COMPREHENSIVE MIX DESIGN: GAINING CONTROL OVER YOUR CONCRETE

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Paul Ramsburg, Sika

CONTENT

• Materials
• Proportioning
• SCC
• Statistics

RAW MATERIALS

AGGREGATES

CRUSHED STONE
AGGREGATES

- Characteristics of Aggregates:
  - Resistance to Freeze/Thaw: The freeze/thaw resistance of an aggregate is related to its porosity, absorption, and pore structure. Specifications require that resistance to weathering be demonstrated by the magnesium sulfate test.
  - Abrasion Resistance: The ability to withstand loads without excessive wear or deterioration of the aggregate.
  - Chemical Stability: Aggregates must not be reactive with cement alkalis. This reaction may cause abnormal expansion and cracking in concrete.
  - Specific Gravity (Density): The ratio of an aggregate’s weight to the weight of an equal volume of water at a given temperature. Most normal weight aggregates have a specific gravity ranging from 2.4 to 2.9. It is not a measure of aggregate quality, it is used for certain computations in a mix design.

AGGREGATES

- Delerious Substances in Aggregates:
  - Organic Impurities: affect setting time and hardening, and may cause deterioration
  - Material finer than the #200 sieve: affect bond and increases water demand
  - Lightweight Materials (coal, lignite): affect durability and wear resistance
  - Friable Particles: affect workability and durability, break up in mixing, and increase water demand
  - Clay Lumps: absorb mixing water or cause pop-outs.
LIMESTONE

AGGREGATE MOISTURE

"I'm your density." - George McFly

SPECIFIC GRAVITY

FINENESS MODULUS (FM)

The specific gravity of any material is the weight of that material in air divided by the weight of an equal volume of water. An aggregate with a specific gravity of 2.50 would thus be two and one-half times as heavy as water for the same volume.

Table 5-4. Determination of Fineness Modulus of Fine Aggregates

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Percentage of individual fraction retained, by mass</th>
<th>Cumulative percentage passing, by mass</th>
<th>Cumulative percentage retained, by mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5 mm (No. 16)</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>4.75 mm (No. 4)</td>
<td>2%</td>
<td>2%</td>
<td>98%</td>
</tr>
<tr>
<td>2.36 mm (No. 10)</td>
<td>13%</td>
<td>15%</td>
<td>85%</td>
</tr>
<tr>
<td>1.18 mm (No. 16)</td>
<td>20%</td>
<td>33%</td>
<td>65%</td>
</tr>
<tr>
<td>0.60 mm (No. 30)</td>
<td>20%</td>
<td>53%</td>
<td>35%</td>
</tr>
<tr>
<td>0.30 mm (No. 50)</td>
<td>24%</td>
<td>77%</td>
<td>25%</td>
</tr>
<tr>
<td>0.15 mm (No. 100)</td>
<td>18%</td>
<td>95%</td>
<td>0%</td>
</tr>
<tr>
<td>Fineness modulus = 250 x 100 / 6.83</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Stone:
Specific Gravity = 2.70 (168.48lbs)

Water:
Specific Gravity = 1.00 (62.4lbs)

Same Volume, but 2.70 Times More Mass

Oven Dry
Air Dry
SSD
Most
ABOUT FINENESS MODULUS

- High FM
  - Less cement necessary
  - Harsher mix (hard to finish)
  - Higher bleed
  - Potential segregation
- Low FM
  - More cement necessary
  - Higher water demand
  - Stickiness
  - Harder to air entrain
  - Higher shrinkage and risk of cracking

DRY RODDED UNIT WEIGHT

- Particle Density
  - 100% Solid
  - Weight = 169.7 lbs
  - Volume = 1 cuft
  - Specific Gravity = 2.72

- Bulk Density
  - 65% Solid, 35% Void
  - Weight = 110.3 lbs
  - Volume = 1 cuft
\[ V_{\text{sphere}} = \frac{4}{3} \pi \times \text{radius}^3 \]

\[ P = \frac{V_{\text{spheres combined}}}{V_{\text{cylinder}}} \]
$V_{\text{SPHERE}} = \frac{4}{3} \pi R^3$

\[
\begin{align*}
V & = 1 \text{ yd}^3 \quad 27 \text{ ft}^3 \\
1 \text{ yd}^3 & = 27 \text{ ft}^3 \\
\end{align*}
\]
Hydraulic Cements may be considered as being composed of the following compounds:
- Tricalcium Silicate = C₃S
- Dicalcium Silicate = C₂S
- Tricalcium Aluminate = C₃A
- Tetracalcium Aluminoferrite = C₄AF

