7

PORTLAND CEMENT CONCRETE

Civil and construction engineers are directly responsible for the quality control of portland cement concrete and the proportions of the components used in it. The quality of the concrete is governed by the chemical composition of the portland cement, hydration and development of the microstructure, admixtures, and aggregate characteristics. The quality is strongly affected by placement, consolidation, and curing, as well.

How a concrete structure performs throughout its service life is largely affected by the methods of mixing, transporting, placing, and curing the concrete in the field. In fact, the ingredients of a "good" concrete may be the same as those of a "bad" concrete. The difference, however, is often the expertise of the engineer and technicians who are handling the concrete during construction.

Because of the advances made in concrete technology in the past few decades, concrete can be used in many more applications. Civil and construction engineers should be aware of the alternatives to conventional concrete, such as lightweight concrete, high-strength concrete, polymer concrete, fiber-reinforced concrete, and roller-compacted concrete. Before using these alternatives to conventional concrete, the engineer needs to study them, and their costs, in detail. This chapter covers basic principles of conventional portland cement concrete, its proportioning, mixing and handling, curing, and testing. Alternatives to conventional concrete that increase the applications and improve the performance of concrete are also introduced.

7.1 Proportioning of Concrete Mixes

The properties of concrete depend on the mix proportions and the placing and curing methods. Designers generally specify or assume a certain strength or modulus of elasticity of the concrete when determining structural dimensions.

The materials engineer is responsible for assuring that the concrete is properly proportioned, mixed, placed, and cured so to have the properties specified by the designer.

The proportioning of the concrete mix affects its properties in both the plastic and solid states. During the plastic state, the materials engineer is concerned with the workability and finishing characteristics of the concrete. Properties of the hardened concrete important to the materials engineer are the strength, modulus of elasticity, durability, and porosity. Strength is generally the controlling design factor. Unless otherwise specified, concrete strength f'_c refers to the average compressive strength of three tests. Each test is the average result of two 0.15-m × 0.30-m (6-in. × 12-in.) cylinders tested in compression after curing for 28 days.

The PCA specifies three qualities required of properly proportioned concrete mixtures (Kosmatka et al. 2002):

1. acceptable workability of freshly mixed concrete
2. durability, strength, and uniform appearance of hardened concrete
3. economy

In order to achieve these characteristics, the materials engineer must determine the proportions of cement, water, fine and coarse aggregates, and the use of admixtures. 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 weight and absolute volume methods prescribed by the American Concrete Institute's Committee 211. The weight method provides relatively simple techniques for estimating mix proportions, using an assumed or known unit weight of concrete. The absolute volume method uses the specific gravity of each ingredient to calculate the unit volume each will occupy in a unit volume of concrete. The absolute volume method is more accurate than the weight method. The mix design process for the weight and absolute volume methods differs only in how the amount of fine aggregates is determined.

7.1.1 Basic Steps for Weight and Absolute Volume Methods

The basic steps required for determining mix design proportions for both weight and absolute volume methods are as follows (Kosmatka et al. 2002):

1. Evaluate strength requirements.
2. Determine the 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. Evaluate the need and application rate of admixtures.
9. Evaluate fine aggregate requirements.
10. Determine moisture corrections.
11. Make and test trial mixes.

Most concrete supply companies have a wealth of experience about how their materials perform in a variety of applications. This experience, accompanied with reliable test data on the relationship between strength and water–cementitious materials ratio, is the most dependable method for selecting mix proportions. However, understanding the basic principles of mixture design and the proper selection of materials and mixture characteristics is as important as the actual calculation. Therefore, the PCA procedure provides guidelines and can be adjusted to match the experience obtained from local conditions. The PCA mix design steps are discussed next.

1. Strength Requirements Variations in materials, and batching and mixing of concrete results in deviations in the strength of the concrete produced by a plant. Generally, the structural design engineer does not consider this variability when determining the size of the structural members. If the materials engineer provides a material with an average strength equal to the strength specified by the designer, then half of the concrete will be weaker than the specified strength. Obviously, this is undesirable. To compensate for the variance in concrete strength, the materials engineer designs the concrete to have an average strength greater than the strength specified by the structural engineer.

In order to compute the strength requirements for concrete mix design, three quantities must be known:

1. the specified compressive strength f'_c
2. the variability or standard deviation s of the concrete
3. the allowable risk of making concrete with an unacceptable strength

The standard deviation in the strength is determined for a plant by making batches of concrete, testing the strength for many samples, and computing the standard deviation using Equation 1.15 in Chapter 1. The allowable risk has been established by the American Concrete Institute (ACI). One of the risk rules states that there should be less than 10% chance that the strength of a concrete mix is less than the specified strength. Assuming that the concrete strength has a normal distribution, the implication of the ACI rule is that 10% of the area of the distribution must be to the left of f'_c, as shown in Figure 7.1.

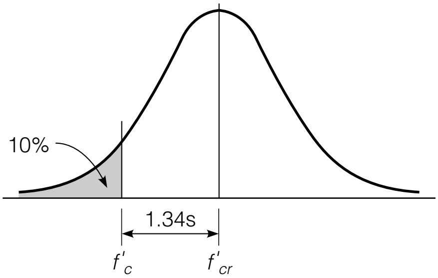

FIGURE 7.1 Use of normal distribution and risk criteria to estimate average required concrete strength.

Using a table of standard z values for a normal distribution curve, we can determine that 90% of the area under the curve will be to the right of f'_c if the average strength is 1.34 standard deviations from f'_c. In other words, the required average strength f'_{cr} for this criterion can be calculated as

$$f'_{\text{cr}} = f'_c + 1.34s \tag{7.1}$$

where

f'_{cr} = required average compressive strength, MPa or psi
f'_c = specified compressive strength, MPa or psi
s = standard deviation, MPa or psi

For mixes with a large standard deviation in strength, the ACI has another risk criterion that requires

$$f'_{\text{cr}} = f'_c + 2.33s - 3.45 \tag{7.2}$$

The required average compressive strength f'_{cr} is determined as the larger value obtained from Equations 7.1 and 7.2.

Equation 7.2 is valid for SI units only. If U.S. customary units are used, f'_{cr}, f'_c, and s are recorded in psi and the constant 3.45 in Equation 7.2 should be changed to 500.

The standard deviation should be determined from at least 30 strength tests. If the standard deviation is computed from 15 to 30 samples, then the standard deviation is multiplied by the following factor, F, to determine the modified standard deviation s'.

Number of Tests	Modification Factor F
15	1.16
20	1.08
25	1.03
30 or more	1.00

Linear interpolation is used for an intermediate number of tests, and s' is used in place of s in Equations 7.1 and 7.2.

If fewer than 15 tests are available, the following adjustments are made to the specified strength, instead of using Equations 7.1 and 7.2:

Specified Compressive Strength f'_c, MPa (psi)	Required Average Compressive Strength f'_{cr}, MPa (psi)
<21 (<3000)	$f'_c + 7.0$ ($f'_c + 1000$)
21 to 35 (3000 to 5000)	$f'_c + 8.5$ ($f'_c + 1200$)
>35 (>5000)	$f'_c + 10.0$ ($f'_c + 1400$)

These estimates are very conservative and should not be used for large projects, since the concrete will be overdesigned and, therefore, not economical.

Sample Problem 7.1

The design engineer specifies a concrete strength of 31.0 MPa (4500 psi). Determine the required average compressive strength for

a. a new plant for which s is unknown
b. a plant for which $s = 3.6$ MPa (520 psi) for 17 test results
c. a plant with extensive history of producing concrete with $s = 2.4$ MPa (350 psi)
d. a plant with extensive history of producing concrete with $s = 3.8$ MPa (550 psi)

Solution

a. $f'_{cr} = f'_c + 8.3 = 31.0 + 8.3 = 39.3$ MPa (5700 psi)

b. Need to interpolate modification factor:

$$F = 1.16 - \left(\frac{1.16 - 1.08}{20 - 15}\right)(17 - 15) \cong 1.13$$

Multiply standard deviation by the modification factor

$$s' = (s)(F) = 3.6(1.13) = 4.1 \text{ MPa } (590 \text{ psi})$$

Determine maximum from Equations 7.1 and 7.2

$f'_{cr} = 31.0 + 1.34(4.1) = 36.5$ MPa (5300 psi)

$f'_{cr} = 31.0 + 2.33(4.1) - 3.45 = 37.1$ MPa (5390 psi)

Use $f'_{cr} = 37.1$ MPa (5390 psi)

c. Determine maximum from Equations 7.1 and 7.2

$f'_{cr} = 31.0 + 1.34(2.4) = 34.2$ MPa (4970 psi)

$f'_{cr} = 31.0 + 2.33(2.4) - 3.45 = 33.1$ MPa (4810 psi)

Use $f'_{cr} = 34.2$ MPa (4970 psi)

d. Determine maximum from Equations 7.1 and 7.2

$f'_{cr} = 31.0 + 1.34(3.8) = 36.1$ MPa (5240 psi)

$f'_{cr} = 31.0 + 2.33(3.8) - 3.45 = 36.4$ MPa (5280 psi)

Use $f'_{cr} = 36.4$ MPa (5280 psi)

2. Water–Cementitious Materials Ratio Requirements The next step is to determine the water–cementitious materials ratio needed to produce the required strength. Historical records are used to plot a strength-versus–water–cementitious materials ratio curve, such as that seen in Figure 7.2. If historical data are not available, three trial batches are made at different water–cementitious materials ratios to establish a curve similar to Figure 7.2. Table 7.1 can be used for estimating the water–cementitious materials ratios for the trial mixes when no other data are available. The required average compressive strength is used with the strength versus water–cementitious materials relationship to determine the water–cementitious materials ratio required for the strength requirements of the project.

