Performance-based Specifications – State of the Industry and Way Forward

NRMCA Engineering Department
NRMCA Research and Engineering Standards Committee

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General Instructions

- Attendees are muted during the webinar and will be unmuted at the end during the Q & A session
- Type questions in the chat or question box in the webinar control panel
- Login problems: Call: 800 263 6317
- Presentation will be recorded and uploaded later
- Email for content / more information
  - Your name: emailid
  - Karthik Obla: kobla@nrmca.org
  - Colin Lobo: clobo@nrmca.org

Initiative by National Ready Mixed Concrete Association (NRMCA)
  - Initiated in 2002
  - Move concrete construction industry forward through communication and education
    - Evolve to performance based criteria
    - Minimize prescriptive criteria
Prescription vs. Performance

- Prescription Specification
  - Recipe for completing project
  - End result intended… not precisely defined
  - Contractor cannot be faulted if result is not achieved!

- Performance Specification
  - Describes end result desired … not how…
  - Must be clearly defined…
  - Contractor can develop methods to achieve result…
  - Needs straightforward testing and inspection…

Definition

What do we mean by performance?

- Performance of concrete materials are based on performance indicators measured by standard test methods with defined acceptance criteria stated in contract documents and with no restrictions on the parameters of concrete mixture proportions

- Responsibility with assigned authority
  - Each party is responsible for own work

- Overall performance for project
  - Impacted by design / specification / construction
Resources for Specifications

Guide to Improving Specifications for Ready Mixed Concrete

Guide Performance-Based Specification for Concrete Materials
Section 03310 for Cast-in-place Concrete

Resources for Specifications

Report on Performance-Based Requirements for Concrete
Reported by ACI Committee 309

ACI 329R-14
NRMCA Quality Certification

- Comprehensive Quality Plan
- Personnel Qualifications
- Testing Capabilities
- Ingredient materials quality
- Production facilities
- Product Management
- Measurement systems – corrective action
First Step - Minimize Prescriptive Requirements

- Limitations on source and composition of materials
- Minimum cement factors
- Limits on amounts of Supplementary Cementitious Matls
- Additional limitations on SCMs
- w/cm limits when durability doesn’t apply
- Aggregate grading requirements
- Requirement to use potable water (C1602 alternate)
- Other limits to composition of mixtures
- Restrictive requirements for slump or air content
- Restrictions on concrete temperature outside standards
- Set requirements for concrete by application

RMC Industry Survey – Most Onerous Prescriptive Requirements?

- How often are these seen?
- Does it restrict optimizing mixtures?
- Does it impact cost?
- Does it improve performance?
  - For the type of application
Rating of Prescriptive Requirements

<table>
<thead>
<tr>
<th>Prescriptive Requirements</th>
<th>Avg. Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invoking maximum w/cm when not applicable</td>
<td>1.6</td>
</tr>
<tr>
<td>Invoking a minimum content for cementitious materials</td>
<td>1.9</td>
</tr>
<tr>
<td>Restriction on quantity of supplementary cementitious material (SCM)</td>
<td>2.0</td>
</tr>
<tr>
<td>Restrictions on characteristics of aggregates - grading etc.</td>
<td>2.1</td>
</tr>
<tr>
<td>Restriction on type and characteristics of SCM</td>
<td>2.3</td>
</tr>
<tr>
<td>Restriction on modifying approved mixtures</td>
<td>2.6</td>
</tr>
<tr>
<td>Restriction on type and source of aggregates</td>
<td>2.8</td>
</tr>
<tr>
<td>Requirement to use potable water</td>
<td>2.8</td>
</tr>
<tr>
<td>Restricting the use of a test record for submittals</td>
<td>2.9</td>
</tr>
<tr>
<td>Restriction on cement alkali content</td>
<td>3.3</td>
</tr>
<tr>
<td>Prescriptive requirements for sustainability</td>
<td>3.3</td>
</tr>
<tr>
<td>Restrictions on Type and source of cement</td>
<td>3.4</td>
</tr>
<tr>
<td>Restriction on use of recycled aggregates and mineral fillers</td>
<td>3.5</td>
</tr>
<tr>
<td>Restriction on type or brands of admixtures</td>
<td>3.8</td>
</tr>
<tr>
<td>Prohibiting cement conforming to ASTM C1157 and ASTM C595</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Quantify Frequency of Top 5

