Concrete Properties and Mix Design

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Making the world’s best pavements even better!
Acknowledgements

The following sources of information were used in the development of this module:

- ACPA
- PCA, “Design and Control of Concrete Mixtures”
- American Concrete Institute (ACI)
- Dr. Peter Taylor, CP Tech Center
- Dr. Ken Hover, Cornell University
Future Directions: Concrete Pavement Road Map

- 12 strategic and coordinated research tracks are contained in the CP Road Map – The Long-Term Plan for Concrete Pavement Research and Technology.
- This document represents a comprehensive plan for research and implementation with input from all major stakeholders.
- Approximately 250 defined research statements designed to “strategize and coordinate” concrete pavement research efforts.
Track 1: Performance-Based Concrete Pavement Mix Design System

The final product of this track will be a practical yet innovative concrete mix design procedure with new equipment, consensus target values, common laboratory procedures, and full integration with both structural design and field quality control – a lab of the future.

This project is currently underway as a joint effort between ACPA, PCA, FHWA and State Highway Agencies. A 2-3 year effort is anticipated, but process improvements will be released as developed.
Definitions

- The water/cement ratio (w/c) is the weight of water divided by the weight of cement.
- When supplementary cementitious materials (SCM’s) are used, the w/c is referred to as the water/cementitious materials ratio (w/cm) and is the weight of water divided by the weight of cement and SCM’s.
- These terms are sometimes used interchangeably.
What is not Covered in Detail?

The following points are not addressed in detail and are the subject of subsequent webinars:

- Concrete mix optimization.
- Optimizing aggregate gradation.
- Materials incompatibility issues.
- Concrete mix evaluation and troubleshooting.
Mix Design

- Mix design is the process of determining required and specifiable characteristics of a concrete mixture.
  - Prescriptive approach (limits on materials).
  - Performance approach (desirable characteristics).
- Mix design requirements are based on intended use, environment, etc.
Mix Design Addresses:

Environment

Intended Use
Basic Mix Proportioning

Mix proportioning is the process of determining the quantities of concrete ingredients that meet the mix design criteria.

- 9–15% Cement
- 15–16% Water
- 25–35% Fine aggregate
- 30–45% Coarse aggregate

SCM’s and admixtures

- Paste (cement + water)
- Mortar (paste + fine aggregate)
- Concrete (mortar + coarse aggregate)
Mix Proportioning

The primary considerations in mix proportioning include:

- The ability to continually meet or exceed specifications (durability and strength).
- Economy.
- Readily available supply of raw materials.
Generate mix proportions “on paper” as a starting point.
Laboratory trial batches required to verify and optimize proportions.
There is no substitute for trial batches!
- Test to determine compatibility of materials and to avoid numerous other potential problems.
- Field trials using regular batching/mixing is the final verification.
A typical laboratory testing plan includes the following mix characteristics:

- Workability.
- Strength.
- Plastic air content.
- Unit weight.
- Permeability.
- Coefficient of thermal expansion.
- Others depending on the mix design requirements.

The relative size and importance of a project determines which of these tests are performed.
Field Testing Plan

**Phase 1**
Prior to production (plant set-up and calibration)

**Phase 2**
Mix design evaluation (full scale)

**Phase 3**
Mixer uniformity testing (consistency).

These procedures are suggested when a new mix is being evaluated, regardless of project size.
Calculating Mix Proportions

Mix design and proportioning requires the following selections:

- Binder types (cement, SCM).
- Binder percentages.
- Aggregate types.
- Aggregate gradation.
- Maximum aggregate size.
- Workability.
- Water/cementitious materials ratio.
- Target entrained air-void system.
- Appropriate admixtures and dosage.
Methods for Proportioning Concrete Mixes

- Water-cement ratio method.
- Weight method.
- Absolute volume method (ACI 211.1).
- Field experience (statistical data).
- New methodologies currently under development
ACI 211.1 Mix Proportioning

Mix Design Requirements
Materials Characteristics
Production Technology

Controlling Relationships

General trends suggested by ACI 211.1

Specifics from user data & experience!
### ACI 211.1 Concrete Mix Proportioning

<table>
<thead>
<tr>
<th>Mixture Proportions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water</strong></td>
</tr>
<tr>
<td><strong>Cement</strong></td>
</tr>
<tr>
<td><strong>Fly ash</strong></td>
</tr>
<tr>
<td><strong>Coarse Aggregate</strong></td>
</tr>
<tr>
<td><strong>Intermediate Aggregate</strong></td>
</tr>
<tr>
<td><strong>Fine Aggregate</strong></td>
</tr>
<tr>
<td><strong>Air content</strong></td>
</tr>
<tr>
<td><strong>Air-entraining admixture</strong></td>
</tr>
<tr>
<td><strong>Water-reducing admixture</strong></td>
</tr>
</tbody>
</table>
Calculations and Worksheets

- Clear accounting/record keeping is **CRITICAL**!
- Round-off guidelines:
  - No need to be more accurate than the scales...

