고성능 콘크리트 공학

High Performance Concrete Engineering

〈Mix design〉

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Factors to be considered

Workability

- Minimum workability for adequate placement

Strength

- Generally 28 days
- Other ages depending on the application

Durability

- Chemical attacks
- Repeated freeze/thaw cycles

Appearance

Economy

Selection of Materials: Cement, SCM, Water, Aggregate, Admixtures, Fiber etc.

Fundamentals of Mix Design

Water-cement ratio (w/c)

Abrams Law: For given materials, the strength depends only on one factor – the ratio of water to cement

$$f_c = \frac{A}{B^{1.5(w/c)}}$$

f_c = compressive strength
A = empirical constant (96.5 MPa)
B = Constant that depends mostly on cement properties (~4)
w/c = water to cement ratio by weight

Aggregate and Air

Ideal aggregate grading

- Most dense aggregate-packing with a minimum content of voids will be the most economical in theory
- In practice, it is adequate to follow the grading limits specified by standards

Some basic rules for workability

- **Flowability**
  - For a given slump, water requirement ↓ when
    - Max aggregate size ↑
    - Content of angular or rough-textured aggregate particles ↓
    - Content of entrained air ↑
- **Cohesiveness**
  - Improve cohesiveness
    - Increase sand/coarse aggregate ratio
    - Partial replacement of coarse sand by a fine sand
    - Increase cement/aggregate ratio (at given w/c)

Aggregate packing

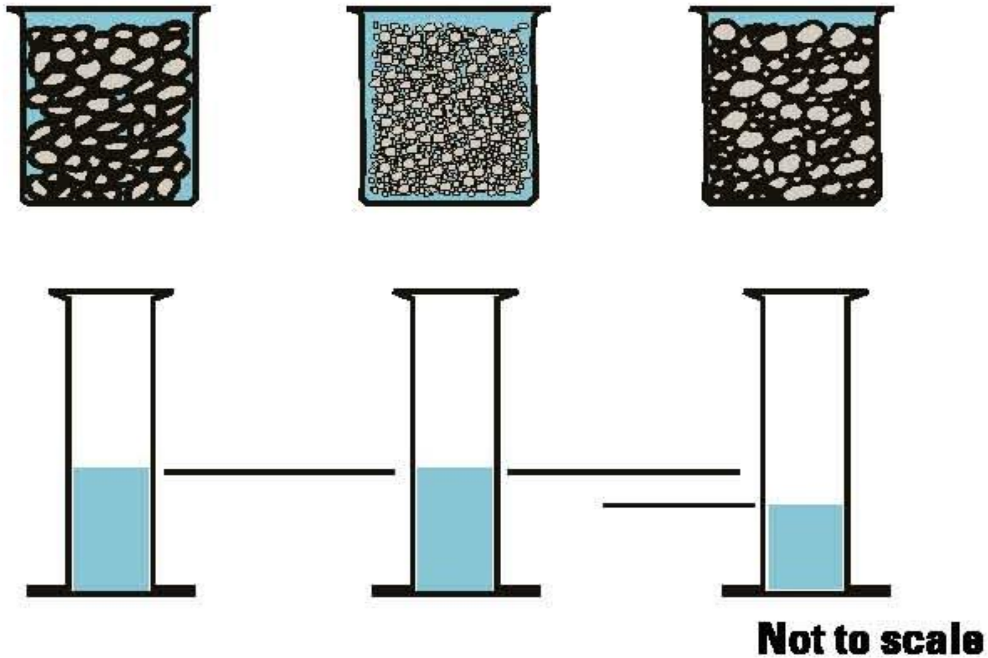

Figure 3-7. The level of liquid in the cylinders, representing voids, is constant for equal absolute volumes of aggregates of uniform (but different) sizes. When different sizes are combined, however, the void content decreases. (PCA)

Mix Design Process

Determine the job parameters

- Strength
- Durability requirements
- Slump
- aggregate properties, max. aggregate size
- w/c
- admixtures

Calculate batch weights

Adjusting to the batch weights based on trial mix

Specification of concrete (SS EN 206-1)

For designed concrete (performance)

- Basic requirements, e.g.
  - Compressive strength class
  - Exposure class
  - Max aggregate size
  - Consistence class or target value of consistence

- Additional requirements, e.g.
  - Special types or classes of cement
  - Requirements for the temperature of fresh concrete
  - Strength development
  - Resistance to abrasion

SS EN 206-1 Annex J (informative) – performance-related design methods with respect to durability

Specification of concrete (SS EN 206-1)

Determining Required Average Compressive Strength from the Specified Design Strength (Mindess 2003 pp. 402-409)

Statistical distribution of concrete strength

- Cannot design concrete on the basis of specified strength
- What constitutes an acceptable percentage of specimens falling below the "minimum" design value? (ACI 318: 1%)

In order to compute the required average compressive strength of concrete mix, three things must be known:

- specified compressive strength f'_c
- variability or standard deviation s of concrete
- allowable risk of having concrete with an unacceptable strength

Required Average Strength

(1) The probable frequency of the average of 3 consecutive tests below specified strength f'_c will not exceed 1 in 100

$$f'cr = f'c + 2.33\frac{s}{\sqrt{3}} = f'c + 1.34s$$

where
f'_{cr} = required average compressive strength
f'_c = specified compressive strength
s = standard deviation

(2) (a) For $f'_c \leq 35$ MPa, the probable frequency of tests more than 3.5 MPa below f'_c should not exceed 1 in 100

$$f'cr = f'c + 2.33s - 3.5\ (\text{MPa})$$

(b) For $f'_c > 35$ MPa, the probable frequency of tests below $0.90f'_c$ should not exceed 1 in 100

$$f'cr = 0.90\,f'c + 2.33s$$

The required average compressive strength f'_{cr} is determined as the larger value of the above

Required Average Strength

(When Data Are Available to Establish a Standard Deviation)

Specified compressive strength, f'_c, MPa	Required average compressive strength, f'_{cr}, MPa
≤ 35	$f'_{cr} = f'_c + 1.34s$ $f'_{cr} = f'_c + 2.33s - 3.5$ Use larger value
> 35	$f'_{cr} = f'_c + 1.34s$ $f'_{cr} = 0.90f'_c + 2.33s$ Use larger value

Required Average Strength

Modification Factor for Standard Deviation (≤ 30 Tests)

s is multiplied by the below factor

Number of tests	Modification factor for standard deviation
Less than 15	Use Table 15.3
15	1.16
20	1.08
25	1.03
30 or more	1.00

Required Average Strength

(When There Are Insufficient Data to Establish S)

These estimates are very conservative, and should not be used for large projects (over-design, non-economical)

Specified compressive strength, f'_c, MPa	Required average compressive strength, f'_{cr}, (MPa)
Less than 20	$f'_c + 7.0$
20 to 35	$f'_c + 8.5$
Over 35	$1.1f'_c + 5.0$

Compressive Strength Classes (SS EN 206-1)

28 days, 150x300 mm cylinder

28 days, 150x150x150 mm cube

Table 7 — Compressive strength classes for normal-weight and heavy-weight concrete

Compressive strength class	Minimum characteristic cylinder strength $f_{ck,cyl}$ N/mm^2	Minimum characteristic cube strength $f_{ck,cube}$ N/mm^2
C8/10	8	10
C12/15	12	15
C16/20	16	20
C20/25	20	25
C25/30	25	30
C30/37	30	37
C35/45	35	45
C40/50	40	50
C45/55	45	55
C50/60	50	60
C55/67	55	67
C60/75	60	75
C70/85	70	85
C80/95	80	95
C90/105	90	105
C100/115	100	115

Cube vs Cylinder Strength

Effect of specimen parameters on strength

- Height/diameter ratio of cylinder ↑, the strength ↓
- In general, larger specimens have lower strength

Ratio between cube and cylinder strength

- Commonly assumed to be

fcu = 1.25 fcyl

- Fcu/ fcyl ranges from 1.3 for low-strength concrete to 1.04 for higher strength concrete

Cylinders are cast and tested in the s ame position, whereas for cubes, the loading direction is perpendicular to the casting direction

