ESSENTIALS of Quality Concrete

1. Suitable Materials
2. Proper Proportioning, Mixing, and Transporting
3. Proper Placing, Consolidation
4. Proper Finishing & Jointing
5. Proper Curing

References
- Design and Control of Concrete Mixtures, EB001.16, PCA 2016
- CH 8: Aggregates
- CH 9: Admixtures

Troubleshooting Aggregates and Admixtures

Portland Cement Association

- Founded in 1916
- Headquarters: Skokie, Illinois USA

Aggregates
Aggregates

Cement Water Air Fine Aggregate Coarse Aggregate

60 - 75% of volume is "stone & sand"

Aggregates: Important but Often Overlooked...

- Aggregates occupy 70 to 80 percent of total volume in concrete.
- Effects on concrete properties often overlooked.
- Test methods often do not evaluate key aggregate properties.
- Good sources are being depleted -- marginal to poor sources are being accessed.
- Understanding how aggregates affect concrete performance will become more important in future.

ACI 221R Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete

Aggregates, the major constituent of concrete, influence the properties and performance of both freshly mixed and hardened concrete. In addition to serving as an inexpensive filler, they impart certain positive benefits that are described in this guide. When they perform below expectation, unsatisfactory concrete may result. Their important role is frequently overlooked because of their relatively low cost as compared to that of cementitious materials.

Influence of Aggregate on Fresh Concrete Properties

<table>
<thead>
<tr>
<th>Aggregate Property</th>
<th>Concrete Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size distribution (grading)</td>
<td>Workability</td>
</tr>
<tr>
<td>Particle shape</td>
<td>Water demand</td>
</tr>
<tr>
<td>Particle texture</td>
<td>Paste content</td>
</tr>
<tr>
<td>Presence of fine material (silt &amp; clay)</td>
<td>Organic impurities</td>
</tr>
</tbody>
</table>

Influence of Aggregate on Hardened Concrete Properties

<table>
<thead>
<tr>
<th>Aggregate Property</th>
<th>Concrete Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size and shape</td>
<td>Mechanical behaviour</td>
</tr>
<tr>
<td>Strength</td>
<td>Strength</td>
</tr>
<tr>
<td>Stiffness</td>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>Organic impurities</td>
<td>Shrinkage</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aggregate Property</th>
<th>Concrete Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of thermal expansion</td>
<td>Coefficient of thermal expansion</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>Specific heat</td>
<td>Specific heat</td>
</tr>
<tr>
<td>Thermal diffusivity</td>
<td>Thermal diffusivity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aggregate Property</th>
<th>Concrete Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soundness</td>
<td>Resistance to freezing and thawing</td>
</tr>
<tr>
<td>Frost resistance</td>
<td>Particle size</td>
</tr>
<tr>
<td>Particle size</td>
<td>Presence of alkali-reactive minerals</td>
</tr>
<tr>
<td>Presence of alkali-reactive minerals</td>
<td>Resistance to alkali-aggregate reaction</td>
</tr>
<tr>
<td>Density</td>
<td>Abrasion resistance</td>
</tr>
<tr>
<td>Porosity</td>
<td>Frictional properties (pavements)</td>
</tr>
<tr>
<td>Volume stability</td>
<td>Aesthetics</td>
</tr>
<tr>
<td>Mineral composition</td>
<td>Economics</td>
</tr>
</tbody>
</table>
Chemical Admixtures

ASTM C260 and C494 (AASHTO M 194)
Classification
Air Entraining
Water Reducing
Set Control Admixtures
Specific Performance

<table>
<thead>
<tr>
<th>Type</th>
<th>Specific Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>Water-reducer</td>
</tr>
<tr>
<td>Type B</td>
<td>Retarding</td>
</tr>
<tr>
<td>Type C</td>
<td>Accelerating</td>
</tr>
<tr>
<td>Type D</td>
<td>Water-reducing &amp; retarding</td>
</tr>
<tr>
<td>Type E</td>
<td>Water-reducing &amp; accelerating</td>
</tr>
<tr>
<td>Type F</td>
<td>Water-reducing, high range</td>
</tr>
<tr>
<td>Type G</td>
<td>Water-reducing, high-range &amp; retarding</td>
</tr>
<tr>
<td>Type S</td>
<td>Specific Performance Admixtures</td>
</tr>
</tbody>
</table>

Why Use Admixtures?

To Modify Fresh Concrete Properties
- decrease water content
- increase workability
- retard or accelerate setting time
- reduce segregation
- reduce the rate of slump loss
- improve pumpability, placeability, finishability
- modify the rate and/or capacity for bleeding

To Modify Hardened Concrete Properties
- Improve strength
- improve freeze-thaw resistance
- improve impact and abrasion resistance
- inhibit corrosion of embedded metals
- reduce plastic shrinkage cracking
- reduce long term drying shrinkage

Designing Concrete Mixtures
Objective:
To determine the most economical and practical combination of readily available materials to produce a concrete that will satisfy the performance requirements under particular conditions of use.

