Is My Concrete Defective?
And what’s the weather got to do with it?

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Learning Objectives

• What is the definition of low concrete strength per the code and per a typical contract?

• What is the statistical basis for the code requirements?

• When is removal of defective concrete required or perhaps recommended? What methods besides removal can be used for acceptance?

• What is considered hot and cold weather concreting and what additional requirements are often specified?
Agenda

• Basics of concrete strength and durability
• Common requirements and perceptions
• Causes of low strength and surface defects
• Possible solutions to consider
• Tips to avoid issues before they occur
• Hot weather concreting
• Cold weather concreting
Basics of concrete strength and durability
Hydration - Developing bonds for a lifetime

- Concrete contains at least cement, aggregates, and water
- Chemical hydration bonds materials together for strength
- Generally slower reactions create stronger bonds
- Temperature, cement type, and pozzolans impact rate
Determining “strength”

- Concrete strength typically refers to compressive strength
- Measured using standard sized cubes or cylinders cured in a specific way
  - For same concrete, cubes will test around 25% higher – adjust for this
- Tested at a specific loading rate and moisture condition
- Multiple specimens are required for a single strength test result
- Does NOT necessarily match the strength of the physical concrete in the field
- A very small sample size represents a much larger volume
  - Thus a bad test can cause much bigger problems

A lot of things can be done to lower concrete strength; very few things will raise it
A word on durability

• Generally discussing strength at a local level

• Durability relates to:
  • Surface toughness (abrasion and scaling resistance)
  • Freeze/thaw resistance
  • Permeability and absorption
  • Cracking resistance

• Addition of water to surface during finishing significantly reduces surface durability
  • Raises surface water to cementitious materials (w/cm) ratio

Actions during placement and curing dramatically impact lifespan
Some factors affecting durability

- Aggregates
  - Size, shape, gradation, freeze/thaw durability of the aggregate, ASR prone, etc
- Placement temperatures
- Cementitious materials – quantity, type
  - Supplementary Cementitious Materials (SCMs)
- Ambient Temperatures – hot/cold
- Wind – plastic shrinkage, finishing, etc
- Type of curing and duration
- Timing of curing – if it dries, it dies
Common requirements and perceptions
Is your concrete defective if...

- A single or perhaps two low strength tests in a row occur, what about three?
- A finisher adds water to the surface to make it easier to finish?
- Shrinkage cracks appear?
- Placement is delayed for more than 90 minutes or too many drum revolutions?
- It rains during a placement?
- Test specimens are improperly stored?
- Curing is delayed or not performed?
Defining low concrete compressive strength

- ACI 301M-16 Section 1.6.6.1 –
  - Two rules – known as the “running average of three” rule and “500 psi” rule
    - Every average of three consecutive strength tests equals or exceeds specified compressive strength, $f_c'$
    - No strength test result falls below $f_c'$ by more than 3.5 MPa if $f_c'$ is 35 MPa or less, or by more than 0.10$f_c'$ if $f_c'$ is greater than 35 MPa
  - One rule catches an accident while the other catches systemic issues

- Project specifications almost always match these requirements
  - Difference is in what is done about a low strength test or other potential defects

- UFGS 03 30 00 (Feb 2019 version) directs user back to ACI 301 for strength

Specifications tend to emphasize strength over durability because of life safety
Checking strength – An example

Specified Concrete Strength ($f'_c$) = 30 MPa

<table>
<thead>
<tr>
<th>Test</th>
<th>Cube A</th>
<th>Cube B</th>
<th>Average</th>
<th>Average of 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34.6</td>
<td>33.1</td>
<td>33.9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>42.1</td>
<td>45.8</td>
<td>44.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>35.1</td>
<td>36.4</td>
<td><strong>35.8</strong></td>
<td><strong>37.9</strong></td>
</tr>
<tr>
<td>4</td>
<td>26.2</td>
<td>24.5</td>
<td><strong>25.4</strong></td>
<td><strong>35.0</strong></td>
</tr>
<tr>
<td>5</td>
<td>31.0</td>
<td>32.2</td>
<td><strong>31.6</strong></td>
<td><strong>30.9</strong></td>
</tr>
<tr>
<td>6</td>
<td>38.4</td>
<td>36.2</td>
<td>37.3</td>
<td>31.4</td>
</tr>
<tr>
<td>7</td>
<td>30.8</td>
<td>29.3</td>
<td><strong>30.1</strong></td>
<td><strong>33.0</strong></td>
</tr>
<tr>
<td>8</td>
<td>28.1</td>
<td>25.6</td>
<td>26.9</td>
<td>31.4</td>
</tr>
<tr>
<td>9</td>
<td>30.5</td>
<td>28.7</td>
<td><strong>29.6</strong></td>
<td><strong>28.8</strong></td>
</tr>
<tr>
<td>10</td>
<td>38.5</td>
<td>36.1</td>
<td>37.3</td>
<td>31.3</td>
</tr>
</tbody>
</table>
Just how strong does it need to be?

