Introduction

• Many types of concrete
• Portland Cement Concrete (PCC) prevalent
  ➢ “concrete” = PC Concrete
• Engineers are directly responsible for the
  ➢ Design of the mix
  ➢ Final quality of concrete
Quality of Concrete

depends on:

– chemical composition
– aggregate
– water
– admixtures
– proportions
– mixing

– transporting
– hydration
– placing
– vibrating
– curing
Order of Operations for Concrete

specific operations must be performed in a certain order
• final quality is influenced by every step

I. mix design (proportioning)
II. trial mixes & testing
III. batching

---------------------------------------------------------------------start the clock
IV. mixing
V. transporting
VI. pouring (placing)
VII. vibrating (consolidating)

---------------------------------------------------------------------initial set here
VIII. finishing

---------------------------------------------------------------------final set here
IX. curing
X. maintenance

Sampling and testing
7.1 Proportioning of Concrete Mixes (Mix Design)

Determine proportions of mix ingredients that will:

- be economical
- be practical
- use available materials
- satisfy requirements & specs
  - acceptable workability of fresh mix
  - quality (durability, strength, appearance) of hardened concrete
  - economy
Several Methods

Depends on project size:

• Arbitrary volume method (1:2:3 = PC:sand:coarse agg.)
• Weight method – easiest design method
• Absolute volume method – most accurate
• Small jobs, non-critical
Mix Design: Volumetric Method

1. Strength requirements
2. Determine W/C
3. Estimate coarse aggregate mass
4. Air entrainment requirements
5. Workability needs
6. Estimate water content
7. Determine cement content requirements
8. Evaluate admixture needs
9. Estimate fine aggregate mass
10. Determine moisture corrections
11. Trial Mix
Step 1. Strength Requirements

- Design engineer “specifies” a strength of concrete used for design calculations – $f'_c$
- Concrete strength is variable
- Material engineer designs concrete so only a small proportion of the concrete will have a strength less than the strength assumed by the design engineer.
Strength Requirements

Normal distribution

½ the concrete has a strength less than average

Average strength

\[ f'_{cr} = f'_c + 1.34s \]

Adding 1.34s to \( f'_c \) – 90% of the concrete will be stronger than specified strength

Standard deviations

Increasing strength
**Strength Requirements**

\[ f'_{cr} = f'_c + (1.34 \times s) \quad \text{when } s < 500 \text{ psi} \]

If \( s > 500 \text{ psi} \):

\[ f'_{cr} = f'_c + (2.33 \times s) - 500 \text{ psi} \]

\( s \) = standard deviation of \( f'_c \) for a particular mixing plant

- If \( s \) is based on fewer than 30 samples, then the standard deviation of the “population” is underestimated
Adjustments for Small Number of Samples

very conservative: *not for large projects*

<table>
<thead>
<tr>
<th>Number of Tests</th>
<th>Modification Factor $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1.16</td>
</tr>
<tr>
<td>20</td>
<td>1.08</td>
</tr>
<tr>
<td>25</td>
<td>1.03</td>
</tr>
<tr>
<td>30 or more</td>
<td>1.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specified Compressive Strength $f'_c$, MPa (psi)</th>
<th>Required Average Compressive Strength $f'_{cr}$, MPa (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;21$ (&lt;3000)</td>
<td>$f'_c + 7.0 (f'_c + 1000)$</td>
</tr>
<tr>
<td>21 to 35 (3000 to 5000)</td>
<td>$f'_c + 8.5 (f'_c + 1200)$</td>
</tr>
<tr>
<td>$&gt;35$ (&gt;5000)</td>
<td>$f'_c + 10.0 (f'_c + 1400)$</td>
</tr>
</tbody>
</table>

15 to 30 tests
multiplication adjustment factor
e.g. 15 samples
multiply $s$ by 1.16

fewer than 15 tests:
*additive factor based on $f'_c$*
Step 2. Determine Water-Cement Ratio

- historical records of strength are used to plot $f'_{c}$ vs. w/c
Water-Cement Ratio check for maximum allowed

– severe exposure conditions require lower w/c ratios

– use lowest w/c ratio of all applicable conditions
  • exposure conditions
  • sulfate exposure
Step 3. Coarse Aggregate Requirements

Gradation & maximum size

- Use large – most dense gradation for economy & specs
  - Large aggregate improves workability (or less water & cement)

- Nature of particles (shape, texture, porosity)
  - Round shape and smooth texture are workability (or less water & cement)

Check maximum aggregate size (use smallest)

This is the only place in the mix design process where maximum aggregate size is used. Nominal maximum aggregate size is used in all other places. Remember the maximum aggregate size is generally one sieve size larger than the nominal maximum aggregate size.