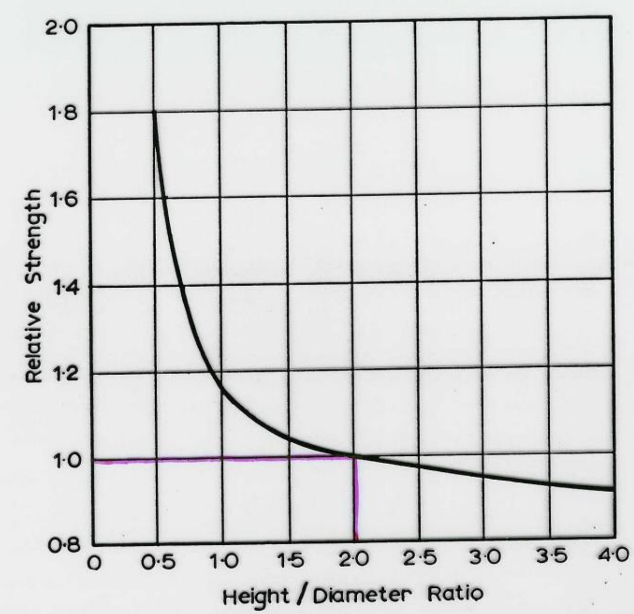

Fig. 12.5 General pattern of influence of the height/diameter ratio on the apparent strength of a cylinder[12.40]

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1. Required information
2. Choice of slump
3. Choice of maximum aggregate size
4. Estimation of mixing water and the air content
5. Selection of w/c or w/cm
6. Calculation of cement or cm content
7. Estimation of coarse aggregate content
8. Estimation of fine-aggregate content
9. Adjustments for moisture in the aggregates
10. Trial batch

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1. Required information

- Sieve analysis of fine and coarse aggregate, fineness modulus
- Dry-rodded unit weight of coarse aggregate
- Bulk specific gravity of materials
- Absorption capacity, or free moisture in the aggregate
- Information on structure including the type and dimensions of structural members, minimum space between reinforcing bars
- Required strength
- Exposure conditions
- Relationship between strength and w/c for available combinations of cement and aggregate
- Job specifications [e.g., max w/c, min. slump, strength at early age (normally 28d), early temperature]

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2. Choice of slump

Concrete 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	50	25

Table 3 — Slump classes

Class	Slump in mm
S1	10 to 40
S2	50 to 90
S3	100 to 150
S4	160 to 210
S5[1)]	≥ 220

Table 4 — Vebe classes

Class	Vebe time in seconds
V0[1)]	≥ 31
V1	30 to 21
V2	20 to 11
V3	10 to 6
V4[1)]	5 to 3

Table 6 — Flow classes

Class	Flow diameter in mm
F1[1)]	≤ 340
F2	350 to 410
F3	420 to 480
F4	490 to 550
F5	560 to 620
F6[1)]	≥ 630

1)Due to the lack of sensitivity of the test methods beyond certain values of consistence, it is recommended to use the indicated tests for:

- Slump: ≥ 10 mm & ≤ 210 mm
- Vebe time: ≤ 30 sec & > 5 sec
- Flow diameter: ≥ 340 mm & ≤ 620 mm

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3. Choice of Max. size of aggregate

- Using a large max size of a well-graded aggregate will produce less void space than using a smaller size
- Large aggregates minimize the amount of water required, therefore reduce the amount of cement required.
- The maximum allowable aggregate size is limited by
  - the dimensions of the structural elements and space between re inforcement
  - capabilities of construction equipment

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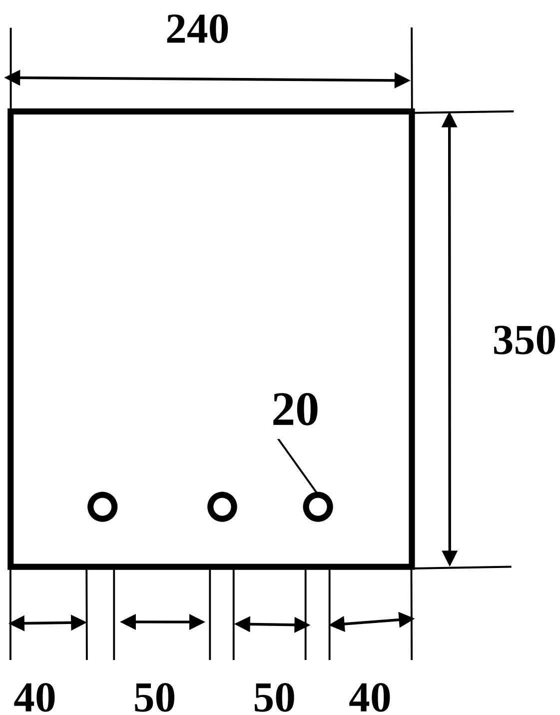
3. Choice of Max. size of aggregate

Situation	Maximum aggregate size
Form dimensions	1/5 of minimum clear distance
Clear space between reinforcement or pre-stressing tendons	3/4 of minimum clear space
Clear space between reinforcement and form	3/4 of minimum clear space
Unreinforced slab	1/3 of thickness



- Form: 240/5= 48 mm
- Space between bars = 50x3/4= 37.5 mm
- Space between bar & form (assume: cover thickness = 40x3/4 = 30 mm

Select aggregate with max. size not more than 30 mm

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4. Estimation of mixing water & air content

The quantity of water required to produce a given slump is

- dependent on the max size, shape and grading of aggregate, amount of entrained air
- not greatly affected by cement content

Estimation of water from Table 10.2 if no data are available for a given aggregate

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4. Estimation of mixing water & air content

- Water and Air Requirements for Different Slumps and Sizes of Aggregate

Non-air-entrained concrete

	Water, kg/m^3 of concrete, for indicated sizes of aggregate							
Slump, mm	9.5/10 mm	12.5 mm	19/20mm	25 mm	37.5 mm	50 mm	75 mm	150 mm
25 to 50	210	200	185	180	160	155	130	113
75 to 100	225	215	200	195	175	170	145	124
150 to 175	240	230	210	205	185	180	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

- Based on well-shaped, angular coarse aggregate

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Air Entrainment Requirements

- Air entrainment is required whenever concrete is exposed to freeze-thaw conditions
- Air entrainment is also used for workability
- The amount of the air required varies with
  - exposure conditions
    - mild: indoor or outdoor service where concrete is not exposed to freezing and de-icing salts. AEA may be used to improve workability
    - moderate: some freezing exposure occurs but concrete not exposed to moisture
    - severe
  - size of the aggregates

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4. Estimation of mixing water & air content

- Water and Air Requirements for Different Slumps and Sizes of Aggregate

Air-entrained concrete

	Water, kg/m³ of concrete, for indicated sizes of aggregate							
Slump, mm	9.5/10 mm	12.5 mm	19/20 mm	25 mm	37.5 mm	50 mm	75 mm	150 mm
25 to 50	180	175	165	160	145	140	120	107
75 to 100	200	190	180	175	160	155	135	119
150 to 175	215	205	190	185	170	165	155	-
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
Severe exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

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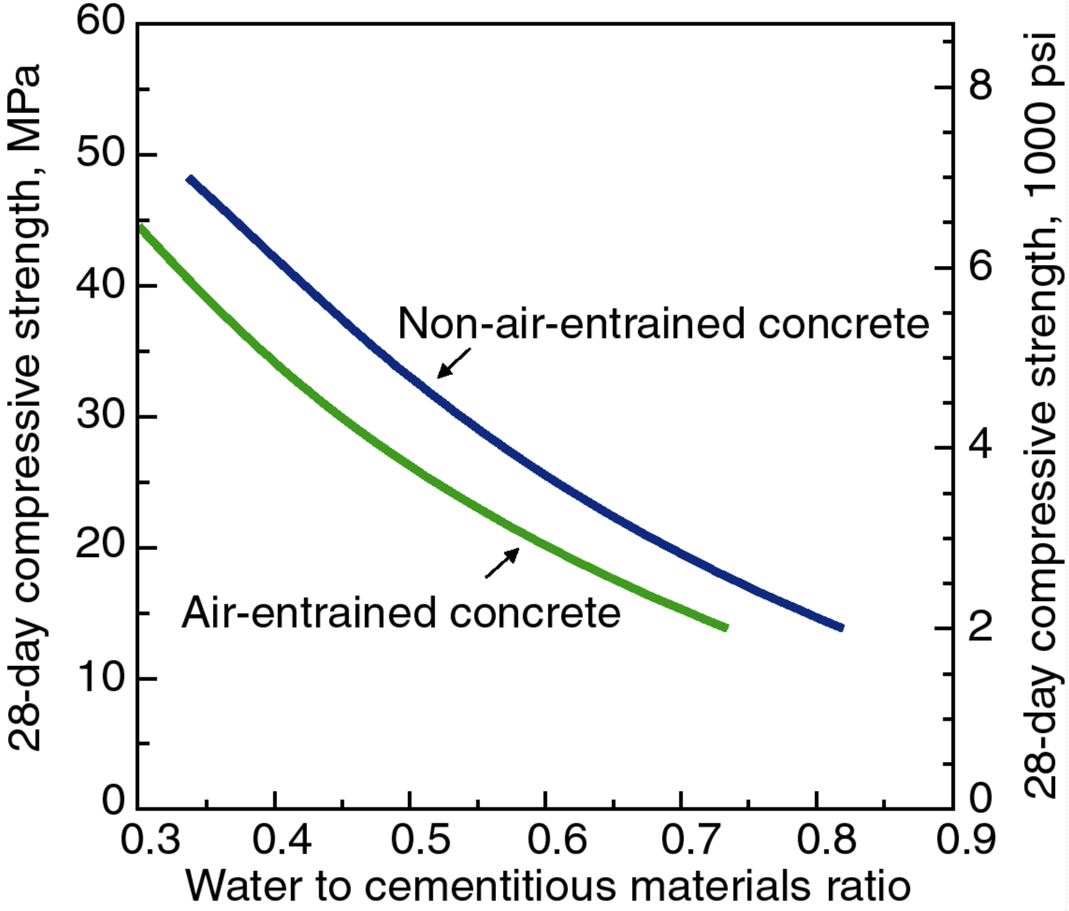
5. Selection of w/c

