CEAS - Civil Engineering and Mechanics

CE 431 Materials of Construction

Lecture 11b

Portland Cement Concrete: Concrete Mix Design

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Concrete Mix Design

The requirements for concrete performance can be different depending on the end use and the production process. The proportioning and choice of concrete ingredients should be such that the appropriate requirements are met satisfactorily. taking into account the properties of the fresh and hardened material and economy (portland cement is the most expensive ingredient).

First, the choice of ingredients (type of cement, aggregates, admixtures) should be made.

The second stage should be proportioning of the ingredients, which include the amount of cement, water, and admixtures and the grading and content of the aggregates.

Concrete Mix Design

The guiding principle is to meet the criteria for design strength and durability. In both cases, the *w/c* ratio is the primary parameter.

Allowance must be made for the variability in strength, which can be described by Gaussian statistics. Thus, the average concrete strength taken for the mix design should be higher than the specified strength, so that the probability of concrete strength falling below the specified value will be small, usually less than 1%. Relations between average and specified strength are usually included in national and international codes, such as the ACI Building Code. The difference between the average and specified strength values is in the range of 3 to 10 MPa. depending on the strength level and the variability in the production process.

Common Technical Requirements for Concrete

Desired Property	Typical application (s)	Materials Section
High workability (without segregation of components)	1. Underwater placements 2. Difficult placement, deep forms, congested reinforcement 3. Self-leveling floors	Water-reducing admixtures Mineral admixtures Small-sized aggregates
Rapid setting	1. Shotcreting	Accelerating admixtures
Slow setting	1. Elimination of cold joints 2. Avoidance of form deflection cracking 3. Offset high temperatures for easier placement	Retarding admixtures
High early strength	1. Early form removal (slip casting, precasiing) 2. Winter concreting 3. Prestressing	High early strength cement (TypeIII) Water-reducing admixtures (plasticizers, superplasticizes) Acceleration admixtures
Low heat of hydration	1. Mass construction: (a) thick slabs, walls (b) dams	Moderate heat of hydration cement (Type II). Blended cement (Type IPM) or mineral admixtures Low heat of hydration cement (Type IV) Blended cement (Type IP) or mineral admixtures

Common Technical Requirements for Concrete

Desired Property	Typical application (s)	Materials Section
High durability	1. Frost resistance 2. Sulfate resistance (sea water, groundwater) 3. Alkai-aggregate resistance	Air-entraining admixtures Sulfate-resistant cement (Type II or V) Blended cements or mineral admixtures; Water-reducing agents; Mineral admixtures; Low alkali cements Unreactive aggregates
Low permeability	1. Water-retaining structures 2. Gas-retaining structures 3. General durability	Water-reducing admixtures Mineral admixtures
Dimensional stability	1. Water-and gas-retaining structures 2. High-rise construction 3. Critical dimensioning	Water-reducing admixtures High modulus aggregates
Low thermal expansion	1. Refractory applications 2. Wide variations in ambient temperatures	Aggregates with low thermal expansion
Low density	1. High rise construction 2. Insulating concretes	Lightweight aggregates
High density	1. Radiation shielding 2. Counter-weighting	Heavyweight aggregates
Low thermal conductivity	1. Insulating concretes	Lightweight aggregate

Concrete Mix Design

Guidance for durability criteria is based on exposure conditions expected; then requirements may be set both for maximum *w/c* ratio and minimum air content when freezing is expected.

Such requirements are usually specified by local standards. Of the two *w/c* ratios determined, on the basis of strength and exposure conditions, the lower one will be taken because it would fulfil both set of conditions.

The required consistency of the fresh concrete is controlled by the water content, which be determined for the specific aggregate used. The choice of consistency is specified in terms of the slump of the concrete, which is a function of the production process of the concrete and the concrete, which is a function of the production process of the concrete and the equipment to be used for its transportation and consolidation.