Portland Cements
ASTM C 150
- Type I: Normal
- Type II: Moderate Sulfate Resistance
- Type II (MH): Moderate Heat of Hydration (and Moderate Sulfate Resistance)
- Type III: High Early Strength
- Type IV: Low Heat Hydration
- Type V: High Sulfate Resistance

Hydraulic Blended Cements
ASTM C 595
- IL: Portland-Limestone Cement
- IS: Portland-Slag Cement
- IP: Portland-Pozzolanic Cement
- IT: Ternary Blended Cement

ASTM C 1157
- GU: General Use
- HE: High Early-Strength
- MS: Moderate Sulfate Resistance
- HS: High Sulfate Resistance
- MH: Moderate Heat of Hydration
- LH: Low Heat of Hydration
FREE TRAINING (LITERACY REQUIRED)

http://precast.org/precast-magazines/

2013 – July-August
How to Read a Cement Mill Certificate: Part 1

2013 – September-October
How to Read a Cement Mill Certificate: Part 2

ASTM C 917 Report
Supplied by your Cement Provider
**- 325 MESH**

- Amount of material remaining on a 325 mesh (325 openings per 1 in²).

  - The coarse particles that remain play a small role in hydration and strength development.
  - In conjunction with the blaine this value can give you a better indication of the particle size distribution.
  - If blaine is very high (ie 4800) and 325 mesh is low (ie 82) it means that there is a large amount of "super" fines, (which have a tendency to function of clinker that has already hydrated…since they have already reacted their presents is detrimental to concrete).

**SET TIME**

- **VICAT**

  - Measure of set time of cement paste.

  - Both initial and final set are measured by determining the length of time it takes the cement paste to resist the penetration of a round needle of prescribed weight.
  - Translates loosely to concrete.
**TOTAL ALKALIS**

- **NaEq**
  - Weighted average of alkalis in cement.
  - $NaEq = Na_2O + 0.659 K_2O$

- Low alkali cements < 0.60 NaEq
- Higher alkali cements typically have better early strengths but lower ultimate strengths.
- Higher alkali cements require less air-entrainment, and change the performance of HRWR's
SUPPLEMENTARY CEMENTITIOUS MATERIALS

FLY ASH

BLAST FURNACE SLAG

SILICA FUME

Silica Fume is a finely-divided mineral admixture, available in both uncompact and compacted forms. This ultra-fine material will better fill voids between cement particles and result in a very dense concrete with higher compressive strengths and extremely low permeability.
Water Cement Ratio is the most significant factor to both early and late compressive strength, as well as long term durability.

- Weight (in pounds) of water per pound of cementitious material

26 gal x 8.33 = 217 lbs

217 / 720 lbs. = 0.30 w/c ratio

- The amount of water needed to fully hydrate a pound of cement is about 0.25 lb

- A typical w/c ratio for precast members is 0.38 to 0.45 (driven by release)

Admixtures

- Dosages depend on a number of variables that are specific to each mix design and production facility.

- Can specify in oz / 100 wt or oz per yard.

- Most mixes will have air entrainer and HRWR.

- Hardening accelerators vs. set accelerators

- ASTM C494 “Standard Specification for Chemical Admixtures for Concrete”
  - Type A Water-reducing admixtures
  - Type B Retarding admixtures
  - Type C Accelerating admixtures
  - Type D Water reducing and accelerating admixtures
  - Type F Water reducing, high-range, admixtures
  - Type G Water reducing, high-range, and retarding admixtures
  - Type S Specific performance admixtures
ADMIXTURES

- Admixture effectiveness varies depending on its concentration in the concrete and the effect of the various other materials.
- Adequate testing should be performed to determine the effects of an admixture on the plastic and hardened properties of concrete
  - Slump
  - Slump Loss
  - Air
  - Set Time
  - Strength
  - Shrinkage
  - Permeability
- A rule of thumb is for all admixtures to be added separately.
- ACI Education Bulletin E4-12 “Chemical Admixtures For Concrete” – Free Resource

1. Electrostatic dispersion, a state created by the admixture which allows it to attach to the cement grains electrically and repel other admixture molecules and cement grains.
2. Steric Hindrance, a state created by the massive size of the admixture molecules attached to the cement grains that prevents contact of the grains and promotes fluidity of the cement paste. It also takes longer for the admixture to be overtaken by the gel formation around the cement grain caused by the hydration reaction.

