American Concrete Institute

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Curing is Good

1

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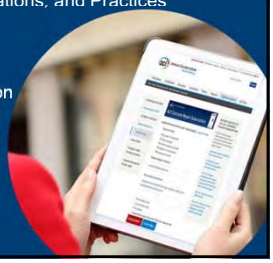

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Curing is Good

Learning Objectives:

1. Define curing and related terms
2. Recall different curing methods
3. Examine research findings on curing
4. Justify curing timing in relation to construction activities

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What is curing?

Initial curing
Early curing
Internal curing
Intermediate curing
Wet curing
External curing
Final curing
Additional curing
Moist curing
Steam curing
Conventional curing
Water curing
Accelerated curing
Traditional curing
Immersion curing
Standard curing
Heat curing
Deliberate curing
Membrane curing
Elevated-temperature curing
Lab curing
Dry curing
Minimum curing
Hot-weather curing
Proper curing
Cold-weather curing
Continuous curing
Sustainable curing

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Why give this talk?

- Durability is often more critical than strength
- Proper curing directly impacts durability
- Curing is often skipped or shorted
  - Especially for residential and commercial
- It's cheap in the big picture



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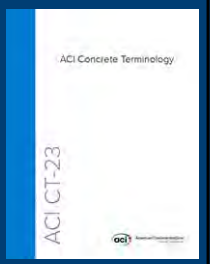
What is curing?

- curing — action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and (if applicable) pozzolanic reactions to occur so that the potential properties of the mixture may develop.



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What is curing?

- Curing depends on three factors
  - ✓ Moisture
  - ✓ Temperature
  - ✓ Time

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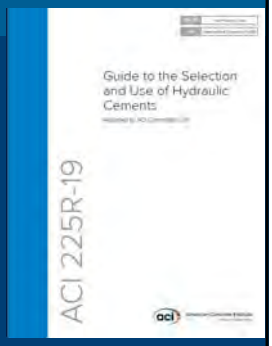
What is curing?

- hydration — the chemical reaction between hydraulic cement and water
  - Slump loss
  - Setting
  - Hardening
  - Evolution of heat of hydration
  - Strength development



13

Why is curing required and why should I care?

1. Short term – plastic shrinkage cracks
2. Long term – strength, durability, …

14

Why do we need curing?

To ensure that water remains in concrete until desired concrete properties are achieved

- Prevent moisture loss
- Replace lost moisture
- Maintain favorable concrete temperature

15

Minimum Curing Requirements

Recommended minimum duration of curing for concrete mixtures

	Minimum curing period
ASTM C150/C150M Type I	7 days
ASTM C150/C150M Type II, Type II (MH)	10 days
ASTM C150/C150M Type III or when accelerators are used to achieve results demonstrated by test to be comparable to those achieved using ASTM C150/C150M Type III cement	3 days
ASTM C150/C150M Type IV or Type V cement	14 days
Blended cement, combinations of cement and other cementitious materials of various types in various proportions in accordance with ASTM C595/C595M, C845/C845M, and C1157/C1157M	Variable

16

Minimum Curing Requirements (ACI 318, 301)

- Concrete shall be maintained:
  - …in moist condition ≥ 7 days
  - …at temperature ≥ 50ºF
- High-early-strength concrete shall be maintained:
  - …in moist condition ≥ 3 days
  - …at temperature ≥ 50ºF
- Curing water ≥ 50ºF and $\Delta T_{(concrete - water)} \leq 35ºF$

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Minimum Curing Requirements

- AASHTO: American Association of State Highway and Transportation Officials
  - Requires 3 days of curing, without comment on temperature
- Bridge Construction: AASHTO LRFD Bridge Construction Specification
  - Min. 7-day curing (other than waterproof cover, steam or radiant heat methods)
  - Min. 10-day curing if pozzolans are used

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Minimum Curing Requirements

- State Department of Transportation (DOT)
  - Many states requires 3 days of curing, with no temperature requirements;
  - Several States require 4 days, with no temperature requirements
  - Some states require 7-14 days of curing
    - Shorter period with strength verified by field-cured cylinders or maturity method

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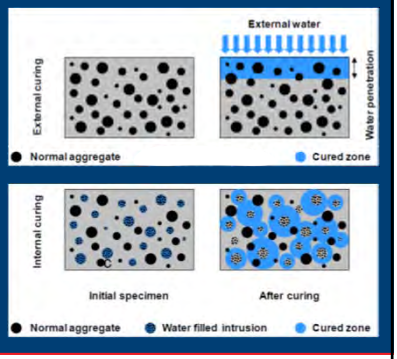
19

Curing Methods

- External Curing
  - Add moisture
  - Trap moisture
- Internal Curing



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Curing Methods: External – Add moisture

- Fogging
  - Can be used before initial set, if required
  - Increases RH of air above concrete
  - Reduces potential for plastic shrinkage cracking

Photo credit: PCA

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21

Curing Methods: External – Add moisture

- Fogging
- Sprinkling
- Ponding
- Soaker hoses

For final curing (after final set)