• $f_c'$ is design strength but batch plants must aim for higher
  • If they only aimed for $f_c'$, they would be low too often
  • $f_{cr}'$ is the required average compressive strength to aim for

• $f_{cr}'$ is based on relevant past records or trial batching
  • With enough records fitting criteria, no trial batches are needed

• Probability of failure is still one test out of 100
  • ACI 318-19 R26.12.3.1 Commentary directs engineer to allow for such statistically expected variations in deciding if strength being produced is adequate

A batch plant with good quality control benefits their bottom line
A bit of statistics is involved to determine fcr’

**Determine fcr’ per ACI 301M-16 Section 4.2.3**

- **Have test data from within past 24 months across at least 45 days and fc’ within 7 MPa?**
  - **YES**
  - **NO**

**Calculate sample standard deviation**

- **At least 15 consecutive tests**
  - \( s_s = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n-1}} \)
- **2 groups of consecutive tests totaling 30 tests, min 10 in group**
  - \( s_s = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \)

**Select fcr’ from Table 4.2.3.1**

<table>
<thead>
<tr>
<th>fc’, MPa</th>
<th>fcr’, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 21</td>
<td>fc’ + 7</td>
</tr>
<tr>
<td>21 to 35</td>
<td>fc’ + 8.3</td>
</tr>
<tr>
<td>Over 35</td>
<td>1.1fc’ + 5</td>
</tr>
</tbody>
</table>

**Calculate fcr’**

<table>
<thead>
<tr>
<th>fc’, MPa</th>
<th>fcr’, MPa</th>
<th>Where k is</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Use larger:</strong></td>
<td>( fcr’ = fc’ + 1.34ks_s )</td>
<td><strong># of Tests</strong></td>
</tr>
<tr>
<td>35 or less</td>
<td>( fcr’ = fc’ + 2.33ks_s - 3.5 )</td>
<td>15</td>
</tr>
<tr>
<td>Over 35</td>
<td>( fcr’ = 0.90fc’ + 2.33ks_s )</td>
<td>20</td>
</tr>
<tr>
<td>30 or more</td>
<td>( fcr’ = fc’ + 1.34ks_s )</td>
<td>25</td>
</tr>
<tr>
<td>30 or more</td>
<td>( fcr’ = fc’ + 2.33ks_s )</td>
<td>30 or more</td>
</tr>
</tbody>
</table>
What else do ACI 301 and UFGS 03 30 00 require?

• UFGS 03 30 00 Paragraph 3.14.2.7 –
  
  The strength of the concrete structure will be considered to be deficient if any of the following conditions are identified:
  • Failure to meet compressive strength tests as evaluated
  • Reinforcement not conforming to requirements specified
  • Concrete which differs from required dimensions or location in such a manner as to reduce strength
  • Concrete curing and protection of concrete against extremes of temperature during curing, not conforming to requirements specified
  • Concrete subjected to damaging mechanical disturbances, particularly load stresses, heavy shock, and excessive vibration
  • Poor workmanship likely to result in deficient strength
Common durability concerns and requirements

**Concerns**
- Alkali-Silica Reaction (ASR)
  - Alkali-Carbonate Reaction (ACR)
- Freeze-thaw (F)
- Sulfates (S)
- Permeability (contact with water) (W)
- Chlorides (reinforcement corrosion) (C)
- Delayed ettringite formation (DEF)

**Requirements**
- Additional testing
- Minimum cement replacement
- Admixtures
  - Air-entraining
  - Water reducers
  - Lithium
- Temperature limits

