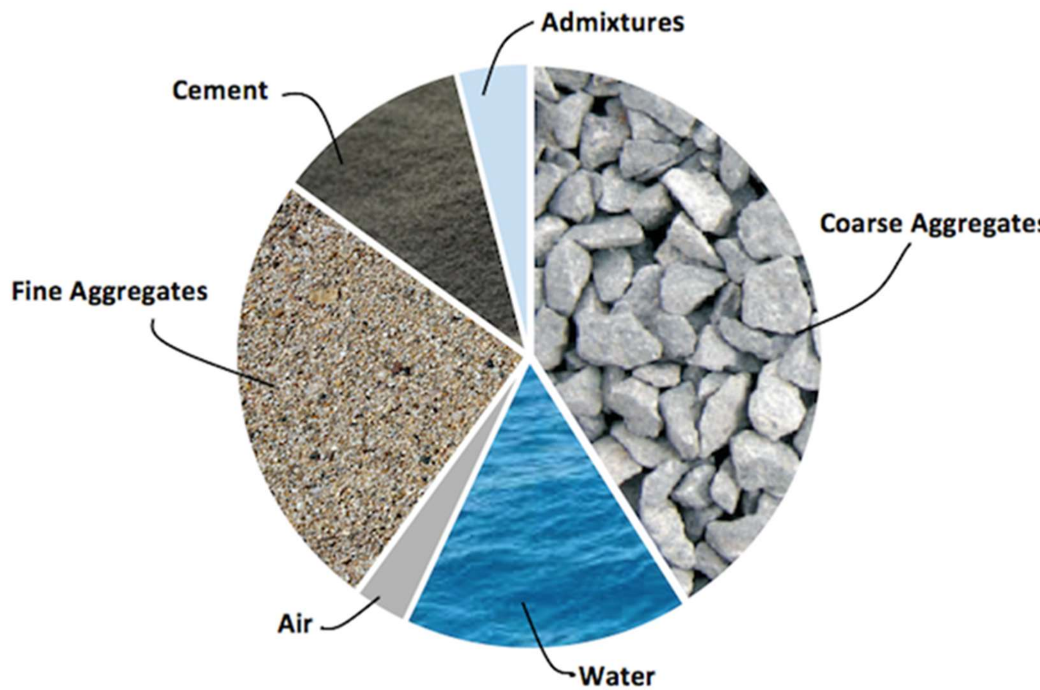
Concrete mix design

Chapter 13

Mix design or Proportioning

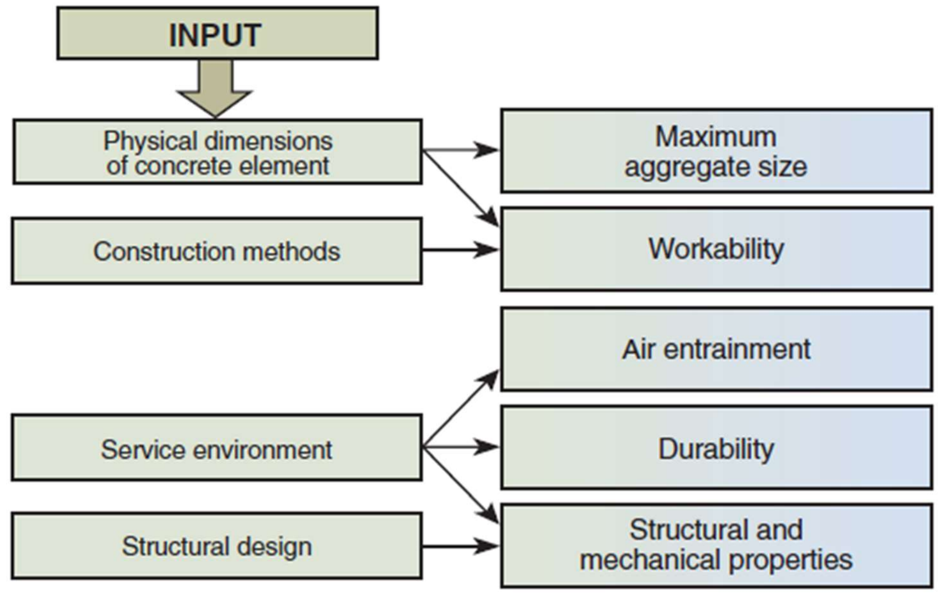
Mix design or Proportioning is the process of selecting suitable ingredients of concrete and determining their relative quantities for producing a unit amount of concrete satisfying the following requirements:

- Strength of hardened concrete
- Workability of fresh concrete
- Economy
- Durability



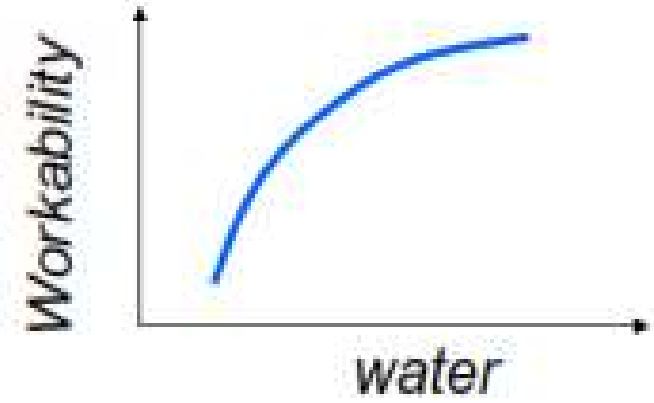
Determination of design requirements

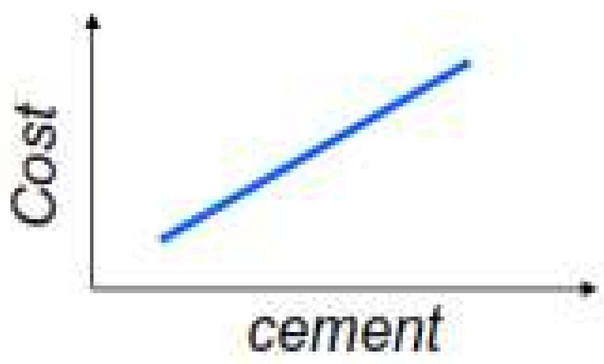
- Strength of hardened concrete is specified by the designer of the structure.
- Workability and other properties of fresh concrete are governed by the type of construction and by the techniques of placing and transporting, taking into consideration the degree of control exercised on site.

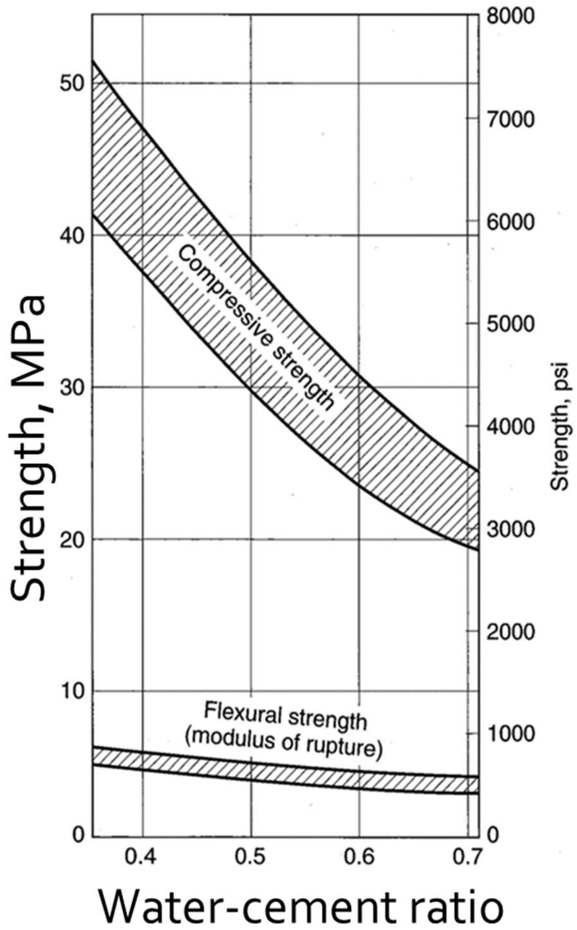


- Durability is usually determined by the applicable specifications that lay down limiting values for a range of properties that must be satisfied. These properties are usually: the maximum water/cement ratio, minimum cement content, minimum strength, and air content for specific application or environment.

