The exciting first day in the life of concrete:
Chemical and physical processes at the micro-level drive macro-level construction operations.

THE FIRST 24 HOURS

- Concrete’s Time Scale
- Liquid to Solid
- Cement and Water
  - Hydration
  - Strength & Porosity
  - w/c and w/cm
  - Curing
- By-Products of Hydration
  - Alkalinity
  - Heat of Hydration
  - Shrinkage

Concrete’s Time Scale

Construction
Concrete Performance

How the First 24 Hours Impacts Precast
NPCA Precast Show

Ken Hover, P.E., Ph.D. (kch7@cornell.edu)
Cornell University, Ithaca, New York
Concrete is hard for a very long time

*It is fresh (and can be influenced for better or worse) for a very short time*

And the rate of transition matters!

Who worries about this transition and its rate?

*The Precast Concrete Producer*

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*The Precaster is in a race with the concrete*
How the First 24 Hours Impacts Precast Concrete Performance

Field Tests: Slump with Time, Reno, Nevada, Hover, 2013

Slump varies with time with constant water content and constant w/cm

Reno 1994 Slump

Slump Loss rate: 3.4 inches/hour
Half life=39 min.

Field Tests: Slump with Time, Reno, Nevada, Hover, 2013

Slump varies with time with constant water content and constant w/cm

Field Tests: Slump with Time, Reno, Nevada, Hover, 2013

Reasonable Models:
- Linear w/time
- Power w/time
- Exp-decay w/time

Unreasonable Model:
- Constant w/time

Concrete Waits for No One!

The concrete stiffens, sets, and gains strength on its schedule, not precaster’s!

Why?
How the First 24 Hours Impacts Precast Concrete Performance

March 1, 2019

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Thickness of Paste Layer Depends on:
Volume of Paste (Cement + Water)
And Size and Surface Area of Aggregates

Cement paste as a lubricant for aggregate particles

Aggregates can Move in Workable Concrete

Nominal Maximum Aggregate Size, mm

Surface Area per Ton For Specific Gravity = 2.65
Density = 165 lb/ft³

100 ft² Agg. Surface Area per Metric Ton

0 1 2 3 4 5 6
0 1/16 1/8 1/4 1/2 3/4 1

0 50 30 19 13 10

0 50 30 19 13 10
**Water Demand**

- Water content increases as aggregate size decreases.

---

**Water Demand**

- Water content increases as aggregate size decreases.

---

**Water Content (kg/m³)**

<table>
<thead>
<tr>
<th>Aggregate Size</th>
<th>1-1/2 in (38 mm)</th>
<th>1 in (25 mm)</th>
<th>3/4 in (19 mm)</th>
<th>1/2 in (13 mm)</th>
<th>3/8 in (10 mm)</th>
<th>2 in (50 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Water Requirement</td>
<td>240</td>
<td>260</td>
<td>280</td>
<td>300</td>
<td>320</td>
<td>340</td>
</tr>
</tbody>
</table>

**About 1-inch slump gain for 1 gallon per yard**

1-inch stone at 4-inch slump

**About 1-inch slump gain for 2 gallons per yard**

3/4-inch stone at 2-inch slump

---

**Gallons Water Added/CY to DOUBLE the slump**

- 2.2
- 2.6
- 2.8
- 3.4

---

**Development of internal Shear Resistance**

- Aggregates
- Fresh Concrete
- Paste
- Lubricant
- Hardened Concrete
- Adhesive
In High-Slump Concrete, paste is a Lubricant

In Lower-Slump Concrete, paste is an Adhesive

**Controlling Factors:**
- How “slippery” is the paste layer?
- How thick is the paste layer?

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**A Deeper Look Inside:**

What causes the paste to become an adhesive?
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Hydration

Velcro:
- Strongest in Compression
- Weakest in Tension
Tensile Strength = f(Compressive Strength)

\[ f_t = 6\sqrt{f_c} \]

\[ f_t = f_c/10 \]
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Tri-calcium silicate (C3S)

\[2(3\text{CaO} \cdot \text{SiO}_2) + 6\text{H}_2\text{O} \rightarrow [3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O}] + 3[\text{Ca(OH)}_2] + 120 \text{ cal/gram}\]

Di-calcium silicate (C2S)

\[2(2\text{CaO} \cdot \text{SiO}_2) + 4\text{H}_2\text{O} \rightarrow [3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O}] + [\text{Ca(OH)}_2] + 62 \text{ cal/gram}\]
So, where’s the water in the hardened concrete?

About 24 lb water / 100 lb cement @ full hydration

- Chemically combined water
- “Non-evaporable Water”
- Capillary Water
- “Evaporable Water”

Total ≈ 43 lb water / 100 lb cement @ full hydration

About 18 lb water / 100 lb cement @ full hydration

- Gel Water
- “Variably-Evaporable Water”
- Saturated Solid Hydrates

Concrete Strength

Time

Concrete Strength-Gain is a Growth Process

“Dry or Hard Concrete”

“Wet Concrete”

Rate of Hydration And Rate of Strength-Gain

Become Slower as closer gets concrete to ultimate strength

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Transitions in Concrete Behavior

Hydration starts slowly during slump-loss period

Picks-up speed during setting and early strength gain

Slows way down after 24 hours

Time (hours to days)

Degree of Hydration

Tri-calcium silicate (C3S)

\[2(3\text{CaO} \cdot \text{SiO}_2) + 6\text{H}_2\text{O} \rightarrow [3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} + 3\text{Ca(OH)}_2]\]

+ 120 cal/gram

Di-calcium silicate (C2S)

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+ 62 cal/gram

Curing, i.e., moisture control is essential for “Growth”

1.) Reaction only proceeds in a “water-filled space”