ACI 318-19 establishes 4 exposure categories to ensure adequate durability
### ACI 318-19 Table 19.3.2.1 – Requirements for concrete by exposure class

<table>
<thead>
<tr>
<th>Exposure class</th>
<th>Maximum w/cm[2][3]</th>
<th>Minimum $f'_c$, psi</th>
<th>Additional requirements</th>
<th>Limits on cementitious materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>N/A</td>
<td>2500</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>F1</td>
<td>0.55</td>
<td>3500</td>
<td>Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete</td>
<td>N/A</td>
</tr>
<tr>
<td>F2</td>
<td>0.45</td>
<td>4500</td>
<td>Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete</td>
<td>N/A</td>
</tr>
<tr>
<td>F3</td>
<td>0.40[3][3]</td>
<td>5000[3]</td>
<td>Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete</td>
<td>26.4.2.2(b)</td>
</tr>
</tbody>
</table>

#### Cementitious materials⁶ — Types

<table>
<thead>
<tr>
<th>Cementitious materials⁶ — Types</th>
<th>ASTM C150</th>
<th>ASTM C595</th>
<th>ASTM C1157</th>
</tr>
</thead>
<tbody>
<tr>
<td>No type restriction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Types with (MS) designation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No type restriction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Types with (HS) designation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No restriction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Types with (HS) designation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not permitted</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Types with (HS) designation plus pozzolan or slag cement⁷</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not permitted</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Types with (HS) designation</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>HS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not permitted</td>
<td></td>
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</tr>
</tbody>
</table>

**Limits on:**
- Maximum w/cm ratio
- Minimum strength ($f'_c$)
- Allowed materials
- Additional requirements
- Minimum air content
- Cement types or SCC’s
- Additional testing
Causes of low strength and surface defects
What causes low concrete strength?

- Poor batch plant quality control or equipment problems
- Addition of unaccounted for water
  - Added post batching and not recorded on batch ticket
- Bad testing
  - Leads to a *perception* of low concrete strength – but may be ok
- Modification of approved mixture design
  - Reduction of cement by accident or to save costs does happen
- Not accounting for weather conditions
  - Hot and cold weather impacts strength gain rate
- Inadequate or no curing post-placement
### Surface defects – common types and causes

<table>
<thead>
<tr>
<th>Common Types</th>
<th>Some Potential Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Scaling</td>
<td>• Addition of water during finishing</td>
</tr>
<tr>
<td>• Delamination</td>
<td>• Plastic shrinkage</td>
</tr>
<tr>
<td>• Craze/map cracking</td>
<td>• Not protected from weather</td>
</tr>
<tr>
<td>• Pitting</td>
<td>• Hard trowel air-entrained concrete</td>
</tr>
<tr>
<td>• Blisters</td>
<td>• Rapid drying</td>
</tr>
<tr>
<td>• Dusted or sandy</td>
<td>• Weak aggregate (chert)</td>
</tr>
<tr>
<td>• Honeycombed or unconsolidated</td>
<td>• Aggregate reactivity</td>
</tr>
<tr>
<td>• Uneven or wavy</td>
<td>• Chemical attack (salts are common)</td>
</tr>
<tr>
<td>• Discolored, splotchy, or mottled</td>
<td>• Curing method or bad application</td>
</tr>
<tr>
<td>• Stained</td>
<td>• Improper consolidation</td>
</tr>
</tbody>
</table>

Sometimes surface defects are caused by a combination of things too.
A few things to look out for

- Things happen fast during a placement
  - A pre-placement meeting is very important
  - Properly staffed quality control can catch a lot of issues
  - Be prepared for changing weather and sudden rain storms

- The cheapest batch plant is sometimes not the best option
  - Quality control issues will cost more money and schedule later
  - Be wary when the yield is suddenly off – check materials
  - Insist on NRMCA certified batch plants and trucks – put in spec

- Make sure testing is being performed properly
  - ACI Field Grade I certification for testers
  - Handle and store test specimens correctly!
Possible solutions to consider
“Rip it out” is not always the best way forward

- While specifications can require removal, is it needed?
- Work with contractor and batch plant to correct future placements as soon as issues are noted
  - May need to stop work on additional placements such as an upper wall or next lift in a tower depending on sequencing
- Most specifications allow for repair plans to be developed
  - Alternate solutions can be presented for evaluation
  - Must be acceptable to Contracting Officer or Client
  - Some reasonable allowance to dictate means and methods