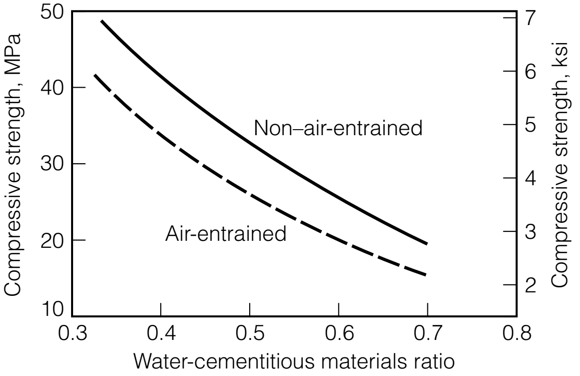

FIGURE 7.2 Example trial mixture or field data strength curves.

TABLE 7.1 Typical Relationship between Water–Cementitious Materials Ratio and Compressive Strength of Concrete*

	Water–Cementitious Materials Ratio by Weight	
Compressive Strength at 28 days, MPa (psi)**	**Non-Air-Entrained Concrete**	**Air-Entrained Concrete**
48 (7000)	0.33	—
41 (6000)	0.41	0.32
35 (5000)	0.48	0.40
28 (4000)	0.57	0.48
21 (3000)	0.68	0.59
14 (2000)	0.82	0.74

*American Concrete Institute (ACI 211.1 and ACI 211.3)

**Strength is based on cylinders moist-cured 28 days in accordance with ASTM C31 (AASHTO T23). Relationship assumes nominal maximum size of aggregate about 19 to 25 mm ($^{3}/_{4}$ to 1 in.).

TABLE 7.2 Maximum Permissible Water–Cementitious Materials Ratios for Concrete when Strength Data from Field Experience or Trial Mixtures are not Available*

Specified 28-day compressive Strength, f'_c, MPa (psi)	Water–Cementitious Materials Ratio by Weight	
	Non-Air-Entrained Concrete	Air-Entrained Concrete
17 (2500)	0.67	0.54
21 (3000)	0.58	0.46
24 (3500)	0.51	0.40
28 (4000)	0.44	0.35
31 (4500)	0.38	**
35 (5000)	**	**

*American Concrete Institute (ACI 318), 1999.

**For strength above 31.0 MPa (4500 psi) (non-air-entrained concrete) and 27.6 MPa (4000 psi) (air-entrained concrete), concrete proportions shall be established from field data or trial mixtures.

For small projects of noncritical applications, Table 7.2 can be used in lieu of trial mixes, with the permission of the project engineer. Table 7.2 is conservative with respect to the strength versus water–cementitious materials ratio relationship. This results in higher cement factors and greater average strengths than would be required if a mix design is performed. This table is not intended for use in designing trial batches; use Table 7.1 for trial batch design.

The water–cementitious materials ratio required for strength is checked against the maximum allowable water–cementitious materials ratio for the exposure conditions. Tables 7.3 and 7.4 provide guidance on the maximum allowable water–cementitious materials ratio and the minimum design compressive strength for exposure conditions. Generally, more severe exposure conditions require lower water–cementitious materials ratios. The minimum of the water–cementitious materials ratio for strength and exposure is selected for proportioning the concrete.

If a pozzolan is used in the concrete, the water–cementitious materials plus pozzolan ratio by weight may be used instead of the traditional water–cementitious materials ratio. In other words, the weight of the water is divided by the sum of the weights of cement plus pozzolan.

3. Coarse Aggregate Requirements The next step is to determine the suitable aggregate characteristics for the project. In general, large dense graded aggregates provide the most economical mix. Large aggregates minimize the amount of water required and, therefore, reduce the amount of cement required per cubic

TABLE 7.3 Maximum Water–Cementitious Material Ratios and Minimum Design Strengths for Various Exposure Conditions*

Exposure Condition	Maximum Water–Cementitious Material Ratio by Mass for Concrete	Minimum Design Compressive Strength, f'_c, MPa (psi)
Concrete protected from exposure to freezing and thawing, application of deicing chemicals, or aggressive substances	Select water–cementitious material ratio on basis of strength, workability, and finishing needs	Select strength based on structural requirements
Concrete intended to have low permeability when exposed to water	0.50	28 (4000)
Concrete exposed to freezing and thawing in a moist condition or deicers	0.45	31 (4500)
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)

*American Concrete Institute (ACI 318), 1999.

meter of mix. Round aggregates require less water than angular aggregates for an equal workability.

The maximum allowable aggregate size is limited by the dimensions of the structure and the capabilities of the construction equipment. The largest maximum aggregate size practical under job conditions that satisfies the size limits in the table should be used.

Situation	Maximum Aggregate Size
Form dimensions	1/5 of minimum clear distance
Clear space between reinforcement or prestressing 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

TABLE 7.4 Requirements for Concrete Exposed to Sulfates in Soil or Water*

Sulfate Exposure	Water-Soluble Sulfate (SO_4) in Soil, Percent by Weight**	Sulfate (SO_4) in Water, ppm**	Cement Type***	Maximum Water–Cementitious Material Ratio by Weight	Minimum Design Compressive Strength, f'_c, MPa (psi)
Negligible	Less than 0.10	Less than 150	No special type required	—	—
Moderate****	0.10–0.20	150–1500	II, MS, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)	0.50	28 (4000)
Severe	0.20–2.00	1500–10,000	V, HS	0.45	31 (4500)
Very Severe	Over 2.00	Over 10,000	V, HS	0.40	35 (5000)

*Adopted from American Concrete Institute (ACI 318), 1999.

**Tested in accordance with the Method for Determining the Quantity of Soluble Sulfate in Solid (Soil and Rock) and Water Samples, Bureau of Reclamation, Denver, 1977.

***Cement Types II and V are in ASTM C150 (AASHTO M85), Types MS and HS in ASTM C1157, and the remaining types are in ASTM C595 (AASHTO M240). Pozzolans or slags that have been determined by test or severe record to improve sulfate resistance may also be used.

****Sea water.

Sample Problem 7.2

A structure is to be built with concrete with a minimum dimension of 0.2 m, minimum space between rebars of 40 mm, and minimum cover over rebars of 40 mm. Two types of aggregate are locally available, with maximum sizes of 19 mm and 25 mm, respectively. If both types of aggregate have essentially the same cost, which one is more suitable for this structure?

Solution

25 mm $<$ (1/5)(200 mm) minimum dimensions.

25 mm $<$ (3/4)(40 mm) rebar spacing.

25 mm $<$ (3/4)(40 mm) rebar cover.

Therefore, both sizes satisfy the dimension requirements. However, 25 mm aggregate is more suitable, because it will produce more economical concrete mix.

The gradation of the fine aggregates is defined by the fineness modulus. The desirable fineness modulus depends on the coarse aggregate size and the quantity of cement paste. A low fineness modulus is desired for mixes with low cement content to promote workability.

Once the fineness modulus of the fine aggregate and the maximum size of the coarse aggregate are determined, the volume of coarse aggregate per unit volume of concrete is determined using Table 7.5. For example, if the fineness modulus of the fine aggregate is 2.60 and the maximum aggregate size is 25 mm (1 in.), the coarse aggregate will have a volume of 0.69 m^3/m^3 (yd^3/yd^3) of concrete. Table 7.5 is based on the unit weight of aggregates in a dry-rodded condition (ASTM C29). The values given are based on experience in producing an average degree of workability. The volume of coarse aggregate can be increased by 10% when less workability is required, such as in pavement construction. The volume of coarse aggregate should be reduced by 10% to increase workability, for example to allow placement by pumping.

4. Air Entrainment Requirements Next, the need for air entrainment is evaluated. Air entrainment is required whenever concrete is exposed to freeze–thaw conditions and deicing salts. Air entrainment is also used for workability in some situations. The amount of air required varies based on exposure conditions

TABLE 7.5 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**			
	Fineness Modulus			
	2.40	2.60	2.80	3.00
9.5 (3/8)	0.50	0.48	0.46	0.44
12.5 (1/2)	0.59	0.57	0.55	0.53
19 (3/4)	0.66	0.64	0.62	0.60
25 (1)	0.71	0.69	0.67	0.65
37.5 (1 1/2)	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

*American Concrete Institute (ACI 211.1).

**Bulk volumes are based on aggregates in a dry-rodded condition as described in ASTM C29 (AASHTO T19).

and is affected by the size of the aggregates. The exposure levels are defined as follows:

> *Mild exposure*—Indoor or outdoor service in which concrete is not exposed to freezing and deicing salts. Air entrainment may be used to improve workability.
>
> *Moderate exposure*—Some freezing exposure occurs, but concrete is not exposed to moisture or free water for long periods prior to freezing. Concrete is not exposed to deicing salts. Examples include exterior beams, columns, walls, etc., not exposed to wet soil.
>
> *Severe exposure*—Concrete is exposed to deicing salts, saturation, or free water. Examples include pavements, bridge decks, curbs, gutters, canal linings, etc.

Table 7.6 presents the recommended air contents for different combinations of exposure conditions and maximum aggregate sizes. The values shown in Table 7.6 are the entrapped air for non–air-entrained concrete and the entrapped plus entrained air in case of air-entrained concrete. The recommended air content decreases with increasing maximum aggregate size.

5. Workability Requirements The next step in the mix design is to determine the workability requirements for the project. Workability is defined as the ease of placing, consolidating, and finishing freshly mixed concrete. Concrete should be workable but should not segregate or excessively bleed (migration

TABLE 7.6 Approximate Target Percent Air Content Requirements for Different Nominal Maximum Sizes of Aggregates*

	Maximum Aggregate Size							
	9.5 mm (3/8 in.)	**12.5 mm ($\frac{1}{2}$ in.)**	**19 mm ($\frac{3}{4}$ in.)**	**25 mm (1 in.)**	**37.5 mm ($1\frac{1}{2}$ in.)**	**50 mm (2 in.)**	**75 mm (3 in.)**	**150 mm (6 in.)**
Non-air-entrained concrete	3	2.5	2	1.5	1	0.5	0.3	0.2
Air-entrained concrete**								
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

*American Concrete Institute (ACI 211.1 and ACI 318).