Concrete Mix Design Relationships







Mix design procedures

- It should be explained that design of the mix in the strict sense of the word is not possible: the materials used are variable in a number of respects and many of their properties cannot be assessed truly quantitatively, so that we are really making no more than an intelligent guess at the optimum combinations of the ingredients on the basis of the relationships established in the earlier chapters. It is not surprising, therefore, that in order to obtain a satisfactory mix we must check the estimated proportions of the mix by making trial mixes and, if necessary, make appropriate adjustments to the proportions until a satisfactory mix has been obtained.
- Several mix design methods have been developed over the years, ranging from an arbitrary volume method (1:2:3 cement: sand: coarse aggregate) to the more accurate methods such as the American (ACI 211.1-91) method of mix design and the British method for normal weight concrete, developed for the Department of the Environment in 1975 and revised in 1988.

American method of mix design (ACI 211.1-91)

The basic steps required for determining mix design proportions are as follows

1. Evaluate strength requirements.
2. Determine the water-cement (water–cementitious materials) ratio required.
3. Evaluate coarse aggregate requirements.
   - maximum aggregate size of the coarse aggregate
   - quantity of the coarse aggregate
4. Determine air entrainment requirements.
5. Evaluate workability requirements of the plastic concrete.
6. Estimate the water content requirements of the mix.
7. Determine cementing materials content and type needed.
8. Determine coarse and fine aggregate content.
9. Determine moisture corrections.
10. Make and test trial mixes.

American method of mix design - Required information

Before starting the mix design process, information is required on both the materials to be used and the structure into which the concrete will be placed. These include

- Raw material properties including sieve analyses of both the fine and coarse aggregates, unit weight of the coarse aggregate, bulk specific gravities, and absorption capacities of the aggregates. In addition to the type and characteristics of the available cement.
- Information on the structure including the type and dimensions of the structural members, the minimum space between reinforcing bars, the required concrete strength, and the exposure conditions to which the concrete will be subjected.

Determination of the Target Strength

- The materials engineer designs the concrete to have an average strength greater than the strength specified by the structural engineer (f_c').
- The specified compressive strength f_c' shall be ≥ the minimum design compressive strength specified in the specifications or the durability requirements (table 3).
- The target strength required in the mix design (the average strength, f'_{cr}) shall be determined from the specified compressive strength (f'_c) based on statistical data if available or the table (1) can be used.

Table 1

Specified compressive strength, f_c', MPa	Required average compressive strength, f_{cr}', MPa
Less than 21	$f_c' + 7.0$
21 to 35	$f_c' + 8.5$
Over 35	$1.10 f_c' + 5.0$

Statistically :

$$f_{cr}' = f_c' + 1.34S$$
$$or\ f_{cr}' = f_c' + 2.33S - 3.54$$

where
f_{cr}' = required average compressive strength, MPa
f_c' = specified compressive strength, MPa
s = standard deviation, MPa

Determination of the mix Workability (slump)

- ***Slump*** is usually indicated in the job specifications (designer requirements) as a range, such as 50 to 100 mm, or as a maximum value not to be exceeded.
- When slump is not specified, an approximate value can be selected from Table (2) for concrete consolidated by mechanical vibration.