- Strength



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5. Selection of w/c

If no historical data are available
- make trial batches with different w/c, establish a relationship btw strength and w/c
- estimation of w/c for the trial mixes from Table 10.3

Cylinder Compressive strength at 28 days, MPa	Water/Cement Ratio by mass	
	Non-air-entrained concrete	Air-entrained concrete
45	0.37	-
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

Not applicable to ASTM Type II, III, IV, and V cements and blended ce
ments with very high quantities of pozzolans or GGBFS

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5. Selection of w/c

- **Durability**
  - Checking w/c against the max. allowable w/c for exposure conditions
    - Generally, more severe exposure conditions require lower w/c
    - The minimum of the w/c for strength and durability is selected for proportioning of the concrete

- **SS EN 544-1: 2009 Complimentary Singapore Standard to SS EN 206-1**
  - To cater to the higher ambient temperatures in Singapore, consider the required concrete for at least one class higher than that based on exposure conditions in accordance with the requirements in BS EN 206

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5. Selection of w/c

TABLE 10.4 Maximum Permissible Water/Cement or Water/Cementitious Material Ratios for Concrete in Severe Exposures.[a,b]

Type of Structure	*Structure Wet Continuously or Frequently, and Exposed to Freezing and Thawing*[c]	*Structure Exposed to Seawater or Sulfates*
Thin sections (railings, curbs, sills, ledges, ornamental work) and sections with less than 25-mm (1-in.) cover over steel	0.45	0.40[d]
All other sections	0.50	0.45[d]

[a] Adapted from ACI 211.1. Reproduced with permission.
[b] Based on report of ACI Committee 201, Durability of Concrete in Service. Cementitious materials other than cement should conform to ASTM C 618 and C 989.
[c] Concrete should also be air entrained.
[d] If sulfate-resisting cement (Type II or Type V of ASTM C 150) is used, permissible water/cement or water/cementitious material ratio may be increased by 0.05.

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5. Selection of w/c

Requirement for Concrete Exposed to Sulfates

Sulfate exposure	Sulfate (SO_4) in soil, % by mass	Sulfate (SO_4) in water, ppm	Cement type	Maximum w/c-ratio, by mass	Minimum strength, f'_c, MPa
Negligible	< 0.10	< 150	No special type required	—	—
Moderate	0.10 to 0.20	150 to 1500	II, MS, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)	0.50	28
Severe	0.20 to 2.00	1500 to 10,000	V	0.45	31
Very severe	> 2.00	> 10,000	V +pozzolans or slag	0.45	31

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5. Selection of w/c

Chemical attacks

Table 2 – Limiting values for exposure classes for chemical attack from natural soil and ground water

The aggressive chemical environments classified below are based on natural soil and ground water at water/-soil temperatures between 5 °C and 25 °C and a water velocity sufficiently slow to approximate to static conditions.

The most onerous value for any single chemical characteristic determines the class.

Where two or more aggressive characteristics lead to the same class, the environment shall be classified into the next higher class, unless a special study for this specific case proves that it is not necessary.

Chemical characteristic	Reference test method	XA1	XA2	XA3
Ground water				
SO_4^{2-} mg/l	EN 196-2	≥ 200 and ≤ 600	> 600 and ≤ 3000	> 3000 and ≤ 6000
pH	ISO 4316	≤ 6,5 and ≥ 5,5	< 5,5 and ≥ 4,5	< 4,5 and ≥ 4,0
CO_2 mg/l aggressive	prEN 13577:1999	≥ 15 and ≤ 40	> 40 and ≤ 100	> 100 up to saturation
NH_4^+ mg/l	ISO 7150-1 or ISO 7150-2	≥ 15 and ≤ 30	> 30 and ≤ 60	> 60 and ≤ 100
Mg^{2+} mg/l	ISO 7980	≥ 300 and ≤ 1000	> 1000 and ≤ 3000	> 3000 up to saturation
Soil				
SO_4^{2-} mg/kg[a] total	EN 196-2[b]	≥ 2000 and ≤ 3000[3)]	> 3000[c] and ≤ 12000	> 12000 and ≤ 24000
Acidity ml/kg	DIN 4030-2	> 200 Baumann Gully	Not encountered in practice	

[a] Clay soils with a permeability below 10^{-5} m/s may be moved into a lower class.

[b] The test method prescribes the extraction of SO_4^{2-} by hydrochloric acid; alternatively, water extraction may be used, if experience is available in the place of use of the concrete.

[c] The 3000 mg/kg limit shall be reduced to 2000 mg/kg, where there is a risk of accumulation of sulfate ions in the concrete due to drying and wetting cycles or capillary suction.

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5. Selection of w/c

Durability

Table F.1 - Recommended limiting values for composition and properties of concrete

	Exposure classes																
	No risk of corro-sion or attack	Carbonation-induced corrosion				Chloride-induced corrosion: Sea water			Chloride-induced corrosion: Chloride other than from sea water			Freeze/thaw attack				Aggressive chemical envi-ronments		
	X0	XC 1	XC 2	XC 3	XC 4	XS 1	XS 2	XS 3	XD 1	XD 2	XD 3	XF 1	XF 2	XF 3	XF 4	XA 1	XA 2	XA 3
Maximum w/c	---	0,65	0,60	0,55	0,50	0,50	0,45	0,45	0,55	0,55	0,45	0,55	0,55	0,50	0,45	0,55	0,50	0,45
Minimum strength class	C12/15	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C35/45	C30/37	C30/37	C35/45	C30/37	C25/30	C30/37	C30/37	C30/37	C30/37	C35/45
Minimum cement content (kg/m^3)	---	260	280	280	300	300	320	340	300	300	320	300	300	320	340	300	320	360
Minimum air content (%)	---	---	---	---	---	---	---	---	---	---	---	---	4,0[a]	4,0[a]	4,0[a]	---	---	---
Other requirements												Aggregate in accordance with prEN 12620:2000 with sufficient freeze/thaw resistance					Sulfate-resisting cement[b]	

[a] Where the concrete is not air entrained, the performance of concrete should be tested according to an appropriate test method in comparison with a concrete for which freeze/thaw resistance for the relevant exposure class is proven.

[b] When SO_4^{2-} leads to exposure classes XA2 and XA3, it is essential to use sulfate-resisting cement. Where cement is classified with respect to sulfate resistance, moderate or high sulfate-resisting cement should be used in exposure class XA2 (and in exposure class XA1 when applicable) and high sulfate-resisting cement should be used in exposure class XA3.