**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.

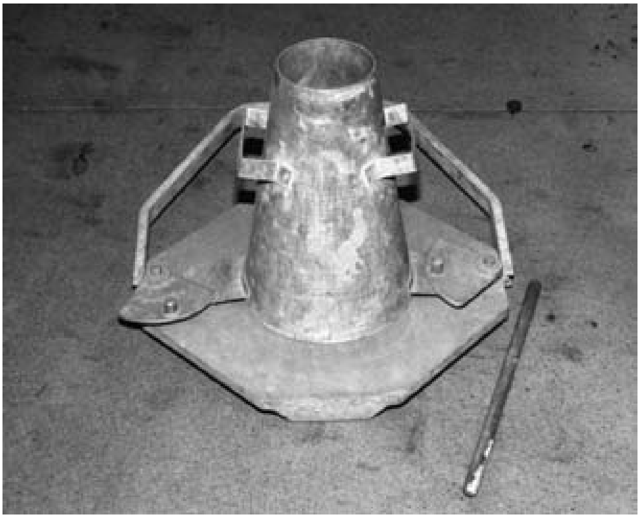

FIGURE 7.3 Slump test apparatus.

of water to the top surface of concrete). The slump test (Figure 7.3) is an indicator of workability when evaluating similar mixtures. This test consists of filling a truncated cone with concrete, removing the cone, then measuring the distance the concrete slumps (ASTM C143). The slump is increased by adding water, air entrainer, water reducer, superplasticizer, or by using round aggregates. Table 7.7 provides recommendations for the slump of concrete used in different types of projects. For batch adjustments, slump

TABLE 7.7 Recommended Slumps for Various Types of Construction*

	Slump, mm (in.)	
Concrete Construction	**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)

*American Concrete Institute (ACI 211.1).

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

increases about 25 mm (1in.) for each 6 kg of water added per m^3 (10 lb per cubic yard) of concrete.

6. Water Content Requirements The water content required for a given slump depends on the maximum size and shape of the aggregates and whether an air entrainer is used. Table 7.8 gives the approximate mixing water requirements for angular coarse aggregates (crushed stone). The recommendations in Table 7.8 are reduced for other aggregate shape as shown in this table.

Aggregate Shape	Reduction in Water Content, kg/m^3 (lb/yd^3)
Subangular	12 (20)
Gravel with crushed particles	21 (35)
Round gravel	27 (45)

These recommendations are approximate and should be verified with trial batches for local materials.

7. Cementing Materials Content Requirements With the water–cementitious materials ratio and the required amount of water estimated, the amount of cementing materials required for the mix is determined by dividing the weight of the water by the water–cementitious materials ratio. PCA recommends a minimum cement content of 334 kg/m^3 (564 lb/yd^3) for concrete exposed to severe freeze–thaw, deicers, and sulfate exposures, and not less than 385 kg/m^3 (650 lb/yd^3) for concrete placed under water. In addition, Table 7.9 shows the minimum cement requirements for proper placing, finishing, abrasion resistance, and durability in flatwork, such as slabs.

8. Admixture Requirements If one or more admixtures are used to add a specific quality in the concrete (as discussed in Chapter 6), their quantities should be considered in the mix proportioning. Admixture manufacturers provide specific information on the quantity of admixture required to achieve the desired results.

9. Fine Aggregate Requirements At this point, water, cement, and coarse aggregate weights per cubic meter (cubic yard) are known and the volume of air is estimated. The only remaining factor is the amount of fine aggregates needed. The weight mix design method uses Table 7.10 to estimate the total weight of a “typical” freshly mixed concrete for different maximum aggregate sizes. The weight of the fine aggregates is determined by subtracting the weight of the other ingredients from the total weight. Since Table 7.10 is based on a “typical” mix, the weight-based mix design method is only approximate.

TABLE 7.8 Approximate Mixing Water in kg/m^3 (lb/yd^3) for Different Slumps and Nominal Maximum Aggregate Sizes*

Slump, mm (in.)	Maximum Aggregate Size in mm (in.)**							
	9.5 (3/8)	12.5 (1/2)	19 (3/4)	25 (1)	37.5 (1 1/2)	50 (2)***	75 (3)***	150 (6)***
				Non-air-entrained concrete				
25 to 50 (1 to 2)	207 (350)	199 (335)	190 (315)	179 (300)	166 (275)	154 (260)	130 (220)	113 (190)
75 to 100 (3 to 4)	228 (385)	216 (365)	205 (340)	193 (325)	181 (300)	169 (285)	145 (245)	124 (210)
150 to 175 (6 to 7)	243 (410)	228 (385)	216 (360)	202 (340)	190 (315)	178 (300)	160 (270)	—
				Air-entrained concrete				
25 to 50 (1 to 2)	181 (305)	175 (295)	168 (280)	160 (270)	150 (250)	142 (240)	122 (205)	107 (180)
75 to 100 (3 to 4)	202 (340)	193 (325)	184 (305)	175 (295)	165 (275)	157 (265)	133 (225)	119 (200)
150 to 175 (6 to 7)	216 (365)	205 (345)	197 (325)	184 (310)	174 (290)	166 (280)	154 (260)	—

*American Concrete Institute (ACI 211.1 and ACI 318).

**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 (1 1/2 in.) are based on slump tests made after removal of particles larger than 37.5 mm by wet screening.

TABLE 7.9 Minimum Requirements of Cementing Materials for Concrete Used in Flatwork*

Maximum Size of Aggregate mm (in.)	Cementing Materials, kg/m^3 (lb/yd^3)**
37.5 ($1\frac{1}{2}$)	280 (470)
25.0 (1)	310 (520)
19.0 ($\frac{3}{4}$)	320 (540)
12.5 ($\frac{1}{2}$)	350 (590)
9.5 (3/8)	360 (610)

*American Concrete Institute (ACI 302).

**Cementing materials quantities may need to be greater for severe exposure. For example, for deicer exposures, concrete should contain at least 335 kg/m^3 (564 lb/yd^3) of cementing materials.

TABLE 7.10 Estimate of Weight of Freshly Mixed Concrete

Maximum Aggregate Size, mm (in.)	Non Air Entrained Concrete kg/m^3 (lb/yd^3)	Air Entrained Concrete kg/m^3 (lb/y^3)
9.5 (3/8)	2276 (3840)	2187 (3690)
12.5 ($\frac{1}{2}$)	2305 (3890)	2228 (3760)
19.0 ($\frac{3}{4}$)	2347 (3960)	2276 (3840)
25.0 (1)	2376 (4010)	2311 (3900)
37.5 ($1\frac{1}{2}$)	2412 (4070)	2347 (3960)
50.0 (2)	2441 (4120)	2370 (4000)
75.0 (3)	2465 (4160)	2394 (4040)
150 (6)	2507 (4230)	2441 (4120)

In the absolute volume method of mix design, the component weight and the specific gravity are used to determine the volumes of the water, coarse aggregate, and cement. These volumes, along with the volume of the air, are subtracted from a unit volume of concrete to determine the volume of the fine aggregate required. The volume of the fine aggregate is then converted to a weight using the unit weight. Generally, the bulk SSD specific gravity of aggregates is used for the weight–volume conversions of both fine and coarse aggregates.

10. Moisture Corrections Mix designs assume that water used to hydrate the cement is the free water in excess of the moisture content of the aggregates at the SSD condition (absorption), as discussed in Chapter 5. Therefore, the final step in the mix design process is to adjust the weight of water and aggregates to account for the existing moisture content of the aggregates. If the moisture content of the aggregates is more than the SSD moisture content, the weight of mixing water is reduced by an amount equal to the free weight of the moisture on the aggregates. Similarly, if the moisture content is below the SSD moisture content, the mixing water must be increased.

11. Trial Mixes After computing the required amount of each ingredient, a trial batch is mixed to check the mix design. Three 0.15 m × 0.30 m (6 in. × 12 in.) cylinders are made, cured for 28 days, and tested for compressive strength. In addition, the air content and slump of fresh concrete are measured. If the slump, air content, or compressive strength does not meet the requirements, the mixture is adjusted and other trial mixes are made until the design requirements are satisfied.

Additional trial batches could be made by slightly varying the material quantities in order to determine the most workable and economical mix.

Sample Problem 7.3

You are working on a concrete mix design that requires each cubic yard of concrete to have a 0.43 water–cementitious materials ratio, 2077 lb/yd^3 of dry gravel, 244 lb/yd^3 of water, and 4% air content. The available gravel has a specific gravity of $G_{\text{gravel}} = 2.6$, a moisture content of 2.3% and absorption of 4.5%. The available sand has a specific gravity of $G_{\text{sand}} = 2.4$, a moisture content of 2.2% and absorption of 1.7%. Air entrainer is to be included using the manufacturers specification of 0.1 fl. oz / 1% air / 100 lb cement.

For each cubic yard of concrete needed on the job, calculate the weight of cement, moist gravel, moist sand, and water that should be added to the batch. Summarize and total the mix design when finished.