Table 2 Recommended Slumps for Various Types of Construction

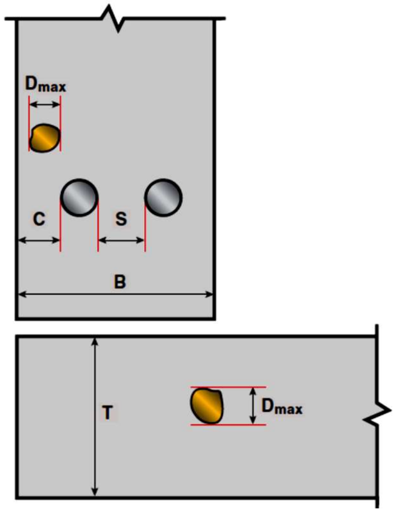
Concrete construction	Slump, mm (in.)	
	Maximum*	Minimum
Reinforced foundation walls and footings	75 (3)	25 (1)
Plain footings, caissons, and substructure walls	75 (3)	25 (1)
Beams and reinforced walls	100 (4)	25 (1)
Building columns	100 (4)	25 (1)
Pavements and slabs	75 (3)	25 (1)
Mass concrete	75 (3)	25 (1)

*May be increased 25 mm (1 in.) for consolidation by hand methods, such as rodding and spading.
Plasticizers can safely provide higher slumps.
Adapted from ACI 211.1.

Determination of maximum size of Coarse aggregate

- Concretes with the larger-sized aggregates require less mortar per unit volume of concrete. Thus the ACI method is based on the principle that the maximum size of aggregate should be the largest available so long it is consistent with the dimensions of the structure.
- The maximum aggregate size can be specified in the job specification or the material engineer shall calculate it based on the information that has been collected about the structure for which the mix will be designed as shown below.

  - One-fifth the narrowest dimension of a vertical concrete member: $D_{max} = 1/5\ B$
  - Three-quarters the clear spacing between reinforcing bars and between the reinforcing bars and forms: $D_{max} = 3/4\ S$, and $3/4\ C$
  - One-third the depth of slabs: $D_{max} = 1/3\ T$



Durability requirements

- It is important that the water/cement ratio selected on the basis of strength and the minimum compressive design strength is satisfactory also for the durability requirements. The tables on the next slide show w/c requirements for various exposure conditions.

- **Air - entrained concrete**. It must be remembered that air – entrained concrete must be considered under conditions of freezing and thawing or exposure to de-icing salts

Durability requirements

Table 3 Maximum Water-Cementitious Material Ratios and Minimum Design Strengths for Various Exposure Conditions

Exposure category	Exposure condition	Maximum water-cementitious material ratio by mass for concrete	Minimum design compressive strength f'_c, MPa (psi)
F0, S0, W0, C0	Concrete protected from exposure to freezing and thawing, application of deicing chemicals, or aggressive substances	Select water-cementitious ratio on basis of strength, workability, and finishing needs	Select strength based on structural requirements
W1, S1	Concrete intended to have low permeability when exposed to water (W1) or moderate sulfates (S1)	0.50	28 (4000)
F1	Concrete exposed to freezing and thawing with limited exposure to moisture	0.55	25 (3500)
F2, S2	Concrete exposed to freezing and thawing with exposure to moisture (F2) or severe sulfates (S2)	0.45	31 (4500)
F3*, S3	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water and exposure to deicing chemicals (F3) or very severe sulfates (S3)	0.40	35 (5000)
C2	For corrosion protection for reinforced concrete exposed to chlorides from deicing salts, salt water, brackish water, seawater, or spray from these sources	0.40	35 (5000)

Adapted from ACI 318-14. The following four exposure categories determine durability requirements for concrete: (1) F – Freezing and Thawing; (2) S – Sulfates; (3) W – Water; and (4) C – Corrosion. Increasing numerical values represent increasingly severe exposure conditions.

* For plain concrete, the maximum w/cm shall be 0.45 and the minimum design strength shall be 31 MPa (4500 psi).