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6. Calculation of cement or cementitious material content

= mixing water (step 4) divided by the w/c (step 5)
if the concrete is used in flatwork, check minimum cement content requirement

Nominal maximum size of aggregate, mm	Cementing materials, kg/m^3
37.5	280
25	310
19	320
12.5	350
9.5	360

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6. Calculation of cement or cementitious material content

Cementitious Materials Requirements for Concrete Exposed to Deicing Chemicals

Cementitious materials	Maximum % of cementitious materials
Fly ash and natural pozzolans	25
Slag	50
Silica fume	10
Total of fly ash, slag, silica fume and natural pozzolans	50
Total of natural pozzolans and silica fume	35

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7. Estimation of coarse aggregate content

- increase V, → less workability (pavement)
- reduce V, → increased workability (pumping, shotcrete)

Volume of Coarse Aggregate per Unit volume of Concrete

Maximum size of aggregate, mm	Fineness modulus of sand			
	2.40	**2.60**	**2.80**	**3.00**
9.5 / 10	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19 / 20	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.76	0.74	0.72	0.70
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

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7. Estimation of coarse aggregate content

Coarse Aggregate Content per m³ of Concrete

Assume: Max. aggregate size =9.5 mm, Fineness modulus of sand = 2.8

Volume of coarse aggregate in concrete
= 0.46 m^3 of coarse aggregate/m^3 concrete

Assume: Dry rodded unit weight = 1567 kg/m^3 (oven dry)

Coarse aggregate content (Oven dry)
= 0.46 • 1567 kg/m^3 = 715.5 kg/m^3

Coarse aggregate content (SSD)
= 715.5 x (1+Absorption capacity)

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7. Estimation of fine aggregate content

Mass (Weight) method

W_{fa} = W_c - Weight of other ingredients

W_{fa} = weight of fine aggregate

W_c = unit weight of concrete

Estimate according to Table 10.9

TABLE 10.9 First Estimate of Weight of Fresh Concrete.[a]

Maximum Size of Aggregate		*First Estimate of Concrete Weight*[b]			
		Non-Air-Entrained Concrete		*Air-Entrained Concrete*	
mm	*in.*	*kg/m³*	*lb/yd³*	*kg/m³*	*lb/yd³*
9.5	$\frac{3}{8}$	2285	3840	2200	3710
12.5	$\frac{1}{2}$	2315	3890	2230	3760
19	$\frac{3}{4}$	2355	3960	2280	3840
25	1	2375	4010	2285	3850
37.5	$1\frac{1}{2}$	2420	4070	2320	3910
50	2	2445	4120	2345	3950
75	3	2490	4200	2400	4040

[a] Adapted from ACI 211.1. Reproduced with permission.

[b] Values calculated by Eqs. (10.6) and (10.7) for concrete containing 330 kg/m³ (550 lb/yd³) of cement, slump of 75 to 100 mm (3 to 4 in.), and aggregate bulk specific gravity of 2.7.

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8. Estimation of fine aggregate content

Volume method

The components weight and specific gravity are used to determine the volumes of the water, coarse aggregate, and cement. These volume + volume of air are subtracted from a unit volume of concrete to determine the V of fine aggregate

$$V_{fa} = V_{con} - V_{cem} - V_{ca} - V_{w} - V_{a}$$

$$= V_{con} - W_{cem}/3.15 - W_{ca}/2.65 - W_{w}/1 - V_{a}$$

1000 liters **kg** **kg/l**

convert the V to weight (generally using bulk SSD specific gravity)

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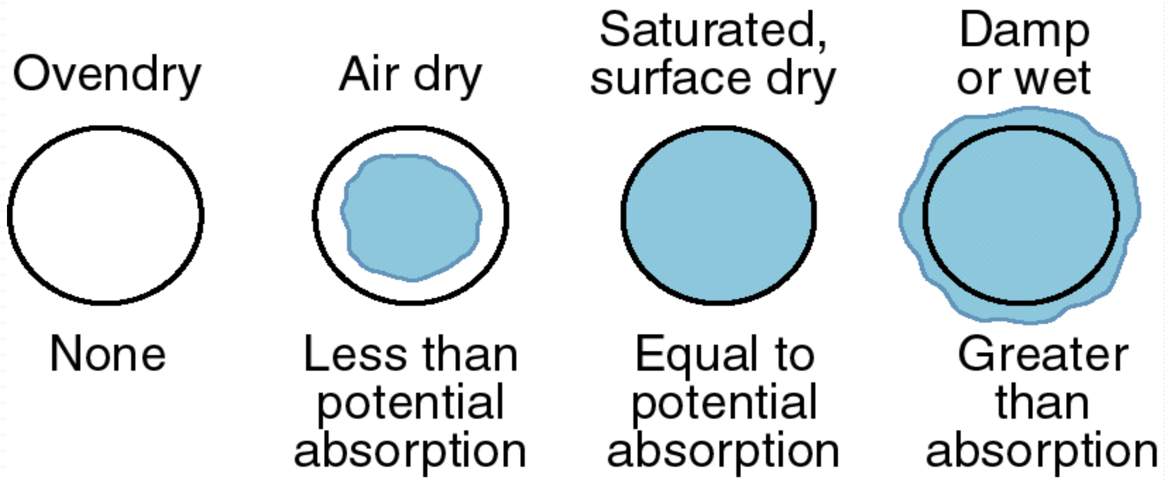
9. Adjustments for aggregate moisture

The mix proportions determined by steps 1 to 7 are assumed to be on a saturated surface dry (SSD) basis.

- If aggregate contains free moisture, the mixing water should be ↓ and aggregates correspondingly ↑ according to the amount of free moisture in the aggregates.
- If aggregate is air dry, the mixing water should be ↑ and aggregates correspondingly ↓

Total water in aggregate – absorption = free moisture



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Example:

- Coarse aggregate, absorption capacity =1%, effective absorption = 0.5%
- Fine aggregate, absorption capacity = 1.3%, total moisture content 4.5%
- Assume a concrete mix proportion based on SSD:
  - Cement = 400 kg/m^3, Water = 200 kg/m^3, Coarse aggregate = 1050 kg/m^3, Fine aggregate = 710 kg/m^3
  - Estimated unit weight = 2360 kg/m^3
- Actual mix proportion with the given aggregates
  - CA: 1050 – 1050x0.5% = 1045 kg/m^3
  - FA: free moisture = 4.5% – 1.3% = 3.2%
    - 710 + 710x3.2% = 733 kg/m^3
  - Water: 200 + 1050x0.5% - 710x3.2% = 182 kg/m^3
  - Estimated unit weight = 2360 kg/m^3

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10. Trial batch

- **Purpose**
  - Verifies that a concrete mixture meets design requirements prior to use in construction.

- **Determine**
  - Fresh concrete: slump, cohesiveness, segregation tendency, unit we ight, air content, finishing
  - Hardened concrete: strength 28 days or other ages
  - Durability parameters if specified

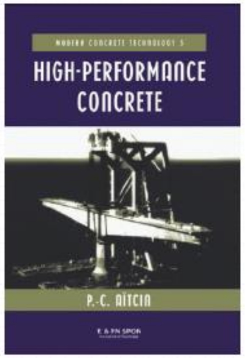
- **Adjust concrete mixture accordingly**
  - Strength does not meet requirement (workability ok)
    - Reduce w/c
      - Keep water content unaltered
      - Increase cement, reduce aggregate

ACI Method of Mix Design

10. Trial batch

- **Adjust concrete mixture accordingly (cont'd)**
  - Workability does not meet requirement (strength ok)
    - Keep w/c unaltered
      - Slump too low
        - Increase water and cement content
        - (↑ 6 kg/m^3 water will ↑ slump by ~25 mm)
        - Use WRA or superplasticizer
      - Slump too high
        - Reduce water and cement content
        - Reduce the dosage of WRA or SP
  - Segregation
    - Increase fine aggregate and reduce coarse aggregate accordingly
    - Replace coarse sand with a finer sand
  - Air content: ↑ 1% air, reduce water by 3 kg/m^3

(Aïtcin 2007)



Considerations for "High-Performance Concrete"

- Cementitious Materials
  - Overall reactivity of the interstitial phase (particularly that of C3A) **– rheological properties**
  - Reactivity of the C3S **– strength properties**
  - Solubility of the different forms of calcium sulfates found in the cement
  - Fineness of cement particles – **two conflicting effects**
  - Solubility of alkalis in concrete
  - Compatibility of superplasticizer with cement
  - Various supplementary cementitious materials
    - Such as blast-furnace slag, fly ash and natural pozzolans, not only reduces the production cost, but also provides answers to the slump loss problem.
    - While silica fume is usually not really necessary for compressive strength under 75 MPa, most cements require it in order to achieve 100 Mpa. Given the materials available to date, it is almost impossible to exceed the 100 MPa threshold without using silica fume.

