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CHAPTER 12

Designing and Proportioning Concrete Mixtures

There are three phases in the development of a concrete mixture for a particular project; specifying, designing, and proportioning.

Contract documents contain performance requirements for fresh and hardened concrete, typically along with criteria for acceptable concrete ingredients including the aggregates, admixtures, water, and cementitious materials. Such requirements differ in the level of detail concerning proportions or ratios of ingredients, varying from a fully prescriptive specification that defines all ingredients and batch weights to a more performance-oriented specification that lists end-result concrete properties with no limitations on ingredients or proportions. Contract documents may either fully state material and mixture requirements or they may incorporate such requirements by making reference to ASTM, AASHTO, ACI, or a variety of public-agency standards and specifications.

The terms "mixture design" (mix design) and "mixture proportioning" are often incorrectly used interchangeably (USDOT 2006). As far back as 1918, this distinction was recognized:

> *The term "design" is used in the title of this article as distinguished from "proportioning" since it is the intention to imply that each element of the problem is approached with a deliberate purpose in view which is guided by a rational method of accomplishment.* (Abrams 1918).

Mixture design is the process by which the concrete mixture performance characteristics are defined. It is in the mixture design process that parameters such as air content, workability, and required strength are established. These parameters are driven by factors such as the concrete's service environment, construction method, and structural requirements as discussed in Chapter 9. Once the mixture design parameters are established, the materials characteristics and production technology are identified and determined. Then, the concrete mixture proportions can be developed using relationships established either through research or from past experience.

The output from the mixture design process becomes part of the input for mixture proportioning. In turn, the output from the mixture proportioning process becomes the actual batch proportions of the various ingredients in the concrete mixture as shown in Figure 12-1.

Figure 12-2 outlines the process of mixture proportioning. Knowledge of the local materials and the relationships among ingredients combine to produce a set of mixture proportions. These proportions are designed to meet the requirements for both fresh and hardened concrete provided that the concrete is properly batched, mixed, transported, placed, consolidated, finished, textured, and cured. For a given concrete there may be many sets of mixture proportions that satisfy the mixture design requirements. Performance records from the lab or field are required to determine whether any given set of materials and proportions can reliably meet the design requirements. Concrete materials are themselves variable, and the relationships among proportions are mixture-and-materials-specific. Therefore, any set of proposed mixture proportions is referred to as a "trial mixture," until satisfactory performance has been demonstrated through laboratory or field testing.

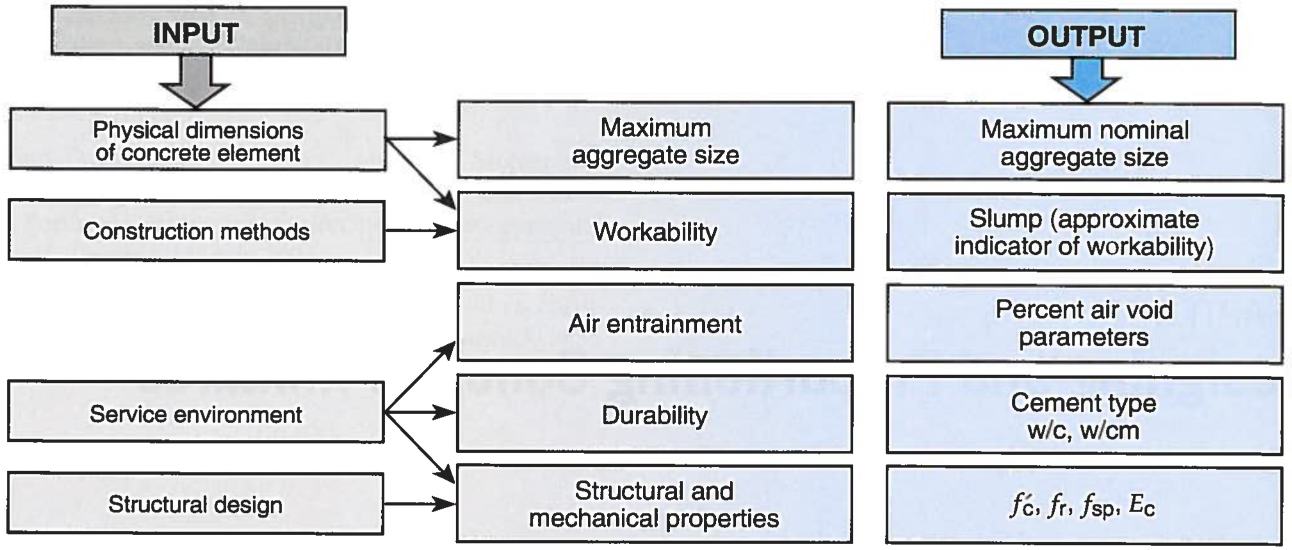

Figure 12-1. Inputs to mixture design include constraints of the concrete element and clear spacing between reinforcing, how the concrete will be batched and placed, the service environment with its associated durability requirements, and the required mechanical properties for the concrete. Output is the set of required characteristics for the mixture and each ingredient (Courtesy of K. Hover).