Solution

Step 7: $W_{\text{cement}} = 244/0.43 = 567 \text{ lb/yd}^3$

Step 8: air entrainer $= (0.1)(4)(567/100) = 2.27$ fl. oz

Step 9: $\gamma_w = 62.4 \text{ lb/ft}^3\ (3 \text{ ft/yd})^3 = 1684.8 \text{ lb/yd}^3$

$$\begin{aligned}
V_{\text{cement}} &= 567.4/(3.15 \times 1684.8) &&= 0.107\ \text{yd}^3\\
V_{\text{water}} &= 244/1684.8 &&= 0.145\ \text{yd}^3\\
V_{\text{gravel}} &= 2077/(2.6 \times 1684.8) &&= 0.474\ \text{yd}^3\\
V_{\text{air}} &= 4\% &&= \underline{0.040\ \text{yd}^3}\\
&\qquad \text{Subtotal} &&= 0.766\ \text{yd}^3
\end{aligned}$$

$$V_{\text{sand}} = 1 - 0.766 = 0.234\ \text{yd}^3$$

$$m_{\text{sand}} = (0.234)(2.4)(1684.8) = 946\ \text{lb/yd}^3$$

Step 10: mix water $= 244 - 2077(0.023 - 0.045) - 946.2(0.022 - 0.017)$

$= 285\ \text{lb/yd}^3$

moist gravel $= 2077(1.023) = 2125\ \text{lb/yd}^3$

moist sand $= 946.2(1.022) = 967\ \text{lb/yd}^3$

cement $= 567\ \text{lb/yd}^3$

air entrainer = 2.27 fl. oz

Sample Problem 7.4

Design a concrete mix for the following conditions and constraints using the absolute volume method:

Design Environment
Bridge pier exposed to freezing and subjected to deicing chemicals
Required design strength = 24.1 MPa (3500 psi)
Minimum dimension = 0.3 m (12 in.)
Minimum space between rebars = 50 mm (2 in.)
Minimum cover over rebars = 40 mm (1.5 in.)
Standard deviation of compressive strength of 2.4 MPa (350 psi) is expected (more than 30 samples)
Only air entrainer is allowed

Available Materials
Cement
  Select Type V due to exposure
Air Entrainer
  Manufacturer specification 6.3 ml/1% air/100 kg cement (0.1 fl oz/1% air/100 lb cement)
Coarse aggregate
  25 mm (1 in.) maximum size, river gravel (round)
  Bulk oven dry specific gravity = 2.621, Absorption = 0.4%

Oven dry-rodded density = 1681 kg/m^3 (105 pcf)
Moisture content = 1.5%

Fine aggregate
Natural sand
Bulk oven-dry specific gravity = 2.572, Absorption = 0.8%
Moisture content = 4%
Fineness modulus = 2.60

Solution

1. Strength Requirements

$$s = 2.4 \text{ MPa (350 psi) (enough samples so that no correction is needed)}$$
$$f'_{cr} = f'_c + 1.34s = 24.1 + 1.34(2.4) = 27.3 \text{ MPa (3960 psi)}$$
$$f'_{cr} = f'_c + 2.33s - 3.45 = 24.1 + 2.33(2.4) - 3.45 = 26.2 \text{ MPa (3810 psi)}$$

f'_{cr} = 27.3 MPa (3960 psi)

2. Water–Cementitious Materials Ratio
Strength requirement (Table 7.1), water–cementitious materials ratio = 0.48 by interpolation
Exposure requirement (Tables 7.3 and 7.4), maximum water–cementitious materials ratio = 0.45

Water–cementitious materials ratio = 0.45

3. Coarse Aggregate Requirements

$$25 \text{ mm} < \frac{1}{5}(300 \text{ mm}) \text{ minimum dimensions}$$
$$25 \text{ mm} < \frac{3}{4}(50 \text{ mm}) \text{ rebar spacing}$$
$$25 \text{ mm} < \frac{3}{4}(40 \text{ mm}) \text{ rebar cover}$$

Aggregate size Okay for dimensions

(Table 7.5) 25 mm maximum size coarse aggregate and 2.60 FM fine aggregate
Coarse aggregate factor = 0.69
Dry weight of coarse aggregate = (1681)(0.69) = 1160 kg/m^3 (1956 lb/yd^3)

Coarse aggregate = 1160 kg/m^3 (1956 lb/yd^3)

4. Air Content
(Table 7.6) Severe exposure, target air content = 6.0%
Job range = 5% to 8% base

Design using 7%

5. Workability
(Table 7.7) Pier best fits the column requirement in the table
Slump range = 25 to 100 mm (1 to 4 in.)

Use 75 mm (3 in.)

6. Water Content
(Table 7.8) 25 mm aggregate with air entrainment and 75 mm slump
Water = 175 kg/m^3 (295 lb/yd^3) for angular aggregates. Since we have round coarse aggregates, reduce by 27 kg/m^3 (45 lb/yd^3)

Required water = 148 kg/m^3 (250 lb/yd^3)

7. Cementing Materials Content
   Water–cementitious materials ratio = 0.45, water = 148 kg/m^3 (250 lb/yd^3)
   Cement = 148/0.45 = 329 kg/m^3 (556 lb/yd^3)
   Increase for minimum criterion of 334 kg/m^3 (564 lb/yd^3) for exposure

   Cement = 334 kg/m^3 (564 lb/yd^3)

8. Admixture
   7% air, cement = 334 kg/m^3 (564 lb/yd^3)
   Admixture = (6.3)(7)(334/100) = 147 ml/m^3 (3.9 fl oz/yd^3)

   Admixture = 147 ml/m^3 (3.9 fl oz/yd^3)

9. Fine Aggregate Requirements
   Find fine aggregate content; use the absolute volume method.
   Water volume = 148/(1 × 1000) = 0.148 m^3/m^3 (4.006 ft^3/yd^3)
   Cement volume = 334/(3.15 × 1000) = 0.106 m^3/m^3 (2.869 ft^3/yd^3)
   Air volume = 0.07 m^3/m^3 (0.07 × 27 = 1.890 ft^3/yd^3)
   Coarse aggregate volume = 1160/(2.621 × 1000) = 0.443 m^3/m^3 (11.960 ft^3/yd^3)
   Subtotal volume = 0.767 m^3/m^3 (20.725 ft^3/yd^3)
   Fine aggregate volume = 1 − 0.767 = 0.233 m^3/m^3 (27 − 20.725 = 6.275 ft^3/yd^3)
   Fine aggregate dry weight = (0.233)(2.572)(1000) = 599 kg/m^3 (1007 lb/yd^3)

   Fine aggregate = 599 kg/m^3 (1007 lb/yd^3)

10. Moisture Corrections
    Coarse aggregate: Need 1160 kg/m^3 (1956 lb/yd^3) in dry condition, so increase by 1.5% for moisture
    Moist coarse aggregate = (1160)(1.015) = 1177 kg/m^3 (1985 lb/yd^3)
    Fine aggregate: Need 599 kg/m^3 (1007 lb/yd^3) in dry condition, so increase 4% for moisture
    Fine aggregate in moist condition = (599)(1.04) = 623 kg/m^3 (1047 lb/yd^3)
    Water: Reduce for free water on aggregates = 148 − 1160(0.015 − 0.004) − 599(0.04 − 0.008) = 116 kg/m^3 (196 lb/yd^3)

Summary

	Batch Ingredients Required	
	1 m^3 PCC	**1 yd^3 PCC**
Water	116 kg	196 lb
Cement	334 kg	564 lb
Fine aggregate	623 kg	1047 lb
Coarse aggregate	1177 kg	1985 lb
Admixture	147 ml	3.9 fl oz

■

7.1.2 Mixing Concrete for Small Jobs

The mix design process applies to large jobs. For small jobs, for which a large design effort is not economical (e.g., jobs requiring less than one cubic meter of concrete), Tables 7.11 and 7.12 can be used as a guide. The values in these tables may need to be adjusted to obtain a workable mix, using the

TABLE 7.11 Relative Components of Concrete for Small Jobs, by Weight*

Maximum Size of Coarse Aggregate mm (in.)	Air-Entrained Concrete				Non-Air-Entrained Concrete			
	Cement	Wet Fine Aggregate	Wet Coarse Aggregate**	Water	Cement	Wet Fine Aggregate	Wet Coarse Aggregate**	Water
9.5 (3/8)	0.210	0.384	0.333	0.073	0.200	0.407	0.317	0.076
12.5 ($^1/_2$)	0.195	0.333	0.399	0.073	0.185	0.363	0.377	0.075
19 ($^3/_4$)	0.176	0.296	0.458	0.070	0.170	0.320	0.442	0.068
25 (1)	0.169	0.275	0.493	0.063	0.161	0.302	0.470	0.067
37.5 ($1^1/_2$)	0.159	0.262	0.517	0.062	0.153	0.287	0.500	0.060

*Portland Cement Association, 2002.

**If crushed stone is used, decrease coarse aggregate by 50 kg and increase fine aggregate by 50 kg for each cubic meter of concrete (or decrease coarse aggregate by 3 lb and increase fine aggregate by 3 lb for each cubic foot of concrete).

TABLE 7.12 Relative Components of Concrete for Small Jobs, by Volume*

Maximum Size of Coarse Aggregate mm (in.)	Air-Entrained Concrete				Non-Air-Entrained Concrete			
	Cement	Wet Fine Aggregate	Wet Coarse Aggregate	Water	Cement	Wet Fine Aggregate	Wet Coarse Aggregate	Water
9.5 (3/8)	0.190	0.429	0.286	0.095	0.182	0.455	0.272	0.091
12.5 ($^1/_2$)	0.174	0.391	0.348	0.087	0.167	0.417	0.333	0.083
19 ($^3/_4$)	0.160	0.360	0.400	0.080	0.153	0.385	0.385	0.077
25 (1)	0.154	0.346	0.423	0.077	0.148	0.370	0.408	0.074
37.5 ($1^1/_2$)	0.148	0.333	0.445	0.074	0.143	0.357	0.429	0.071

*Portland Cement Association, 2002.

The combined volume is approximately 2/3 of the sum of the original bulk volumes.

locally available aggregates. Recommendations related to exposure conditions discussed earlier should be followed.

Tables 7.11 and 7.12 are used for proportioning concrete mixes by weight and volume, respectively. The tables provide ratios of components, with a sum of one unit. Therefore, the required total weight or volume of the concrete mix can be multiplied by the given ratios to obtain the weight or volume of each component. Note that for proportioning by volume, the combined volume is approximately two-thirds of the sum of the original bulk volumes of the components, since water and fine materials fill the voids between coarse materials.

Sample Problem 7.5

Determine the required weights of ingredients to make a 3500-lb batch of non-air-entrained concrete mix with a maximum gravel size of 1/2 in.

Solution
From Table 7.11:

Weight of cement = $3500 \times 0.185 = 647.5$ lb
Weight of wet fine aggregate = $3500 \times 0.363 = 1270.5$ lb
Weight of wet coarse aggregate = $3500 \times 0.377 = 1319.5$ lb
Weight of water = $3500 \times 0.075 = 262.5$ lb

■

Sample Problem 7.6

Determine the required volumes of ingredients to make a 0.5-m^3 batch of air-entrained concrete mix with a maximum gravel size of 19 mm.