Considerations for "High-Performance Concrete"

- **Aggregates**
  - The higher the targeted compressive strength, the smaller the maximum si ze of the coarse aggregate should be. While 75 MPa compressive strength concretes can easily be produced with a good coarse aggregate of a maxi mum size raning from 20 to 28 mm, aggregate with a maximum size of 10 to 20 mm should instead be used to produce 100 MPa compressive streng th concrete. Concretes with compressive strengths over 125 MPa have bee n produced to date, with coarse aggregate having a maximum size of 10 t o 14 mm.
  - Sand coarseness much increase proportionally to compressive strength and cement dosage; a fineness modulus in the 2.7 to 3 range is preferred if ava ilable.

Considerations for "High-Performance Concrete"

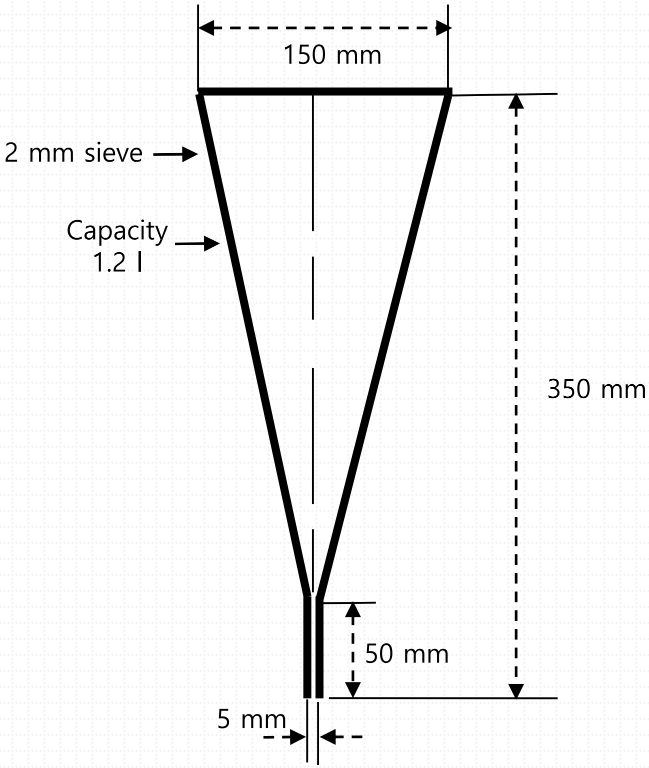
- **Curing**
  - All high-performance concrete **must** be water-cured as soon as possible be fore hydration starts.
  - In usual concrete, a great part of the mixing water is contained in large ca pillaries, so the drying due to self-desiccation creates menisci that are so la rge that they develop only weak tensile stresses and therefore induce negli gible autogenous shrinkage.
  - When the drying phenomenon associated with self-desiccation develops in a high-performance concrete that contains very few large capillaries, the m enisci rapidly develop in small capillaries, where they create large stresses a nd therefore induce a rapid and significant autogenous shrinkage in the ab sence of any external supply of water.
  - No curing membrane on the surface of usual concrete (does not provide w ater)
  - Don't wait until 24 hours to start wet curing because autogenous shrinkag e starts as soon as the hydration begins (before 24 hours).

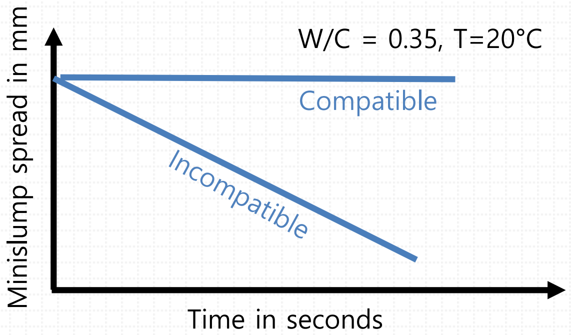
Considerations for "High-Performance Concrete"

- Superplasticizer
  - **Cement-superplasticizer compatibility issue**
  - The solubility rate of all calcium sulfate phases is not the same and can be strongly modified in the presence of a SP, so the equilibrium between the s olubility rate of the C3A phase of the cement and that of the calcium sulfa te can be strongly modified.
  - This can result in either a flash set or a false set situation in spite of the fac t that the cement producer adjusted the calcium sulfate content according to the standard testing procedure, though this adjustment was done in the absence of any water reducer or superplasticizer.
  - Incompatibility problems will occur more frequently as the use of high-perf ormance concrete grows.
  - One should choose a cement containing as little C3A as possible for high-performance concrete, if available.

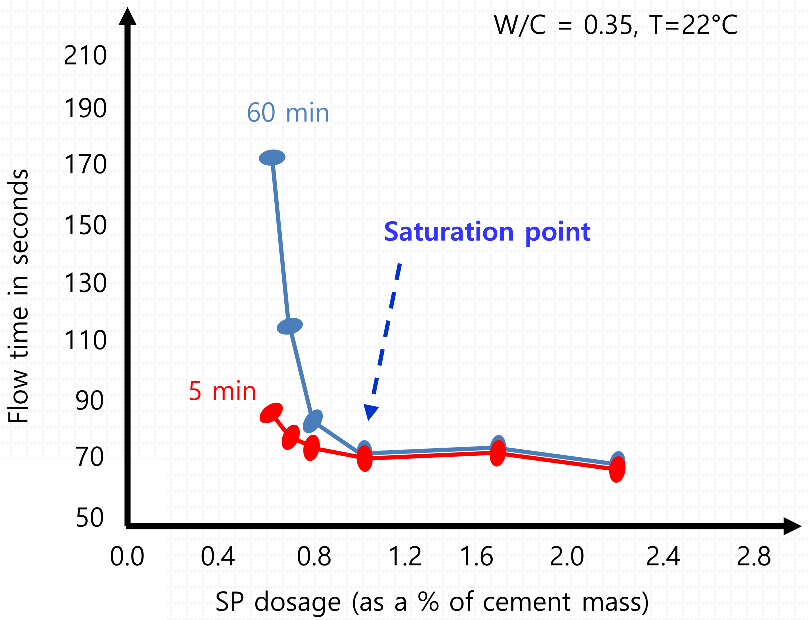
Considerations for “High-Performance Concrete”

- **Superplasticizer-cement compatibility**
  - **Marsh cone method**
  - Water, cement, and superplasticizer