- Requested producers for actual specifications (past 12 months)
  - Private work
  - Application type
  - No residential
- NRMCA staff reviewed specifications
  - For just top 5 items
Review of Specifications

- 102 project specifications
- Types of Projects
  - 39% commercial buildings
  - 23% educational / public buildings
  - 18% public works
  - 14% environmental structures
  - 13% floors

State of Prescription

<table>
<thead>
<tr>
<th>Prescription</th>
<th>% of specs</th>
<th>Industry Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restriction on SCM quantity</td>
<td>85%</td>
<td>Exposure F3</td>
</tr>
<tr>
<td>Max w/cm (when not applicable)</td>
<td>73%</td>
<td>ACI 318 – Durability</td>
</tr>
<tr>
<td>Minimum cementitious content</td>
<td>46%</td>
<td>ACI 301 – floors</td>
</tr>
<tr>
<td>Restriction on SCM type, characteristics</td>
<td>27%</td>
<td>None</td>
</tr>
<tr>
<td>Restriction on aggregate grading</td>
<td>25%</td>
<td>Suggested for floors</td>
</tr>
<tr>
<td><strong>Overall average</strong></td>
<td><strong>51%</strong></td>
<td></td>
</tr>
</tbody>
</table>

If ACI standards are followed – these would not be an issue!
Prescriptive Specifications

A realistic check


About a decade ago, the American Ready-Mix
Concrete Association (NRMCA) undertook an
effort to evolve specifications for concrete to be
more prescriptive. The title, "P2P," was coined to
reflect the effort’s focus on prescriptive to
performance. The initiative was driven in part by
the desire to impose quality standards on the
delivery of concrete by producers. P2P was also
organized to fill the functional requirements of
different types of concrete production and
improve the long-term development of concrete
technology. The principal benefits of the effort
are that prescriptive specifications:

- Should be applied to the use of the concrete
  producer and the contractor—on a
- Realistic approach to promoting
  development of concrete technologies;
- Is this in industry standards?
- Basis for this? Real or perceived?
- Implications
- Suggested alternative
- Benefit of the alternative

Many of these principles are available at the NRMCA

The ACI Strategic Development Council (SDC) is charged
with the development of performance-based specifications;
the ACI Committee 220, Performance-Based Concrete
Requirements for Concrete, ACI 220.3R-06, which is
based on the 220.3R-06 report, and is currently
underway on a guide to writing a performance-based
specification, ACI 220.2R, Performance-Based
Concrete, ACI 220.2R-06, also developed durability
criteria and specifications that established requirements
for concrete in support of the improved exposure; and

http://www.nrmca.org/p2p
#1 – Limits on SCM Quantity

**Typical Clause**

- **Max Limits on Cementitious Materials:**
  - 1. Fly Ash: 25 percent.
  - 4. Silica Fume: 10 percent…

**Industry Average Use of SCM**

- **Overall industry average (lb/yd³):**
  - Cement = 457
  - Fly ash = 83
  - Slag cement = 18
  - Silica fume = 0.2
  - Blended cement = 2.7

- **Based on annual consumption of materials**

- **Increased use curtailed because of limits on SCM quantities in specifications**
#1 – Limits on SCM Quantity

**ACI 318**

- Exposure Class F3—Concrete exposed to freezing-and-thawing cycles with frequent exposure to water, deicing chemicals

<table>
<thead>
<tr>
<th>Cementitious Materials</th>
<th>Maximum Percent of Total Cementitious Materials by Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash or other pozzolans conforming to ASTM C618</td>
<td>25</td>
</tr>
<tr>
<td>Slag cement conforming to ASTM C989</td>
<td>50</td>
</tr>
<tr>
<td>Silica fume conforming to ASTM C1240</td>
<td>10</td>
</tr>
<tr>
<td>Total of fly ash or other pozzolans and silica fume</td>
<td>35</td>
</tr>
<tr>
<td>Total of fly ash or other pozzolans, slag cement and silica fume</td>
<td>50</td>
</tr>
</tbody>
</table>

**Misapplication of ACI requirement**

**Possible Basis**

- Implicit attempt to control
  - setting time
  - early age strength

- Mixtures with same fly ash content from different sources vary considerably in setting time, strength (Malhotra 1994)
#1 – Limits on SCM Quantity

What if more SCM is needed for durability?