Solution
Sum of the original bulk volumes of the components = $0.5 \times 1.5 = 0.75$ m^3. From Table 7.12:

Volume of cement = $0.75 \times 0.160 = 0.12$ m^3
Volume of wet fine aggregate = $0.75 \times 0.360 = 0.27$ m^3
Volume of wet coarse aggregate = $0.75 \times 0.400 = 0.3$ m^3
Volume of water = $0.75 \times 0.080 = 0.06$ m^3

■

7.2 Mixing, Placing, and Handling Fresh Concrete

The proper batching, mixing, and handling of fresh concrete are important prerequisites for strong and durable concrete structures. Next we will discuss the basic steps and precautions to be followed in mixing and handling fresh concrete (Mehta and Monteiro 1993; American Concrete Institute 1982; American Concrete Institute 1983).

Batching is measuring and introducing the concrete ingredients into the mixer. Batching by weight is more accurate than batching by volume, since weight batching avoids the problem created by bulking of damp sand. Water and liquid admixtures, however, can be measured accurately either by weight or volume. On the other hand, batching by volume is commonly used with continuous mixers and when hand mixing.

Concrete should be mixed thoroughly, either in a mixer or by hand, until it becomes uniform in appearance. Hand mixing is usually limited to small jobs or situations in which mechanical mixers are not available. Mechanical mixers include on-site mixers and central mixers in ready-mix plants. The capacity of these mixers varies from 1.5 m^3 to 9 m^3 (2 yd^3 to 12 yd^3). Mixers also vary in type, such as tilting, nontilting, and pan-type mixers. Most of the mixers are batch mixers, although some mixers are continuous.

Mixing time and number of revolutions vary with the size and type of the mixer. Specifications usually require a minimum of 1 minute of mixing for stationary mixers of up to 0.75 m^3 (1 yd^3) of capacity, with an increase of 15 seconds for each additional 0.75 m^3 of capacity. Mixers are usually charged with 10% of the water, followed by uniform additions of solids and 80% of the water. Finally, the remainder of the water is added to the mixer.

7.2.1 Ready-Mixed Concrete

Ready-mixed concrete is mixed in a central plant, and delivered to the job site in mixing trucks ready for placing (Figure 7.4). Three mixing methods can be used for ready mixed concrete:

1. Central-mixed concrete is mixed completely in a stationary mixer and delivered in an agitator truck (2 rpm to 6 rpm).
2. Shrink-mixed concrete is partially mixed in a stationary mixer and completed in a mixer truck (4 rpm to 16 rpm).
3. Truck-mixed concrete is mixed completely in a mixer truck (4 rpm to 16 rpm).

Truck manufacturers usually specify the speed of rotation for their equipment. Also, specifications limit the number of revolutions in a truck

FIGURE 7.4 Concrete ready mix plant.

mixer in order to avoid segregation. Furthermore, the concrete should be discharged at the job site within 90 minutes from the start of mixing, even if retarders are used (ASTM C94).

7.2.2 Mobile Batcher Mixed Concrete

Concrete can be mixed in a mobile batcher mixer at the job site (Figure 7.5). Aggregate, cement, water, and admixtures are fed continuously by volume, and the concrete is usually pumped into the forms.

7.2.3 Depositing Concrete

Several methods are available to deposit concrete at the jobsite. Concrete should be deposited continuously as close as possible to its final position. Advance planning and good workmanship are essential to reduce delay, early stiffening and drying out, and segregation. Figures 7.6–7.9 show different methods used to deposit concrete at the jobsite.

FIGURE 7.5 Mobile batcher mixer at the job site.

FIGURE 7.6 Loading concrete in a wheelbarrow.

FIGURE 7.7 Pouring concrete slab.

FIGURE 7.8 Placing concrete pavement with a slip-form paver.

FIGURE 7.9 Depositing concrete using a 2-1/2 cubic yard bucket.

7.2.4 Pumped Concrete

Pumped concrete is frequently used for large construction projects. Special pumps deliver the concrete directly into the forms (see Figure 7.10). Careful attention must be exercised to ensure well-mixed concrete with proper workability. The slump should be between 40 mm to 100 mm (1-1/2 in. to 4 in.) before pumping. During pumping, the slump decreases by about 12 mm to 25 mm (1/2 in. to 1 in.), due to partial compaction. Blockage could happen during pumping, due to either the escape of water through the voids in the mix or due to friction if fines content is too high (Neville 1981).

7.2.5 Vibration of Concrete

Quality concrete requires thorough consolidation to reduce the entrapped air in the mix. On small jobs, consolidation can be accomplished manually by ramming and tamping the concrete. For large jobs, vibrators are used to consolidate the concrete. Several types of vibrators are available, depending

FIGURE 7.10 Pumping concrete in a retaining wall.

on the application. *Internal vibrators* are the most common type used on construction projects (see Figure 7.11). These consist of an eccentric weight housed in a spud. The weight is rotated at high speed to produce vibration. The spud is slowly lowered into and through the entire layer of concrete, penetrating into the underlying layer if it is still plastic. The spud is left in place for 5 seconds to 2 minutes, depending on the type of vibrator and the consistency of the concrete. The operator judges the total vibration time required. Over-vibration causes segregation as the mortar migrates to the surface.

Several specialty types of vibrators are used in the production of precast concrete. These include *external vibrators, vibrating tables, surface vibrators, electric hammers,* and *vibratory rollers* (Neville 1981).

7.2.6 Pitfalls and Precautions for Mixing Water

Since the water–cementitious materials ratio plays an important role in concrete quality, the water content must be carefully controlled in the field. Water should not be added to the concrete during transportation. Crews frequently want to increase the amount of water in order to improve workability. If water is added, the hardened concrete will suffer serious loss in quality and strength. The engineer in the field must prevent any attempt to

FIGURE 7.11 Consolidating concrete with an internal vibrator.

increase the amount of mixing water in the concrete beyond that which is specified in the mix design.

7.2.7 Measuring Air Content in Fresh Concrete

Mixing and handling can significantly alter the air content of fresh concrete. Thus, field tests are used to ensure that the concrete has the proper air content prior to placing. Air content can be measured with the pressure, volumetric, gravimetric, or Chace air indicator methods.

The pressure method (ASTM C231) is widely used, since it takes less time than the volumetric method. The pressure method is based on Boyle's law, which relates pressure to volume. A calibrated cylinder (Figure 7.12) is filled with fresh concrete. The vessel is capped and air pressure is applied. The applied pressure compresses the air in the voids of the concrete. The volume of air voids is determined by measuring the amount of volume reduced by the pressure applied. This method is not valid for concrete made with lightweight aggregates, since air in the aggregate voids is also compressed, confounding the measurement of the air content of the cement paste.

The volumetric method for determining air content (ASTM C173) can be used for concrete made with any type of aggregate. The basic process involves placing concrete in a fixed volume cylinder, as shown in Figure 7.13. An equal volume of water is added to the container. Agitation of the container allows the excess water to displace the air in the cement paste voids.

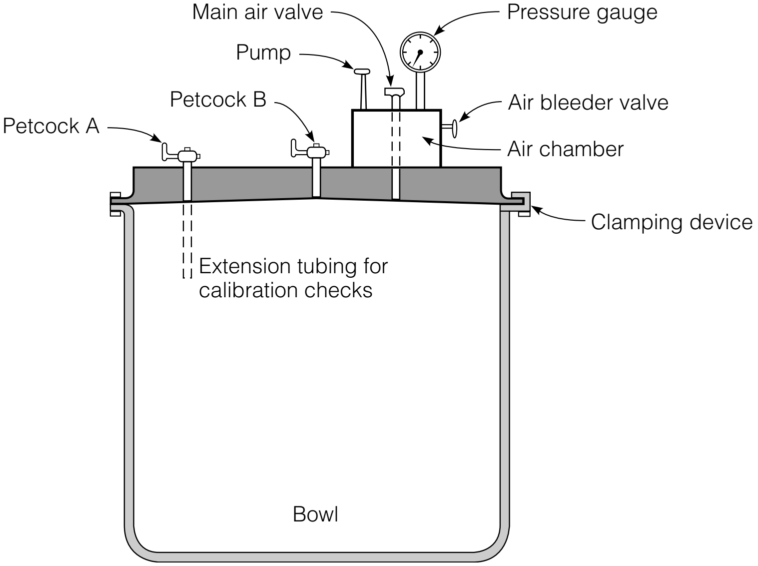

FIGURE 7.12 Pressure method apparatus for determining air voids in fresh concrete – Type B Meter (ASTM C231). (Copyright ASTM. Reprinted with permission.)

The water level in the container falls as the air rises to the top of the container. Thus, the volume of air in the cement paste is directly measured. The accuracy of the method depends on agitating the sample enough to remove all the air from it.

The gravimetric method (ASTM C138) compares the unit weight of freshly mixed concrete with the theoretical maximum unit weight of the mix. The theoretical unit weight is computed from the mix proportions and

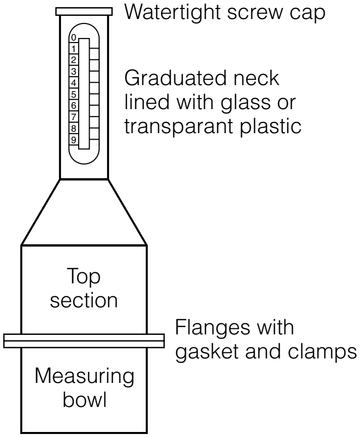

FIGURE 7.13 Volumetric method (Roll-A-Meter) apparatus for determining air voids in fresh concrete (ASTM C173). (Copyright ASTM. Reprinted with permission.)

FIGURE 7.14 Chace air indicator.

the specific gravity of each ingredient. This method requires very accurate specific gravity measurements, and thus is more suited to the laboratory rather than the field.