What specific properties must we be interested in when designing concrete mixtures?
**Fundamentals of Concrete**

- Desired Properties of Concrete
  - Fresh (Contractor)
  - Hardened (Engineer)
  - Aesthetics (Architect/Owner)

**Desired Fresh Concrete Properties**

- Workability
- Density
- Temperature
- Air Content
- Bleeding/Segregation
- Setting & Hardening

**Factors Impacting Workability**

- w/cm
- Cement Fineness
- Use of SCM’s,
- Aggregates
  - Shape & Gradation
- Admixtures
  - Water Reducers, Retarders
  - Admixture Compatibility
  - Slump Loss
- Method of Placement

**Influence of Aggregates**

- Specified by ASTM C33
  - Gradation
  - Shape
  - Size
  - Surface texture

**Aggregate Grading**

- Single-sized
- Poorly-graded
- Well-graded

- Volume of paste (cement + water) to fill voids

**Mortar Factor:**

<table>
<thead>
<tr>
<th>Aggregates</th>
<th>Mortar Factor (% of volume of concrete)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well-graded</td>
<td>30 to 35</td>
</tr>
<tr>
<td>Poorly-graded</td>
<td>40 to 50</td>
</tr>
<tr>
<td>Single-sized</td>
<td>50 to 60</td>
</tr>
</tbody>
</table>

| Workability (Contractor) | 30 to 35 |
| Temperature (Engineer)   | 40 to 50  |
| Air Content (Architect)  | 50 to 60  |
| Bleeding/Segregation (Owner) | 60 to 70 |
Effect of air content on water demand

Rule of thumb: decrease water by 3 kg/m³ (5 lb/yd³) for each 1% air

Achieving Consistency

Moisture Conditions

State

- Oven dry
- Air dry
- Saturated, surface dry
- Greater than absorption

Total moisture

Segregation

Stickiness

- Fines
- Aggregate cleanliness and gradation
- Cement
- Air-entrainment
- Pumping
Less than expected Water Reduction

Abnormal Slump Loss
The rate of slump loss depends on:
- C\textsubscript{3}A, SO\textsubscript{3} & alkali
- temperature
- fineness

Controlling Density
- w/cm
- Yield
- Specific Gravity of Individual Materials
- Air Content
- Aggregates:
  - S.G.
  - Absorption
  - Moisture Content
  - Beneficiation

Aggregate Density
- Specific Gravity
  - Lightweight
  - Normalweight
  - Heavyweight
  - Gradation

High or Low Unit Weight/Off Yield
- Control Air Content
- Saturate Aggregates
- Tolerances

Controlling Concrete Temperature
- Material Temperature
- Use of Retarders/Accelerators
- Cement Type
- Thermal Control Plan
- Cold/Hot Weather Precautions
Effect of Temperature of Materials on Concrete Temperatures

\[ T = \frac{0.22(T_aM_a + T_cM_c + T_wM_w + T_waM_wa)}{0.22(M_a + M_c + M_w + M_wa)} \]

\( T \) = temperature of the freshly mixed concrete, °C (°F)

\( T_a, T_c, T_w, \) and \( T_wa \) = temperature in °C (°F) of aggregates, cement, added mixing water, and free water on aggregates, respectively

\( M_a, M_c, M_w, \) and \( M_wa \) = mass, kg (lb), of aggregates, cementing materials, added mixing water, and free water on aggregates, respectively

Controlling Air Content

- Cement content;
  - fineness, alkali
- Aggregates;
  - fineness, shape
- Admixtures
  - Dosage, other adm
- w/c
- Slump;
  - <3-in., >6-in.
- Temperature
- Altitude
- Mixing speed, time, capacity

High/Low Air Content

Air-Void Clusters at Interface

Factors Impacting Bleeding Rate and Capacity

- w/cm
- Cement Finesness
- Use of SCM’s
- Aggregate
  - Gradation
- Admixtures
  - Air, WRA, Air
- Temp., RH, Wind
Factors Impacting Setting & Hardening

- w/cm
- Use of SCM’s
- Admixtures
  - Retarders, Accelerators
- Temperature
- Rate & Heat of Hydration
- Cement
  - Gypsum (CaSO₄)
- Content & Form

Anticipated Setting Time

Abnormally retarded setting and Strength Gain

- Low C₃A, high C₄AF and low SO₃ cement plus CLS admixture
- Too much admixture, too much water
- Low C₃S, high C₅S
- Low C₃S reactivity
- Dosage of SCMs
- Low temperature