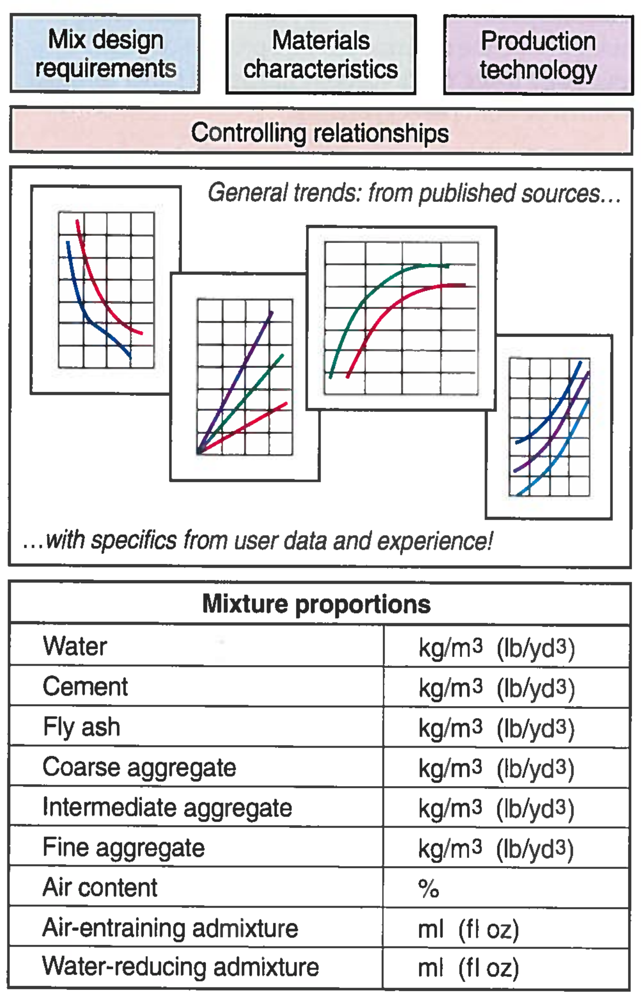

Figure 12-2. Inputs to mixture proportioning include mixture design requirements, characteristics of the specific materials to be used, and requirements based on production technology. Output is a set of mixture proportions expressed as batch weights (Courtesy of K. Hover).

A trial batch should be produced with the mixer that will be used for the project. All relevant concrete properties (such as workability, density, air content, and strength) should be measured to ensure that the mixture performs as desired. Appropriate adjustments should be made, when necessary, and subsequent trial batches produced. This iterative process continues until a satisfactory combination of the constituent materials is identified. The entire process should establish the most economical and practical combination of readily available constituent materials that will meet the requirements of the mixture design.

Understanding the basic principles of mixture design is as important as the actual calculations used to establish mix proportions. Only with proper selection of materials and mixture characteristics can the above qualities be obtained in concrete construction (Abrams 1918, Hover 1998, and Shilstone 1990).

Mix Design (Selecting Characteristics)

Before a concrete mixture can be proportioned, mixture characteristics are selected based on the intended use of the concrete, the exposure conditions, the size and shape of building elements, and the physical properties of the concrete required for the structure. This is the mix design process. Although strength is an important characteristic, other properties such as durability, permeability, and wear resistance are just as important, especially when considering life-cycle design of structures. The mixture characteristics should reflect the needs of the structure; for example, resistance to chloride ions should be verifiable and the appropriate test methods specified.

Once the mix design characteristics are selected, the mixture can be proportioned from field or laboratory data. Since most of the desirable properties of hardened concrete depend primarily upon the quality of the cementitious paste, the first step in proportioning a concrete mixture is the selection of the appropriate water-cementing materials ratio for the durability and strength needed. Concrete mixtures should be kept as simple as possible. An excessive number of ingredients often makes a concrete mixture difficult to reliably produce. However, opportunities provided by modern concrete technology should not be overlooked.

Strength

Strength (compressive or flexural) is the most universally used performance measure for concrete quality. Within the normal range of strengths used in concrete construction, the compressive strength is inversely related to the water-cementitious materials ratio. For fully compacted concrete made with clean, sound aggregates, the strength and other desirable properties of concrete under given job conditions are governed by the quantity of mixing water used per unit of cement or cementing materials (Abrams 1918).

The strength of the cementitious paste binder in concrete depends on the quality and quantity of the reacting paste components and on the degree to which the hydration reaction has progressed. Concrete becomes stronger with time as long as there is moisture and a favorable temperature available. Therefore, the strength at any particular age is both a function of the original water cementitious material ratio and the degree to which the cementitious materials have hydrated. The importance of prompt and thorough curing is easily recognized.

Differences in concrete strength for a given water cementing materials ratio may result from: (1) changes in the aggregate size, grading, surface texture, shape, strength, and stiffness; (2) differences in types and sources of cementing materials; (3) entrained-air content; (4) the presence of admixtures; and (5) the length of curing time and temperature.

The specified compressive strength, f'_c, at 28 days is the strength that is expected to be equal to or exceeded by the average of any set of three consecutive strength tests. ACI 318 requires for f'_c to be at least 17.5 MPa (2500 psi). No individual test (average of two cylinders) can be more than 3.5 MPa (500 psi) below the specified strength. Specimens must be cured under laboratory conditions for an individual class of concrete (ACI 318). Some specifications allow alternative requirements.

The average strength should equal the specified strength plus an allowance to account for variations in materials; variations in methods of mixing, transporting, and placing the concrete; and variations in making, curing, and testing concrete cylinder specimens. The average strength, which is greater than f'_c, is called f'_{cr}; it is the strength required in the mix design. Requirements for f'_{cr} are discussed in detail under Proportioning later in this chapter. Tables 12-1 and 12-2 show strength requirements for various exposure conditions.