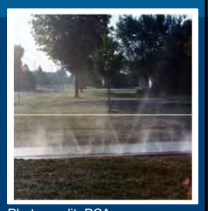

Photo credit: PCA

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Curing Methods: External – Add moisture

- Fogging
- Sprinkling
- Ponding
- Soaker hoses
- Absorbent coverings: burlap, cotton mats
- Wet sand
- Wet straw or hay

For final curing (after final set)

Photo credit: PCA

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Curing Methods: External – Trap moisture

- Plastic sheeting

Photo credit: PCA

Photo credit: Ron Kozikowski, NorthStarr Concrete

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Curing Methods: External – Trap moisture

- Plastic sheeting
- Evaporation retardants
- Curing compounds

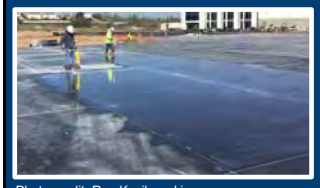

Photo credit: Ron Kozikowski, NorthStarr Concrete

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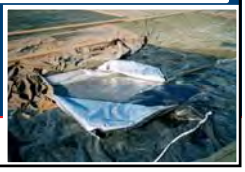
Curing Methods: External – Trap moisture

- Plastic sheeting
- Evaporation retardants
- Curing compounds
- Curing blankets
- Waterproof (reinforced) paper

Photo credit: PCA



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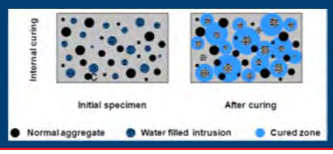
Curing Methods: Internal

- Uses prewetted absorptive materials:
  - Pre-wetted lightweight aggregate (PLA)
  - Super-absorbent particles (SAP)
  - Other (wood fibers, absorbent limestone aggregate, …)
- Beneficial in concretes with low *w/cm*



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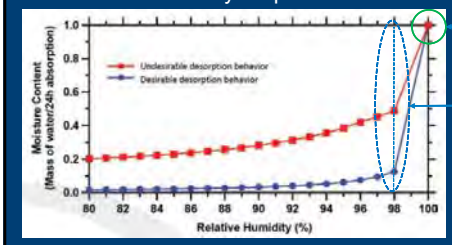
Curing Methods: Internal

- Release moisture as concrete internal humidity drops below 100%



Concrete is cast

Cement hydrates and starts to draw moisture from the aggregate

Castro, J.; Keiser, L.; Golias, M.; and Weiss, J., 2011, "Absorption and Desorption Properties of Fine Lightweight Aggregate for Application to Internally Cured Concrete Mixtures," Cement and Concrete Composites, V. 33, No. 10, Nov., pp. 1001-1008.

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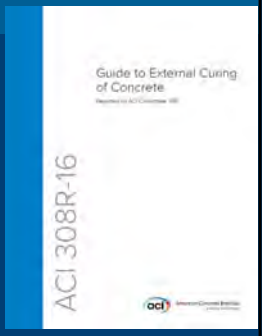
What is adequate curing?

- Adequate curing — properties of in-place concrete equal or exceed design properties (of concrete)



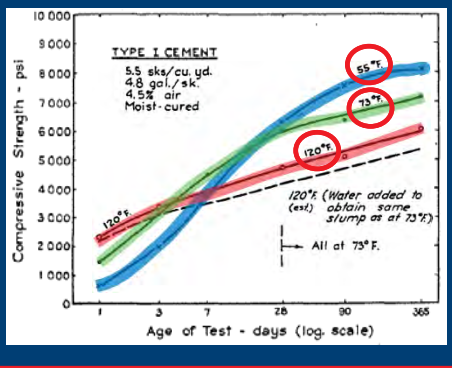
29

What is adequate curing?

- Design (Desired) Concrete Properties
  - Higher strength
  - Resistance to cracking
  - Better durability
  - Tougher surface
  - Improved appearance
  - More sustainable

30

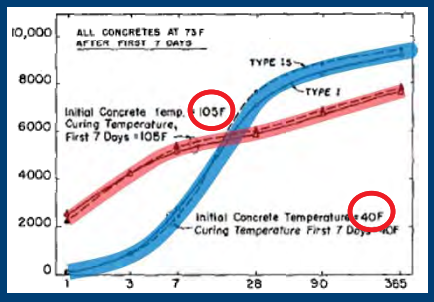
Curing Temperature v. Strength



Lower curing temp. → high long-term strength

31

Curing Temperature v. Strength



Blended cements
Lower curing temp. → high long-term strength

32

Curing Moisture & Temperature v. Strength

- Curing at different humidity

Fog room:	73ºF + 95%RH
Warm-Dry:	113ºF + 20%RH
Warm-Wet:	113ºF + water
Dry:	73ºF + 40%R


Some Concretes Need 7 Days Initial Curing

M.N. Haque, "Some Concretes Need 7 Days Initial Curing," Concrete International, February 1990

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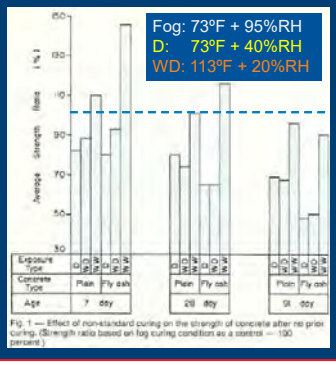
Curing Moisture & Temperature v. Strength