<table>
<thead>
<tr>
<th>Batch Weight/Cubic Yard</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate</td>
<td>nearest 10 lbs</td>
</tr>
<tr>
<td>Cement</td>
<td>nearest 5 lbs</td>
</tr>
<tr>
<td>Water</td>
<td>nearest 5 lbs</td>
</tr>
<tr>
<td>Volumes/Cubic Yard</td>
<td>2 decimal places</td>
</tr>
</tbody>
</table>
Example Using the Absolute Volume Method (ACI 211.1)

- Although not the only way to do a quality mix design, the ACI procedure is widely used.
- The absolute volume method specified by ACI 211.1 consists of 8 steps plus adjustments.
- The goal of the following example is to show the basic steps and how important minor changes in proportions can be on workability, durability, strength, etc.
Step 1: Specify Required Strength

- The strength requirements are based on specifications and design assumptions.
- Strength may be specified as compressive strength \( f'c \) or flexural strength (MR) or both.
- Keep in mind that variability exists in both materials and testing procedures.

Example:

4500 psi at 28 days
Step 2: Determine Required w/c Ratio

- Establish w/c based on strength and durability requirements.
- The most limiting criteria is selected (lowest w/c-ratio, highest strength).
- Ensure w/c ratio satisfies both the strength and durability requirements.

Example:
4500 psi at 28 days
w/c ratio = 0.44
## Requirements for Exposure Conditions

<table>
<thead>
<tr>
<th>Exposure condition</th>
<th>Maximum w/c-ratio by mass</th>
<th>Min. strength, $f'_{c}$, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>No freeze-thaw, deicers, aggressive substances</td>
<td>Select for strength, workability, and finishing needs</td>
<td>Select for structural requirements</td>
</tr>
<tr>
<td>Concrete with low permeability; exposed to water</td>
<td>0.50</td>
<td>4000</td>
</tr>
<tr>
<td>Concrete exposed to freezing and thawing in a moist condition or deicers</td>
<td>0.45</td>
<td>4500</td>
</tr>
<tr>
<td>For corrosion protection for reinforced concrete exposed to chlorides</td>
<td>0.40</td>
<td>5000</td>
</tr>
</tbody>
</table>
## Requirement for Concrete Exposed to Sulfates

<table>
<thead>
<tr>
<th>Sulfate exposure</th>
<th>Sulfate ((SO_4)) in soil, % by mass</th>
<th>Sulfate ((SO_4)) in water, ppm</th>
<th>Cement type</th>
<th>Maximum w/c-ratio, by mass</th>
<th>Minimum strength, (f'_c), psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible</td>
<td>Less than 0.10</td>
<td>Less than 150</td>
<td>No special type required</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.10 to 0.20</td>
<td>150 to 1500</td>
<td>II, MS, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)</td>
<td>0.50</td>
<td>4000</td>
</tr>
<tr>
<td>Severe</td>
<td>0.20 to 2.00</td>
<td>1500 to 10,000</td>
<td>V, HS</td>
<td>0.45</td>
<td>4500</td>
</tr>
<tr>
<td>Very severe</td>
<td>Over 2.00</td>
<td>Over 10,000</td>
<td>V, HS</td>
<td>0.40</td>
<td>5000</td>
</tr>
</tbody>
</table>
## Relationship Between w/cm Ratio and Strength

<table>
<thead>
<tr>
<th>Compressive strength at 28 days, psi</th>
<th>Water-cementitious materials ratio by mass</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Non-air-entrained concrete</td>
<td>Air-entrained concrete</td>
</tr>
<tr>
<td>7000</td>
<td>0.33</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>0.41</td>
<td>0.32</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>
<tr>
<td>2000</td>
<td>0.82</td>
<td>0.74</td>
<td></td>
</tr>
</tbody>
</table>

**Air-entrained concrete**

**Non-air-entrained concrete**
Compressive Strength vs. w/cm Ratio

28-day compressive strength, MPa

Water to cementitious materials ratio

28-day compressive strength, 1000 psi

Non-air-entrained concrete
Air-entrained concrete
Step 3: Determine Aggregate Grading Requirements

The maximum aggregate size (MAS) depends on a number of factors.