PROPORTIONING

MIX DESIGN

REQUIREMENTS

5.5% air content
688 lbs cement
250 lbs water

.055 X 27 = 1.485
MIX DESIGN

REQUIREMENTS

5.5% air content
688 lbs cement
250 lbs water

\[
\frac{688}{3.15} / 62.4 = 3.5
\]

MIX DESIGN

REQUIREMENTS

5.5% air content
688 lbs cement
250 lbs water

\[
\frac{250}{62.4} = 4
\]

MIX DESIGN

REQUIREMENTS

5.5% air content
688 lbs cement
250 lbs water

18 Cubic Yards Remain
9 Course

MIX DESIGN

REQUIREMENTS

5.5% air content
688 lbs cement
250 lbs water

18 Cubic Yards Remain
9 Fine

STEPS:

1. Slump and Nominal Max. Agg. Size
2. Mixing Water Requirement
3. Air Content
4. Cement Content
5. Coarse Aggregate
   5.1. Nominal Max. Aggregate Size
   5.2. DRUW
   5.3. Weight of Coarse Aggregate
6. Calculate Absolute Volume (except sand)
7. Fine Aggregate (sand)
   7.1 Determine volume of Fine Aggregate
   7.2 Convert volume of fine agg. to Weight
8. Tabulate weights and Volumes of basic ingredients

STEP 1

• Slump definition (ACI 116):
  A measure of consistency of freshly mixed concrete, mortar, or stucco equal to the subsidence measured to the nearest ¼ in. (6 mm) of the molded specimen immediately after removal of the slump cone.
• How to measure slump (ASTM C143)
• *Select a Slump value…
**STEP 1... CONTINUE**

- Nominal Max. Aggregate Size:
  Is the sieve size next larger than the largest sieve on which at least 15% of the coarse aggregate is retained

- Standard Specification for Concrete Aggregates (ASTM C33 Table 2)
  - *Select an aggregate size

---

**MAXIMUM W/C RATIO FOR CONCRETE IN SEVERE EXPOSURE (FROM ACI 211.1)**

<table>
<thead>
<tr>
<th>Type of Structure</th>
<th>Structure wet continuously or frequently and exposed to freezing and thawing*</th>
<th>Structure exposed to sea water or sulfates</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 m</td>
<td>0.45</td>
<td>0.40**</td>
</tr>
<tr>
<td>0.2 m</td>
<td>0.45</td>
<td>0.40**</td>
</tr>
</tbody>
</table>

*Concrete should also be air entrained.

**STEP 2: MIXING WATER & B3: AIR CONTENT**

<table>
<thead>
<tr>
<th>Type of Structure</th>
<th>Structure wet continuously or frequently and exposed to freezing and thawing*</th>
<th>Structure exposed to sea water or sulfates</th>
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<tr>
<td>0.2 m</td>
<td>0.45</td>
<td>0.40**</td>
</tr>
</tbody>
</table>

*Concrete should also be air entrained.

**STEP 3: AIR CONTENT**

- **Entrained Air (ACI 116):**
  Air voids in concrete that are not purposely entrained and that are larger, mainly irregular in shape, and less useful than those of entrained air, and 1 mm or larger in size.

- **Entrained Air (ACI 116):**
  Microscopic air bubbles intentionally incorporated in mortar or concrete during mixing, usually by use of a surface-active agent; typically between 10 and 1000 μm (1 mm) in diameter and spherical or nearly so.
MODERATE EXPOSURES

- Where freezing temperature are expected, but concrete will not be saturated for extended periods prior to freezing, and will not be exposed to deicing salts.
- Examples: Exterior beams
- Columns
- Walls
- Abutments
- Exterior slabs under roofs

SEVERE EXPOSURE

- Where concrete will be exposed to deicing salts, or where concrete will be in contact with water and will potentially be saturated prior to freezing
- Examples: Pavements
- Bridge decks
- Curbs
- Gutters
- Sidewalks
- Canal and pond linings
- Tanks