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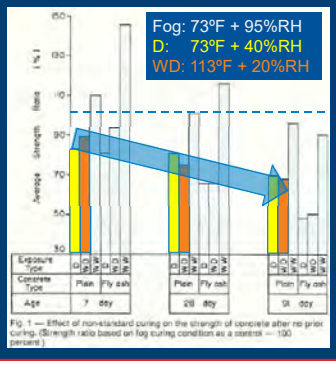
Curing Moisture & Temperature v. Strength



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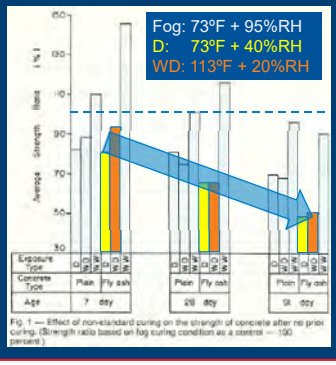
Curing Moisture & Temperature v. Strength



M.N. Haque, "Some Concretes Need 7 Days Initial Curing," Concrete International, February 1990

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Curing Strength Cylinders – initial curing temperature

Table 1:
Effect of nonstandard initial curing on compressive strength[5]

Initial curing conditions	Relative 28-day strength, %*		
Temperature	37°F (3°C) at 100% RH	73°F (23°C) at 60% RH	100°F (38°C) at 25% RH
1 day in air†	100	92	88
3 days in air†	93	89	78

*In comparison with compressive strength of 5590 psi (38.5 MPa) determined for specimens moist cured at 73°F and 100% RH from the time of molding until testing
†Specimens were molded at 73°F, subjected to initial curing conditions, and transferred to standard moist room at 73°F for curing until test age of 28 days

37

Curing Strength Cylinders - initial curing humidity and temperature

Table 2:
Compressive strength as a function of initial curing at minimum and maximum temperatures and moisture conditions allowed by ASTM C31/C31M[2,6]

Initial curing condition*	Relative 28-day strength, %	
	Cement A	Cement B
60°F (16°C) in water	100% (6080 psi [41.9 MPa])	100% (6090 psi [42 MPa])
60°F in air	92	97
80°F (27°C) in water	89	93
80°F in air*	81	88

*Specimens were molded at 73°F, subjected to initial curing condition for 22 hours, and transferred to standard moist room at 73°F for curing until test age of 28 days

38

Curing Strength Cylinders

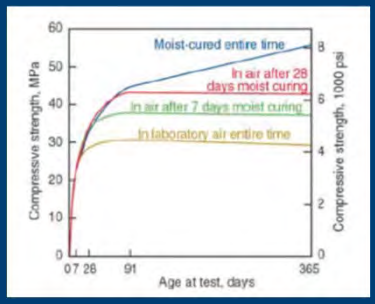
Table 3:
Effect of initial curing under hot weather conditions on compressive strength[7]

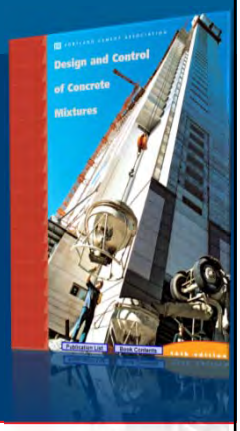
Type of 1-day initial curing	Temperature range, °F (°C)	Relative strength, %
Outdoor exposure: curing box with thermostatic control; in water	71 to 76 (22 to 24)	100
Laboratory: immersed in lime water (control)	76 to 82 (24 to 28)	100
Laboratory: in air	78 to 82 (26 to 28)	88
Outdoor exposure to sunlight: not protected	71 to 107 (22 to 42)	85
Outdoor exposure: covered with wet burlap and plastic	94 to 140 (34 to 60)	83

Note: Specimens were molded at 86°F (30°C) at the jobsite and subjected to the initial curing condition for 24 hours; transferred to standard moist room at 73°F (23°C) for curing until test age of 28 days

39

Curing Method v. Strength





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Curing Method v. Strength

Table 2—Curing methods with description, composition, and dosage characteristics

Legend	Curing method description	Composition	Dosages
C1	Air-cured	Ambient conditions	Air exposed throughout
C2	Water-immersed	Water	Submerged throughout
C3	Liquid membrane-forming compound-cured	Water-based concrete curing compound	5 to 6 m^2/L (200 to 250 ft^2/gal.)
C4	Wet burlap-cured	Burlap cloth wrapped around specimens	Three times a day soak watering of burlap cloth
C5	Combination of admixture and liquid membrane-forming compound-cured	Set-retarding admixture combined with C3	4.5 kg/m^3 (7.59 lb/yd^3)
C6	Combination of admixture and burlap-cured	Admixture in C5 combined with C4	C4 and C5
C7	Lightweight aggregate (LWA) internally cured	Aggregate from crushed fired masonry bricks	230 kg/m^3 (388 lb/yd^3)
C8	Super-absorbent polymers (SAPs) internally cured	Polyacrelate	1.35 kg/m^3 (2.26 lb/yd^3)
C9	Shrinkage-reducing admixture (SRA) internally cured	Shrinkage-reducing admixture	4.5 L/m^3 (116.34 oz/yd^3)