Flexural strength is commonly used for design of pavements. However, flexural strength testing is generally avoided due to greater testing variability. Strength tests of standard cured compressive strength cylinders can be correlated to the flexural strength of concrete (Kosmatka 1985). Because of the robust empirical relationship between these two strengths and the economics of testing cylinders instead of beams, most state departments of transportation are now using compression tests of cylinders to monitor concrete quality for their pavement and bridge projects. For more information on flexural strength, see Strength in Chapter 9 and Strength Specimens in Chapter 18.

Table 12-1. 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, SO, P0, CO	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
P1	Concrete intended to have low permeability when exposed to water	0.50	28 (4000)
F1, F2, F3	Concrete exposed to freezing and thawing in a moist condition or deicers	0.45	31 (4500)
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 318-08. The following four exposure categories determine durability requirements for concrete: (1) F – Freezing and Thawing; (2) S – Sulfates; (3) P – Permeability; and (4) C – Corrosion. Increasing numerical values represent increasingly severe exposure conditions.

Table 12-2. Types of Cement Required for Concrete Exposed to Sulfates in Soil or Water*

Exposure class		Sulfate exposure**		Cementitious materials requirements†			Maximum w/cm
		Water-soluble sulfate in soil, % by mass	Dissolved sulfate in water, ppm	C150	C595	C1157	
S0	Negligible	$SO_4 < 0.10$	$SO_4 < 150$	NSR	NSR	NSR	None
S1	Moderate‡	$0.10 < SO_4 < 0.20$	$150 < SO_4 < 1500$	II or II(MH)	IP(MS) IS(< 70)(MS) IT(P ≥ S)(MS) IT(P < S < 70)(MS)	MS	0.50
S2	Severe	$0.20 < SO_4 < 2.00$	$1500 < SO_4 < 10,000$	V	IP(HS) IS(< 70)(HS) IT(P ≥ S)(HS) IT(P < S < 70)(HS)	HS	0.45
S3§	Very severe	$SO_4 > 2.00$	$SO_4 > 10,000$	V	IP(HS) IS(< 70)(HS) IT(P ≥ S)(HS) IT(P < S < 70)(HS)	HS	0.40

* Adapted from Bureau of Reclamation Concrete Manual, ACI 201 and ACI 318. "NSR" indicates no special requirements for sulfate resistance.

** Soil is tested per ASTM C1580 and water per ASTM D516.

† Pozzolans and slag that have been determined by testing according to ASTM C1012 or by service record to improve sulfate resistance may also be used in concrete. Maximum expansions when using ASTM C1012: Moderate exposure – 0.10% at 6 months; Severe exposure – 0.05% at 6 months or 0.10% at 12 months; Very Severe exposure – 0.10% at 18 months. Refer to ACI 201.2R for more guidance. ASTM C595 Type IT was adopted in 2009 and has not been reviewed by ACI at the time of printing.

‡ Includes seawater.

§ ACI 318 requires SCMs (tested to verify improved sulfate resistance) with Types V, IP(HS), IS(< 70)(HS) and HS cements for exposure class S3. ACI 318 requires a maximum water:cement ratio of 0.45 for exposure class S3.

Water-Cementitious Material Ratio

The water-cementitious material ratio is simply the mass of water divided by the mass of cementitious material (portland cement, blended cement, fly ash, slag cement, silica fume, and natural pozzolans). The water-cementitious material ratio selected for mix design must be the lowest value required to meet strength and anticipated exposure conditions. Tables 12-1 and 12-2 show w/cm requirements for various exposure conditions.

When durability is not critical, the water-cementitious materials ratio should be selected on the basis of concrete compressive strength. In such cases the water-cementitious materials ratio and mixture proportions for the required strength should be based on adequate field data or trial mixtures made with actual job materials to determine the relationship between the ratio and strength. Figure 12-3 or Table 12-3 can be used to select a water-cementitious materials ratio with respect to the required average strength, f'_{cr}, as a starting point for trial mixtures when no other data are available.

In mix design, the water to cementitious materials ratio, w/cm, is often used synonymously with water to cement ratio (w/c); however, some specifications differentiate between the two ratios.

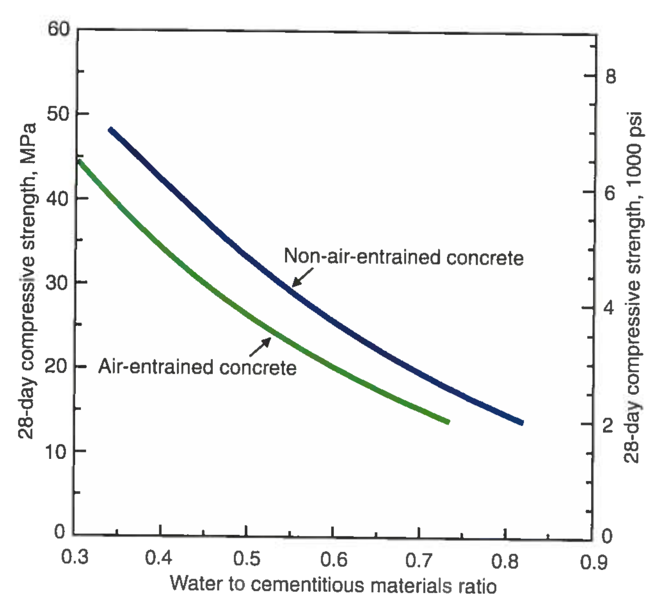

Figure 12-3. Approximate relationship between compressive strength and water to cementing materials ratio for concrete using 19-mm to 25-mm (3/4-in. to 1-in.) nominal maximum size coarse aggregate. Strength is based on cylinders moist cured 28 days per ASTM C31 (AASHTO T 23). Adapted from Table 9-3, ACI 211.1, ACI 211.3, and Hover 1995.