STEP 4: CEMENT CONTENT

<table>
<thead>
<tr>
<th>Water Cement Ratio, by weight</th>
<th>Compressive strength, psi*</th>
<th>Non-air entrained concrete</th>
<th>Air-entrained Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>7000</td>
<td>0.34</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>6000</td>
<td>0.41</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>5000</td>
<td>0.48</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>0.57</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>0.68</td>
<td>0.59</td>
<td></td>
</tr>
</tbody>
</table>

At release with accelerated curing**

| 5000                         | 0.33                      | --                        | --                    |
| 4500                         | 0.39                      | 0.33                      |                       |
| 4000                         | 0.45                      | 0.37                      |                       |
| 3500                         | 0.50                      | 0.42                      |                       |
| 3000                         | 0.56                      | 0.46                      |                       |

*Values are estimated strength for concrete with no more than 2% air for non-air-entrained concrete and less than 6% air in air-entrained concrete.

**With type III cement, release at 16 hours after casting

STEP 5.1: Coarse Aggregate Content

<table>
<thead>
<tr>
<th>Nominal Maximum Size Coarse Aggregate</th>
<th>b/bₙ for Different Fineness Modulus of Fine Aggregate (Sand)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.20  2.40  2.60  2.80  3.00</td>
</tr>
<tr>
<td>3/8 in.</td>
<td>0.52  0.50  0.48  0.46  0.44</td>
</tr>
<tr>
<td>1/2 in.</td>
<td>0.61  0.59  0.57  0.55  0.53</td>
</tr>
<tr>
<td>3/4 in.</td>
<td>0.68  0.66  0.64  0.62  0.60</td>
</tr>
<tr>
<td>1 in.</td>
<td>0.73  0.71  0.69  0.67  0.65</td>
</tr>
<tr>
<td>1 1/2 in.</td>
<td>0.77  0.75  0.73  0.71  0.69</td>
</tr>
<tr>
<td>2 in.</td>
<td>0.80  0.78  0.76  0.74  0.72</td>
</tr>
<tr>
<td>3 in.</td>
<td>0.84  0.82  0.80  0.78  0.76</td>
</tr>
</tbody>
</table>

b/bₙ is the volume of dry-rodded coarse aggregate in a unit volume of concrete.

STEP 5.2: DRUW (DRY RODDED UNIT WEIGHT)

- The maximum weight of coarse aggregate that can be consolidated into a 1 cubic foot bucket.
- The “DRUW” of a coarse aggregate is determined by ASTM C29
- The max. weight of coarse aggregate in a volume of 1 cu.yd = DRUW, lb/cu.ft. x 27

Step 5.3: Weight of dry Coarse Aggregate

Wt. of dry CA = b/bₙ x DRUW, lb/cu.ft. x 27

NPCC
**STEP 6: ABSOLUTE VOLUME OF INGREDIENTS**

- Wt. of ingredient, lb
- Absolute vol., cu.ft. = \( \frac{\text{Wt. of ingredient, lb}}{\text{SG x Unit Wt of water, lb/cu.ft}} \)

Step 6.1: Cement, cu.ft.
Step 6.2: Water, cu.ft.
Step 6.3: Coarse Aggregate, cu.ft
Step 6.4: Air \( \Rightarrow \) air content x 27 cu.ft.
Step 6.5: Sum up the absolute volumes of cement, water, air, and coarse aggregate

**6.1: CEMENT**

- CONDITIONS:
  - 650lbs Type 3 Portland Cement
  - SP.GR. = 3.15

  \[ \text{Wt of material} \times \frac{\text{Vol}}{\text{SG of material} \times \text{ut.wt of H}_2\text{O}} \]

  \[ \frac{650}{\frac{3.15 \times 62.4}{1}} \]

**6.2 WATER**

- CONDITIONS:
  - w/c R = .38
  - Weight = 8.33lbs/gal.

  \[ \text{Weight H}_2\text{O} = \text{lbs cem x w/c R} \]

  \[ \text{Weight H}_2\text{O} = 650 \times .38 \]

  \[ \frac{\text{Weight}}{\text{Vol.}} = \frac{1}{1 \times 62.4} \]