Requirements for Concrete Subjected to Harsh Exposure Conditions (CSA A23.1)

Exposure Classification	Exposure Condition	Typical Examples	Min. Specified 28-day Compressive Strength (MPa)	Max.Water: Cementing Materials Ratio	Air Content for 20 mm Aggregate Concrete (% Vol.)
C-l	Concrete for which protection against corrosion of reinforcement is deemed critical	Bridge decks, suspended parking floors and ramps: portions of marine structures located within the tidal zone	35	0.40	5-8
C-2	Concrete not falling under C-l but subjected to cycles of freezing and thawing	Pavements, side-walks, curbs, and gutters	32	0.45	5-8

Requirements for Concrete Subjected to Harsh Exposure Conditions (CSA A23.1)

Exposure Classification	Exposure Condition	Typical Examples	Min. Specified 28-day Compressive Strength (MPa)	Max.Water: Cementing Materials Ratio	Air Content for 20 mm Aggregate Concrete (% Vol.)
C-3	Concrete in a saturated condition, not falling under C-l and not subjected to cycles of freezing and thawing	Portions of marine structures permanently submerged	30	0.50	4-7
C-4	Concrete in a relatively dry condition, not falling under C-l and not subjected to cycles of freezing and thawing	Slabs on grade in heated buildings	25	0.55	4-7

Requirements for Concrete Subjected to Harsh Exposure Conditions (CSA A23.1)

Exposure Classification	Exposure Condition	Typical Examples	Min. Specified 28-day Compressive Strength (MPa)	Max.Water: Cementing Materials Ratio	Air Content for 20 mm Aggregate Concrete (% Vol.)
F-l	Concrete subjected to freezing and thawing in a saturated condition		30	0.50	5-8
F-2	Concrete subjected to freezing and thawing in an unsaturated condition		25	0.55	4-7

CONCRETE MIX DESIGN

Having established the *w/c* ratio and water content, the cement content (in units of mass, kilograms, per cubic meter of concrete) can be calculated.

At this stage the volume content of the aggregates can be determined as the difference between one cubic meter and the sum of the volumes of the cement and water calculated from their weight and density and the estimated content of air.

The last step will determine the distribution of the various fractions of the aggregate and the content of each fraction per unit volume of concrete (1 m^3).

CONCRETE MIX DESIGN

The grading should provide densest packing, but with sufficient content of fine materials to assure cohesiveness of the fresh mix. This will minimize the paste requirements and make more economical concrete. This is the stage at which different mix design procedures become available.

One of them, developed by the American Concrete Institute, Standard Practice for Selecting Proportions for Normal, Heavy-weight and Mass Concrete, is based on determining the volume of the coarse aggregate per unit volume of concrete as a function of the maximum size of coarse aggregate and the fineness modulus of the fine aggregate.

CONCRETE MIX DESIGN

Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91)

(Reapproved 2002)

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CONCRETE MIX DESIGN

A2.1 *Example 1* -- Example 1 presented in Section 6.2 will be solved here using metric units of measure. Required average strength will be 24 MPa with slump of 75 to 100 mm. The coarse aggregate has a nominal maximum size of 37.5 mm and dry-rodded mass of 1600 kg/m^3. As stated in Section 6.1, other properties of the ingredients are: cement -- Type I with specific gravity of 3.15; coarse aggregate -- bulk specific gravity 2.68 and absorption 0.5 percent; fine aggregate -- bulk specific gravity 2.64, absorption 0.7 percent, and fineness modulus 2.8.

Step 1.
Choice of slump

TABLE A1.5.3.1 — RECOMMENDED SLUMPS FOR VARIOUS TYPES OF CONSTRUCTION (SI)

Types of construction	Slump, mm	
	Maximum*	**Minimum**
Reinforced foundation walls and footings	75	25
Plain footings, caissons, and substructure walls	75	25
Beams and reinforced walls	100	25
Building columns	100	25
Pavements and slabs	75	25
Mass concrete	75	25