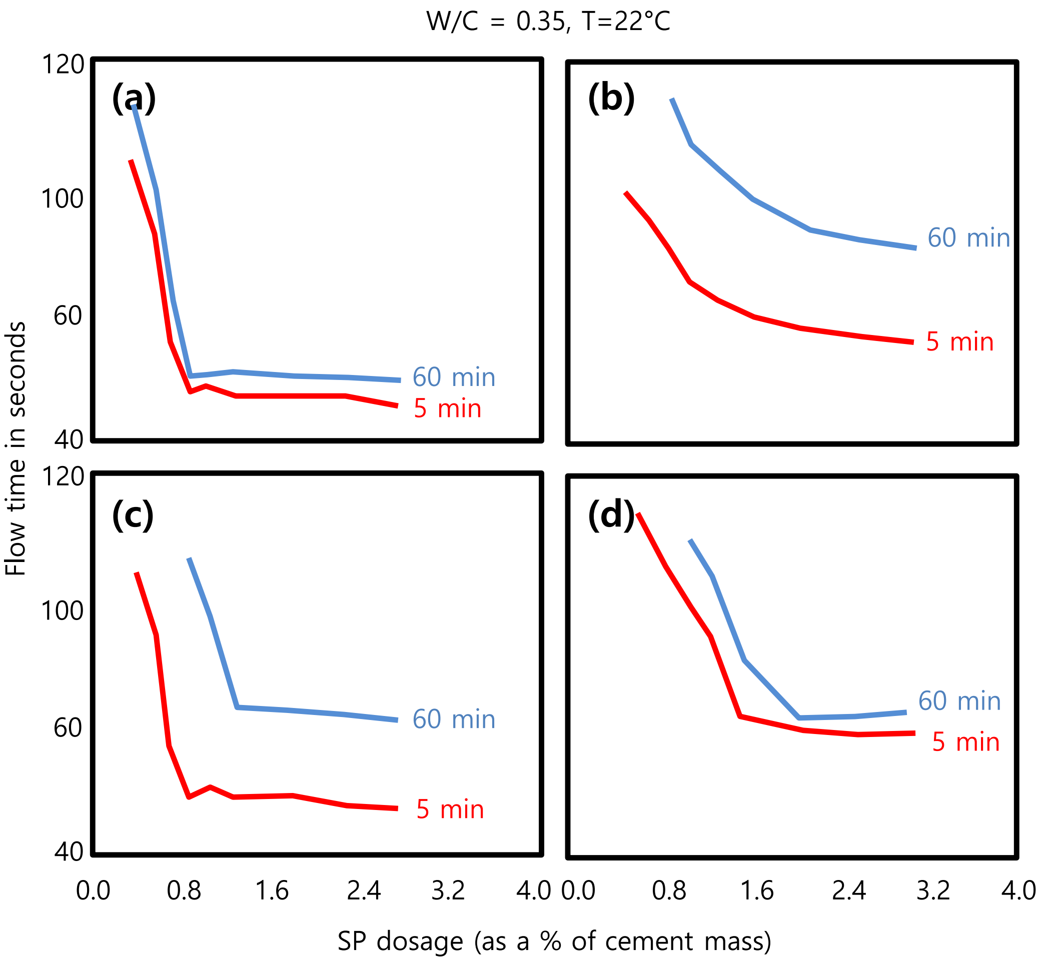


Example of minislump results for a compatible and an incompatible cement/superplasticizer combination



Considerations for "High-Performance Concrete"

- **Superplasticizer/cement compatibility**
  - (a) a fully compatible combination of cement and superplastizier: the SP dosage at the point of saturati on is low (around 1.0%) and the 6 0 min curve is close to the 5 min ute one. Thus, the increased flow time is maintained for 1 hour
  - (b) a case of incompabilibity: the SP dosage at the less well-define d saturation point is quite high an d the 60 min curve is much higer than the 5 min curve
  - (c) and (d) intermediate cases.



Considerations for "High-Performance Concrete"

- **Silica fume**
  - Bulk unit weight ranges from 200 to 250 kg/m3, so the usual 30 tonne ce ment tanker can transport only around 11 to 12 tonnes of bulk silica fume.
  - Densified silica fume has its bulk density from 400 to 500 kg/m3.
  - Silica fume has a specific surface are of between 150,000 and 30,000 m2/k g, while Type I Portland cement has a specific surface of 1200 to 1500 m2/ kg.
  - In order to fix all the potential lime liberated by the hydration of C3S and C2S, the silica fume dosage should be 25 to 30%. Such high dosage have occasionally been used in the laboratory but not often in field applications , owing to the high amount of SP needed. Usually, silica fume has been us ed in high-performance concrete at a dosage rate of **between 3 and 10 %** .
  - Usually the silica fume dosage is expressed as **a percentage of the mass of cement** used in the particular mixture and not as a percentage of the t otal cementitious materials, except in the case of a blended cement.

(Rougeron and Aitcin, 1994)

Considerations for "High-Performance Concrete"

- Economic factor
  - A given low water/binder ratio can be achieved in different ways: by increasing the amount of binder, by decreasing the amount of water or by doing both at the same time, while in each case adjusting the amount of SP and retarding agent to obtain the required slump for an easy placement, in the **most economical way possible.**
  - Therefore, what is saved in cement is not necessarily transformed into a global saving in cost at the high-performance concrete level, because this saving in the cement could be absorbed by the extra cost of the superplasticizer needed to be able to decrease the amount of mixing water to save on the cement.

(Rougeron and Aitcin, 1994)

Considerations for “High-Performance Concrete”

- **Economic factor**
  - **Factorial Design Plan**

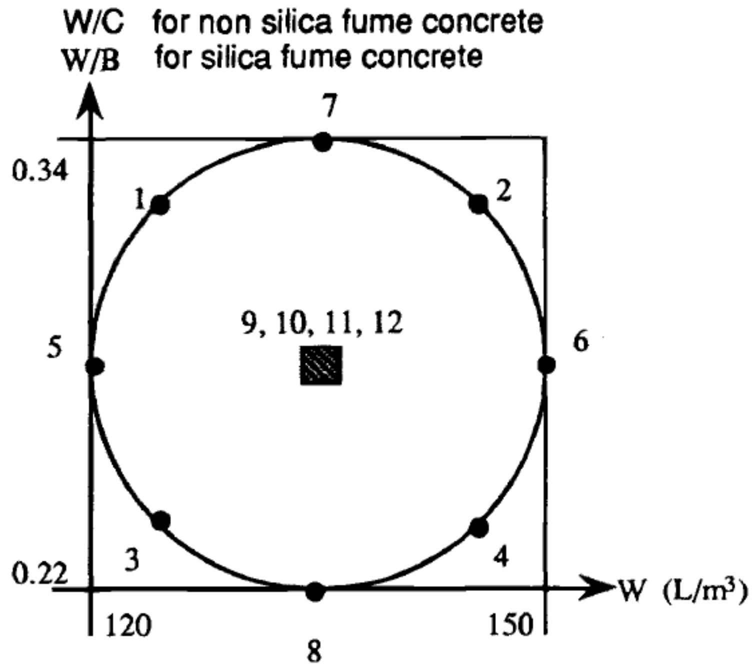


FIG. 2—*Experimental plan.*

TABLE 1—*Compositions without silica fume.*

	W/C	Cement kg/m³	Coarse Aggregate, kg/m³	Fine Aggregate, kg/m³	Superplasticizer, L/m³	Slump, mm
1	0.30	430	1100	798	12	200
2	0.31	480	1100	720	10	180
3	0.25	520	1100	710	25	210
4	0.25	570	1100	630	19	200
5	0.28	435	1100	810	18	190
6	0.28	560	1100	620	13	190
7	0.22	640	1100	570	35	200
8	0.34	400	1100	800	12	190
9, 10, 11, 12	0.28	500	1100	720	13	200

(Rougeron and Aitcin, 1994)

Considerations for "High-Performance Concrete"

- **Economic factor**
  - **Factorial Design Plan**

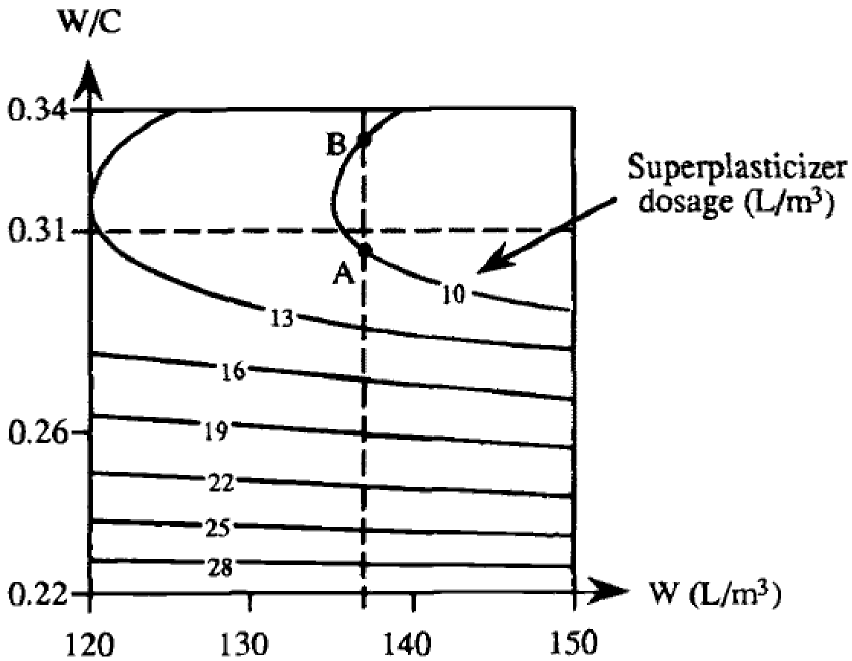


FIG. 3—*Isodosage (L/m³) for the superplasticizer for non-silica-fume concretes.*