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Curing Method v. Strength

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Air-dry

Water

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Curing Method v. Strength

Wet Burlap

Table 2—Curing methods with description, composition, and dosage characteristics

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Curing Method v. Strength

Wet Burlap

Curing Compound

Table 2—Curing methods with description, composition, and dosage characteristics

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C1	Air-cured	Ambient conditions	Air exposed throughout
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Curing Method v. Strength

Wet Burlap

Curing Compound

Internal Curing

Table 2—Curing methods with description, composition, and dosage characteristics

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C1	Air-cured	Ambient conditions	Air exposed throughout
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C7	Lightweight aggregate (LWA) internally cured	Aggregate from crushed fired masonry bricks	230 kg/m^3 (388 lb/yd^3)
C8	Water-absorbent polymers (SAPs) internally cured	Polyacrylate	1.35 kg/m^3 (2.26 lb/yd^3)
C9	Shrinkage-reducing admixture (SRA) internally cured	Shrinkage-reducing admixture	4.5 L/m^3 (116.34 oz/yd^3)

45

Curing Method v. Strength

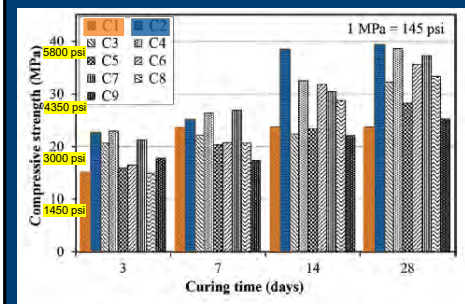

Fig. 20—Comparison of compressive strength development with time for different curing techniques.

- C1 – air
- C2 – water

46

Curing Method v. Strength

Wet Burlap

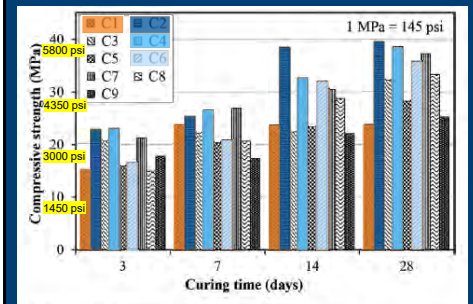

Fig. 20—Comparison of compressive strength development with time for different curing techniques.

- C1 – air
- C2 – water
- C4 – wet burlap
- C6 – wet burlap and set retarder

47

Curing Method v. Strength

Curing Compound

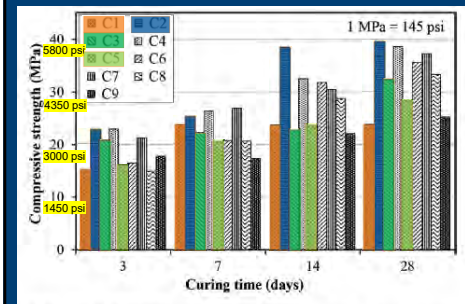

Fig. 20—Comparison of compressive strength development with time for different curing techniques.

- C1 – air
- C2 – water
- C3 – curing compound
- C5 – curing compound and set retarder

48

Curing Method v. Strength

Internal Curing

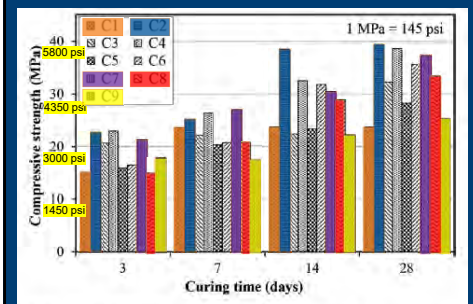

Fig. 20—Comparison of compressive strength development with time for different curing techniques.

- C1 – air
- C2 – water
- C7 – LWA
- C8 – SAP
- C9 – SRA

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Efficiency Comparison of Conventional and Unconventional Curing Methods in Concrete

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Desired Concrete Properties – Abrasion resistance

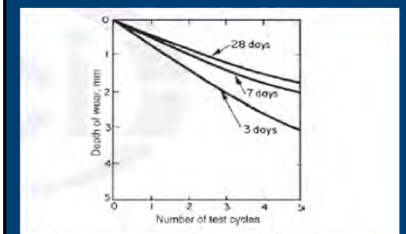

Fig. 1.6d—Sawyer (1957) demonstrated effects of curing on abrasion resistance by Standard DIN 51951. (Note: 1 mm = 0.04 in.)

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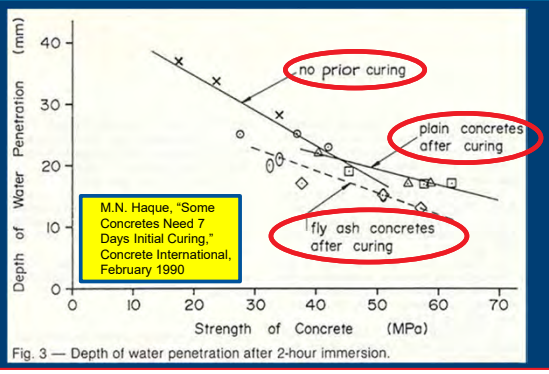
Wet Curing v. Water Penetration



M.N. Haque, "Some Concretes Need 7 Days Initial Curing," Concrete International, February 1990

Fig. 3 — Depth of water penetration after 2-hour immersion.