![Graph showing ASTMC1567 - Mortar-Bar Expansion Results](image)

<table>
<thead>
<tr>
<th>Days in Solution</th>
<th>Length Change, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>0.10</td>
</tr>
<tr>
<td>6</td>
<td>0.15</td>
</tr>
<tr>
<td>8</td>
<td>0.20</td>
</tr>
<tr>
<td>10</td>
<td>0.25</td>
</tr>
<tr>
<td>12</td>
<td>0.30</td>
</tr>
<tr>
<td>14</td>
<td>0.35</td>
</tr>
<tr>
<td>16</td>
<td>0.40</td>
</tr>
<tr>
<td>18</td>
<td>0.45</td>
</tr>
<tr>
<td>20</td>
<td>0.50</td>
</tr>
<tr>
<td>22</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

Restrictions Caused

- Quantity of SCM may be inadequate for later-age durability problems
  - ASR
  - Sulfate resistance
- Reduces ability to impact permeability
  - Corrosion of reinforcing steel
- Temperature control in mass concrete
- Later-age strength and durability is curtailed
#1 – Limits on SCM Quantity

Suggested Alternative

- State SCM limits only for members assigned to Exposure Class F3
- State early age strength requirements as applicable
- Setting time can be addressed between contractor and concrete producer

Benefits Due to the Suggested Alternatives

- Assured resistance to ASR and sulfate attack
  - With performance testing
- Desired set time times and early age strengths can be evaluated by testing
- Enhanced durability to chloride induced corrosion
- Continued improvement in later age properties
- Supports sustainability
#1 – Limits on SCM Quantity

Example of Innovation Possible
I-35W bridge, MN – Concrete International, Feb 2009

<table>
<thead>
<tr>
<th>Member</th>
<th>$f_c'$, psi</th>
<th>w/cm</th>
<th>CM, lb/yd$^3$</th>
<th>PC, %</th>
<th>FA, %</th>
<th>SL, %</th>
<th>SF, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super structure</td>
<td>6500</td>
<td>0.35</td>
<td>700</td>
<td>71</td>
<td>25</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Piers</td>
<td>4000</td>
<td>0.45</td>
<td>575</td>
<td>15</td>
<td>18</td>
<td>67</td>
<td>-</td>
</tr>
<tr>
<td>Footings</td>
<td>5500</td>
<td>0.45</td>
<td>&lt;600</td>
<td>40</td>
<td>18</td>
<td>42</td>
<td>-</td>
</tr>
<tr>
<td>Drilled Shafts</td>
<td>5000</td>
<td>0.38</td>
<td>&lt;600</td>
<td>40</td>
<td>18</td>
<td>42</td>
<td>-</td>
</tr>
</tbody>
</table>

Performance Achieved

<table>
<thead>
<tr>
<th>Member</th>
<th>Performance Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super structure</td>
<td>Air entrained; PT; Strength &gt; 8000 psi; RCP &lt;250 Coulombs (90 d); shrinkage &lt;0.04% (56d drying)</td>
</tr>
<tr>
<td>Piers</td>
<td>Conventional slump; thermal control for 3 d; strength &gt; specified; RCP 500 coulombs (90 d)</td>
</tr>
<tr>
<td>Footings</td>
<td>Similar to drilled shaft mix; conventional slump; shrinkage = 0.04% (28d drying)</td>
</tr>
<tr>
<td>Drilled Shafts</td>
<td>Strength &gt; 10,000 psi (cores); RCP 750 coulombs (28d) Low heat considerations (mass concrete); SCC mix</td>
</tr>
</tbody>
</table>
Typical Clause
- The maximum w/cm ratio for all concrete on this project shall be 0.XX
- Compressive strength for different members in the structure shall be as indicated on the drawings

ACI 318
- Max w/cm and min strength required with assigned durability exposure class (permeability)
- w/cm and strength stated as a pair - consistent

<table>
<thead>
<tr>
<th>Exposure Class</th>
<th>Max w/cm</th>
<th>Min $f'_{c}$, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>0.55</td>
<td>3500</td>
</tr>
<tr>
<td>W1, S1</td>
<td>0.50</td>
<td>4000</td>
</tr>
<tr>
<td>F2, F3 (plain concrete), S2, S3</td>
<td>0.45</td>
<td>4500</td>
</tr>
<tr>
<td>F3 (structural), C2</td>
<td>0.40</td>
<td>5000</td>
</tr>
</tbody>
</table>
#2 – Max w/cm (when not applicable)

Misapplication of industry standards
Possible basis

- Low w/cm is always good quality concrete
  - Lower the better!