- Availability of materials.
- Economy.
- Placement method.
- Required workability.

Note that many factors are influenced by this decision.

Example:

4500 psi at 28 days
w/c ratio = 0.44
MAS = 1.5 in.
Nominal MAS = 1.0 in.
Definitions

- The maximum aggregate size is the smallest sieve through which 100 percent of the sample must pass.
- The nominal maximum aggregate size is the smallest sieve size through which the majority of the sample passes (up to 15 percent can be retained).
- The bulk volume of the coarse aggregate is based on the dry rodded aggregate volume and empirical data related to workability and the FM of the sand.
- The fineness modulus (FM) of the fine aggregate is defined as the cumulative percent retained on the 3/8 in., #4, #8, #16, #30, #50 and #100 sieves/100.
Aggregate Grading Basics

Aggregate

Paste
Aggregates are the most dimensionally stable and least expensive ingredient. It is desirable to minimize the amount of paste required by optimizing aggregate gradation. Optimized gradation simply means combining available aggregates in the proper proportions so that void space is minimized.
Economy requires use of largest practical size.
Durability also suggests largest practical size.
General rules:
- 1/5 narrowest dimension between forms or molds
- 1/3 depth of slabs
## Bulk Volume of Coarse Aggregate

<table>
<thead>
<tr>
<th>Maximum size of aggregate, (in.)</th>
<th>Fineness modulus of sand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.40</td>
</tr>
<tr>
<td>3/8</td>
<td>0.50</td>
</tr>
<tr>
<td>1/2</td>
<td>0.59</td>
</tr>
<tr>
<td>3/4</td>
<td>0.66</td>
</tr>
<tr>
<td>1</td>
<td>0.71</td>
</tr>
<tr>
<td>1-1/2</td>
<td>0.75</td>
</tr>
<tr>
<td>2</td>
<td>0.78</td>
</tr>
<tr>
<td>3</td>
<td>0.82</td>
</tr>
<tr>
<td>6</td>
<td>0.87</td>
</tr>
</tbody>
</table>
Bulk Volume of Coarse Aggregate

![Graph showing the bulk volume of coarse aggregate vs. nominal maximum aggregate size. The graph includes curves for different fineness modulus values: 2.4, 2.6, 2.8, and 3.0.](image)
Calculate the Absolute Volume of Coarse Aggregate per yd$^3$ of Concrete

Given: The bulk volume of coarse aggregate = 0.73
    Bulk density = 98 lb/ft$^3$ (dry rodded)
    Relative density = 2.65
    Water = 62.4 lb/ft$^3$

0.73 x 27 = 19.7 ft$^3$
19.7 x 98 = 1930 lb
Absolute volume =
1930/(2.65 x 62.4) = 11.67
11.67/27 = 0.43

The coarse aggregate occupies 43% of concrete volume
Step 4: Establish Target Air Content

Establish target air content based on exposure conditions and nominal maximum aggregate size.

Example:

4500 psi at 28 days

w/c ratio = 0.44

MAS = 1.5 in.
Nominal MAS = 1.0 in.

6.0% air
Air Content and Aggregate Size

The graph shows the relationship between the nominal maximum aggregate size (in inches and millimeters) and the target air content, expressed as a percentage. The graph includes data points for different exposure conditions:

- **Severe exposure (deicers)**: The points are denoted by red diamonds.
- **Moderate exposure**: The points are denoted by blue triangles.
- **Mild exposure**: The points are denoted by green circles.
- **Non-air-entrained concrete**: The points are denoted by purple squares.

The graph illustrates how the target air content decreases as the nominal maximum aggregate size increases, with distinct trends observed for each exposure condition.
Step 5: Establish Target Workability

Target workability (in terms of slump) is based on method of placement.

Example:

4500 psi at 28 days
w/c ratio = 0.44
MAS = 1.5 in.
Nominal MAS = 1.0 in.
6.0% air
Slump = 1.5 in.
Workability Requirements

Increased risk of segregation

0 25 50 75 100 125 150 175 200

Slump (mm)

Increased risk of unworkable concrete

0 1 2 3 4 5 6 7 8

Slump (in.)