Table 12-3 (Metric). 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.

Table 12-3 (Inch-Pound Units). Relationship Between Water to Cementitious Material Ratio and Compressive Strength of Concrete

Compressive strength at 28 days, psi	Water-cementitious materials ratio by mass	
	Non-air-entrained concrete	Air-entrained concrete
7000	0.33	—
6000	0.41	0.32
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

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 ¾ in. to 1 in.
Adapted from ACI 211.1 and ACI 211.3.

Aggregates

The grading characteristics and nature of aggregate particles have an important influence on proportioning concrete mixtures because they affect the workability of the fresh concrete, as well as other concrete properties such as shrinkage, flexural strength, and to a certain extent, compressive strength.

Grading is important for attaining an economical mixture. It affects the amount of concrete that can be made with a given amount of cementitious materials and water. Coarse aggregates should be graded up to the largest size practical under job conditions. The maximum size that can be used depends on factors such as the size and shape of the concrete member to be cast, the amount and distribution of reinforcing steel in the member, and the thickness of slabs. Grading also influences the workability and placeability of the concrete. Sometimes mid-sized aggregate, around the 9.5 mm (⅜ in.) size, is lacking in an aggregate supply. This can result in a concrete with high shrinkage properties, high water demand, poor workability, and poor placeability. Durability may also be affected. Various options are available for obtaining optimal grading of aggregate (Shilstone 1990).

Requirements for limits on nominal maximum size of aggregate particles are covered by ACI 318 (ACI 318-08). The nominal maximum size of aggregate should not exceed:

1. One-fifth the narrowest dimension of a vertical concrete member;
2. Three-quarters the clear spacing between reinforcing bars and between the reinforcing bars and forms; and
3. One-third the depth of slabs.

These requirements may be waived if, in the judgment of the designer, the mixture possesses sufficient workability that the concrete can be properly placed without honeycomb or voids. Smaller sizes can be used when availability or economic consideration require them.

The amount of mixing water required to produce a unit volume of concrete of a given slump is dependent on the shape and the maximum size and amount of coarse aggregate. Larger sizes minimize the water requirement and thus potentially allow the cement content to be reduced. Also, rounded aggregate requires less mixing water than crushed aggregate in concretes of equal slump (see Water Content).

The maximum size of coarse aggregate that will produce concrete of maximum strength for a given cement content depends upon the aggregate source as well as its shape and grading. For high compressive-strength concrete (greater than 70 MPa or 10,000 psi), the maximum size is about 19 mm (¾ in.). Higher strengths can also sometimes be achieved through the use of crushed stone aggregate rather than rounded-gravel aggregate.

The most desirable fine-aggregate grading will depend upon the type of work, the paste content of the mixture, and the size of the coarse aggregate. For leaner mixtures, a fine grading (lower fineness modulus) is desirable for workability. For richer mixtures, a coarse grading (higher fineness modulus) is used for greater economy.

In some areas, the chemically bound chloride in aggregate may make it difficult for concrete to pass chloride limits set by ACI 318 or other specifications. However, some or all of the chloride in the aggregate may not be available for participation in corrosion of reinforcing steel, thus that chloride may be ignored. ASTM C1524, *Standard Test Method for Water-Extractable Chloride in Aggregate (Soxhlet Method)*, can be used to evaluate the amount of chloride available from aggregate. ACI 222.1 also provides guidance.

The bulk volume of coarse aggregate can be determined from Figure 12-4 or Table 12-4. These bulk volumes are based on aggregates in a dry-rodded condition as described in ASTM C29, *Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate* (AASHTO T 19). They are selected from empirical relationships to produce concrete with a degree of workability suitable for general reinforced concrete construction. For less workable concrete, such as required for concrete pavement construction, they may be increased about 10%. For more workable concrete, such as may be required when placement is by pump, they may be reduced up to 10%.

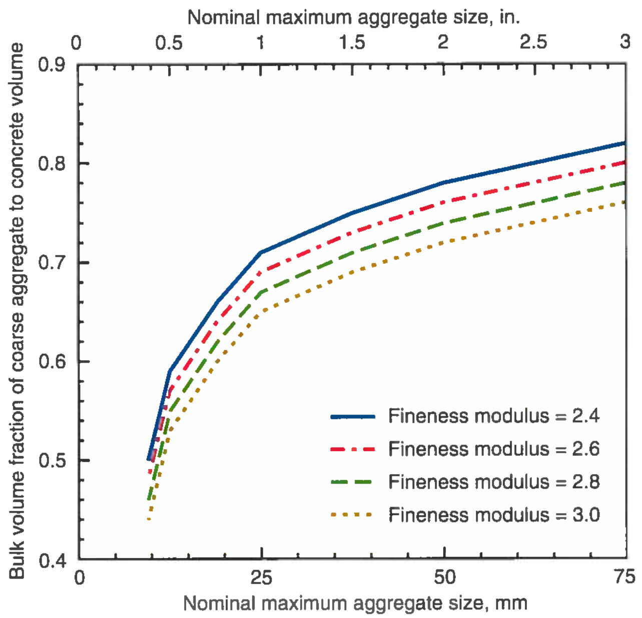

Figure 12-4. Bulk volume of coarse aggregate per unit volume of concrete. Bulk volumes are based on aggregates in a dry-rodded condition as described in ASTM C29 (AASHTO T 19). For more workable concrete, such as may be required when placement is by pump, they may be reduced up to 10%. Adapted from Table 12-4, ACI 211.1 and Hover (1995 and 1998).