No. 8 aggregate non-air topping mix (interior)

- w/cm = 0.40; 4000 psi
- Mixture required 290 lb/yd³, WR admixture
- Total CM = 725 lb/yd³

Mixture very susceptible to cracking

Application did not require 0.40 restriction

- With w/cm=0.50, Total CM=580 lb/yd³
- Cracking would be considerably reduced
## Avg. Strength vs. w/cm

<table>
<thead>
<tr>
<th>w/cm</th>
<th>Non air</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>6900</td>
<td>6200</td>
</tr>
<tr>
<td>0.45</td>
<td>6000</td>
<td>5400</td>
</tr>
<tr>
<td>0.50</td>
<td>5200</td>
<td>4700</td>
</tr>
<tr>
<td>0.55</td>
<td>4500</td>
<td>4000</td>
</tr>
</tbody>
</table>

- Design for 3500 psi
- If w/c is specified (0.40)
  - And not applicable
- Actual strength >> Design strength
- Strength acceptance criteria will not assure required concrete is being furnished

Source: NRMCA Survey (2014)

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## #2 – Max w/cm (when not applicable)

### Restrictions Caused

- Workability can be adversely impacted
- If specified strength is low, including w/cm
  - Increases strength – acceptance criteria do not work
  - Increases paste volume – and associated problems
  - Concrete not optimized for member as designed

- Specifying w/cm less than 0.40 can impact workability, and increase potential for cracking
#2 – Max w/cm (when not applicable)

Suggested Alternative
- Specify w/cm and companion strength when applicable to exposure conditions (ACI 318)
  - Do not specify w/cm when not applicable – such as for interior members
- Avoid disconnect between strength and w/cm
  - Eg. 3000 psi and 0.40
- Avoid specifying w/cm considerably below 0.40
  - Consider alternative performance based tests

Benefits Due to the Suggested Alternative
- Concrete applicable and optimized to specific application
- Reduces potential constructability problems when a low w/cm is specified
- Ensures w/cm requirements can be enforced by the strength acceptance criteria
- Improved sustainability
Performance Alternative
Bridge decks, marine structures, parking garages

- Low permeability concrete
- Reduced potential for cracking

<table>
<thead>
<tr>
<th>Prescription</th>
<th>Performance Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low w/cm</td>
<td>Strength and concomitant w/cm</td>
</tr>
<tr>
<td>Minimum CM content</td>
<td>ASTM C1202–1500 coulombs or Resistivity (AASHTO T 358-15) (standard cure 56 days OR accelerated cure 28 days)</td>
</tr>
<tr>
<td>SCM types/dosages</td>
<td>ASTM C157 - 0.05% (7 day cure; 28 days drying)</td>
</tr>
</tbody>
</table>

WA DOT Bridge Deck Spec
(source: WA-RD 845.1 June 2015)

<table>
<thead>
<tr>
<th></th>
<th>Original Class 4000D</th>
<th>Revised Class 4000D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum 28-day Compressive Strength</td>
<td>4,000 psi</td>
<td>4,000 psi</td>
</tr>
<tr>
<td>Cement</td>
<td>Type I or II Portland</td>
<td>Type I or II Portland</td>
</tr>
<tr>
<td>Cementitious Content</td>
<td>735 lbs minimum (680 lbs cement &amp; 75 lbs fly ash)</td>
<td>No set limits</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>Required</td>
<td>Optional</td>
</tr>
<tr>
<td>Nominal Max. Aggregate Size</td>
<td>1-inch</td>
<td>1½-inch</td>
</tr>
<tr>
<td>Water Reducing Admixture</td>
<td>Required</td>
<td>Optional</td>
</tr>
<tr>
<td>Air Content</td>
<td>4.5% to 7.5%</td>
<td>4.5% to 7.5%</td>
</tr>
<tr>
<td>Freeze-Thaw Durability Test (instead of above air content requirement)</td>
<td>Not an Option</td>
<td>3.0% min. air content 90% minimum durability factor after 300 cycles per AASHTO T 161</td>
</tr>
<tr>
<td>Permeability</td>
<td>No Requirement</td>
<td>Less than 2000 coulombs at 56 days per AASHTO T 277</td>
</tr>
<tr>
<td>Length Change (“shrinkage”)</td>
<td>No Requirement</td>
<td>Less than 0.032% (320 microstrain) at 28 days per AASHTO T 160</td>
</tr>
<tr>
<td>Scaling</td>
<td>No Requirement</td>
<td>Visual rating ≤ 2 after 50 cycles per ASTM C 672</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>No Requirement</td>
<td>Measured and Submitted per ASTM C 469</td>
</tr>
<tr>
<td>Density</td>
<td>No Requirement</td>
<td>Measured and Submitted per ASTM C 138</td>
</tr>
</tbody>
</table>
#3 – Min cementitious content