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Desired Concrete Properties –Resistance to freeze-thaw

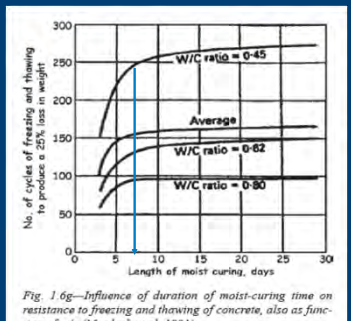

Fig. 1.6g—Influence of duration of moist-curing time on resistance to freezing and thawing of concrete, also as function of w/c (Murdock et al. 1991).

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52

Curing Temperature v. Shrinkage

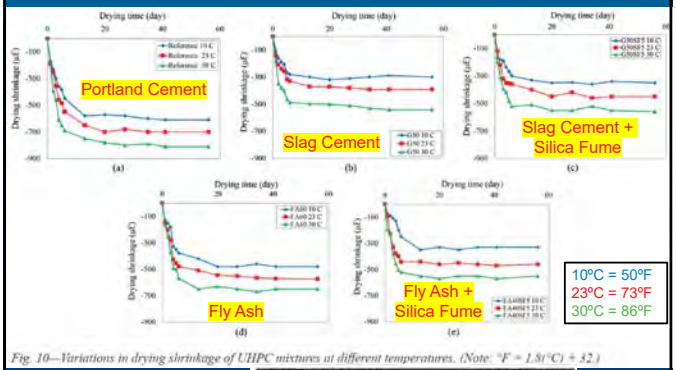

Fig. 10—Variations in drying shrinkage of UHPC mixtures at different temperatures. (Note: °F = 1.8(°C) + 32.)

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Curing Method v. Shrinkage

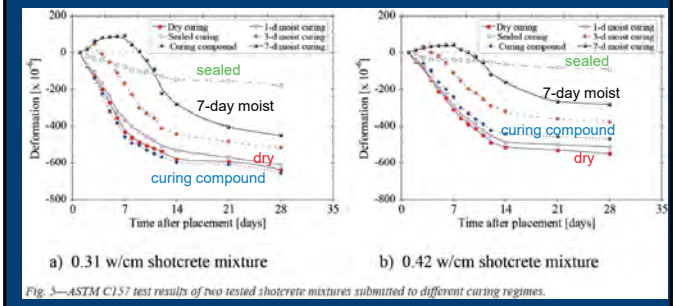

Fig. 5—ASTM C157 test results of two tested shotcrete mixtures submitted to different curing regimes.

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Influence of Curing Methods on Moisture Loss and Drying Shrinkage of Shotcrete at Early Age

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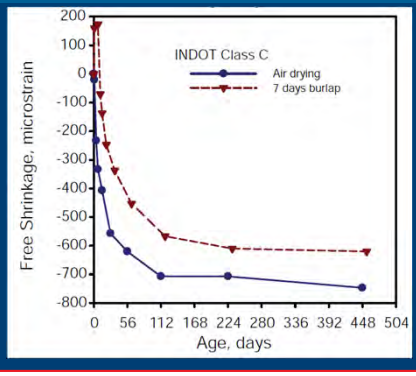
Curing Method v. Shrinkage



Shrinkage and Cracking of Ternary Concrete under Various Curing Conditions

Concrete international / JANUARY 2011 49

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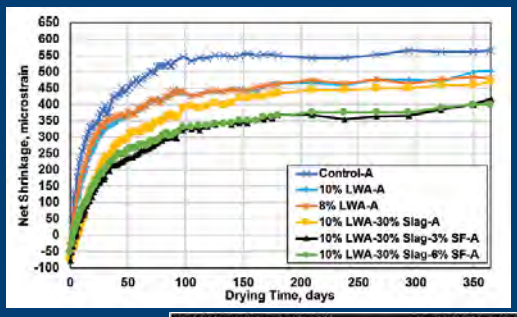
Internal Curing v. Shrinkage



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Effects of Internal Curing, Slag, and Silica Fume on Concrete Shrinkage

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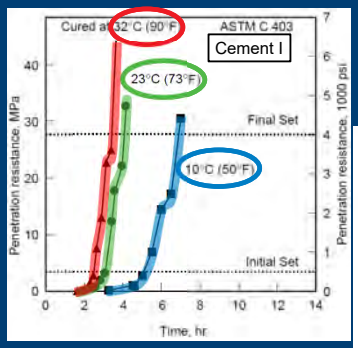
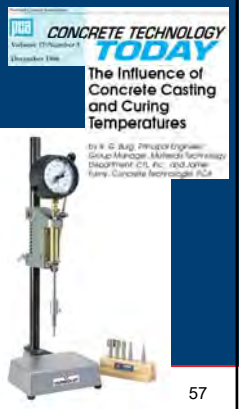
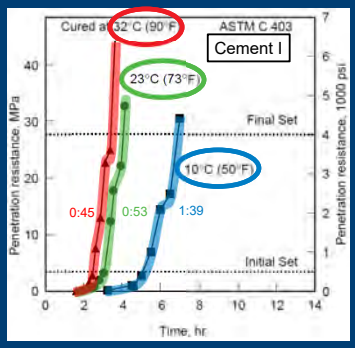
Curing Temperature v. Time of Set