<table>
<thead>
<tr>
<th>Situation</th>
<th>Maximum Aggregate Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form dimensions</td>
<td>1/5 of minimum clear distance</td>
</tr>
<tr>
<td>Clear space between reinforcement or prestressing tendons</td>
<td>3/4 of minimum clear space</td>
</tr>
<tr>
<td>Clear space between reinforcement and form form</td>
<td>3/4 of minimum clear space</td>
</tr>
<tr>
<td>Unreinforced slab</td>
<td>1/3 of thickness</td>
</tr>
</tbody>
</table>
Coarse aggregate bulk volume

<table>
<thead>
<tr>
<th>Nominal Maximum Size of Aggregate, mm (in.)</th>
<th>Bulk Volume of Dry-Rodded Coarse Aggregate Per Unit Volume of Concrete for Different Fineness Moduli of Fine Aggregate**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fineness Modulus</td>
</tr>
<tr>
<td></td>
<td>2.40</td>
</tr>
<tr>
<td>9.5 (3/8)</td>
<td>0.50</td>
</tr>
<tr>
<td>12.5 (1/2)</td>
<td>0.59</td>
</tr>
<tr>
<td>19 (3/4)</td>
<td>0.66</td>
</tr>
<tr>
<td>25 (1)</td>
<td>0.71</td>
</tr>
<tr>
<td>37.5 (1 1/2)</td>
<td>0.75</td>
</tr>
<tr>
<td>50 (2)</td>
<td>0.78</td>
</tr>
<tr>
<td>75 (3)</td>
<td>0.82</td>
</tr>
<tr>
<td>150 (6)</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Multiply 0.63 by the dry rodded unit weight of the coarse aggregate to determine the mass of coarse aggregate.

\[
\text{Mass CA} = 120 \times 0.63 \times 27 = 75.6 \text{ lb/ft}^3 = 2041 \text{ lb/yd}^3
\]

NMAS 19 mm
FM = 2.7
Dry rodded unit weight = 120 lb/ft³

lb of coarse aggregate per cubic yard of concrete
Coarse Aggregate Adjustment

- increase CA volume by 10% to reduce slump:
  e.g., pavement construction
- decrease CA volume by 10% to increase slump:
  e.g., for placement by pumping
### Step 4. Air Entrainment Requirements

<table>
<thead>
<tr>
<th>Nominal</th>
<th>Maximum Aggregate Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5 mm</td>
<td>12.5 mm</td>
</tr>
<tr>
<td>(3/8 in.)</td>
<td>(1/2 in.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Non-air-entrained concrete</th>
<th>3</th>
<th>2.5</th>
<th>2</th>
<th>1.5</th>
<th>1</th>
<th>0.5</th>
<th>0.3</th>
<th>0.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-entrained concrete**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild Exposure</td>
<td>4.5</td>
<td>4.0</td>
<td>3.5</td>
<td>3.0</td>
<td>2.5</td>
<td>2.0</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Moderate Exposure</td>
<td>6.0</td>
<td>5.5</td>
<td><strong>5.0</strong></td>
<td>4.5</td>
<td>4.5</td>
<td>4.0</td>
<td>3.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Severe Exposure</td>
<td>7.5</td>
<td>7.0</td>
<td>6.0</td>
<td>6.0</td>
<td>5.5</td>
<td>5.0</td>
<td>4.5</td>
<td>4.0</td>
</tr>
</tbody>
</table>

*American Concrete Institute (ACI 211.1 and ACI 318).*

**The air content in job specifications should be specified to be delivered within −1 to +2 percentage points of the table target value for moderate and severe exposures.

19 mm
Moderate exposure
Estimated air for non-air-entrained concrete
Needed for volumetric analysis
Step 5. Workability Requirements

Slump is ease of placing, consolidating, and finishing.