Pre-plasticized (ACI 301)

Concrete floors (See ACI 302)
General purpose concrete (SEE ACI 301)

Pavement and slabs (ACI 211.1)

Beams, reinforced walls and building columns (ACI 211.1)

Plain and reinforced foundation & substructure walls, footings, and caissons (ACI 211.1)

Mass concrete (ACI 211.1)

Various slip-formed applications

"Zero Slump" or "No Slump" concrete

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# Recommended Slump Ranges

<table>
<thead>
<tr>
<th>Concrete construction</th>
<th>Slump, in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
</tr>
<tr>
<td>Reinforced foundation walls and footings</td>
<td>3</td>
</tr>
<tr>
<td>Plain footings, caissons, and substructure walls</td>
<td>3</td>
</tr>
<tr>
<td>Beams and reinforced walls</td>
<td>4</td>
</tr>
<tr>
<td>Building columns</td>
<td>4</td>
</tr>
<tr>
<td><strong>Pavements and slabs</strong></td>
<td><strong>3</strong></td>
</tr>
<tr>
<td>Mass concrete</td>
<td>3</td>
</tr>
</tbody>
</table>
Step 6: Determine Water Requirement

The amount of water to be added to the mix is a function of the nominal maximum aggregate size and required slump.

Example:

4500 psi at 28 days
w/c ratio = 0.44
MAS = 1.5 in.
Nominal MAS = 1.0 in.
6.0% air
Slump = 1.5 in.
265 lb. water/cubic yard
Approximate Water Requirements for Various Aggregate Sizes and Slumps

- 250 to 175 mm (6 to 7 in.) slump
- 75 to 100 mm (3 to 4 in.) slump
- 25 to 50 mm (1 to 2 in.) slump

Nominal maximum aggregate size, in.

Nominal maximum aggregate size, mm

Water requirement (kg/m³)

Water requirement (lb/yd³)
## Water Requirement Adjustments

### Adjustments to Basic Water Requirement

<table>
<thead>
<tr>
<th>Water adjustment</th>
<th>Water adjustment range</th>
<th>Adjustment Percentage Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Aggregate shape &amp; texture</td>
<td>(-5 to +5%)</td>
<td></td>
</tr>
<tr>
<td>Baseline = cubical crushed stone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Rounded deduct 0-3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Elongated add 0-3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Combined aggregate grading</td>
<td>(-10 to +10%)</td>
<td></td>
</tr>
<tr>
<td>(0 for ACI 211.1 Assumptions)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Air entraining admixture</td>
<td>(-10 to 0%)</td>
<td></td>
</tr>
<tr>
<td>Effect varies with higher air content and other factors. Zero at 2% air, 10% for about 6% air.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Normal range water reducing admixture</td>
<td>(-10 to -5%)</td>
<td></td>
</tr>
<tr>
<td>5. Mid-range water reducing admixture (MRWRA)</td>
<td>(-15 to -8%)</td>
<td></td>
</tr>
<tr>
<td>6. High-range water reducing admixture (HRWRA = Superplasticizer)</td>
<td>(-30 to -12%)</td>
<td></td>
</tr>
<tr>
<td>7. Mineral Admixtures</td>
<td>(-10 to +15%)</td>
<td></td>
</tr>
<tr>
<td>Flyash to Silica Fume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Other factors such as: w/c, cement fineness, temperature</td>
<td>(-10 to +10%)</td>
<td></td>
</tr>
<tr>
<td>9. Cumulative adjustment percentage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>= sum of all values.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Suggested maximum reduction recognizing overlapping effects of individual factors</td>
<td>-30%</td>
<td></td>
</tr>
<tr>
<td>11. Water Adjustment Factor</td>
<td>= 1.00 + (sum/100)</td>
<td></td>
</tr>
</tbody>
</table>
Step 7: Determine Cementitious Materials Content

- The cementitious materials content is based on the previously determined w/c ratio and the total water content.
Calculate Required Cementitious Materials Content

Cement Content = \[ \frac{\text{Required Water Content}}{\text{Water-Cement Ratio}} \]

\[
\begin{align*}
265 \text{ lb/yd}^3 \text{ water} & \quad \frac{\text{water}}{0.44 \text{ w/c ratio}} \\
& = 602 \text{ lb. cement per yd}^3 \\
& \text{of concrete}
\end{align*}
\]