**6.3 COARSE AGGREGATE**

- CONDITIONS:
  - Volume of dry-rodded coarse aggregate = 0.62
  - Dry-rodded unit weight = 98.6
  - Cubic feet in a cubic yard = 27
  - Specific Gravity = 2.73

  \[ \text{Weight} = 0.62 \times 98.6 \times 27 \]

  \[ \frac{\text{Weight}}{\text{Vol.}} = \frac{2.73 \times 62.4}{1} \]

**6.4 AIR**

- CONDITIONS:
  - Air specification = 6.0%

  \[ \text{Vol.} = \text{Air \% x 27 cubic ft.} \]

  \[ \text{Vol.} = 0.06 \times 27 \]

**STEP 7: FINE AGGREGATE**

- Abs. Vol. of Fine Agg. = 27 – Abs. Vol. of (Cement + Water + Coarse Aggregate + Air)

**Step 7.1:**

Wt. of Fine Agg. = \( \text{Abs. Vol. of Fine Agg.} \times \text{SG} \times 62.4 \)
STEP 8: TABULATE WEIGHTS & VOLUME

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight, lb.</th>
<th>Absolute volume, cu.ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>280</td>
<td>2.68</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>120</td>
<td>1.00</td>
</tr>
<tr>
<td>Mixing Water</td>
<td>285</td>
<td>6.57</td>
</tr>
<tr>
<td>Coarse Aggregate 1</td>
<td>1006</td>
<td>5.95</td>
</tr>
<tr>
<td>Coarse Aggregate 2</td>
<td>793</td>
<td>6.31</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>1180</td>
<td>7.19</td>
</tr>
<tr>
<td>Air, _____ %</td>
<td>--</td>
<td>1.05</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>27.00</td>
</tr>
</tbody>
</table>

Changing Aggregate

<table>
<thead>
<tr>
<th>Material</th>
<th>lb/cy.</th>
<th>S.G.</th>
<th>cu.ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMENT</td>
<td>300</td>
<td>3.15</td>
<td>0.64</td>
</tr>
<tr>
<td>FLY ASH</td>
<td>110</td>
<td>2.90</td>
<td>0.40</td>
</tr>
<tr>
<td>SILICA FUME</td>
<td>0</td>
<td>2.20</td>
<td>0.08</td>
</tr>
<tr>
<td>WATER</td>
<td>285</td>
<td>1.0</td>
<td>2.88</td>
</tr>
<tr>
<td>COARSE AGGREGATE 1</td>
<td>1000</td>
<td>3.75</td>
<td>3.60</td>
</tr>
<tr>
<td>COARSE AGGREGATE 2</td>
<td>0</td>
<td>2.98</td>
<td>0.00</td>
</tr>
<tr>
<td>AIR</td>
<td>0.05</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>VOLUME FILLED</td>
<td>1.07</td>
<td></td>
<td>1.87</td>
</tr>
<tr>
<td>FINE AGGREGATE</td>
<td>27.00</td>
<td>0.10</td>
<td>7.05</td>
</tr>
</tbody>
</table>

DETERMINATION OF ABSOLUTE VOLUME

<table>
<thead>
<tr>
<th>Material</th>
<th>S.G.</th>
<th>kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMENT</td>
<td>3.15</td>
<td>900</td>
</tr>
<tr>
<td>FLY ASH</td>
<td>2.90</td>
<td>880</td>
</tr>
<tr>
<td>WATER</td>
<td>1.0</td>
<td>1000</td>
</tr>
<tr>
<td>COARSE AGGREGATE 1</td>
<td>3.75</td>
<td>719</td>
</tr>
<tr>
<td>COARSE AGGREGATE 2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AIR</td>
<td></td>
<td>0.05</td>
</tr>
<tr>
<td>VOLUME FILLED</td>
<td></td>
<td>1.07</td>
</tr>
<tr>
<td>FINE AGGREGATE</td>
<td></td>
<td>27.00</td>
</tr>
</tbody>
</table>

SELF-CONSOLIDATION CONCRETE (SCC)

A highly flowable, yet stable concrete that can spread readily into place and fill the formwork without any consolidation and without undergoing significant separation."