Required water/cement ratio

- The water/cement ratio required to produce a given mean compressive strength is best determined from previously established relations for mixes made from similar ingredients or by carrying out tests using trial mixes made with the actual ingredients to be used in the construction, including admixtures. However, Table (4) may be used to estimate the approximate water/cement ratio.
- It is important that the water/cement ratio selected on the basis of strength is satisfactory also for the durability requirements.
- Interpolation can be used to obtain w/c value for intermediate strength.

Table 4 Relationship Between Water to Cementitious Material Ratio and Compressive Strength of Concrete

Compressive strength at 28 days, MPa	Water-cementitious materials ratio by mass	
	Non-air-entrained concrete	Air-entrained concrete
45	0.38	0.30
40	0.42	0.34
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

Strength is based on cylinders moist-cured 28 days in accordance with ASTM C31 (AASHTO T 23). Relationship assumes nominal maximum size aggregate of about 19 to 25 mm. Adapted from ACI 211.1 and ACI 211.3.

Water Content

- Based on the chosen workability, and nominal aggregate size we can estimate the water content of the mix (mass of water per unit volume of concrete) from table (5).
- As shown in Table 5, ACI 211.1-91 gives the water content for various maximum sizes of aggregate and workability's, with and without air entrainment. The values apply for well-shaped angular coarse aggregates.

Water Content

Table 5 Recommended water content for various maximum sizes of aggregate and workability's

Slump, mm	Water, kilograms per cubic meter of concrete, for indicated sizes of aggregate*							
	9.5 mm	12.5 mm	19 mm	25 mm	37.5 mm	50 mm**	75 mm**	150 mm**
	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 concrete, 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 (Class F1)	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe exposure (Class F2 and F3)	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

* These quantities of mixing water are for use in computing cementitious material contents for trial batches. They are maximums for reasonably well-shaped angular coarse aggregates graded within limits of accepted specifications.

** The slump values for concrete containing aggregates larger than 37.5 mm are based on slump tests made after removal of particles larger than 37.5 mm by wet screening.

† 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.

Adapted from ACI 211.1 and ACI 318. Hover (1995) presents this information in graphical form.

Cement content

- The cement content is governed by the mixing water requirement and the water/cement ratio as shown below.

$$\{\boldsymbol{weight\ of\ cement}\} = \frac{\boldsymbol{weight\ of\ water}}{\boldsymbol{w/c}}$$

- <u>The calculated cement content has to be at least equal to that laid down by specifications or durability considerations.</u>

Aggregate Content – Coarse aggregates

- The dry bulk volume of coarse aggregate per unit volume of concrete is taken to depend on the fineness modulus of the fine aggregate and on the maximum size of aggregate as shown by table (6).
- The oven dry (OD) weight of coarse aggregate required per cubic meter of concrete is simply equal to the value from Table (6) multiplied by the dry-rodded unit weight of the aggregate in kg/m^3.
- To convert from OD to SSD weights, multiply by (1 + Ab/100) where Ab is the absorption.

Table 6 Bulk Volume of Coarse Aggregate Per Unit Volume of Concrete

Nominal maximum size of aggregate, mm (in.)	Bulk 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 (⅜)	0.50	0.48	0.46	0.44
12.5 (½)	0.59	0.57	0.55	0.53
19 (¾)	0.66	0.64	0.62	0.60
25 (1)	0.71	0.69	0.67	0.65
37.5 (1½)	0.75	0.73	0.71	0.69
50 (2)	0.78	0.76	0.74	0.72
75 (3)	0.82	0.80	0.78	0.76
150 (6)	0.87	0.85	0.83	0.81

*Bulk volumes are based on aggregates in a dry-rodded condition as described in ASTM C29 (AASHTO T 19). Adapted from ACI 211.1.