Typical Clause

- Concrete for XXX members shall comply with the following:
  - Minimum cementitious content of xxx lb/yd³
  - …

Seen in 46% of specs

#3 – Min cementitious content

Industry Standards

- No requirement in ACI 318
- Some cases in ACI 350 (Environmental Structures)
- ACI 301 for floors - finishability

<table>
<thead>
<tr>
<th>Nominal maximum size of aggregate, in.</th>
<th>Minimum cementitious material content, lb/yd³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1/2</td>
<td>470</td>
</tr>
<tr>
<td>1</td>
<td>520</td>
</tr>
<tr>
<td>3/4</td>
<td>540</td>
</tr>
<tr>
<td>3/8</td>
<td>610</td>
</tr>
</tbody>
</table>
A Job Specification

- Specification required
  - Min. CM = 650 lb/yd$^3$; 15% fly ash; 4000 psi
- 25% fly ash needed for ASR
  - Spec allowed only 15% cement replacement
- Mixture finally used
  - Total CM = 714 lb/yd$^3$ (552/162)

Only 70% of the fly ash by weight may be counted as cement in computing W/C ratio.

#3 – Min cementitious content

Possible Basis

- Ensure durability – to force a low w/cm
- Improve corrosion resistance of rebar
- Adequate paste in the mix
  - Workability
  - Finishability
- Inertia due to historical requirements
#3 – Min cementitious content

## 28-day strength

### RCPT (accelerated curing)

### Length Change (shrinkage) at 3 months
Spec Max w/cm OR Min CM content

- Example: Low Quality – complies with spec!

![Graph](image)

- $f_{c} = 6130$ psi
- St Dev = 1122 psi
- COV = 18.3%
- Poor per ACI 214!

**Compressive Strength, psi**

- Test ID
- $f_{cr}' = 4000$ psi

Optimized Prescriptive Mix?

- Good materials engineer can optimize mix
- Specifying this is difficult

- Prescriptive Specs are then over-designed
  - Minimum CM = 600 lb/yd$^3$,
  - w/cm = 0.45
  - Will obtain 3000 psi even with substandard materials, production, testing
- Penalizes better performers
#3 – Min cementitious content

Restrictions Caused
- Impacts workability
- Increases paste volume – potential for cracking
- Increase alkali content in mixture – ASR
- Expected durability may not be achieved
- No incentives for higher quality
  - Detrimental to all stakeholders
- Not supportive of sustainability initiatives

Suggested Alternative
- Do not specify min CM content
- Use ACI durability requirements when applicable
  - If intent is for low w/cm, specify appropriate $f'_{c}$
- Specify the intended performance
  - No technical basis for min CM if this is done
- ACI 301 permits test slab placement (mock-up) in lieu of CM limit
#3 – Min cementitious content

Benefits Due to the Suggested Alternative

- Concrete performance can be verified, when specified including workability
- Incentivizes quality focus
- Knowledgeable producer can better optimize mixture for specified performance
- Can reduce potential cracking, ASR
- Supports sustainability

#4 – SCM Type / Characteristics

Typical Clauses

- Class C fly ash is not permitted
- The CaO content of fly ash shall not exceed XX%.
- Slag Cement is not permitted
- The Loss on Ignition (LOI) of fly ash shall not exceed X.X% (more restrictive than ASTM C618)
- Fly ash fineness - The percent retained on the 45 μm (No. 325) sieve shall not exceed XX% (more restrictive than ASTM C618)
- The [available] alkali content of fly ash shall not exceed X.X%
#4 – SCM Type / Characteristics