The Chace air indicator test (AASHTO T199) is a quick method used to determine the air content of freshly mixed concrete. The device consists of a small glass tube with a stem, a rubber stopper, and a metal cup mounted on the stopper, as shown in Figure 7.14. The metal cup is filled with cement mortar from the concrete to be tested. The indicator is filled with alcohol to a specified level, and the stopper is inserted into the indicator. The indicator is then closed with a finger and gently rolled and tapped until all of the mortar is dispersed in the alcohol and all of the air is displaced with alcohol. With the indicator held in a vertical position, the alcohol level in the stem is read. This reading is then adjusted using calibration tables or figures to determine the air content. The Chace air indicator test can be used to rapidly monitor air content, but it is not precise, nor does it have the repeatability required for specification control. It is especially useful for measuring the air content of small areas near the surface that may have lost air content by improper finishing.

These methods of measuring air content determine the total amount of air, including entrapped air and entrained air, as well as air voids in aggregate particles. Only minute bubbles produced by air-entraining agents impart durability to the concrete. However, the current state of the art is unable to distinguish between the types of air in fresh concrete.

7.2.8 Spreading and Finishing Concrete

Different methods are available to spread and finish concrete, depending on the nature of the structure and the available equipment. Tools and equipment used for spreading and finishing concrete include hand floats, power floats, darbies, bullfloats, straightedges, trowels, vibratory screed, and slip forms. (See Figures 7.8, 7.15–7.18).

FIGURE 7.15 Spreading concrete with a straightedge.

FIGURE 7.16 Finishing concrete with a straightedge.

FIGURE 7.17 Finishing concrete with a power float.

FIGURE 7.18 Finishing concrete with a laser level.

7.3 Curing Concrete

Curing is the process of maintaining satisfactory moisture content and temperature in the concrete for a definite period of time. Hydration of cement is a long-term process and requires water and proper temperature. Therefore, curing allows continued hydration and, consequently, continued gains in concrete strength. In fact, once curing stops, the concrete dries out, and the strength gain stops, as indicated in Figure 7.19. If the concrete is not cured and is allowed to dry in air, it will gain only about 50% of the strength of continuously cured concrete. If concrete is cured for only three days, it will reach about 60% of the strength of continuously cured concrete; if it is cured for seven days, it will reach 80% of the strength of continuously cured concrete. If curing stops for some time and then resumes again, the strength gain will also stop and reactivate.

Increasing temperature increases the rate of hydration and, consequently, the rate of strength development. Temperatures below 10°C (50°F) are unfavorable for hydration and should be avoided, if possible, especially at early ages.

Although concrete of high strength may not be needed for a particular structure, strength is usually emphasized and controlled since it is an indication of the concrete quality. Thus, proper curing not only increases strength, but also provides other desirable properties such as durability, water tightness, abrasion resistance, volume stability, resistance to freeze and thaw, and resistance to deicing chemicals.

Curing should start after the final set of the cement. If concrete is not cured after setting, concrete will shrink, causing cracks. Drying shrinkage can be prevented if ample water is provided for a long period of time. An example of improper curing would be a concrete floor built directly over the

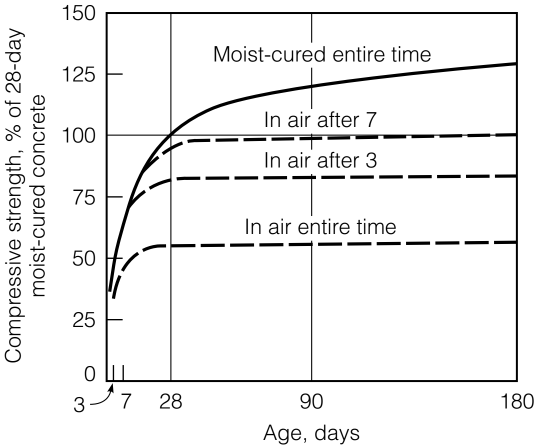

FIGURE 7.19 Compressive strength of concrete at different ages and curing levels.

subgrade, not cured at the surface, with the moisture in the soil curing it from the bottom. In this case the concrete slab may curl due to the relative difference in shrinkage.

Curing can be performed by any of the following methods:

1. maintaining the presence of water in the concrete during early ages. Methods to maintain the water pressure include pounding or immersion, spraying or fogging, and wet coverings.
2. preventing loss of mixing water from the concrete by sealing the surface. Methods to prevent water loss include impervious papers or plastic sheets, membrane-forming compounds, and leaving the forms in place.
3. accelerating the strength gain by supplying heat and additional moisture to the concrete. Accelerated curing methods include steam curing, insulating blankets or covers, and various heating techniques.

Note that preventing loss of mixing water from the concrete by sealing the surface is not as effective as maintaining the presence of water in the concrete during early ages. The choice of the specific curing method or combination of methods depends on the availability of curing materials, size and shape of the structure, in-place versus plant production, economics, and aesthetics (Kosmatka et al. 2002; American Concrete Institute 1986a).

7.3.1 Ponding or Immersion

Ponding involves covering the exposed surface of the concrete structure with water. Ponding can be achieved by forming earth dikes around the concrete surface to retain water. This method is suitable for flat surfaces such as floors and pavements, especially for small jobs. The method requires intensive labor and supervision. Immersion is used to cure test specimens in the laboratory, as well as other concrete members, as appropriate.

7.3.2 Spraying or Fogging

A system of nozzles or sprayers can be used to provide continuous spraying or fogging (see Figures 7.20 and 7.21). This method requires a large amount of water and could be expensive. It is most suitable in high temperature and low humidity environments. Commercial test laboratories generally have a controlled temperature and humidity booth for curing specimens.

7.3.3 Wet Coverings

Moisture-retaining fabric coverings saturated with water, such as burlap, cotton mats, and rugs are used in many applications (see Figure 7.22). The fabric can be kept wet, either by periodic watering or covering the fabric with

FIGURE 7.20 Curing concrete by spraying.

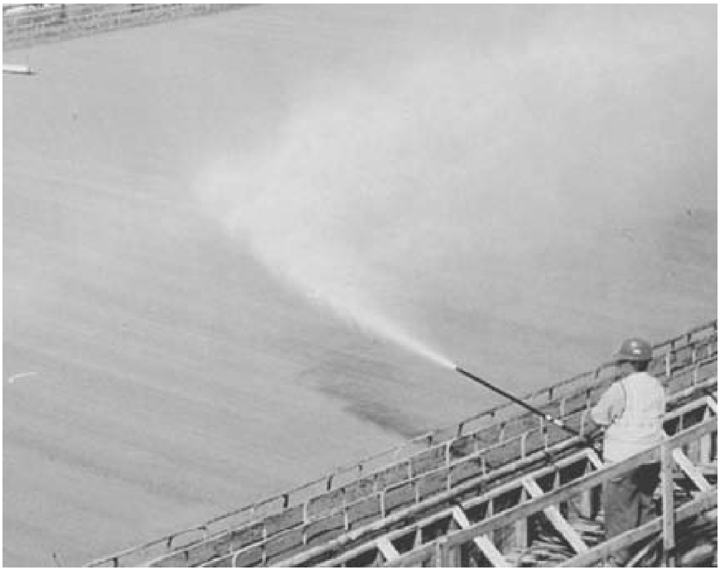

FIGURE 7.21 Curing concrete by fogging.

polyethylene film to retain moisture. On small jobs, wet coverings of earth, sand, saw dust, hay, or straw can be used. Stains or discoloring of concrete could occur with some types of wet coverings.

FIGURE 7.22 Curing concrete by wet covering.

7.3.4 Impervious Papers or Plastic Sheets

Evaporation of moisture from concrete can be reduced using impervious papers, such as kraft papers, or plastic sheets, such as polyethylene film (see Figures 7.23 and 7.24). Impervious papers are suitable for horizontal surfaces

FIGURE 7.23 Curing concrete with impervious fabrics.

FIGURE 7.24 Curing concrete with plastic sheets.

and simply shaped concrete structures, while plastic sheets are effective and easily applied to various shapes. Periodic watering is not required when impervious papers or plastic sheets are used. Discoloration, however, can occur on the concrete surface.

7.3.5 Membrane-Forming Compounds

Various types of liquid membrane-forming compounds can be applied to the concrete surface to reduce or retard moisture loss. These can be used to cure fresh concrete, as well as to hardened concrete, after removal of forms or after moist curing. Curing compounds can be applied by hand or by using spray equipment (see Figures 7.25 and 7.26). Either one coat or two coats (applied perpendicular to each other) are used. Normally, the concrete surface should be damp when the curing compound is applied. Curing compounds should not be used when subsequent concrete layers are to be placed, since the compound hinders the bond between successive layers. Also, some compounds affect the bond between the concrete surface and paint.

FIGURE 7.25 Curing concrete by manually applying membrane forming compound.

FIGURE 7.26 Curing concrete by machine applying membrane forming compound.

7.3.6 Forms Left in Place

Loss of moisture can be reduced by leaving the forms in place as long as practical, provided that the top concrete exposed surface is kept wet. If wood forms are used, the forms should also be kept wet. After removing the forms, another curing method can be used.

7.3.7 Steam Curing

Steam curing is used when early strength gain in concrete is required or additional heat is needed during cold weather. Steam curing can be attained either with or without pressure. Steam at atmospheric pressure is used for enclosed cast-in-place structures and large precast members. High-pressure steam in autoclaves can be used at small manufactured plants.

7.3.8 Insulating Blankets or Covers

When the temperature falls below freezing, concrete should be insulated using layers of dry, porous material such as hay or straw. Insulating blankets manufactured of fiberglass, cellulose fibers, sponge rubber, mineral wool, vinyl foam, or open-cell polyurethane foam can be used to insulate formwork. Moisture proof commercial blankets can also be used.

7.3.9 Electrical, Hot Oil, and Infrared Curing

Precast concrete sections can be cured using electrical, oil, or infrared curing techniques. Electrical curing includes electrically heated steel forms, and electrically heated blankets. Reinforcing steel can be used as a heating element, and concrete can be used as the electrical conductor. Steel forms can also be heated by circulating hot oil around the outside of the structure. Infrared rays have been used for concrete curing on a limited basis.