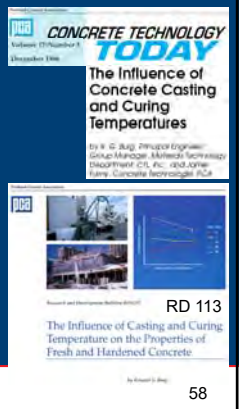




57

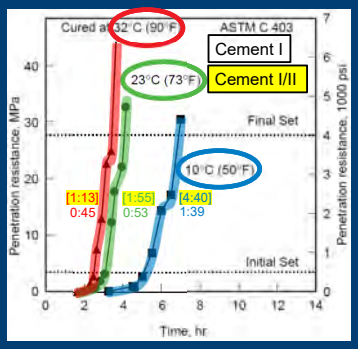
Curing Temperature v. Time of Set

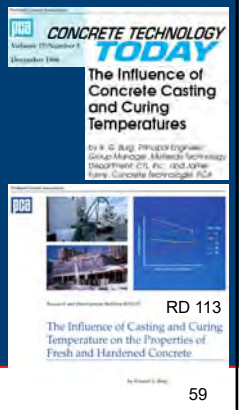




58

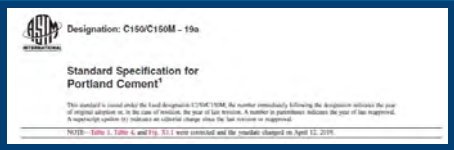
Curing Temperature v. Time of Set





59

Initial and Final Set Time Limits



- ASTM C150, Cement Types I, II, III, IV, and V

Initial set ≥ 1 hour	(ASTM C266)
Initial set < 6 hours 15 minutes	(ASTM C191)
Final set ≤ 10 hours	(ASTM C266)

60

Curing Temperature v. Time of Set

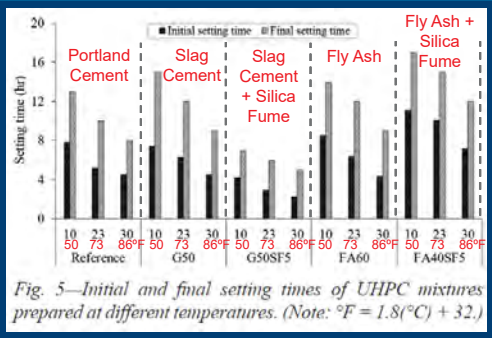


Fig. 5—Initial and final setting times of UHPC mixtures prepared at different temperatures. (Note: °F = 1.8(°C) + 32.)

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Robustness of Ultra-High-Performance Concrete to Changes in Material Temperature

61

When should we start curing?

- Initial curing
  - Procedures implemented any time between placement and final finishing of the concrete to reduce moisture loss from the surface.
- Intermediate curing
  - Procedures implemented when finishing is completed but before the concrete has reached final set.
- Final Curing
  - Procedures implemented after final finishing and after the concrete has reached final set

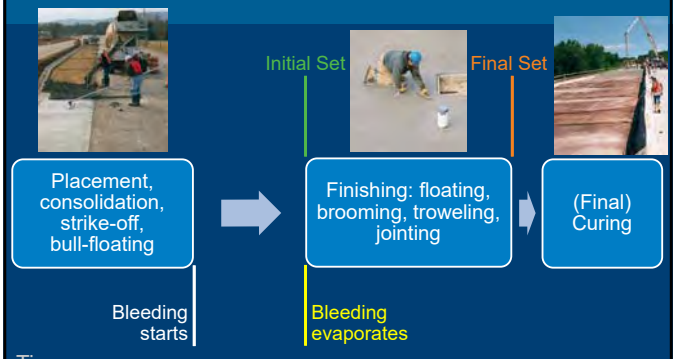
62

Sequence of Activities Before (Final) Curing

- Concrete delivery
- Placement (spreading/consolidating)
- Strike-off (straightedge / screed)
- Bull floating / darbying (smoothing surface)
- Bleed water period
- Floating
- Troweling (if required)
- Sawing joints (as needed)