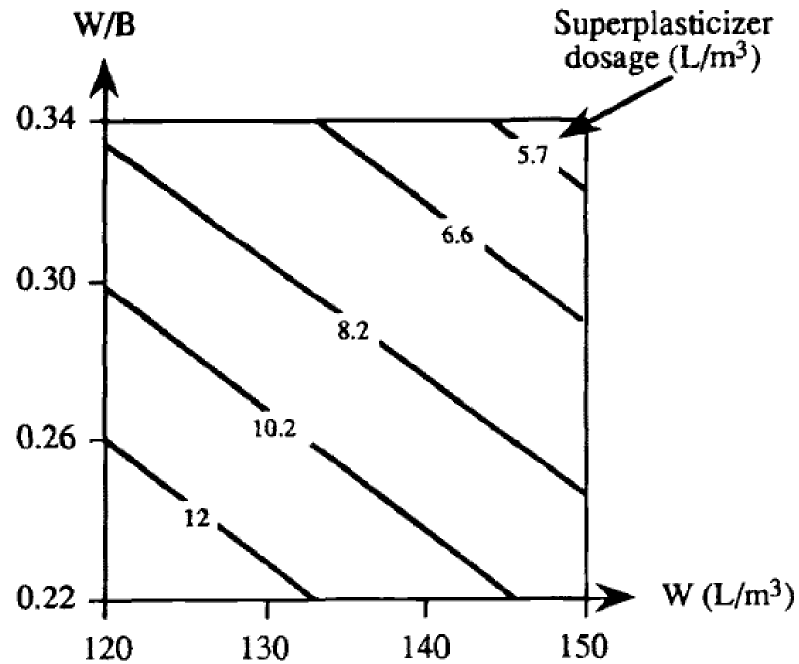
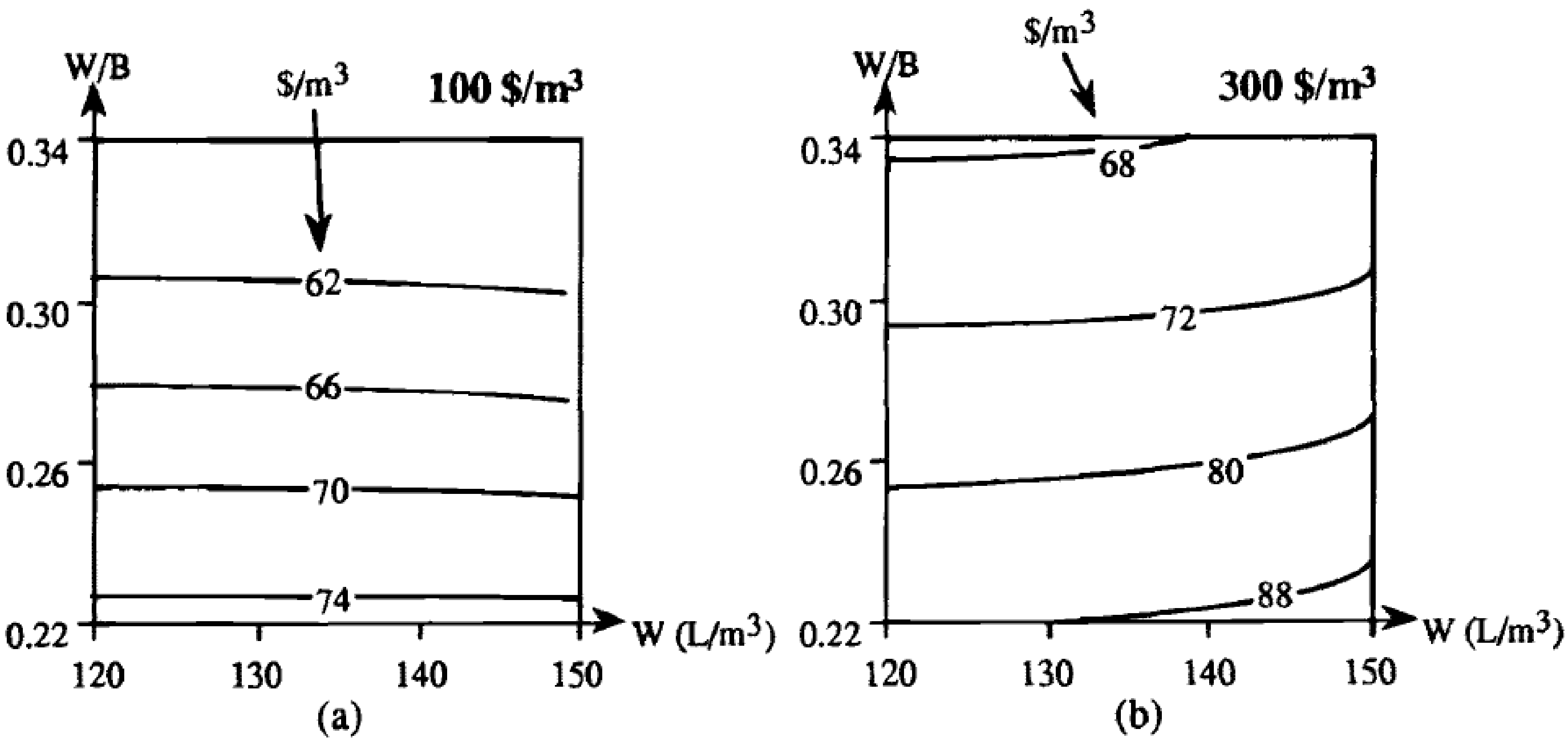


FIG. 6—*Isodosage graphs (L/m³) for the superplasticizer for silica-fume concretes.*

(Rougeron and Aitcin, 1994)

Considerations for "High-Performance Concrete"

- Economic factor
  - Factorial Design Plan
  - (a) SF cost $100/m3 & (b) SF cost $300/m3

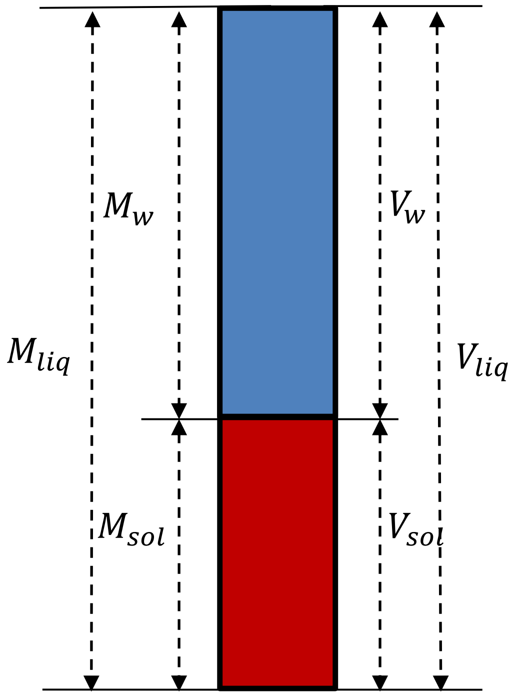


Considerations for “High-Performance Concrete”

- **Mix design method**
  - Silica fume content calculation
  - Case 1
    - A high-performance concrete is made in a concrete plant using 400 kg of Portland cement, 100 kg of fly ash and 40 kg of silica fume that are added separately in the mixer. What is the supplementary cementitious materials content of this concrete?
  - Case 2
    - A high-performance concrete is made using 400 kg of a blended cement containing 7.5% silica fume. What is the actual amount of cement introduced in the mixer?

Considerations for "High-Performance Concrete"

- **Mix design method**
  - Solid/water content in superplasticizer calculation
  - Specific gravity of superplasticizer (Gsup), Solid content (s)