7.3.10 Curing Period

The curing period should be as long as is practical. The minimum time depends on several factors, such as type of cement, mixture proportions, required strength, ambient weather, size and shape of the structure, future exposure conditions, and method of curing. For most concrete structures the curing period at temperatures above 5°C (40°F) should be a minimum of seven days or until 70% of specified compressive or flexure strength is attained. The curing period can be reduced to three days if high early strength concrete is used and the temperature is above 10°C (50°F).

7.4 Properties of Hardened Concrete

It is important for the engineer to understand the basic properties of hardened portland cement concrete and to be able to evaluate these properties. The main properties of hardened concrete that are of interest to civil and construction engineers include the early volume change, creep, permeability, and stress–strain relation.

7.4.1 Early Volume Change

When the cement paste is still plastic it undergoes a slight decrease in volume of about 1%. This shrinkage is known as *plastic shrinkage* and is due to the loss of water from the cement paste, either from evaporation or from suction by dry concrete below the fresh concrete. Plastic shrinkage may cause cracking (Figure 7.27); it can be prevented or reduced by controlling water loss.

In addition to the possible decrease in volume when the concrete is still plastic, another form of volume change may occur after setting, especially at early ages. If concrete is not properly cured and is allowed to dry, it will shrink. This shrinkage is referred to as *drying shrinkage*, and it also causes cracks. Shrinkage takes place over a long period of time, although the rate of shrinkage is high early, then decreases rapidly with time. In fact, about 15% to 30% of the shrinkage occurs in the first two weeks, while 65% to 85% occurs in the first year. Shrinkage and shrinkage-induced cracking are increased by several factors, including lack of curing, high water–cementitious

FIGURE 7.27 Plastic shrinkage cracking.

materials ratio, high cement content, low coarse aggregate content, existence of steel reinforcement, and aging. On the other hand, if concrete is cured continuously in water after setting, concrete will swell very slightly due to the absorption of water. Since swelling, if it happens, is very small, it does not cause significant problems. *Swelling* is accompanied by a slight increase in weight (Neville 1981).

How much drying shrinkage occurs depends on the size and shape of the concrete structure. Also, nonuniform shrinkage could happen due to the nonuniform loss of water. This may happen in mass concrete structures, where more water is lost at the surface than at the interior. In cases such as this, cracks may develop at the surface. In other cases, curling might develop due to the nonuniform curing throughout the structure and, consequently, nonuniform shrinkage.

7.4.2 Creep Properties

Creep is defined as the gradual increase in strain, with time, under sustained load. Creep of concrete is a long-term process, and it takes place over many years. Although the amount of creep in concrete is relatively small, it could affect the performance of structures. The effect of creep varies with the type of structure. In simply supported reinforced concrete beams, creep increases the deflection and, therefore, increases the stress in the steel. In reinforced concrete columns, creep results in a gradual transfer of load from the concrete to the steel. Creep also could result in losing some of the prestress in prestressed concrete structures, although the use of high-tensile stress steel reduces this effect. Rheological models, discussed in Chapter 1, have been used to analyze the creep response of concrete (Neville 1981).

7.4.3 Permeability

Permeability is an important factor that largely affects the durability of hardened concrete. Permeable concrete allows water and chemicals to penetrate, which, in turn, reduces the resistance of the concrete structure to frost, alkali–aggregate reactivity, and other chemical attacks. Water that permeates into reinforced concrete causes corrosion of steel rebars. Furthermore, impervious concrete is a prerequisite in watertight structures, such as tanks and dams.

Typically, the air voids in the cement paste and aggregates are small and do not affect permeability. However, the air voids that do affect permeability of hardened concrete are obtained from two main sources: incomplete consolidation of fresh concrete and voids resulting from evaporation of mixing water that is not used for hydration of cement.

Therefore, increasing the water–cementitious materials ratio in fresh concrete has a severe effect on permeability. Figure 7.28 shows the typical relationship between the water–cementitious materials ratio and the coefficient of permeability of mature cement paste (Powers 1954). It can be seen

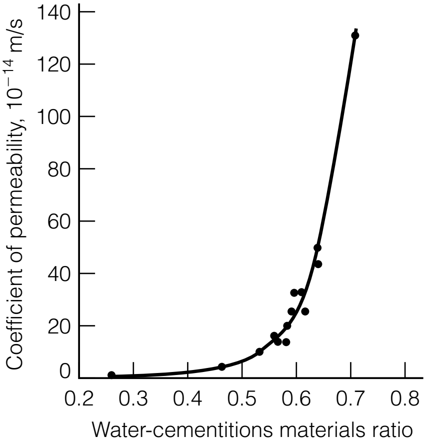

FIGURE 7.28 Relation between water-cementitious materials ratio and permeability of mature cement paste.

from the figure that increasing the water–cementitious materials ratio from 0.3 to 0.7 increases the coefficient of permeability by a factor of 1000. For a concrete to be watertight, the water–cementitious materials ratio should not exceed 0.48 for exposure to fresh water and should not be more than 0.44 for exposure to seawater (American Concrete Institute 1975).

Other factors that affect the permeability include age of concrete, fineness of cement particles, and air-entraining agents. Age reduces the permeability, since hydration products fill the spaces between cement grains. The finer the cement particles, the faster is the rate of hydration and the faster is the development of impermeable concrete. Air-entraining agents indirectly reduce the permeability, since they allow the use of a lower water–cementitious materials ratio.

7.4.4 Stress–Strain Relationship

Typical stress–strain behavior of 28-day-old concrete with different water–cementitious materials ratios are shown in Figure 7.29 (Hognestad et al. 1955). It can be seen that increasing the water–cementitious materials ratio decreases both strength and stiffness of the concrete. The figure also shows that the stress–strain behavior is close to linear at low stress levels, then becomes nonlinear as stress increases. With a water–cementitious materials ratio of 0.50 or less and a strain of up to 0.0015, the stress–strain behavior is almost linear. With higher water–cementitious materials ratios, the stress–strain behavior becomes nonlinear at smaller strains. The curves also show that high-strength concrete has sharp peaks and sudden failure characteristics when compared to low-strength concrete.

As discussed in Chapter 1, the elastic limit can be defined as the largest stress that does not cause a measurable permanent strain. When the concrete is loaded slightly beyond the elastic range and then unloaded, a small amount of strain might remain initially, but it may recover eventually due to creep. Also, since concrete is not perfectly elastic, the rate of loading affects

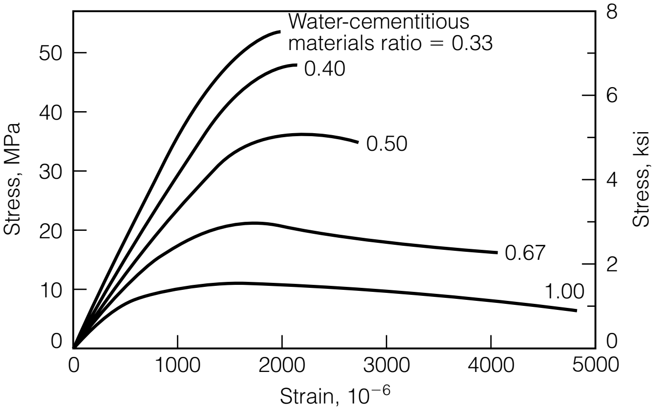

FIGURE 7.29 Typical stress–strain relations for compressive Tests on 0.15 x 0.30-m concrete cylinders at an age of 28 days.

the stress–strain relation to some extent. Therefore, a specific rate of loading is required for testing concrete. It is interesting to note that the shape of the stress–strain relationship of concrete is almost the same for both compression and tension, although the tensile strength is much smaller than the compressive strength. In fact, the tensile strength of concrete typically is ignored in the design of concrete structures.

The modulus of elasticity of concrete is commonly used in designing concrete structures. Since the stress–strain relationship is not exactly linear, the classic definition of modulus of elasticity (Young's modulus) is not applicable. The initial tangent modulus of concrete has little practical importance. The tangent modulus is valid only for a low stress level where the tangent is determined. Both secant and chord moduli represent "average" modulus values for certain stress ranges. The chord modulus (referred to as the modulus of elasticity) in compression is more commonly used for concrete and is determined according to ASTM C469. The method requires three or four loading and unloading cycles, after which the chord modulus is determined between a point corresponding to a very small strain value and a point corresponding to either 40% of the ultimate stress or a specific strain value. Normal-weight concrete has a modulus of elasticity of 14 GPa to 40 GPa (2,000 ksi to 6,000 ksi).

Poisson's ratio can also be determined using ASTM C469. Poisson's ratio is used in advanced structural analysis of shell roofs, flat-plate roofs, and mat foundations. Poisson's ratio of concrete varies between 0.11 and 0.21, depending on aggregate type, moisture content, concrete age, and compressive strength. A value of 0.15 to 0.20 is commonly used.

It is interesting to note that both aggregate and cement paste, when tested individually, exhibit linear stress–strain behavior. However, the stress–strain relation of concrete is nonlinear. The reason for this behavior is attributed to the microcracking in concrete at the interface between aggregate particles and the cement paste (Shah and Winter 1968).

The modulus of elasticity of concrete increases when the compressive strength increases, as demonstrated in Figure 7.29. There are several empirical relations between the modulus of elasticity of concrete and the compressive strength. For normal-weight concrete, the relationship used in the United States for designing concrete structures is defined by the ACI Building Code as

$$E_c = 4{,}731\sqrt{f'_c} \tag{7.3a}$$

or

$$E_c = 57{,}000\sqrt{f'_c} \tag{7.3b}$$

where

E_c = the modulus of elasticity,
f'_c = the compressive strength.

Equation 7.3a is used for SI units, where both E_c and f'_c are in MPa, whereas Equation 7.3b is used for the U.S. customary units, where both E_c and f'_c are in psi. This relation is useful, since it relates the modulus of elasticity (needed for designing concrete structures) with the compressive strength, which can be measured easily in the laboratory.