Less than expected Retardation

- Increased C₃A content (increases adsorption of water reducer by C₃A hydrates)
**Hardened Concrete Properties**
- Strength
- Abrasion Resistance
- Freeze-thaw Resistance
- Alkali-Aggregate Reactivity
- Volume Stability
- Aesthetics
  - Bug Holes
  - Blistering
  - Discoloration
  - Popouts

**Factors Impacting Strength**
- w/cm
- Age
- Air Content
- Aggregate Bond
- Handling
- Curing Temperature
- Testing Errors

*Aggregate strength only matters when transition zone is strong (e.g., high-strength concrete, use of SCMs)*

**Aggregate Transition Zone**

**Failure of Normal Strength Concrete**
- Coarse Aggregate
- Mortar
- Weak Transition Zone
- Crack around aggregate

**Failure of HPC**
- Coarse Aggregate
- Mortar
- Strong Transition Zone
- Crack through aggregate

Coarse aggregate strength is limiting factor!!
Factors Impacting Durability

- W/CM
- Curing
- Material fineness
  - Aggregate Gradation
- Paste/aggregate ratio
  - Cement content
- Aggregate-paste bond
- Reactive Ingredients

Harmful Materials

<table>
<thead>
<tr>
<th>Substances</th>
<th>Effect on concrete</th>
<th>Test designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic impurities</td>
<td>Affects setting and hardening, may cause deterioration</td>
<td>ASTM C40, ASTM C87</td>
</tr>
<tr>
<td>Materials finer than the 75-µm (No. 200) sieve</td>
<td>Affects bond, increases water requirement</td>
<td>ASTM C117</td>
</tr>
<tr>
<td>Coal, lignite, or other lightweight materials</td>
<td>Affects durability, may cause stains and popouts</td>
<td>ASTM C123</td>
</tr>
<tr>
<td>Soft particles</td>
<td>Affects durability</td>
<td>ASTM C235</td>
</tr>
<tr>
<td>Clay lumps and friable particles</td>
<td>Affects workability and durability, may cause popouts</td>
<td>ASTM C142</td>
</tr>
<tr>
<td>Chart of less than 2.40 relative density</td>
<td>Affects durability, may cause popouts</td>
<td>ASTM C123, ASTM C296</td>
</tr>
<tr>
<td>Alkal-reactive aggregates</td>
<td>Causes abnormal expansion, map cracking and popouts</td>
<td>ASTM C227, C289, C295, C342, C366, C1260, C1293, ASTM C1778</td>
</tr>
</tbody>
</table>

Limits for Deleterious Substances in Fine Aggregate for Concrete

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight Percent of Total Sample, max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay lumps and friable particles</td>
<td>3.0</td>
</tr>
<tr>
<td>Material finer than No. 200 (75µm) sieve:</td>
<td>3.0*</td>
</tr>
<tr>
<td>Concrete subject to abrasion</td>
<td>5.0*</td>
</tr>
<tr>
<td>All other Concrete</td>
<td>5.0*</td>
</tr>
<tr>
<td>Coal and lignite:</td>
<td>0.5</td>
</tr>
<tr>
<td>Where surface appearance of concrete is of importance</td>
<td>1.0</td>
</tr>
<tr>
<td>All other concrete</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*In the case of manufactured sand, if the material finer than the No. 200 (75µm) sieve consists of the dust of fracture, essentially free of clay or shale, these limits may be increased to 5 and 7%, respectively.

Factors Impacting Abrasion Resistance

- w/cm
- Curing
- Type of Aggregate
- Surface Finish
- Surface Treatment
- Exposure

Resistance to Freeze-Thaw

Criteria:
- The aggregate is frost-resistant
- Sufficient strength is attained prior to first freezing (> 3.5 MPa or 500 psi)
- Sufficient strength is attained prior to cyclic freezing & thawing (> 28 MPa or 4000 psi) 318- min. 4500 psi.
- Adequate Air Void System
Mechanism of Protection by Air Voids

Air-entrained

Saturation > 91.7%

32°F
23°F

Saturation > 91.7%

2019 Quality Concrete Conference
Resistance to Alkali-Aggregate Reactivity

**ASR-**
- Prism Test- ASTM C1293
  < 0.04% expansion (1 year)
- Mortar Bar Test- ASTM C1260
  < 0.10% expansion (14 days)
- Use of SCMs ASTM C1567
  < 0.10% expansion (14 days)

**Caution:** Limiting the alkali level of cement (<0.6%) may not be enough to mitigate ASR- focus must be on TOTAL alkalies in concrete.
Classification of Aggregate Reactivity  
ASTM C1778