## Industry Standards

- **ACI 318 permits fly ash conforming to ASTM C618**
  - No additional restrictions
- **ASTM C618 requirements**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Class F</th>
<th>Class C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$, min %</td>
<td>70.0</td>
<td>50.0</td>
</tr>
<tr>
<td>LOI, max %</td>
<td>6.0*</td>
<td>6.0</td>
</tr>
<tr>
<td>Fineness, retained on 45 $\mu$m (No. 325) sieve, max %</td>
<td>34</td>
<td>34</td>
</tr>
</tbody>
</table>

Additional requirements and reporting apply

## Possible Basis

- Class C fly ash may not be effective for ASR or sulfate resistance (CaO content)
- Restrictive LOI limits to control air content
- Fineness to impact rate of strength gain
- No experience with slag cement
- Control alkali content to avoid ASR
Restrictions Caused

- Available fly ash with performance history and service records cannot be used
- Fly ash may need to be shipped in from long distances
- False sense of security of achieving intended performance
#4 – SCM Type / Characteristics

Suggested Alternative

- Consider performance based evaluation of fly ash for ASR and sulfate resistance
  - **ASR** – use ASTM C1567
    - < 0.1% at 16 days (ASTM C1778)
  - **Sulfate resistance** – ASTM C1012
    - Moderate < 0.10% at 6 m
    - Severe < 0.10 at 12 m
    - Very Severe < 0.10% at 18 m

- Do not include more restrictive requirements on fly ash, such as LOI and fineness, than those in ASTM C618
  - Market will control use of unacceptable product
#4 – SCM Type / Characteristics

Benefits Due to the Suggested Alternative

- Assurance of improved durability when specified
  - ASR
  - Sulfate Resistance
- Restrictions do not assure intended performance
- Improved sustainability and lower cost
  - Permits use of local materials with service records and producer experience

#5 – Aggregate Grading Limits

Typical Clauses

- Grading of the combined aggregate shall conform to the % retained on individual sieves between 8 and 18% (or 6 and 22%), with the exception of the smaller and higher sieves.
- The Coarseness Factor and the Workability Factor determined from the combined aggregate grading shall be within the [required] Zone on the Aggregate Constructability Chart.
- The combined aggregate grading when plotted on a 0.45 power chart of the sieve size shall not deviate from a line drawn from the origin to the largest aggregate size within a tolerance of 2%.
#5 – Aggregate Grading Limits

Industry Standards
- ACI 318 – aggregates conform to ASTM C33
  - No requirements on grading of combined aggregate
- ASTM C33 – grading bands for aggregates
- ACI 302.1R non-mandatory guide – suggests requirements on combined aggregate grading
  - For proportioning concrete mixtures for floors

Possible Basis
- Improve aggregate packing
  - Reduce paste
- Improve workability / finishability
- Reduce shrinkage
  - Joint spacing
  - Curling
#5 – Aggregate Grading Limits

Restrictions Caused
- Intended performance may not be achieved
  - False sense of security
  - Improper assignment of responsibility
- Requirement cannot be verified during project
- Availability of sizes and storage at plants
- Some local sources cannot achieve grading requirements easily

Optimizing grading is a tool for proportioning – should not be a specification requirement

Suggested Alternative
- Consider performance test for shrinkage
  - ASTM C157 – 0.05% at 28 days drying
- Consider test slab placement to evaluate workability/finishability with proposed placement equipment
- Consider successful service record with floor mixtures
#5 – Aggregate Grading Limits

Benefits Due to the Suggested Alternative

- Assurance of reduced shrinkage, cracking, finishability
- Appropriate assignment of responsibility
- Reduces cost due to local use of materials, and reduced storage
- Supports sustainability

Performance Options – Floor Slabs

- Reduced potential for cracking and curling
- Consistent setting time
- Workability and finishability
- Achieve flatness tolerances