- highest slump with no **segregation** or excessive bleeding
  - CA migrates to bottom & water migrates to top

- Increase slump with
  - admixtures
  - rounded aggregates

<table>
<thead>
<tr>
<th>Concrete Construction</th>
<th>Maximum**</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced foundation walls and footings</td>
<td>75 (3)</td>
<td>25 (1)</td>
</tr>
<tr>
<td>Plain footings, caissons, and substructure walls</td>
<td>75 (3)</td>
<td>25 (1)</td>
</tr>
<tr>
<td>Beams and reinforced walls</td>
<td>100 (4)</td>
<td>25 (1)</td>
</tr>
<tr>
<td>Building columns</td>
<td>100 (4)</td>
<td>25 (1)</td>
</tr>
<tr>
<td>Pavements and slabs</td>
<td>75 (3)</td>
<td>25 (1)</td>
</tr>
<tr>
<td>Mass concrete</td>
<td>75 (3)</td>
<td>25 (1)</td>
</tr>
</tbody>
</table>
Step 6. Water Content

- For a given slump it depends on maximum size and shape of aggregates
- Table 7.8: for angular shaped CA
  - reduce water requirement for other shapes
- Considers SSD condition (adjust in step 10)

- Never let workers add water in truck or at the jobsite
Step 7. Cement Content

- Check minimum requirements
  - Flatwork

\[ W_{\text{cement}} = \frac{W_{\text{water}}}{W/C} \]

\[ W_{\text{cement}} = \frac{280}{0.45} = 622 \text{ lb/yard}^3 \]

- severe exposure – minimum of 334 kg/m\(^3\) (564 lb/yard\(^3\))
- under water minimum of 385 kg/m\(^3\) (650 lb/yard\(^3\))
Step 8. Admixtures

- follow instructions from manufacturers
- generally small quantities
  - volume or mass should be considered in mix proportioning
Step 9. Fine Aggregate Requirements

\[ V_{\text{concrete}} = V_{\text{water}} + V_{\text{cement}} + V_{\text{air}} + V_{\text{coarse aggregate}} + V_{\text{fine aggregate}} \]

Assume \( V_{\text{concrete}} = 1 \) either \( m^3 \) or \( yd^3 \) of concrete

Metric
\[ V_{\text{fine aggregate}} = 1 - V_{\text{water}} - V_{\text{cement}} - V_{\text{air}} - V_{\text{coarse aggregate}} \]

U.S. customary
\[ V_{\text{fine aggregate}} = 27 - V_{\text{water}} - V_{\text{cement}} - V_{\text{air}} - V_{\text{coarse aggregate}} \]

Mass (or weight) of components used with density (unit weight) to determine volume of each component
**Step 10. Moisture Corrections**

- Adjust the weight of water and aggregates to account for the existing moisture content of the aggregate
  - wet aggregate weighs more than dry agg. (we used dry density)
  - we assumed SSD and must adjust free mix water if not SSD.

<table>
<thead>
<tr>
<th></th>
<th>Mass</th>
<th>Absorption</th>
<th>Moisture content</th>
<th>Mass with moisture</th>
<th>Free moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td>2041</td>
<td>0.80%</td>
<td>2.30%</td>
<td>2088</td>
<td>31</td>
</tr>
<tr>
<td>FA</td>
<td>1019</td>
<td>1.70%</td>
<td>4.50%</td>
<td>1065</td>
<td>29</td>
</tr>
</tbody>
</table>

New water weight = 280 – 60 = 220

| Total excess moisture | 60 |

*Adjusted aggregate weights*
Step 11. Trial Mixes

- check proportions with trial batches
  - air content
  - slump
  - 28 day compressive strength:
    - 3 cylinders – 6” Dia. x 12” H
  - adjust for optimum workability & economy
7.2 Mixing, Placing, & Handling of PCC

**Batching**
- Measuring correct proportions of components and placing in the mixer
- By weight is more accurate because air voids don't matter

**Mixing**
- Until uniform appearance
- Usually batch mixers (one at a time), but sometimes continuous (conveyors automatically feed components into mixer)
- Usually start with 10% of the water in the mixer, then solids with 80% of the water, and then remaining water
Central Batch Concrete Plant

- Mix ingredients in predetermined proportions
- Place in trucks
Slipform Paver
Sampling and Testing

- Pull samples at the job site
- Test on site
  - Slump
  - Air content
- Prepare samples for later testing
  - Cylinders
  - Beams
Air Content Test for Fresh Concrete

- Measures total air content (entrapped and entrained)
- Only entrained is good but we can't tell the difference from this test

1) Pressure Method
2) Volumetric Method
3) Gravimetric Method
4) Chase Air Indicator
Vibration of Concrete

• Consolidation (compaction) complete before initial set

• Manually by
  – ramming
  – tamping

• Mechanically using vibrators
  – Internal – poker
    • 5 sec to 2 min in one spot
    • <10 sec. typical
    • avoid segregation
    • through entire depth
    • penetrate layer below if still plastic
  – External –
    • tables and rollers for precast concrete
7.3 Curing Concrete