Table 12-4. 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.

Air Content

Entrained air should be used in all concrete that will be exposed to freezing and thawing and deicing chemicals. It can also be used to improve workability even where not required. Air entrainment is accomplished using an air-entraining portland cement or by adding an air-entraining admixture at the mixer. The amount of admixture should be adjusted to meet variations in concrete ingredients and job conditions. The amount recommended by the admixture manufacturer will, in most cases, produce the desired air content.

Recommended target air contents for air-entrained concrete are shown in Figure 12-5 and Table 12-5. Note that the amount of air required to provide adequate freeze-thaw resistance is dependent upon the nominal maximum size of aggregate and the level of exposure. In properly proportioned mixtures, the mortar content decreases as maximum aggregate size increases; decreasing the required concrete air content. This is evident in Figure 12-5. The levels of exposure are defined by ACI 318-08 as follows:

Mild Exposure, F0. Exposure Class F0 is assigned to concrete that will not be exposed to cycles of freezing and thawing or deicing agents. When air entrainment is desired for a beneficial effect other than durability, such as to improve workability or cohesion or in low cement content concrete to improve strength, air contents lower than those needed for durability can be used.

Moderate Exposure, F1. Exposure Class F1 is assigned to concrete exposed to cycles of freezing and thawing and that will be occasionally exposed to moisture before freezing and will not be exposed to deicing or other aggressive chemicals. Examples include exterior beams, columns, walls, girders, or slabs that are not in contact with wet soil and are located where they will not receive direct applications of deicing chemicals.

Severe Exposure, F2. Exposure Class F2 is assigned to concrete exposed to cycles of freezing and thawing that is in continuous contact with moisture before freezing where exposure to deicing salt is not anticipated. An example is an exterior water tank or vertical members in contact with soil.

Very Severe Exposure, F3. Exposure Class F3 is assigned to concrete exposed to cycles of freezing and thawing, in continuous contact with moisture, and where exposure to deicing chemicals is anticipated. Examples include pavements, bridge decks, curbs, gutters, sidewalks, canal linings, or exterior water tanks or sumps.

When mixing water is held constant, the entrainment of air will increase slump. When cement content and slump are held constant, the entrainment of air results in the need for less mixing water, particularly in leaner concrete mixtures. In batch adjustments, to maintain a constant slump while changing the air content, the water should be decreased by about 3 kg/m³ (5 lb/yd³) for each percentage point increase in air content or increased 3 kg/m³ (5 lb/yd³) for each percentage point decrease.

A specific air content may not be readily or repeatedly achieved because of the many variables affecting air content; therefore, a permissible range of air contents around a target value must be provided. Although a range of ±1% of the Figure 12-5 or Table 12-5 values is often used in project specifications, it is sometimes an impractical limit. The appropriate solution is to use a wider range, such as −1 to +2 percentage points of the target values. For example, for a target value of 6% air, the specified range for the concrete delivered to the jobsite could be 5% to 8%.

Slump

Concrete must always be made with a workability, consistency, and plasticity suitable for job conditions. Workability is a measure of how easy or difficult it is to place, consolidate, and finish concrete. Consistency is the ability of freshly mixed concrete to flow. Plasticity determines concrete's ease of molding. If more aggregate is used in a concrete mixture, or if less water is added, the mixture becomes stiff (less plastic and less workable) and difficult to mold. Neither very dry, crumbly mixtures nor very watery, fluid mixtures have sufficient plasticity.

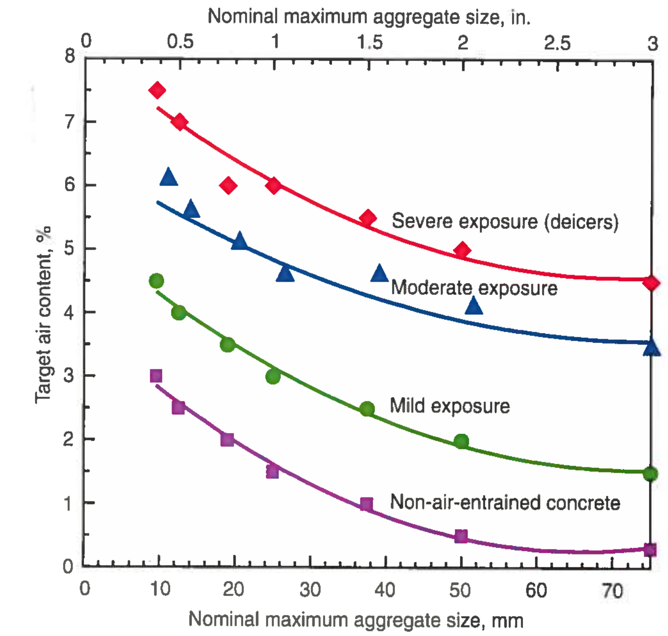

Figure 12-5. Target total air content requirements for concretes using different sizes of aggregate. The air content in job specifications should be specified to be delivered within −1 to +2 percentage points of the target value for moderate and severe exposures. Adapted from Table 12-5, ACI 211.1, and Hover (1995 and 1998).

Table 12-5 (Metric). Approximate Mixing Water and Target Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregate

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 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 (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.