<table>
<thead>
<tr>
<th>Prescription</th>
<th>Performance Alternative</th>
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</thead>
<tbody>
<tr>
<td>Cement content</td>
<td>ASTM C157 - 0.05% (7 day cure; 28 days drying)</td>
</tr>
<tr>
<td>Aggregate grading</td>
<td>Setting time (C403)</td>
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<tr>
<td>Water content</td>
<td>Test slab placement</td>
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<td>Mortar content</td>
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<td>SCM limits</td>
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Suggestions for Specifications

Evolution to Performance

- The Engineer specifies
  - Basic requirements (Code)

<table>
<thead>
<tr>
<th>Primary Requirements</th>
<th>Mix ID</th>
<th>Durability Exposure</th>
<th>Specified Strength $f'_{c}$ psi</th>
<th>Max w/cm</th>
<th>Nom. max aggregate, in</th>
<th>Agg. source</th>
<th>Shrinkage</th>
<th>Chloride limit</th>
<th>Temp. min/max limits</th>
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<tbody>
<tr>
<td>Footings</td>
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Evolution to Performance

- The Engineer specifies
  - Performance requirements as applicable

<table>
<thead>
<tr>
<th>Member</th>
<th>Mix ID</th>
<th>RCP, Coulomb</th>
<th>Shrinkage</th>
<th>Freeze-Thaw</th>
<th>ASR</th>
<th>MOE</th>
<th>Thermal Control Plan</th>
<th>Density</th>
<th>Other</th>
<th>Other</th>
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</table>

Chloride exposure (PFS Report)

<table>
<thead>
<tr>
<th>Chloride Penetrability Level</th>
<th>Specified RCPT, Coulombs</th>
<th>Specified Compressive Strength* at 28 days, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low</td>
<td>≤ 1000</td>
<td>≥ 5000</td>
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<tr>
<td>Low</td>
<td>1000 to 2500</td>
<td>≥ 4000</td>
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</tbody>
</table>

*For non-air-entrained concrete mixtures increase strengths by 20%
Freezing and Thawing Exposure (PFS Report)

<table>
<thead>
<tr>
<th>ACI 318 Exposure Class</th>
<th>Strength</th>
<th>Air Content</th>
<th>w/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>3500</td>
<td>4.5%*</td>
<td>0.55</td>
</tr>
<tr>
<td>F2</td>
<td>4500</td>
<td>6.0%*</td>
<td>0.45</td>
</tr>
<tr>
<td>F3</td>
<td>4500</td>
<td>6.0%*</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Sulfate Exposure (PFS Report)

<table>
<thead>
<tr>
<th>Exposure Class (Concrete in contact with soluble sulfates in soil/sea water)</th>
<th>Minimum $f_{c}^*$, psi</th>
<th>w/cm</th>
<th>ASTM C1012 expansion limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0 – Low</td>
<td>2500</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>S1 - Moderate</td>
<td>4000</td>
<td>0.50</td>
<td>0.10% at 6 m</td>
</tr>
<tr>
<td></td>
<td>3500</td>
<td>0.55</td>
<td>0.05% at 6 m</td>
</tr>
<tr>
<td>S2 - Severe</td>
<td>4500</td>
<td>0.45</td>
<td>0.10% at 12m</td>
</tr>
<tr>
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<td>4000</td>
<td>0.50</td>
<td>0.05% at 12m</td>
</tr>
<tr>
<td>S3 – Very severe</td>
<td>4500</td>
<td>0.45</td>
<td>0.10% at 18m</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>0.50</td>
<td>0.05% at 18m</td>
</tr>
</tbody>
</table>
Physical Salt Attack (PSA) (PFS Report)

<table>
<thead>
<tr>
<th>Resistance to PSA</th>
<th>Prescriptive option</th>
<th>Performance Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>w/cm ≤ 0.45</td>
<td>Compressive Strength at 28 days ≥ 4500*</td>
</tr>
</tbody>
</table>

*For non-air-entrained concrete mixtures increase strengths by 20%

Conclusions

- Consideration of the performance alternatives can result in:
  - Assured (not assumed) performance
  - Mixtures optimized for the design and application
    - 10% material cost savings possible
  - Higher quality; incentivized to achieve performance
  - Appropriate assignment of responsibility
  - Producer that can technically support project
  - Reduced time and cost to address project problems
  - Greater confidence in concrete construction
  - Supports sustainability
Thank you!

Performance-based Specifications – State of the Industry and Way Forward

For more information please contact kobla@nrmca.org or clobo@nrmca.org