<table>
<thead>
<tr>
<th>Aggregate Reactivity Class</th>
<th>Description of Aggregate Reactivity</th>
<th>1-Year Expansion, % ASTM C1293</th>
<th>14-Day Expansion, % ASTM C1293</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>Non-reactive</td>
<td>&lt;0.06</td>
<td>&lt;0.06</td>
</tr>
<tr>
<td>R1</td>
<td>Moderately reactive</td>
<td>≥0.06, &lt;0.12</td>
<td>≥0.06, &lt;0.12</td>
</tr>
<tr>
<td>R2</td>
<td>Highly reactive</td>
<td>≥0.12, &lt;0.24</td>
<td>≥0.10, &lt;0.30</td>
</tr>
<tr>
<td>R3</td>
<td>Very highly reactive</td>
<td>≥0.24</td>
<td>≥0.40</td>
</tr>
</tbody>
</table>

ASR Inhibitors  
Primarily lithium are used to mitigate alkali-silica reactivity in concrete.

Factors Impacting Volume Stability
- Restraint, Jointing
- w/cm
- Amount of Aggregate
- Properties of Aggregate
- Size & Shape of Member
- RH and Temp
- Method of Curing & Drying
- Degree of Hydration
- Time

Aggregate Interlock

Minimal Opening Required
< 0.035 in.
Minimize Concrete Shrinkage and Joint Spacing

Shrinkage Reducing Admixtures
- Shrinkage Reducing Admixtures are used to minimize drying shrinkage cracking in concrete.

ACI 301 Aggregate Requirements

4.1.2.3(b) For aggregates: types, pit or quarry locations, producer's names, aggregate supplier statement of compliance with ASTM C33/C33M, and ASTM C1293 expansion data not more than 18 months old.
Effect of Aggregate Type on Coefficient of Expansion of Concrete

<table>
<thead>
<tr>
<th>Aggregate type (from one source)</th>
<th>Coefficient of expansion, millionths per °C</th>
<th>Coefficient of expansion, millionths per °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>11.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Sandstone</td>
<td>11.7</td>
<td>6.5</td>
</tr>
<tr>
<td>Gravel</td>
<td>10.8</td>
<td>6.0</td>
</tr>
<tr>
<td>Granite</td>
<td>9.5</td>
<td>5.3</td>
</tr>
<tr>
<td>Basalt</td>
<td>8.6</td>
<td>4.8</td>
</tr>
<tr>
<td>Limestone</td>
<td>6.8</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Impact on Aesthetics

- Materials Selection
- Incompatibility
- Surface Defects
In Summary...

- Aggregates – Important but often overlooked
- Major impact on concrete properties
- Many good sources being depleted....
- Must understand how to optimize aggregates for applications of interest

What to look at in aggregate?

- Organic impurities
- Clay
- Gradation
- Fineness
- Moisture Content
Summary

- Tests for aggregate properties

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition of constituents</td>
<td>ASTM C125, ASTM C294</td>
</tr>
<tr>
<td>Particle shape and surface texture</td>
<td>ASTM C295, ASTM D4791, ASTM C1252</td>
</tr>
<tr>
<td>Relative density</td>
<td>ASTM C127 (fine), ASTM C128 (coarse)</td>
</tr>
<tr>
<td>Absorption and surface moisture</td>
<td>ASTM C70, ASTM C127, ASTM C128, ASTM C66</td>
</tr>
<tr>
<td>Grading</td>
<td>ASTM C117, ASTM C136</td>
</tr>
<tr>
<td>Void content</td>
<td>ASTM C1252, ASTM C29</td>
</tr>
<tr>
<td>Bulk density</td>
<td>ASTM C29</td>
</tr>
</tbody>
</table>

- Tests for aggregate performance

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasion resistance</td>
<td>ASTM C131, ASTM C335, ASTM C779</td>
</tr>
<tr>
<td>Freeze-thaw resistance</td>
<td>ASTM C666</td>
</tr>
<tr>
<td>Sulfate resistance</td>
<td>ASTM C88</td>
</tr>
<tr>
<td>Concrete Strength</td>
<td>ASTM C39, ASTM C78</td>
</tr>
<tr>
<td>Fine aggregate degradation</td>
<td>ASTM C1157</td>
</tr>
</tbody>
</table>

What to look at in chemical admixtures?

- Chemical composition
- Dosage rate
- Time of addition in the batching cycle

Questions and Further Information

Michelle L. Wilson  
Director, Concrete Technology  
5420 Old Orchard Road  
Skokie, IL 60077  
847.972.9034 (phone)  
mwilson@cement.org  
www.cement.org

The Effectiveness of an Admixture

- Depends on:
  - The Type & Brand
  - Amount of Cement
  - Water Content
  - Temperature
  - Aggregate Shape
  - Proportions
  - Mixing Time
  - Consistency of the Mix
  - Sequencing