Table 12-5 (Inch-Pound Units). Approximate Mixing Water and Target Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregate

Slump, in.	Water, pounds per cubic yard of concrete, for indicated sizes of aggregate*							
	⅜ in.	½ in.	¾ in.	1 in.	1½ in.	2 in.**	3 in.**	6 in.**
	Non-air-entrained concrete							
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	—
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							
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	225	200
6 to 7	365	345	325	310	290	280	260	—
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 (Class F1)	6.0	5.5	5.0	4.5	4.5	3.5	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 cement factors 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 1½ in. are based on slump tests made after removal of particles larger than 1½ in. 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. Hover (1995) presents this information in graphical form.

The slump test is used to measure concrete consistency. For a given proportion of cement and aggregate without admixtures, the higher the slump, the wetter the mixture. Slump is indicative of workability when assessing similar mixtures. However, slump should not be used to compare mixtures of different proportions, or make assumptions of hardened concrete properties. When used with different batches of the same mix design, a change in slump indicates a change in consistency and in the characteristics of materials, mixture proportions, water content, mixing, time of test, or the testing itself.

Different slumps are needed for various types of concrete construction. Slump is usually indicated in the job specifications as a range, such as 50 mm to 100 mm (2 in. to 4 in.), or as a maximum value not to be exceeded. Slump should be specified based on the method of placement. Slumps vary by application. For example: for pavements placed by mechanical paver, slump is typically 25 mm to 75 mm (1 in. to 3 in.); for floors placed by chute or pump, slump is typically 75 mm to 125 mm (3 in. to 5 in.); for walls and foundations placed by chute or pump, slumps typically range from 100 mm to 200 mm (4 in. to 8 in.). ASTM C94, *Standard Specification for Ready-Mixed Concrete*, addresses slump tolerances in detail. For minor batch adjustments, the slump can be increased by about 10 mm by adding 2 kilograms of water per cubic meter of concrete (1 in. by adding 10 lb of water per cubic yard of concrete). Slumps may also be modified with the use of a water-reducing admixture, plasticizer, or viscosity modifier.

Water Content

The water content of concrete is influenced by: aggregate size, aggregate shape, aggregate texture, slump, water to cementing materials ratio, air content, cementing materials type and content, admixtures, and environmental conditions. An increase in air content and aggregate size, a reduction in water-cementing materials ratio and slump, and the use of rounded aggregates, water-reducing admixtures, or fly ash will reduce water demand. On the other hand, increased temperatures, cement contents, slump, water-cement ratio, aggregate angularity, and a decrease in the proportion of coarse aggregate to fine aggregate will increase water demand.

The approximate water contents in Table 12-5 and Figure 12-6, used in proportioning, are for angular coarse aggregates (crushed stone). For some concretes and aggregates, the water estimates in Table 12-5 and Figure 12-6 can be reduced by approximately 10 kg (20 lb) for subangular aggregate, 20 kg (35 lb) for gravel with some crushed particles, and 25 kg (45 lb) for a rounded gravel. This illustrates the need for trial batch testing of local materials, as each aggregate source is different and can influence concrete properties differently.

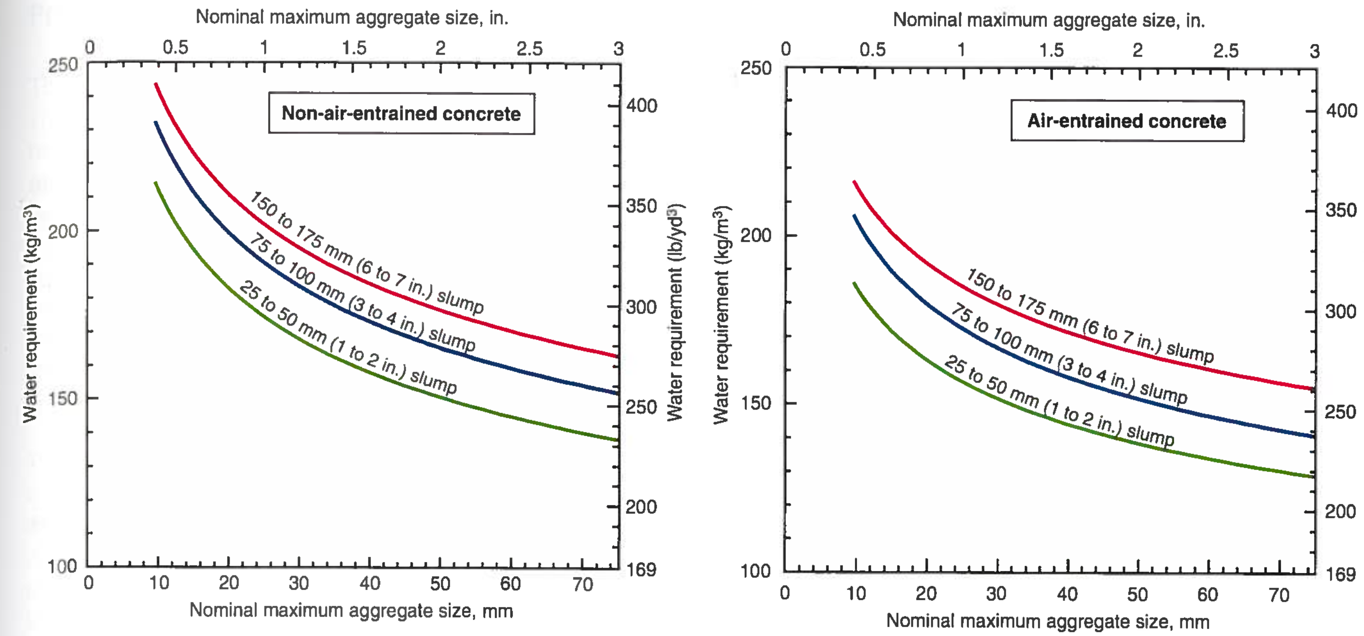

Figure 12-6. Approximate water requirement for various slumps and crushed aggregate sizes for (left) non-air-entrained concrete and (right) air-entrained concrete. Adapted from Table 12-5, ACI 211.1, and Hover (1995 and 1998).

