on Sulfate Resistance



ASTM C1012 only tests the resistance of the cementing materials---but not the resistance of concrete

- Concrete quality has a large impact on sulfate resistance, so w/cm limits and curing are important.
- **Regardless of cement type, concrete must be resistant to ingress of sulfates.**
- In situations where there is **temperature or wetting and drying cycles**, or **evaporative transport** where limiting concrete permeability by low w/cm is more important.

ASTM C09.51 is developing a Guide for sulfate resistant concrete

After 38 years: 50,000ppm Na_2SO_4, Slag Cement concretes combined with 12% C_3A cement

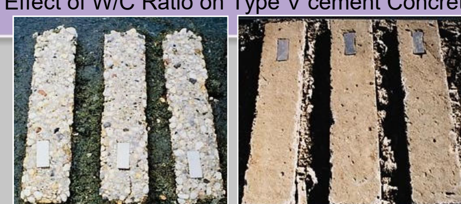
Alapour & Hooton ACI 2017

Cast in 1977, The 0.50 mixes would not meet current ACI 318 requirements (Would now need to be 0.40)

Minor cracks on 45% slag @ 0.50 w/cm

PCA, Sacramento California Test Site

Effect of W/C Ratio on Type V cement Concretes



Visual Rating of Concrete: 5 @ 12 yrs
Type V Sulfate Resistant Cement
W/C = 0.65

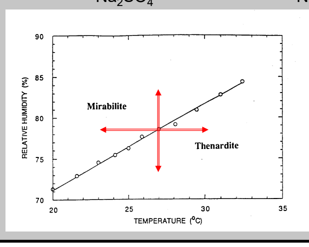
(mainly Physical Attack)

Visual Rating of Concrete: 2 @ 16 yrs
Type V Sulfate Resistant Cement
W/C = 0.39

D. Stark 2002

Sulfate salts precipitate due to evaporation, then cyclic phase changes occur with changes in RH & Temp.—causing expansion due to accumulated crystal growth in pores

Thenardite Na_2SO_4 ↔ Mirabilite $Na_2SO_4 \cdot 10H_2O$



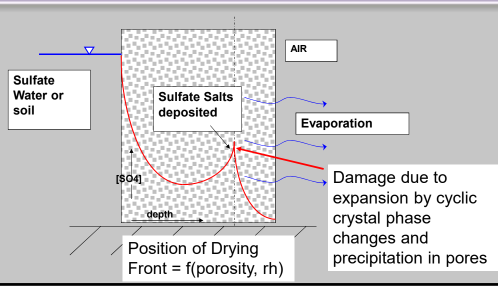
Sandberg & Folliard, 1994

Port Pirie, South Australia
(very hot and dry climate with sulfate soils)

Damage stops at capillary break at interface of foundation with support concrete

James Aldred

Wick Action due to Evaporation



Mitigating Physical Sulfate Attack (Sulfate salt Crystallization)

- Best solution is to reduce capillary pore continuity & permeability of concrete
- **Specify w/cm < 0.45** and preferably 0.40 (ACI 201.2R)
- **Curing is also important to develop low permeability in the outer surfaces of concrete** to prevent sulfates from being wicked up and precipitating sulfate salts in the near-surface pores.
- SCMs will reduce permeability, pore connectivity, and capillary rise.

Draft ACI 321 Durability Code
Sulfate Exposure Classes

		Water-soluble sulfate (SO_4^{2-}) in soil, % by mass	Dissolved sulfate (SO_4^{2-}) in water, mg/L
Chemical sulfate attack (S)	S0 no attack	$SO_4^{2-} < 0.10$	$SO_4^{2-} < 150$
	S1 moderate	$0.10 \le SO_4^{2-} < 0.20$	$150 \le SO_4^{2-} < 1500$ or seawater
	S2 severe	$0.20 \le SO_4^{2-} \le 2.00$	$1500 \le SO_4^{2-} \le 10{,}000$
	S3 very severe	$SO_4^{2-} > 2.00$	$SO_4^{2-} > 10{,}000$
Physical sulfate attack (P)	P0 no attack	$SO_4^{2-} < 0.10$ and concrete surface exposed to wetting and drying conditions	$SO_4^{2-} < 150$ and concrete surface exposed to drying conditions
	P1 risk of attack	$SO_4^{2-} \ge 0.10$ and concrete surface exposed to wetting and drying conditions	$SO_4^{2-} \ge 150$ and concrete surface exposed to drying conditions

Draft ACI 321 Durability Code
Performance Requirements for Chemical Sulfate Exposures

Class	Minimum f'_c, psi	Resistance to fluid penetration testing requirements [a] Note: choose one of the following testing options.		Expansion testing requirements	
		Option 1 **ASTM C1202 Charge Passed, Coulombs** (Maximum for 28 d accelerated curing or 90 d normal curing)	Option 2 **ASTM C1876 Bulk Resistivity, ohm-m** (Minimum for 28 d accelerated curing or 90 d normal curing)	ASTM C1012 Expansion, % (Maximum at 6 months)	ASTM C1012 Expansion, % (Maximum at 12 months)
S0	2500	No requirement	No requirement	No requirement	No requirement
S1	4000	2500	75	0.10	No requirement
S2	4500	2000	90	0.05	0.10 [b]
S3	5000	1500	120	0.05	0.10 [b]

Note: Accelerated moist curing: 7d at 23°C, then 21d at 38°C

Draft ACI 321 Durability Code
Performance Option for Physical Sulfate Exposure

Exposure Class	Strength Requirements	Resistance to Fluid Penetration Testing Requirements [a]	
	Minimum f'_c, (psi)	ASTM C1202 **Charge Passed, Coulombs** (Maximum for 28 d accelerated curing or 90 d normal curing)	ASTM C1876 **Bulk Resistivity**, ohm-m (Minimum for 28 d accelerated curing or 90 d normal curing)
P0	No Requirements	No Requirements	No Requirements
P1	**> 4500 psi**	**< 2000 Coulombs**	**> 90 ohm-m**

The proposed P1 prescriptive option requires **4500 psi (31 MPa) and max. w/cm = 0.45**

Specifying and Obtaining Durable Concrete
Summary

1. Keep aggressive fluids out (low w/cm, use SCMs)
2. Minimize paste content (optimize combined aggregate gradings to lower [W]
3. Design to minimize cracking (thermal and drying shrinkage)
4. Specify durability performance tests and limits
5. Inspect to minimize construction variability and defects
6. Proper testing

Thank you

Questions?

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