Khayat, Hu and Monty

MOISTURE CONTROL

- Aggregate moisture control can be one of the biggest issues in concrete production
- Absorbed vs. Free Moisture
- Drying aggregates can be an issue, must not take them below absorption
- Light Weight Aggregates
  - KEEP SATURATED
- Allow water on aggregate to before loading into batchplant
- Exterior aggregate bins must aggregate stockpile
**THE POLYCARBOXYLATE**

A Polycarboxylate based High Range Water Reducer

1. **Electrostatic dispersion**, a state created by the admixture which allows it to attach to the cement grains electrically and repel other admixture molecules and cement grains.
2. A much larger than normal **molecular weight** (size).
3. **Steric Hindrance**, a state created by the massive size of the admixture molecules attached to the cement grains that prevents contact of the grains and promotes fluidity of the cement paste. It also takes longer for the admixture to be overtaken by the gel formation around the cement grain caused by the hydration reaction.
4. Up to **40 percent** water reduction capabilities.

**WHAT IS BLOCKING OR PASSING ABILITY?**

- Size, volume, & blend of aggregate
- Sufficient volume of paste

**AGGREGATES**

- Many coarse aggregates available in North America are Gap Graded, and thus have low volumes of No. 8 and No. 16 sieve size particles
- The optimized grading curve for SCC is much tighter than for conventional concrete
- Optimizing mix packing density is critical for many SCC mixes, so it may be necessary to blend aggregate sources

**AGGREGATE GRADING**

- An example of a typical # 57 blend, indicating a Gap Graded Aggregate
- An optimized SCC aggregate grading with blended aggregates

**SCC MIX DESIGN**

- What’s important when looking at gradation and aggregate size.

**BUGHOLES**

Best FM for SCC? - 2.50 – 2.70

Bugholes can be decreased by providing a sufficient quantity of fine aggregate with high surface area (minus No.8 sieve). Larger amounts of sand are not as effective as finer sand.

Changing the cement content of a mixture by 94lbs. generally has the same effect on workability as changing the minus No.8 fraction of the combined aggregate by 2.5%
The basic statistical methods discussed here are valuable tools for evaluating the test results of a concrete mix design. It is important that those who design precast/prestress mixes have a basic understanding of statistics and how they are used to evaluate test results.

**CONTENT**

- Average
- Range
- Standard Deviation
- Over Design

**AVERAGE**

- The average, or Mean, is calculated by adding up all the test results and dividing that by the total number of test results.

\[
X = \frac{\sum X_i}{n}
\]

where \( \Sigma \) is “Sum”

\( X_i \) is each individual test result

\( n \) is the total number of test results

\( X \) is Average

**Example:**

These compressive strength results were acquired

\[
X_1 = 7200 \text{ psi} \\
X_2 = 6900 \text{ psi} \\
X_3 = 7500 \text{ psi} \\
X_4 = 7800 \text{ psi} \\
X_5 = 6850 \text{ psi} \\
X_6 = 7400 \text{ psi} \\
X_7 = 7200 \text{ psi}
\]

\[
X = \frac{7200 + 6900 + 7500 + 7800 + 6850 + 7400 + 7200}{7} = 7264 \text{ psi}
\]

**RANGE**

- Range (R) is a simple measure of variability. It's the difference between the maximum and minimum values of the results. It's useful when a limited number of test results are available.

- From the previous results:

\[
\text{Max} = 7800 \text{ psi} \\
\text{Min} = 6850 \text{ psi} \\
\text{Range} = (7800 - 6850) = 950 \text{ psi}
\]
STANDARD DEVIATION

- The deviations (difference) from the average of each result are squared and summed.
- The sum is divided by one less the total number of results (n - 1)
- The square root of that quantity gives the standard deviation

\[ S = \sqrt{\frac{\sum(x - \bar{x})^2}{n - 1}} \]

Example:

Deviations
\[ (X_i - \bar{X}) \]
Deviations Squared
\[ (X_i - \bar{X})^2 \]

\begin{align*}
8550 - 8677 &= -127 \\
8900 - 8677 &= +223 \\
8140 - 8677 &= -537 \\
9120 - 8677 &= +443 \\
8650 - 8677 &= +173 \\
8700 - 8677 &= +23 \\
\end{align*}

TOTAL = 671,734

\[ S = \sqrt{\frac{671,734}{6 - 1}} = \sqrt{134,346} = 367 \]