This is a business – avoid emotions controlling your actions
Solving the dreaded low strength issue

- ACI 301M-16 and other specs have procedures in place – follow them
- Understand a 7-day break is a warning in most specs, not an actual failure
- Determine approximate location and control future work in area
  - Rebound hammer can be used to locate suspect areas
- Take steps to increase the average of subsequent test results
- Request engineer to determine if a lower strength would be acceptable
- ACI 318-19 treats failing the 3.5 MPa rule more severely
  - Requires further investigation, possibly obtaining cores and load testing

Rebound hammer should never be used for final determination of in-place strength
Testing in-place strength with cores

- Coring is destructive and messy
- Thin slabs or heavy reinforcement can be troublesome
  - Correction factors can only help so much
- Often need either rebar locator or ground penetrating radar
- Slows down a project and adds cost but is needed at times
- Core diameter generally depends on aggregate size
  - Common diameter is 100 mm (4 inch)

Cores can also be useful with other defects and for petrography
Evaluating a core test

• Obtain and test per ASTM C42/C42M
  • Requires specific moisture conditioning post-coring
  • Per 301M, test between 48 hours (318-19 says 5 days) after coring or last wetting and no later than 7 days after coring
  • Trim core ends within 2 days if trimming is required

• Considered *structurally* adequate if meeting the following:
  • Average of 3 cores is equal to at least 85 percent of $f_c'$
  • No single core is less than 75 percent of $f_c'$
  • Use additional cores for erratic results, not if simply low strength

• Reduction in acceptance criteria recognizes damage from act of coring and other variances will lower test results
Dealing with surface defects

• Understand impacts of increased maintenance or reduced service life
  • Most repairs will require additional maintenance – factor this in

• Is slab in exposed area and needs to look good or withstand punishment?
  • Contracting Officer or Client is paying for new and expects longevity of the finish

• Goal of a good repair is to regain lost service life with minimal maintenance

<table>
<thead>
<tr>
<th>Some Potential Repair Methods</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding and patching</td>
<td></td>
</tr>
<tr>
<td>Sealers (penetrating or topical)</td>
<td></td>
</tr>
<tr>
<td>Waterproofers (crystalline or surface only)</td>
<td></td>
</tr>
<tr>
<td>Topping slab</td>
<td></td>
</tr>
<tr>
<td>Partial depth removal</td>
<td></td>
</tr>
<tr>
<td>Full removal</td>
<td></td>
</tr>
</tbody>
</table>
Some thoughts formed by my experiences

- It is easy to get 20 MPa (3 ksi) strength, the last 10-15 MPa is the trick
  - Don’t forget this if trying to ratio a cost reduction in lieu of correction
- Load testing costs a lot of money and time – removal is often better
  - At some point the evaluation has to end and decisions made – time is money
- Separate technical acceptance and contract issues
  - Will the concrete meet the performance needed in that specific location?
  - Performance means not only strength – durability is often more critical
  - If acceptable, may only be a contractual money issue for deficient work
- Formed surfaces are allowed to have imperfections unless specifically not
  - ACI 301M-16 has 3 classes of form finish with defaults plus architectural finishes
Tips to avoid issues before they occur
Proper planning prevents poor performance

• Pre-placement meetings allow expectations to be set
  • Create a detailed agenda
  • All players should be there including batch plant representative
  • USACE’s 3-phase prep meeting can work with modifications

• Check equipment and have spares for critical items
  • Trucks, vibrators, floats, possibly pump truck (or bucket)

• Ensure crew size is large enough
  • Plan for breaks or shift work on large jobs
  • Stagger finishers based on weather

Most specs require some form of planning and spare equipment
Have answers to these topics before concrete is ordered

- What will cause rejection of a truck
  - How many check tests are permitted
  - Time limits and drum revolutions
  - High air content or high slump
- If air content is low, are corrections ok
- Procedures for rain
- Allowance to add water to truck

- How will test specimens be stored
  - Need curing buckets or a cooler
  - Will pump truck be set up for best angle
  - What is placement path or lift plan
  - Limit risk for cold joints or segregation
- If batch plant has other large jobs
- Gate access to bases expedited

Cement hydration doesn’t wait for discussions and decisions to be made
A few words of advice

• Some days just aren’t good to place concrete – accept this
• Establish clear lines of communication and roles
• Communicate required adjustments quickly to batch plant
  • Make sure they are alerting you to truck delays or issues too
• Consider a trip to the batch plant to check it out
  • Scales working and calibrated
  • Truck chutes and drums clean
  • Batch variance from mixture design reasonable
• May need to change placement time to avoid traffic or for better weather conditions
• If concerned, perform a small trial placement
Hot weather concreting
What is “hot” and when to worry about it?