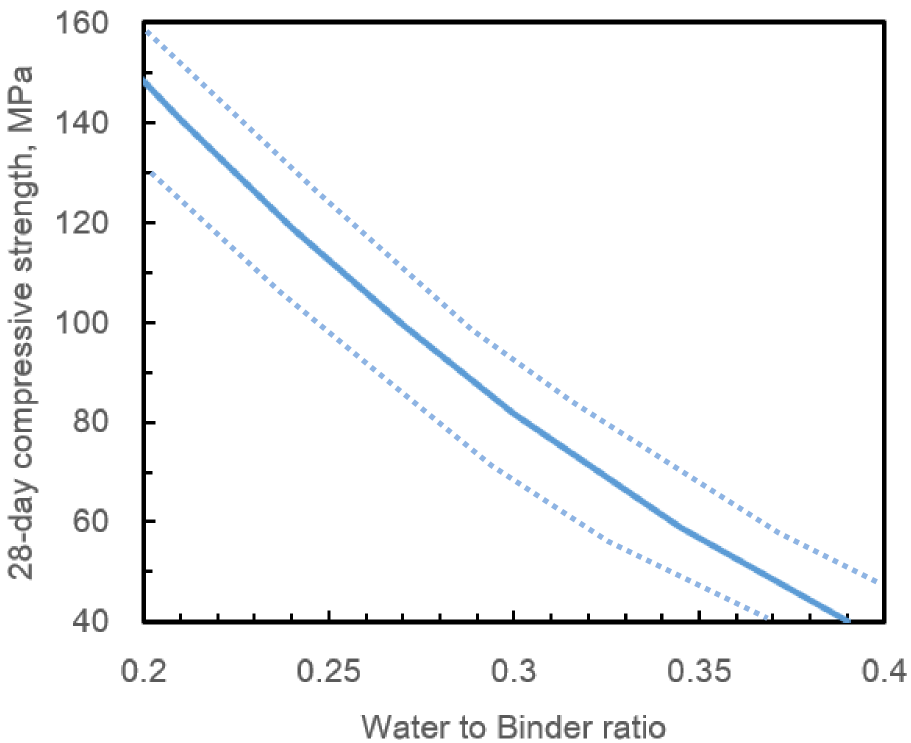
$$G_{sup} = \frac{M_{liq}}{V_{liq}} \qquad s = \frac{M_{sol}}{M_{liq}} \times 100$$

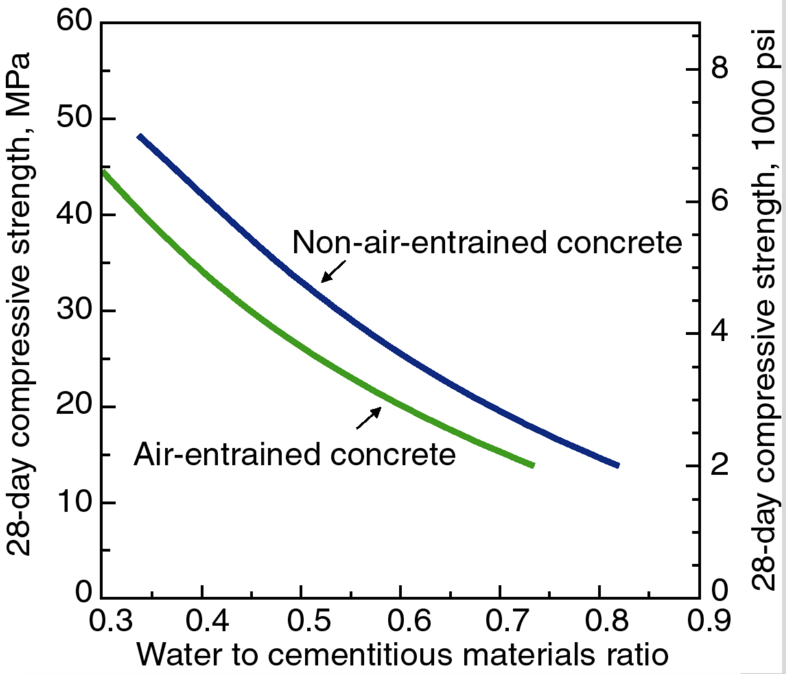
$$\text{e.g.}, M_{sol} = \frac{s \times G_{sup} \times V_{liq}}{100}$$

  - Ex) 8.25 liters of naphthalene superplasticizer with a specific gravity of 1.21 and a solids content of 40% have been used in a concrete in order to obtain the desired slump. What is the volume of water, Vw that is added to the concrete when using the solution of commercial superplasticizer?

Considerations for "High-Performance Concrete"

- **Mix design method**
  - Proposed W/B vs compressive strength relationship



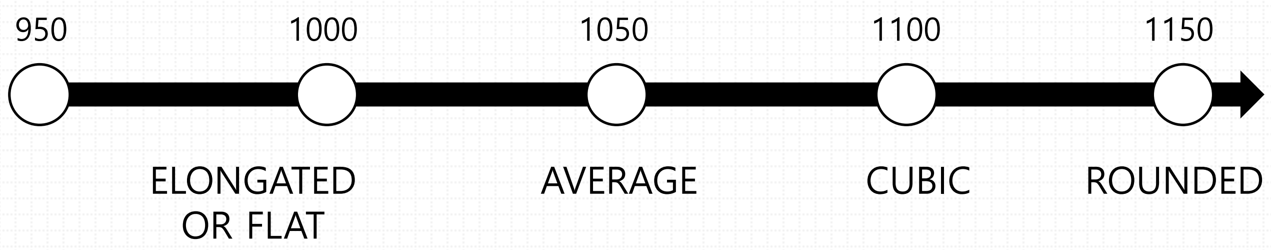


Considerations for "High-Performance Concrete"

- **Mix design method**
  - Determination of the minimum water dosage

Saturation point	0.6	0.8	1.0	1.2	1.4	percent
Water dosage	120 to 125	125 to 135	135 to 145	140 to 155	155 to 165	l/m

  - Coarse aggregate content (kg/m3)



Considerations for "High-Performance Concrete"

- **Mix design method**
  - **Example**
  - Suppose that a 100 MPa concrete has to be made with:
    - A Type I Portland cement;
    - A naphthalene-type superplasticizer with a total solids content of 40% and speci fic gravity of 1.21, and the shape of the particles can be described as between a verage and cubic;
    - A dolomitic limestone of Dmax=10 mm, SG (SSD) = 2.80, absorption capacity = 0.8%, effective absorption = 0.5%
    - A siliceous natural sand of SG (SSD) = 2.65, absorption capacity = 1.2%, total m oisture content = 3.5%
    - Silica fume at 10% replacement (of total cementitious material) is to be used; its specific gravity is 2.20;
    - The dosage of solids superplasticizer at the saturation point is 1.0%

Considerations for “High-Performance Concrete”

- **Mix design method**
  - **W/B ratio**
    - Choose W/B of 0.27
  - **Water content**
    - Choose 140 l/m3 (between 135 and 145 l/m3 with 1% saturation point)
  - **Binder content**
    - B = 140/0.27 = 518.5 kg/m3
    - SF content = 51.9 kg/m3 & cement content = 518.5-51.9 = 466.6 kg/m3
  - **Coarse aggregate content**
    - Choose 1075 kg/m3
  - Assume a 1.5% volume of entrapped air
  - **SP**

M_{sol} = 518.5 kg x 1% = 5.2 kg/m3

V_{liq} = 5.2/[(40/100) x 1.21] = 10.7 l/m3

V_{w} = 10.7 x 1.21 x (100-40)/100 = 7.8 l/m3

V_{sol} = 10.7-7.8 = 2.9 l/m3

Considerations for "High-Performance Concrete"

- **Mix design method**
  - **Sand content**
    - Vol. of cement = 466.6 / 3.14 = 148.6 l/m3
    - Vol. of silica fume = 51.9 / 2.2 = 23.6 l/m3
    - Vol. of coarse aggregate (SSD) = 1075/2.80 = 383.9 l/m3
    - Vol. of entrapped air = 1.5 x 10 = 15 l/m3
    - Sum of all except sand = 140 + 148.6 + 23.6 + 383.9 + 15 + 2.9 = 714.0 l/m3
    - Vol. of sand = 1000 – 714 = 286 l/m3
    - Mass (SSD) of sand is 286 x 2.65 = 757.9 kg/m3
  - **Mass of concrete**
    - 140 + 466.6 + 51.9 + 1075 + 757.9 + 5.2 = 2496.6 kg/m3
  - Lastly, moisture correction considering SP content, moisture conditions of fine and coarse aggregates

Considerations for "High-Performance Concrete"

- ## Mix design method
  - **Moisture correction**
    - Mass of dry coarse aggregate to be weighted is 1075[1-(0.5/100)] = **1069.6 kg/m3**
      -> It will absorb 1075-1069.6 = 5.4 kg of water
    - Mass of fine aggregate to be weighted is 757.9 x (1+2.3/100)=**775.3 kg/m3**
      -> It will release 775.3-757.9 = 17.4 kg of water
    - V_w = 7.8 kg
    - Finally, the necessary volume of mixing water to be measured is:
      -> 140 + 5.4 – 17.4 – 7.4 = **120.6 l/m3 or kg/m3**

  - **Batch calculation example**
    - Calculate the mass of each components in the concrete for following specimens (assuming 10% extra materials to compensate for losses:
      - Twelve 100 x 200 mm specimens
      - Six 150 x 300 mm specimens
      - Ten 100 x 100 x 400 mm prisms