*May be increased 25 mm for methods of consolidation other than vibration

Step 2.
Choice of maximum size of aggregate

Large nominal maximum sizes of well graded aggregates have less voids than smaller sizes. Hence, concretes with the larger-sized aggregates require less mortar per unit volume of concrete. Generally, the nominal maximum size of aggregate should be the largest that is economically available and consistent with dimensions of the structure. In no event should the nominal maximum size exceed one-fifth of the narrowest dimension between sides of forms, one-third the depth of slabs, nor three-fourths of the minimum clear spacing between individual reinforcing bars, bundles of bars, or pretensioning strands. These limitations are sometimes

Step 3.
Estimation of mixing water and air content

TABLE A1.5.3.3 — APPROXIMATE MIXING WATER AND AIR CONTENT REQUIREMENTS FOR DIFFERENT SLUMPS AND NOMINAL MAXIMUM SIZES OF AGGREGATES (SI)

Slump, mm	Water, Kg/m³ of concrete for indicated nominal maximum sizes of aggregate							
	9.5*	12.5*	19*	25*	37.5*	50†*	75†‡	150†‡
Non-air-entrained concrete								
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	—
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1	0.5	0.3	0.2
Air-entrained concrete								
25 to 50	181	175	168	160	150	142	122	107
75 to 100	202	193	184	175	165	157	133	119
150 to 175	216	205	197	184	174	166	154	—
Recommended average§ total air content, percent for level of exposure:								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5**††	1.0**††
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5**††	3.0**††
Extreme exposure‡‡	7.5	7.0	6.0	6.0	5.5	5.0	4.5**††	4.0**††

*The quantities of mixing water given for air-entrained concrete are based on typical total air content requirements as shown for "moderate exposure" in the Table above. These quantities of mixing water are for use in computing cement contents for trial batches at 20 to 25 C. They are maximum for reasonably well-shaped angular aggregates graded within limits of accepted specifications. Rounded coarse aggregate will generally require 18 kg less water for non-air-entrained and 15 kg less for air-entrained concretes. The use of water-reducing chemcial admixtures. ASTM C 494, may also reduce mixing water by 5 percent or more. The volume of the liquid admixtures is included as part of the total volume of the mixing water.

†The slump values for concrete containing aggregate larger than 40 mm are based on slump tests made after removal of particles larger than 40 mm by wet-screenmg.

‡These quantities of mixing water are for use in computing cement factors for trial batches when 75 mm or 150 mm normal maximum size aggregate is used. They are average for reasonably well-shaped coarse aggregates, well-graded from coarse to fine.

§Additional recommendations for air-content and necessary tolerances on air content for control in the field are given in a number of ACI documents, including ACI 201, 345, 318, 301, and 302. ASTM C 94 for ready-mixed concrete also gives air content limits. The requirements in other documents may not always agree exactly so in proportioning concrete consideration must be given to selecting an air content that will meet the needs of the job and also meet the applicable specifications.

**For concrete containing large aggregates which will be wet-screened over the 40 mm sieve prior to testing for air content, the percentage of air expected in the 40 mm minus material should be as tabulated in the 40 mm column. However, initial proportioning calculations should include the air content as a percent of the whole.

††When using large aggregate in low cement factor concrete, air entrainment need not be detrimental to strength. In most cases mixing water requirement is reduced sufficiently to

Step 3. Estimation of mixing water and air content

A2.2.3 *Step* 3 -- The concrete will be non-air-entrained since the structure is not exposed to severe weathering. From Table A1.5.3.3, the estimated mixing water for a slump of 75 to 100 mm in non-air-entrained concrete made with 37.5 mm aggregate is found to be 181 kg/m^3.

Step 4.
Selection of water-cement ratio

TABLE A1.5.3.4(a) — RELATIONSHIPS BETWEEN WATER-CEMENT RATIO AND COMPRESSIVE STRENGTH OF CONCRETE (SI)

Compressive strength at 28 days, MPa*	Water-cement ratio, by mass	
	Non-air-entrained concrete	Air-entrained concrete
40	0.42	—
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

*Values are estimated average strengths for concrete containing not more than 2 percent air for non-air-entrained concrete and 6 percent total air content for air-entrained concrete. For a constant water-cement ratio, the strength of concrete is reduced as the air content is increased.