- Maintain moisture and temperature in the concrete to promote continued hydration and strength gain
- Hydration will resume if curing is stopped and resumed
- Curing affects:
  - durability
  - strength
  - water-tightness
  - abrasion resistance
  - volumetric stability
  - resistance to freezing and thawing
  - resistance to de-icing chemicals
Compressive strength of PCC at different ages & curing levels
7.4 Properties of Hardened Concrete

1. Early Volume Change
2. Creep
3. Permeability
4. Stress-Strain Relationship
Early Volume Change

• Plastic shrinkage – plastic concrete – 1% shrinkage from evaporation – cracking

• Drying shrinkage – after setting if not cured – cracking

• If wetted continuously – very slight swelling

• Curling from non-uniform drying
Creep

• long term, gradual, deformation under sustained load

• small strain but transfers load from concrete to steel in beams & columns
Permeability

- As w/c = 0.3 to 0.7:
  coefficient of permeability increases by a factor of 1000
- Caused by voids: poor consolidation & excess water
- Allows water & chemicals to penetrate
- Reduces durability & resistance to frost, alkali reactivity, and other chemical attacks
**Stress-Strain Relationship**

- Typical $\sigma$-$\varepsilon$ of 28 day concrete
- Increasing w/c decreases both strength ($f'_c$) and stiffness ($E$)
- Stronger concrete is more brittle
- Almost linear at small strains
• Usually use chord modulus for $E_c$
  – Very small strain and 40% $s_u$ or specific strain (1%)
  – 3 or 4 loading cycles
• $E_c = 2000 - 6000$ ksi, Poisson's ratio, $n = 0.11 - 0.21$
• ACI building code:
  \[ E_c = 4731 \sqrt{f'_c}, \text{ MPa} \]
  \[ E_c = 57000 \sqrt{f'_c}, \text{ psi} \]
Compressive Strength ($f'_c$) Test

- Most common test by far (even more than slump)
- 2:1 cylinders cast in 3 layers rodded 25 times each layer and cured at 95% humidity
- Or specimens are cored from finished structure
- 7 day = 60% of 28 day and 28 day = 80% ultimate strength
- Typical compressive strength is 3,000 - 6,000 psi
• 6” diameter x 12” long is ASTM standard and close approximate to actual structures

➢ Smaller sizes (4” x 8”, 3” x 6”)
  • usually stronger because smaller volume has fewer defects in specimen
  • use more specimens because more variation and less representative
  • ease of handling, less accidental damage, less concrete, smaller machine, less curing, & storage space
Split Tension Test

• To measure tensile strength
• about 10% of $f'_c$

\[ T = \frac{2P}{\pi Ld} \]

where

\[ T = \text{tensile strength, MPa (psi)}, \]
\[ P = \text{load at failure, N (psi)}, \]
\[ L = \text{length of specimen, mm (in.)}, \text{ and} \]
\[ d = \text{diameter of specimen, mm (in.)} \]
Flexural Strength

Important for pavements

Simply supported 6” x 6” beam loaded on the 1/3 points

\[ R = \frac{Mc}{I} = \frac{PL}{bd^2} \]

where

- \( R \) = flexure strength, MPa (psi),
- \( M \) = maximum bending moment = \( PL/6 \), N.mm (lb.in.),
- \( c = d/2 \), mm (in.),
- \( I \) = moment of inertia = \( bd^3/12 \), mm\(^4\) (in.\(^4\)),
- \( P \) = maximum applied load, which is distributed evenly (1/2 to each) over the two loading points, N (lb),
- \( L \) = span length, mm (in.),
- \( b \) = average width of specimen, mm (in.), and
- \( d \) = average depth of specimen, mm (in.)

**Metric (MPa)**

\[ R = (0.62 \text{ to } 0.83) \sqrt{f'_c} \]

**US Customary (psi)**

\[ R = (7.5 \text{ to } 10) \sqrt{f'_c} \]
Lightweight Concrete

• Floating concrete (ASCE concrete canoe)
• Costs more but need less because of reduced weight

Heavyweight Concrete

• Massive walls for nuclear, medical, and atomic shielding
• Very heavy weight aggregates (barite, magnetite, hematite, lead, steel)
High-Strength Concrete

- At least 6,000 psi strength with normal weight aggregates
- Very low w/c with superplasticizers up to 20,000 psi
Shrinkage Compensating

• Alumina causes a little expansion to compensate for normal shrinkage
  – Type K cement

Polymer Concrete

• Very quick set (1 hr.) or super high strength ( >20,000 psi)
• Polymer-PC concrete
  – latex is mixed with Portland cement
• Roller Compacted Concrete (RCC)

• No slump concrete compacted in-place by heavy equipment
• Much cheaper for many reasons
• Large dams
• Parking areas