Aggregate content – Fine aggregates

- The fine aggregate content per unit volume of concrete is then estimated using either the mass method or the volume method. The volume method is more accurate procedure for calculating the required amount of fine aggregate and will be applied here.
- The mass of fine aggregate using the volume method , A_f, is given by the following equation:

$$A_f = \gamma_f \left[1000 - \left(W + \frac{C}{\gamma} + \frac{A_c}{\gamma_c} + 10A\right)\right]$$

where
A_c = coarse aggregate content, kg/m³
C = cement content, kg/m³
W = mixing water requirement, kg/m³

A = air content, per cent;
γ = specific gravity of cement (generally 3.15)
γ_c = bulk specific gravity (SSD) of coarse aggregate
γ_f = bulk specific gravity (SSD) of fine aggregate

Adjustments for Aggregate Moisture

- **Aggregate weights.** Aggregate volumes are calculated based on oven dry unit weights, but aggregate is typically batched based on actual weight. Therefore, any moisture in the aggregate will increase its weight. stockpiled aggregates almost always contain some moisture. Without correcting for this, the batched aggregate volumes will be incorrect.
- **Amount of mixing water.** If the batched aggregate is anything but saturated surface dry it will absorb water (if oven dry or air dry) or give up water (if wet) to the cement paste. This causes a net change in the amount of water available in the mix and must be compensated for by adjusting the amount of mixing water added.

Trial Batch Adjustments.

- Having now estimated the proportions of all the ingredients, the next step is to prepare a trial batch using these estimates.
- The fresh concrete should be tested for slump, unit weight, air content, and its tendencies to segregate, bleed, and finishing characteristics. Also, hardened samples should be tested for compressive and flexural strength.
- Modification shall be carried out based on the trial mix results.

Example

Concrete is required for an exterior column to be located above ground level in an area where it will be mostly dry but subjected to mild freezing and thawing. The concrete is required to have an average 28-day compressive strength ***of 20 Mpa***. For the conditions of placement, the slump should be between 75 and 100 mm. The column is 650 mm square with a minimum clear space for aggregate of 50 mm The properties of the materials are as follows:

- **Cement:** Type I, specific gravity = 3.15
- **Fine aggregate:** Bulk specific gravity (SSD) = 2. 63; absorption capacity = 1.3 % ; surface moisture = 4.2 % based on SSD state; fineness modulus = 2. 70
- **Coarse aggregate:** Maximum size = 19 mm; bulk specific gravity (SSD) = 2.68; absorption capacity = 1.0%; surface moisture = 0.5% based on SSD state; dry-rodded unit weight = 1600 kg/m3.
- The sieve analyses of the coarse and fine aggregates fall within the limits specified in ASTM C 33. Design the required mix.

Review of given data

- **Choice of slump**. The required slump (75 and 100) is consistent with the typical values given in Table 1 for building columns (25 -100 mm) →OK
- **Maximum aggregate size**. The available maximum aggregate size, 19 mm, meets the limitations of one-fifth of the minimum dimension between forms (650/5=130) and three-fourths of the minimum clear space.(3/4*50=37.5) → OK

Concrete construction	Slump, mm (in.)	
	Maximum*	Minimum
Reinforced foundation walls and footings	75 (3)	25 (1)
Plain footings, caissons, and substructure walls	75 (3)	25 (1)
Beams and reinforced walls	100 (4)	25 (1)
Building columns	100 (4)	25 (1)
Pavements and slabs	75 (3)	25 (1)
Mass concrete	75 (3)	25 (1)

Durability requirements - Exposure condition

- Since the concrete will be subjected to limited moisture in mild freezing – thawing zone (F1), ordinary Portland (Type I) cement can be used, but concrete must be air entrained.
- According to table 3, and for exposure category F1, the maximum allowable w/c is 0.55 and minimum design strength of 25 Mpa > 20 Mpa required → $f_c' = 25\ Mpa$.