Strength is based on 152 x 305 mm cylinders moist-cured for 28 days in accordance with the sections on "Initial Curing" and "Curing of Cylinders for Checking the Adequacy of Laboratory Mixture Proportions for Strength or as the Basis for Acceptance or for Quality Control" of ASTM Method C 3 I for Making and Curmg Concrete Specimens in the Field. These are cylinders cured moist at 23 ± 1.7 C prior to testing.

The relationship in this Table assumes a nominal maximum aggregate size of about I9 to 25 mm. For a given source of aggregate, strength produced at a given water-cement ratio will increase as nominal maximum size of aggregate decreases; see Sections 3.4 and 5.3.2.

TABLE A1.5.3.4(b) — MAXIMUM PERMISSIBLE WATER-CEMENT RATIOS FOR CONCRETE IN SEVERE EXPOSURES (SI)*

Type of structure	Structure wet continuously or frequently and exposed to freezing and thawing†	Structure exposed to sea water or sulfates
Thin sections (railings, curbs, sills, ledges, ornamental work) and sections with less than 5 mm cover over stee	0.45	0.40‡
All other structures	0.50	0.45‡

*Based on ACI 201.2R.
†Concrete should also be air-entrained.
‡If sulfate resisting cement (Type II or Type V of ASTM C 150) is used, permissible water-cement ratio may be Increased by 0.05.

Step 4.
Selection of water-cement ratio

A2.2.4 *Step 4* -- The water-cement ratio for non-air-entrained concrete with a strength of 24 MPa is found from Table Al.5.3.4(a) to be 0.62.

Step 5.
Calculation of cement content

$$C = W / (W/C)$$

A2.2.5 *Step 5* -- From the information developed in Steps 3 and 4, the required cement content is found to be $181/0.62 = 292\ kg/m^3$.

Step 6.
Estimation of coarse aggregate content

TABLE A1.5.3.6 — VOLUME OF COARSE AGGREGATE PER UNIT OF VOLUME OF CONCRETE (SI)

Nominal maximum size of aggregate, mm	Volume of dry-rodded coarse aggregate* per unit volume of concrete for different fineness moduli† of fine aggregate			
	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

*Volumes are based on aggregates in dry-rodded condition as described in ASTM C 29.

These volumes are selected from empirical relationships to produce concrete with a degree of workability suitable for usual reinforced construction. For less workable concrete such as required for concrete pavement construction they may be increased about 10 percent. For more workable concrete. such as may sometimes be required when placement is to be by pumping, they may be reduced up to 10 percent.

†See ASTM Method 136 for calculation of fineness modulus.

For a fine aggregate having a fineness modulus of 2.8 and a 37.5 mm nominal maximum size of coarse aggregate, the table indicates that 0.71 m^3 of coarse aggregate, on a dry-rodded basis, may be used in each cubic meter of concrete. The required dry mass is, therefore:

$$0.71 \times 1600 = 1136 \text{ kg}$$

Step 7.
Estimation of fine aggregate content

TABLE A1.5.3.7.1 — FIRST ESTIMATE OF MASS OF FRESH CONCRETE (SI)

Nominal maximum size of aggregate, mm	First estimate of concrete unit mass, kg/m³*	
	Non-air-entrained concrete	Air-entrained concrete
9.5	2280	2200
12.5	2310	2230
19	2345	2275
25	2380	2290
37.5	2410	2350
50	2445	2345
75	2490	2405
150	2530	2435

*Values calculated by Eq. (A1.5.3.7) for concrete of medium richness (330 kg of cement per m3) and medium slump with aggregate specific gravity of 2.7. Water requirements based on values for 75 to 100 mm slump in Table A1.5.3.3. If desired, the estimate of unit mass may be refined as follows if necessary information is available: for each 5 kg difference in mixing water from the Table A1.5. 3.3 values for 75 to 100 mm slump, correct the mass per m^3 8 kg in the opposite direction; for each 20 kg difference in cement content from 330 kg, correct the mass per m^3 3 kg in the same direction; for each 0.1 by which aggregate specific gravity deviates from 2.7, correct the concrete mass 60 kg in the same direction. For air-entrained concrete the air content for severe exposure from Table A.1.5.3.3 was used. The mass can be increased 1 percent for each percent reduction in air content from that amount.