Changing the amount of any single ingredient in a concrete mixture normally effects the proportions of other ingredients. The properties of the mixture are also altered. For example, the addition of 2 kg of water per cubic meter of concrete will increase the slump by approximately 10 mm (10 lb of water per cubic yard of concrete will increase the slump by approximately 1 in.); it will also increase the air content and paste volume, decrease the aggregate volume, and lower the density of the concrete. For the same slump, a decrease in air content by 1 percentage point will increase the water demand by about 3 kg/m³ of concrete (5 lb/yd³ of concrete).

Cementing Materials Content and Type

The cementing materials content is usually determined from the selected water-cementing materials ratio and water content. However, minimum cement content frequently is included in specifications in addition to a maximum water-cementing materials ratio. Minimum cement content requirements serve to ensure satisfactory durability and finishability, to improve wear resistance of slabs, and to guarantee a suitable appearance of vertical surfaces. This is important even though strength requirements may be met at lower cementing materials contents. However, excessively large amounts of cementing materials should be avoided to maintain economy in the mixture and to avoid adversely affecting workability and other properties.

For severe freeze-thaw, deicer, and sulfate exposures, it is desirable to specify only enough mixing water to achieve the desired consistency without exceeding the maximum water-cementitious materials ratios shown in Tables 12-1 and 12-2. For concrete placed underwater, usually not less than 390 kg of cementing materials per cubic meter of concrete (650 lb/yd³) should be used with a maximum w/cm of 0.45. For workability, finishability, and abrasion resistance in flatwork, the quantity of cementing materials to be used should be not less than shown in Table 12-6. To obtain economy, proportioning should minimize the amount of cement required without sacrificing concrete quality.

Table 12-6. Minimum Requirements of Cementing Materials for Concrete Used in Flatwork

Nominal maximum size of aggregate, mm (in.)	Cementing materials, kg/m³ (lb/yd³)*
37.5 (1½)	280 (470)
25 (1)	310 (520)
19 (¾)	320 (540)
12.5 (½)	350 (590)
9.5 (⅜)	360 (610)

* Cementing materials quantities may need to be greater for severe exposure.

Adapted from ACI 302.

Since quality depends primarily on water-cementing materials ratio, the water content should be held to a minimum to reduce the cement requirement. Steps to minimize water and cement requirements include: (1) the stiffest practical mixture, (2) the largest practical maximum size of aggregate, and (3) the optimum ratio of fine-to-coarse aggregate. Concrete that will be exposed to sulfate conditions should be made with the cement type shown in Table 12-2.

Seawater contains significant amounts of sulfates and chlorides. Although sulfates in seawater are capable of attacking concrete, the presence of chlorides in seawater inhibits the expansive reaction that is characteristic of sulfate attack. This explains observations from a number of sources that the performance of concretes in seawater have shown satisfactory durability. This is despite the fact these concretes were made with portland cements having tricalcium aluminate (C_3A) contents as high as 10%, and sometimes greater. However, the permeability of these concretes was low, and the reinforcing steel had adequate cover. Portland cements meeting a C_3A requirement of not more than 10% or less than 4% (to ensure durability of reinforcement) are acceptable (ACI 357R).

Supplementary cementitious materials have varied effects on water demand and air contents. The addition of fly ash will generally reduce water demand and decrease the air content if no further adjustment in the amount of air-entraining admixture is made. Silica fume increases water demand and decreases air content. Slag and metakaolin have a minimal effect at normal dosages.

Table 12-7 shows limits on the amount of supplementary cementing materials in concrete exposed to deicers. Local practices should be consulted as dosages different than those shown in Table 12-7 may be used without jeopardizing scale-resistance, depending on the exposure severity.

Table 12-7. Cementitious Materials Requirements for Concrete Exposed to Deicing Chemicals (Exposure Class F3)

Cementitious materials*	Maximum percent of total cementitious materials by mass**
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†

* Includes portion of supplementary cementing materials in blended cements.
** Total cementitious materials include the summation of portland cements, blended cements, fly ash, slag, silica fume and other pozzolans.
† Silica fume should not constitute more than 10% of total cementitious materials and fly ash or other pozzolans shall not constitute more than 25% of cementitious materials.
Adapted from ACI 318.

Chemical Admixtures

Water-reducing admixtures are added to concrete to reduce the water-cementing materials ratio, reduce cementing materials content, reduce water content, reduce paste content, or to improve the workability of a concrete without changing the water-cementing materials ratio. Water reducers will usually decrease water contents by 5% to 10% and some will also increase air contents by 0.5 to 1 percentage points. Retarders may also increase the air content.

High-range water reducers (plasticizers) reduce water contents between 12% and 30% and some can simultaneously increase the air content up to 1 percentage point; others can reduce or have no affect the air content.

Calcium chloride-based admixtures reduce water contents by about 3% and increase the air content by about 0.5 percentage point.