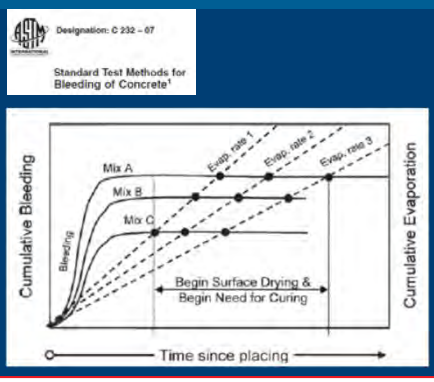
63

Sequence of Activities Before (Final) Curing



64

Bleeding v. Evaporation Rate



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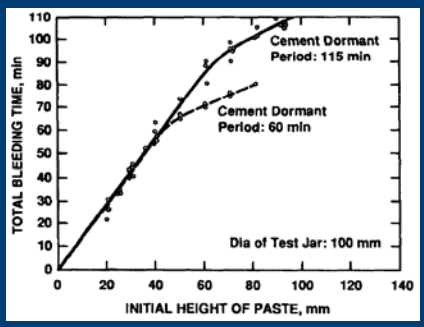
Bleeding v. Thickness



66

Sequence of Activities Before (Final) Curing

Placement, consolidation, strike-off, bull-floating

Finishing: floating, brooming, troweling, jointing

Bleeding starts

Bleeding evaporates

Time

67

Sequence of Activities Before (Final) Curing

What happens if you start finishing before bleed water evaporates?

Placement, consolidation, strike-off, bull-floating

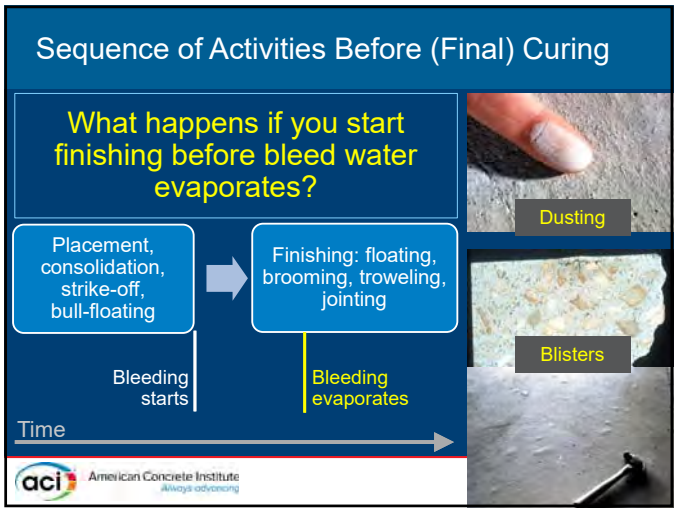
Finishing: floating, brooming, troweling, jointing

Bleeding starts

Bleeding evaporates

Time

68


Sequence of Activities Before (Final) Curing
What happens if you start finishing before bleed water evaporates?
Placement, consolidation, strike-off, bull-floating
Finishing: floating, brooming, troweling, jointing
Bleeding starts
Bleeding evaporates
Time
Dusting
Blisters
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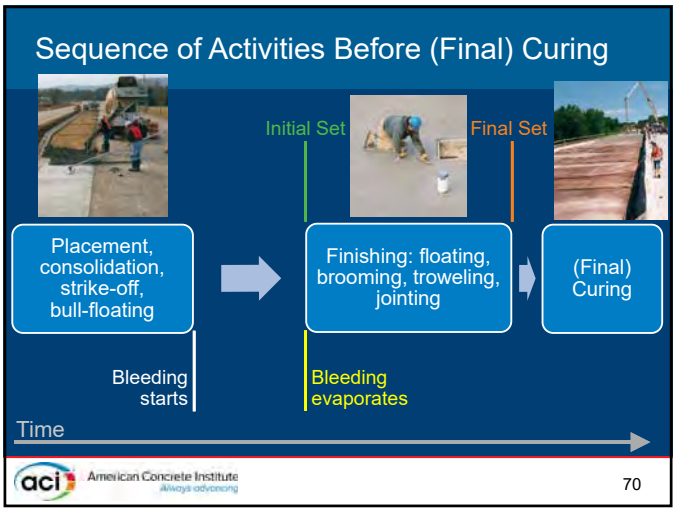
Sequence of Activities Before (Final) Curing
Initial Set
Final Set
Placement, consolidation, strike-off, bull-floating
Finishing: floating, brooming, troweling, jointing
(Final) Curing
Bleeding starts
Bleeding evaporates
Time
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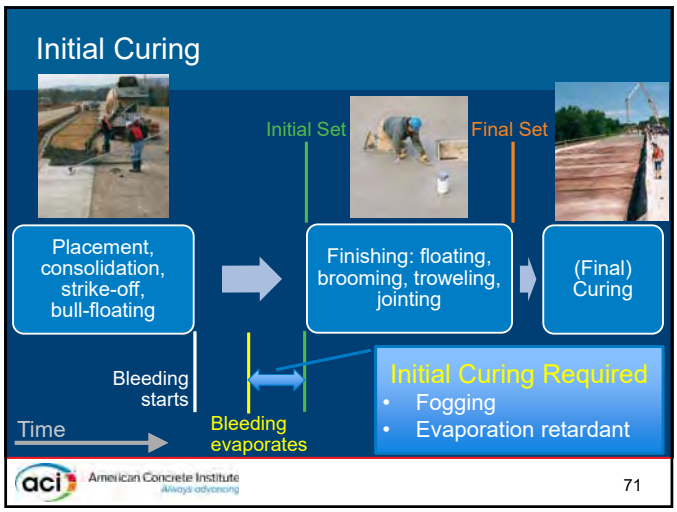
70