Step 7a.
Mass basis

A2.2.7.1 *Mass basis* -- From Table A1.5.3.7.1, the mass of a cubic meter of non-air-entrained concrete made with aggregate having a nominal maximum size of 37.5 mm is estimated to be 2410 kg. (For a first trial batch, exact adjustments of this value for usual differences in slump, cement factor, and aggregate specific gravity are not critical.) Masses already known are:

Water (net mixing)	181 kg
Cement	292 kg
Coarse aggregate	1136 kg
Total	1609 kg

The mass of fine aggregate, therefore, is estimated to be

$$2410 - 1609 = 801 \text{ kg}$$

Step 7b.
Absolute volume basis

A2.2.7.2 *Absolute volume basis* -- With the quantities of cement, water, and coarse aggregate established, and the approximate entrapped air content (as opposed to purposely entrained air) of 1 percent determined from Table Al.5.3.3, the sand content can be calculated as follows:

Volume of water $= \dfrac{181}{1000}$ $0.181\ m^3$

Solid volume of cement $= \dfrac{292}{3.15 \times 1000}$ $0.093\ m^3$

Step 7b. Absolute volume basis

Solid volume of coarse aggregate =	$\frac{1136}{2.68 \times 1000}$	0.424 m^3
Volume of entrapped air =	0.01 x 1.000	0.010 m^3
Total solid volume of ingredients except fine aggregate		0.708 m^3
Solid volume of fine aggregate required =	1.000 - 0.705	0.292 m^3
Required weight of dry = fiie aggregate	0.292 x 2.64 x 1000	771 kg

Step 7c.
Comparison of two methods

A2.2.7.3 Batch masses per cubic meter of concrete calculated on the two bases are compared below:

	Based on estimated concrete mass, kg	Based on absolute volume of ingredients, kg
Water (net mixing)	181	181
Cement	292	292
Coarse aggregate (dry)	1136	1136
Sand (dry)	801	771

Step 8.
Adjustments for aggregate moisture

A2.2.8 *Step 8* -- Tests indicate total moisture of 2 percent in the coarse aggregate and 6 percent in the fine aggregate. If the trial batch proportions based on assumed concrete mass are used, the adjusted aggregate masses become

Coarse aggregate (wet) = 1136(1.02) = 1159 kg
Fine aggregates (wet) = 801(1.06) = 849kg

Absorbed water does not become part of the mixing water and must be excluded from the adjustment in added water. Thus, surface water contributed by the coarse aggregate amounts to 2 - 0.5 = 1.5 percent; by the fine aggregate 6 - 0.7 = 5.3 percent. The estimated requirement for added water, therefore, becomes

$$181 - 1136(0.015) - 801(0.053) = 122 \text{ kg}$$

Step 8.
Adjustments for aggregate moisture

The estimated batch masses for a cubic meter of concrete are:

Water (to be added)	122 kg
Cement	292 kg
Coarse aggregate (wet)	1159 kg
Fine aggregate (wet)	849 kg
Total	2422 kg

Step 9.
Trial batch adjustments

A2.2.9 *Step 9* -- For the laboratory trial batch, it is found convenient to scale the masses down to produce 0.02 m3 of concrete. Although the calculated quantity of water to be added was 2.44 kg, the amount actually used in an effort to obtain the desired 75 to 100 mm slump is 2.70 kg. The batch as mixed, therefore, consists of

Water (added)	2.70 kg
Cement	5.84 kg
Coarse aggregate (wet)	23.18 kg
Fine aggregate (wet)	16.98 kg
Total	48.70 kg

Step 9.
Trial batch adjustments

Next Step?

Calculate the amount of water
Adjust cement content for selected W/C
Recalculate aggregates content
Make another batch

Other adjustments/modifications

Use concrete with few W/C for fine tuning of nominal strength
Use concrete with different fine to coarse aggregate ratio
Use different dosage of superplasticizer