When using a chloride-based admixture, the risks of reinforcing steel corrosion should be considered. Table 12-8 provides recommended limits on the water-soluble chloride-ion content in reinforced and prestressed concrete for various conditions.

When using more than one admixture in concrete, the compatibility of intermixing admixtures should be assured by the admixture manufacturer or the combination of admixtures should be tested in trial batches. The water contained in admixtures should be considered part of the mixing water if the admixture's water content is sufficient to affect the water-cementing materials ratio by 0.01 or more.

Excessive use of multiple admixtures should be minimized to allow better control of the concrete mixture in production and to reduce the risk of admixture incompatibility.

Table 12-8. Maximum Chloride-Ion Content for Corrosion Protection

Type of member	Maximum water-soluble chloride ion (Cl^-) in concrete, percent by mass of cement*
Prestressed concrete (Classes C0, C1, C2)	0.06
Reinforced concrete exposed to chloride in service (Class C2)	0.15
Reinforced concrete that will be dry or protected from moisture in service (Class C0)	1.00
Other reinforced concrete construction (Class C1)	0.30

*ASTM C1218.
Adapted from ACI 318.

Proportioning

The design and proportioning of concrete mixtures involves: (1) the establishment of specific concrete characteristics and (2) the selection of proportions of available materials to produce concrete of required properties, with the greatest economy. Proportioning methods have evolved from the arbitrary volumetric method (1:2:3 – cement:sand: coarse aggregate) of the early 1900s (Abrams 1918) to the present-day weight and absolute-volume methods described in ACI's Committee 211, *Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete* (ACI 211.1).

Weight proportioning methods are fairly simple and quick for estimating mixture proportions using an assumed or known weight of concrete per unit volume. A more accurate method, absolute volume, involves use of relative density (specific gravity) values for all the ingredients to calculate the absolute volume occupied by each other in a specific unit volume of concrete. The absolute volume method will be illustrated. A concrete mixture also can be proportioned from field experience (statistical data) or from trial mixtures.

Other valuable documents to help proportion concrete mixtures include the *Standard Practice for Selecting Proportions for Structural Lightweight Concrete* (ACI 211.2); *Guide for Selecting Proportions for No-Slump Concrete* (ACI 211.3); *Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash* (ACI 211.4R); and *Guide for Submittal of Concrete Proportions* (ACI 211.5). Hover (1995 and 1998) provides a graphical process for designing concrete mixtures in accordance with ACI 211.1.

Proportioning from Field Data

Existing or previously used concrete mixture proportions can be used for a new project provided strength-test data and standard deviations show that the mixture is acceptable. Durability aspects previously presented must also be met. Standard deviation computations are outlined in ACI 318. The statistical data should essentially represent the same materials, proportions, and concreting conditions to be used in the new project. The data used for proportioning should also be from concrete with an f'_c that is within 7 MPa (1000 psi) of the strength required for the proposed work. Also, the data should represent at least 30 consecutive tests or two groups of consecutive tests totaling at least 30 tests (one test is the average strength of two cylinders from the same sample). If only 15 to 29 consecutive tests are available, an adjusted standard deviation can be obtained by multiplying the standard deviation (S) for the 15 to 29 tests and a modification factor from Table 12-9. The data must represent 45 or more days of tests.

Table 12-9. Modification Factor for Standard Deviation When Less Than 30 Tests Are Available

Number of tests*	Modification factor for standard deviation**
Less than 15	Use Table 9-11
15	1.16
20	1.08
25	1.03
30 or more	1.00

* Interpolate for intermediate numbers of tests.
** Modified standard deviation to be used to determine required average strength, f'_{cr}.
Adapted from ACI 318.

The standard or modified deviation is then used in Equations 12-1 to 12-3. The average compressive strength from the test record must equal or exceed the ACI 318 required average compressive strength, f'_{cr}, in order for the concrete proportions to be acceptable. The f'_{cr} for the selected mixture proportions is equal to the larger of Equations 12-1 and 12-2 (for $f'_c \leq 35$ MPa[5000 psi]) or Equations 12-1 and 12-3 (for $f'_c > 35$ MPa [5000 psi]).

$$f'_{cr} = f'_c + 1.34S \quad \text{Eq. 12-1}$$

$$f'_{cr} = f'_c + 2.33S - 3.45 \text{ (MPa)} \quad \text{Eq. 12-2}$$

$$f'_{cr} = f'_c + 2.33S - 500 \text{ (psi)} \quad \text{Eq. 12-2}$$

$$f'_{cr} = 0.90\, f'_c + 2.33S \quad \text{Eq. 12-3}$$

where

f'_{cr} = required average compressive strength of concrete used as the basis for selection of concrete proportions, MPa (psi)

f'_c = specified compressive strength of concrete, MPa (psi)

S = standard deviation, MPa (psi)

When field strength test records do not meet the previously discussed requirements, f'_{cr} can be obtained from Table 12-10. A field strength record, several strength test records, or tests from trial mixtures must be used for documentation showing that the average strength of the mixture is equal to or greater than f'_{cr}.

If less than 30, but not less than 10 tests are available, the tests may be used for average strength documentation if the time period is not less than 45 days. Mixture proportions may also be established by interpolating between two or more test records if each meets the above requirements and the project requirements. If a significant difference exists between the mixtures that are used in the interpolation, a trial mixture should be considered to check strength gain. If the test records meet the above requirements and limitations of ACI 318, the proportions for the mixture may then be considered acceptable for the proposed work.