2.) Rate of reaction exponentially dependent on temperature

3.) Volume depends on extent of reaction and loss of water

42 to 44 kg water required to fully hydrate 100 kg cement
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Penetration of Salts, Liquids, and Gases into the Concrete

H₂O  Salts  CO₂  Sulfates

w/cm = Weight of Water
Weight of Cement + SCM

The higher the w/c or w/cm, the more dilute the adhesive!
Approximate 28-Day Compressive Strength as a function of Water/Cement Ratio. Adapted from ACI 211.1-91, Table 6.3.4(a)

Permeability as a function of Water/Cement Ratio. Data from Bureau of Reclamation Concrete Manual, 8th Edition, 1975, Figure 17, page 37.
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**Water Reducing Admixtures**

- Normal
- Mid-Range
- High-Range

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**Before Water-Reducer**

10% water reduction

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**After Water-Reducer**

15% water reduction

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Cement and water paste

Hydration in water-filled space

Continued Hydration

Continued Hydration in water-filled space

Suspended Hydration

7-day COMPRESSIVE strength not very sensitive to curing
Influence of Curing on Permeability

Benefit of Each Additional Day of Wet Curing

“Flat-Lines” mean Strength & Durability No longer Earning Interest

These curves apply to cylinders. Concrete surface is far more sensitive.

6 inch slab 6-sack mix

25,000 gal per Acre

6 inch slab 6-sack mix

5 gal / S.Y.
One 5-gal water jug / SY

Just sealing the concrete surface to prevent or slow evaporation not enough for full yield.

Concrete (Cement) Needs Water

High Yields and Durable Structures Through Irrigation (or Curing)

To Cure or Not to Cure?
By Evan Gurley

Greater attention to curing yields less permeable concrete. Drying is more pronounced with higher wet civil

Curing Time (hr)

Permeability

Strength

Curing Time (hr)

Greater attention to curing yields stronger concrete.
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Steam Curing

Initial concrete temp. = 21°C (70°F), until desired concrete strength is developed

By-products of Hydration

- POROSITY
- HIGH pH
- HEAT
- Shrinkage

Strength vs. Steam Curing
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Chert, or Flint, or Jasper

Microcrystalline Quartz: Four varieties of microcrystalline quartz and names that might be used for them. Clockwise from top left: Chert, red jasper, novaculite, and flint. Geology.com
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About 190 BTU per lb Cement

Slightly Less than 10% of Heat Energy input at Cement Plant returned to Contractor (at no extra charge)

6 Sack Mix = 564 lb x 190 BTU = 107,000 BTU / CY

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Precast Advantage: Reduced restraint at early age

Concrete Restraint
- Shrinkage without restraint
  Loss of Volume, but No Cracking
- Shrinkage with restraint
  Loss of Volume by Cracking

precast.org/education
Shrinkage with restraint and reinforcement
Smaller cracks, maybe more regularly spaced

Regardless of Base Restraint and Reinforcement
The Top Surface of a slab is restrained by the concrete below.

Volume of Components

Low or No Shrinkage  High Shrinkage
Aggregate  Paste

Aggregate shrinkage depends on source.
Paste: Primary Source of Concrete Shrinkage

Volume of Components

Cement Paste
Drying Shrinkage  Chemical Shrinkage
Water  Cementitious Material

External Water Loss  Internal Water Consumption  Hydration Volume Reduction

Shrinkage and Paste Volume
Why Drying Leads to Shrinkage…

- Fully Saturated Particles—No Attraction
- Dry Particles—No Attraction
Fully Saturated Particles—No Attraction

Drying Particles—Attraction

And Volume Reduction = Shrinkage!

Soil Tensiometer Testing

Concrete Tensiometer Testing
Instrument Limitation

**Initial Volumes**
- 100 parts total volume
- Water 57 parts
- Cement 43 parts

**Origin of Chemical Shrinkage of Paste**
- **Final Volume**
  - 89 parts Hydrated cement
  - 11 parts void space

**Greater void space if water lost!**

**Early Age Tensile Strength**

**W/C**

<table>
<thead>
<tr>
<th>Tensile Strength</th>
<th>Age in Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>3</td>
</tr>
<tr>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>40</td>
<td>6</td>
</tr>
<tr>
<td>30</td>
<td>7</td>
</tr>
<tr>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>

**Ken Hover, P.E., Ph.D.** (kch7@cornell.edu)
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Plastic Shrinkage Cracking
1.) Bleed water appears on concrete surface
2.) Rate of evaporation exceeds bleed rate
3.) Concrete surface dries....
4.) Concrete surface tries to shrink....
5.) Moist concrete resists shrinkage...
6.) Stress develops in soft “plastic” concrete...
7.) “Plastic” shrinkage cracks form

Drying Shrinkage Cracking
1.) Curing is applied to concrete surface
2.) Curing is removed or becomes ineffective
3.) Concrete surface dries....
4.) Concrete surface tries to shrink....
5.) Moist concrete resists shrinkage...
6.) Stress develops in hard, brittle concrete...
7.) “Drying” shrinkage cracks form
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Case Study

Monitoring the Liquid to Solid Transition in Concrete with Conventional Tests
Jon Abel, Roberto Pinto and Ken Hover

Abel, J.H., Pinto, R.C.A., Hover, K.C., Monitoring the liquid to solid transition in concrete with standard tests, ACI Special Publication SP-259: Transition from Fluid to Solid: Re-Examining the Behavior of Concrete at Early Ages, Kyle Riding, Editor, American Concrete Institute.

A Single Case History
- 4000 psi mix
- Air Entrained
- 564 lb cem/cy
- 5 in slump @45 min
- ¾ stone
- Ready-mixed (Dry Batch Plant)
- Summer
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