**Example:**

- 4500 psi at 28 days
- w/c ratio = 0.44
- MAS = 1.5 in.
- Nominal MAS = 1.0 in.
- 6.0% air
- Slump = 1.5 in.
- 265 lb. water
- 602 lb. Cement(itious)
Minimum Cementing Materials Content for Flatwork

<table>
<thead>
<tr>
<th>Nominal maximum size of aggregate, in.</th>
<th>Cementing materials, lb/yd³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1½</td>
<td>470</td>
</tr>
<tr>
<td>1</td>
<td>520</td>
</tr>
<tr>
<td>¾</td>
<td>540</td>
</tr>
<tr>
<td>½</td>
<td>590</td>
</tr>
<tr>
<td>3/8</td>
<td>610</td>
</tr>
</tbody>
</table>
## Cementitious Materials Requirements for Concrete Exposed to Deicing Chemicals

<table>
<thead>
<tr>
<th>Cementitious materials</th>
<th>Maximum of cementitious materials, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash and natural pozzolans</td>
<td>25 (25)</td>
</tr>
<tr>
<td>Slag</td>
<td>40 (50)</td>
</tr>
<tr>
<td>Silica fume</td>
<td>0 (10)</td>
</tr>
<tr>
<td>Total of fly ash, slag, silica fume and natural pozzolans</td>
<td>50 (50)</td>
</tr>
<tr>
<td>Total of natural pozzolans and silica fume</td>
<td>*(35)</td>
</tr>
</tbody>
</table>

( ) denotes ACI recommendations
Non-bracketed numbers are ACPA recommendations
Step 8: Determine Fine Aggregate Content

- Determining the fine aggregate content is based on the previous calculations for volume of water, coarse aggregate, entrained air and cement.
- The following slides illustrate the calculations required to “finish” the mix proportioning process.
Absolute Volume Computation for Fine Aggregate Content

Water = \frac{265}{1 \cdot 62.4} = 4.25 \text{ ft}^3

Air = \frac{6.0 \cdot 27}{100} = 1.62 \text{ ft}^3

Cement = \frac{602}{3.15 \cdot 62.4} = 3.06 \text{ ft}^3

Coarse aggregate = \frac{1930}{2.65 \cdot 62.4} = 11.67 \text{ ft}^3

Subtotal = 20.60 \text{ ft}^3

Admixture dosages are too small to account for in the volumetric method, but play a vital role in the mix.
Absolute Volume Computation for Fine Aggregate Content

Fine aggregate volume = 27.00 – 20.60 = 6.40 ft³

Fine aggregate mass = 6.40 • 2.65 • 62.4 = 1058 lb
The following weights (mass) of materials form the basis for a trial batch:

- Coarse aggregate = 1930 lbs./cy
- Fine Aggregate = 1058 lbs./cy
- Cement = 602 lbs./cy
- Water = 265 lbs./cy
- Air content = 6 percent

What assumptions were made and what are we missing?
We now have the proportions of a **trial batch**.

Job not done until the batch is **tested** and **adjusted**.

- Adjust for aggregate moisture.
- Make batches: check workability, freedom from segregation, finishing, etc.
- Make appropriate adjustments and rebatch.
- If satisfactory fresh properties, make samples for hardened properties.
Adjusting Properties

- Subject to the results of the trial batches, adjustments to the mix are likely.
- The most typical mix proportion adjustments are made to control or affect:
  - Workability.
  - Stiffening/setting.
  - Bleeding.
  - Air void system.
  - Unit weight.
  - Others.
Effect of w/c Ratio on Strength

- Compressive Strength, psi
  - 7 days
  - 28 days

- Water-cementitious materials ratio
  - 0.2 to 0.8

- 0 to 12,000 psi

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Estimated Effects of Added Water

- Adding 1 gal. of water to 1 yd$^3$ of concrete:
  - Increases slump 1 inch.
  - Decreases compressive strength by 200 psi.
  - Wastes the effect of 1/4 sack (23.5 lbs) of cement.
  - Increases shrinkage by 10%.
  - Increases permeability by up to 50%.
Summary

- Concrete mix design establishes the requirements (strength, air, etc.).
- Mix proportioning determines the amount of each material required to meet the mix design criteria.
- Field trials are required to validate the mix proportioning.
- Strength, durability and economy all play a major role in mix design and proportioning.