Initial Curing
Initial Set
Final Set
Placement, consolidation, strike-off, bull-floating
Finishing: floating, brooming, troweling, jointing
(Final) Curing
Bleeding starts
Bleeding evaporates
Initial Curing Required
• Fogging
• Evaporation retardant
Time
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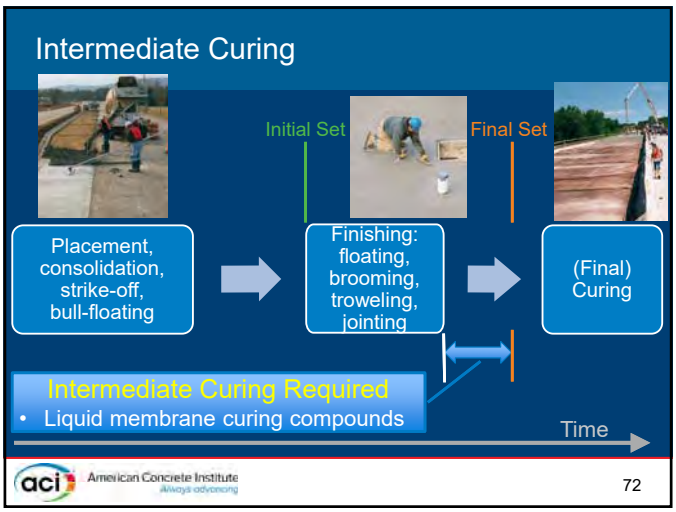
71


Intermediate Curing
Initial Set
Final Set
Placement, consolidation, strike-off, bull-floating
Finishing: floating, brooming, troweling, jointing
(Final) Curing
Intermediate Curing Required
• Liquid membrane curing compounds
Time
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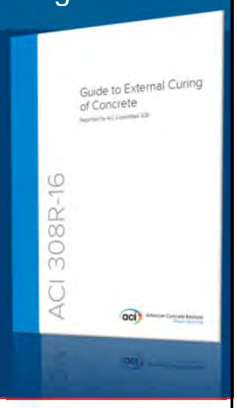
72

How long should we continue curing?

…long enough to ensure that all specified concrete properties (strength/durability) will be developed in a reasonable time period after deliberate curing measures have been terminated



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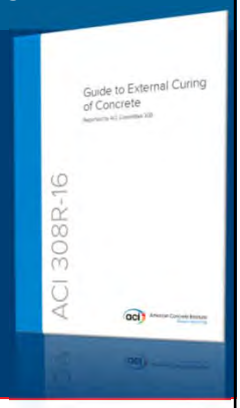
Curing Guidance for Specialty Concrete

Specialty concrete	ACI committee document
Insulating concrete	523.1R
Shrinkage-compensating concrete	223R
Roller-compacted concrete	207.5R
Self-consolidating concrete	237R
Floor and slab construction	302.1R
Slabs that receive moisture sensitive flooring material	302.2R
Architectural concrete	303R
Decorative concrete	310R
Vertical slipform construction	313
High-strength concrete	363R; 363.2R
Shotcrete	506.2
Pervious concrete	522R
Fiber-reinforced concrete	544.3R
Latex-modified concrete	548.1R



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Conclusions

- Curing directly impacts concrete's ability to gain strength and develop durable properties
- Start curing as soon as you can
- There are lots of different methods – pick what fits
- Everyone is responsible for good curing

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Need More Information?

- ACI 308R-16 – Guide to External Curing of Concrete
- ACI 308.1–Specification for Curing Concrete
- ACI (308-213)R – Report on Internally Cured Concrete Using Prewetted Absorptive Lightweight Aggregate
- ACI 305 and ACI 306 – Guides to hot weather and cold weather concreting
- Concrete Craftsmen Series: Slabs on Grade

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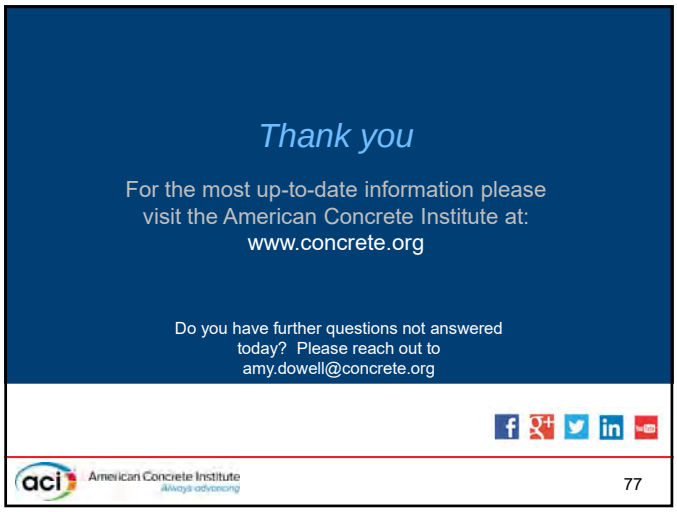
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www.concrete.org
Do you have further questions not answered today? Please reach out to amy.dowell@concrete.org
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77

77