FREQUENCY DISTRIBUTION

- Frequency distribution is a helpful way to view test data to show statistical reasoning and predictions for a mix design
- It forms what is called a “Normal Distribution” curve. This curve is developed by grouping and counting concrete compressive strength data for a particular mix design
- The curve is symmetrical about the average (50% of the tests will be on either side of the average)
- The peak of the curve occurs at the average (mean) of the data
- The curve is generated from the Standard Deviation
  - The greater the spread of the curve the higher the deviation for the mix
- The area under the bell curve equals:
  - 1 standard deviation = 68.27% of the break data
  - 2 standard deviation = 95.45% of the break data

MIX DESIGN APPROVAL

- The Concrete Producer as part of the submittal process must establish data to demonstrate that the mix being proposed will produce the required strength for a given project. This can be completed by the following methods:
  - Strength data from between 10-30 consecutive test points
  - Laboratory Trial batches in accordance with guidelines in ASTM C192
  - Three Point Curve Trial testing
    - Range of W/C ratio
    - Slump ± 0.75 in.
    - Air Content ± 0.5 Percent
CONTROL OF STRENGTH PER ACI 318

- ACI 318 allows revision of a concrete mix which is producing consistently overstrength tests. A sufficient number of tests to provide statistically significant data are required and as the number and reliability of the tests improve, the required safety factor or overstrength decreases. At least 15 tests (three 4x8 cylinders per test) are required and 30 is considered a standard minimum. The Standard Deviation of the results is computed. The required strength must equal the average, plus a safety factor, times the standard deviation:

\[
\text{Required Average Compressive Strength} = f_{c} + k \cdot \sigma
\]

\[
\text{where:}
\begin{align*}
    f_{c} & \text{ Specified Compressive Strength (psi)} \\
    k & \text{Safety Factor:} \\
    \sigma & \text{Standard Deviation of the results}
\end{align*}
\]

CONTROL OF STRENGTH PER ACI 318

- Required Average Compressive Strength When Data are available to establish a Standard Deviation
  - \( f'_{c} \leq 5000 \)
    - \( f'_{cr} = f'_{c} + 1.34\sigma \)
    - \( f'_{cr} = f'_{c} + 2.33\sigma - 500 \)
    - Use the larger value computed
  - \( f'_{c} > 5000 \)
    - \( f'_{cr} = f'_{c} + 1.34\sigma \)
    - \( f'_{cr} = 0.90f'_{c} + 2.33\sigma \)
    - Use the larger value computed

CONTROL OF STRENGTH PER ACI 318

- Less than 15 tests available:

<table>
<thead>
<tr>
<th>Specified Comp Strength (psi)</th>
<th>Required Avg Comp Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 3000</td>
<td>( f'_{c} + 1000 )</td>
</tr>
<tr>
<td>3000 to 5000</td>
<td>( f'_{c} + 2000 )</td>
</tr>
<tr>
<td>Over 5000</td>
<td>( f'_{c} + 700 )</td>
</tr>
</tbody>
</table>

- For 15 or more tests available:

<table>
<thead>
<tr>
<th>Number of tests</th>
<th>Modified Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1.16\sigma</td>
</tr>
<tr>
<td>20</td>
<td>1.08\sigma</td>
</tr>
<tr>
<td>25</td>
<td>1.03\sigma</td>
</tr>
<tr>
<td>30 or more</td>
<td>1.00\sigma</td>
</tr>
</tbody>
</table>

EVALUATION AND ACCEPTANCE

- When the Mix Design for a given project is approved for use and the Job has started test specimens shall be made in accordance with PCI MNL-116 guidelines.
  - The strengths for the mixture shall be reported and must satisfy the following two criteria before the concrete will be considered acceptable for the Project:
    1. The Average of all sets of three consecutive strength tests equal or exceed the specified strength (\( f'_{c} \))
    2. No single strength test (average of 2 cylinders) falls below the specified strength (\( f'_{c} \)) by more than 500 psi if \( f'_{c} \) is 5000 psi or lower, or falls below \( f'_{c} \) by more than 10% if \( f'_{c} \) is greater than 5000 psi

COMPREHENSIVE MIX DESIGN: GAINING CONTROL OVER YOUR CONCRETE

Frank Bowen, Piedmont Precast
Paul Ramsburg, Silka