- ACI 305R-10 intentionally does not specifically define
  - Depends on a combination of high air temperature, high concrete temperature, low humidity, and high wind
- Start advanced planning around 25-30 degrees C (75-85° F)
- Several days of hotter weather heat up aggregate piles
- Large flatwork projects
- Mass concrete

If the workers are looking to cool down, so is your concrete!
What can go wrong?

**FRESH CONCRETE**
- Increased water demand
- Accelerated rate of slump loss
- Increased potential for cold joints
- Difficulty controlling entrained air content
- Increased rate of setting
- Difficulty with placing and finishing concrete
- Plastic shrinkage & thermal cracking

**HARDENED CONCRETE**
- More drying shrinkage
- Higher permeability
- Lower strength
- Reduced abrasion resistance
- Decreased durability
Plastic shrinkage cracks – a battle of rates!

bleed rate < evaporation rate = potential cracking

Start precautions at 1 kg/m²/hr
What can you do?

- Minimize delays
- Use temporary sunshade or windbreaks
- Place concrete at night
- Protect surface against rapid moisture loss
- Lower concrete temperature

- Use a different mixture design
  - Consider retarding admixtures
  - Increase fly ash or slag cement
  - Reduce cement if possible
  - May need initial curing with foggers
  - Properly store test cubes or cylinders
Cold weather concreting
What is “cold” and why worry about it?

- ACI 306R-16: Air temperature has fallen to, or is expected to fall to, 4 degrees C (40° F) during protection period
- Hydration and strength gain virtually stop at 4 degrees C
- Concrete freezing prior to 3.5 MPa (500 psi) strength gain has ultimate strength reduced by 50 percent
- Concrete frozen even a single time has increased permeability and reduced durability – shorter lifespan
- Non-air entrained concrete more susceptible

Fresh is fragile! Your concrete may need extra protection.
What to watch for in cold weather

- Slower setting times
- Slow strength development
- Longer construction times
- Loss of generated heat into cold subgrade
- Surface blisters
- Surface delamination
- Surface scaling
  - Often due to premature or over finishing

Crow’s feet from concrete frozen when still fresh
Possible actions to take in cold weather

- Use heated water
- Use temporary heated enclosure
- Use heated aggregates
- Insulation blankets during curing
  - May need multiple layers
  - Other materials such as straw
  - Insulation blocks available
- Cover subgrade before placement
  - Do not place on frozen subgrade
- Use an alternate winter mix
- Increase or change cement type
- Add accelerating admixtures
- Work with batch plant
- Adjust timing of surface finishing
- Try to keep concrete temperature above 10 degrees C
- Use dark colored curing materials
- Wait for better weather
Some cautionary tales

- Heated enclosures need venting and possibly sheeting to retain moisture in concrete
  - Do not blow heated air directly onto concrete surface – carbonation
  - Watch out for toxic carbon monoxide and risk of fire – 24 hour watch needed?
- Control excessive water runoff if using wet cure methods
  - Stop water application 24 hours prior to stopping thermal control
- Plastic shrinkage cracking is still possible if dry and windy
- Beware of thermal shock and scalding with heated water

Make your plan well before placement day
Final thoughts

- Acceptable concrete encompasses both strength and durability
- Strength evaluation is statistically based and calibrated for minimal failures
- Durability is affected by weather, finishing, materials, and curing
- While concrete removal is sometimes needed, perform an evaluation first
- Core testing may be required but several prior steps should be taken
- Pre-planning and good communication will avoid a lot of issues
- Hot weather speeds up hydration and problems can develop quickly
- Surface defects are more common in hot weather
- Cold weather requires special protections
- Frozen concrete lowers strength and causes durability issues
Thank You!

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