Exposure category	Exposure condition	Maximum water-cementitious material ratio by mass for concrete	Minimum design compressive strength f_c', MPa (psi)
F0, S0, W0, C0	Concrete protected from exposure to freezing and thawing, application of deicing chemicals, or aggressive substances	Select water-cementitious ratio on basis of strength, workability, and finishing needs	Select strength based on structural requirements
W1, S1	Concrete intended to have low permeability when exposed to water (W1) or moderate sulfates (S1)	0.50	28 (4000)
F1	Concrete exposed to freezing and thawing with limited exposure to moisture	0.55	25 (3500)
F2, S2	Concrete exposed to freezing and thawing with exposure to moisture (F2) or severe sulfates (S3)	0.45	31 (4500)
F3*, S3	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water and exposure to deicing chemicals (F3) or very severe sulfates (S3)	0.40	35 (5000)
C2	For corrosion protection for reinforced concrete exposed to chlorides from deicing salts, salt water, brackish water, seawater, or spray from these sources	0.40	35 (5000)

f'_{cr} and required W/C ratio

- Using table 1, the required average strength $f'_{cr} = f'_c + 8.5 = 25 + 8.5 = 33.5$ Mpa.
- From Table 4, for air-entrained concrete, by interpolation, the required W/C ratio for a required strength of 33.5 Mpa is **0.4** (< .55 required by the durability requirement).

33.5

Compressive strength at 28 days, MPa	Water-cementitious materials ratio by mass	
	Non-air-entrained concrete	Air-entrained concrete
45	0.38	0.30
40	0.42	0.34
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

Water and air contents

- Entering the lower part of table 5 with a maximum aggregate size of 19 mm and a slump of 75-100 mm,
  - Required water (W) = 184 Kg
  - Air Content (A) = 3.5% for mild exposure
  - → The required cement content (C) = 184/0.4 = 460 kg/m^3

Slump, mm	Water, kilograms per cubic meter of concrete, for indicated sizes of aggregate*							
	9.5 mm	12.5 mm	19 mm	25 mm	37.5 mm	50 mm**	75 mm**	150 mm**
	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
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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
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Recommended average total air concrete, 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 (Class F1)	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe exposure (Class F2 and F3)	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

Estimation of coarse aggregate content

- Entering table 6 with max. CA size of 19 mm an FM of FA = 2.7, by Interpolation the volume of dry-rodded coarse aggregate per unit volume of concrete = 0.63 m^3/m^3

- The OD weight of the coarse aggregate = 0.63 X 1600 = 1008 kg

- Given that absorption = 1% → The CA (SSD) weight = $(1+A_b/100)$
  = 1008x1.01 = ***<u>1018kg.</u>***

2.70

Nominal maximum size of aggregate, mm (in.)	Bulk 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 (⅜)	0.50	0.48	0.46	0.44
12.5 (½)	0.59	0.57	0.55	0.53
19 (¾)	0.66	0.64	0.62	0.60
25 (1)	0.71	0.69	0.67	0.65
37.5 (1½)	0.75	0.73	0.71	0.69
50 (2)	0.78	0.76	0.74	0.72
75 (3)	0.82	0.80	0.78	0.76
150 (6)	0.87	0.85	0.83	0.81

0.63

fine aggregate content and aggregate adjustment

$$A_f = \gamma_f \left[1000 - \left(W + \frac{C}{\gamma} + \frac{A_c}{\gamma_c} + 10A\right)\right]$$

- Given that : W = 184 Kg; C = 460 Kg (SG = 3.15); Ac = 1018 Kg (SG = 2.68) ; A = 3.5%

$$A_f = 2.63 \left[1000 - \left(184 + \frac{460}{3.15} + \frac{1018}{2.68} + 10(3.5)\right)\right] = 671 \text{ Kg}$$

- Adjustment for moisture in the aggregate: for the given moisture contents the adjusted aggregate weights are
  - Coarse aggregate (wet) (SM .5%)= 1018 (1.005) =1023kg/m^3
  - Fine aggregate (wet)(SM 4.2%) =671(1.042) =699kg/m^3
  - The mixing water adjustment 184 - 1018(0.005) – 671(0.042) = 151kg/m^3

Batch weights

The estimated batch weights per m^3

Water	151 Kg
Cement	460 Kg
Coarse Aggregates	1023 Kg
Fine Aggregates	699 Kg
Total	2333 Kg