Sample Problem 7.7

A normal-weight concrete has an average compressive strength of 30 MPa. What is the estimated modulus of elasticity?

Solution

$$E_c = 4731\sqrt{f'_c} = 4731(30)^{1/2} = 25{,}913 \text{ MPa} = 25.9 \text{ GPa}$$

7.5 Testing of Hardened Concrete

Many tests are used to evaluate the hardened concrete properties, either in the laboratory or in the field. Some of these tests are destructive, while others are nondestructive. Tests can be performed for different purposes; however, they are mostly conducted to control the quality of the concrete and to check specification compliance. Probably the most common test performed on hardened concrete is the compressive strength test, since it is relatively easy to perform and since there is a strong correlation between the compressive strength and many desirable properties (Neville 1981; Mehta and Monteiro 1993). Other tests include split tension, flexure strength, rebound hammer, penetration resistance, ultrasonic pulse velocity, and maturity tests.

7.5.1 Compressive Strength Test

The compressive strength test is the test most commonly performed on hardened concrete. Compressive strength is one of the main structural design requirements to ensure that the structure will be able to carry the intended load. As indicated earlier, compressive strength increases as the water–cementitious materials ratio decreases. Since the water–cementitious materials ratio is directly related to the concrete quality, compressive strength is also used as a measure of quality, such as durability and resistance to weathering. Thus, in many cases, designers specify a high compressive strength of the concrete to ensure high quality, even if this strength is not needed for structural support. The compressive strength f'_c of normal-weight concrete is between 20 MPa to 40 MPa (3000 psi to 6000 psi). In the United States, the test is performed on cylindrical specimens and is standardized by ASTM C39. The specimen is prepared, either in the lab or in the field, according to ASTM C192 or C31, respectively. Cores could also be drilled from the structure following ASTM C42. The standard specimen size is 0.15 m (6 in.) in diameter and 0.30 m (12 in.) high, although other sizes with a height–diameter ratio of two can also be used. The diameter of the specimen must be at least three times the nominal maximum size of the coarse aggregate in the concrete.

In the lab, specimens are prepared in three equal layers and are rodded 25 times per layer. After the surface is finished, specimens are kept in the mold for the first 24 ± 8 hours. Specimens are then removed from the mold and cured at 23 ± 1.7°C (73.4 ± 3°F), either in saturated-lime water or in a moist cabinet having a relative humidity of 95% or higher, until the time of testing. Before testing, specimens are capped at the two bases to ensure parallel surfaces. High-strength gypsum plaster, sulfur mortar, or a special capping compound can be used for capping and is applied with a special alignment device (ASTM C617). Using a testing machine, specimens are tested by applying axial compressive load with a specified rate of loading until failure (Figure 7.30). The compressive strength of the specimen is determined by dividing the maximum load carried by the specimen during the test by the average cross-sectional area. The number of specimens and the number of test batches depend on established practice and the nature of the test program. Usually three or more specimens are tested for each test age and test condition. Test ages often used are 7 days and 28 days.

Note that the test specimen must have a height–diameter ratio of two. The main reason for this requirement is to eliminate the end effect due to the friction between the loading heads and the specimen. Thus, we can guarantee a zone of uniaxial compression within the specimen. If the height–diameter ratio is less than two, a correction factor can be applied to the results as indicated in ASTM C39.

The compressive strength of the specimen is affected by the specimen size. Increasing the specimen size reduces the strength, because there is a greater probability of weak elements where failure starts in large specimens

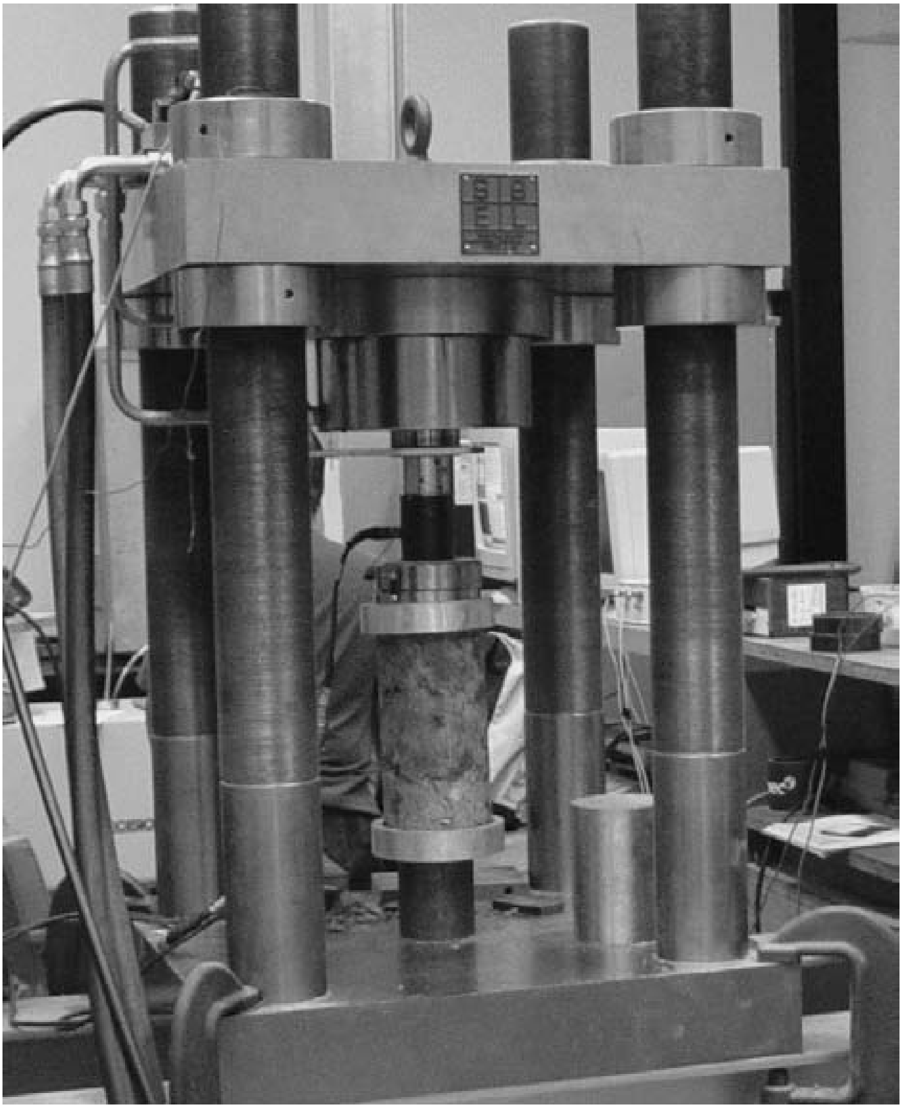

FIGURE 7.30 Compressive strength test.

than in small specimens. In general, large specimens have less variability and better representation of the actual strength of the concrete than small specimens. Therefore, the 0.15-m by 0.30-m (6-in. by 12-in.) size is the most suitable specimen size for determining the compressive strength. However, some agencies use 0.10-m (4-in.) diameter by 0.20-m (8-in.) high specimens. The advantages of using smaller specimens are the ease of handling, less possibility of accidental damage, less concrete needed, the ability to use a

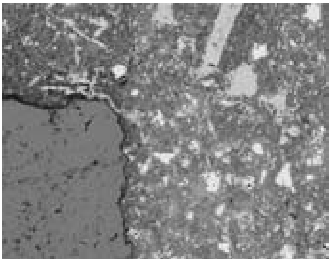

FIGURE 7.31 Scanning electron image showing the interface between a sand grain (lower left corner) and the paste.

low-capacity testing machine, and less space needed for curing and storage. Because of the strength variability of small specimens, more specimens should be tested for smaller specimens than are tested for standard-sized specimens. In some cases, five 0.10-m by 0.20-m replicate specimens are used instead of the three replicates commonly used for the standard-sized specimens. Also, when small-sized specimens are used, the engineer should understand the limitations of the test and consider these limitations in interpreting the results.

The interface between the hardened cement paste and aggregate particles is typically the weakest location within the concrete material. When concrete is stressed beyond the elastic range, microcracks develop at the cement paste–aggregate interface and continuously grow until failure. Figure 7.31 shows a scanning electron microscope micrograph of the fractured surface of a hardened cement mortar cylinder at 500x. The figure shows that the cleavage fracture surfaces where sand particles were dislodged during loading. The figure also shows the microcracks around some sand particles developed during loading.

7.5.2 Split-Tension Test

The split-tension test (ASTM C496) measures the tensile strength of concrete. In this test a 0.15-m by 0.30-m (6-in. by 12-in.) concrete cylinder is subjected to a compressive load at a constant rate along the vertical diameter until failure, as shown in Figure 7.32. Failure of the specimen occurs along its vertical diameter, due to tension developed in the transverse direction. The split tensile (indirect tensile) strength is computed as

$$T = \frac{2P}{\pi L d} \tag{7.4}$$

where

T = tensile strength, MPa (psi),
P = load at failure, N (psi),
L = length of specimen, mm (in.), and
d = diameter of specimen, mm (in.).

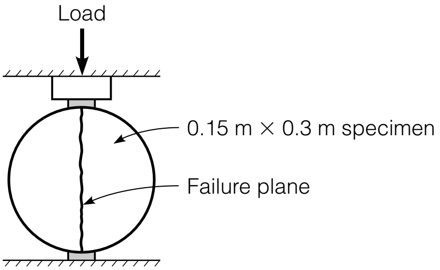

FIGURE 7.32 Split-tension test.

Typical indirect tensile strength of concrete varies from 2.5 MPa to 3.1 MPa (360 psi to 450 psi) (Neville 1981). The tensile strength of concrete is about 10% of its compressive strength.

7.5.3 Flexure Strength Test

The flexure strength test (ASTM C78) is important for design and construction of road and airport concrete pavements. The specimen is prepared either in the lab or in the field in accordance with ASTM C192 or C31, respectively. Several specimen sizes can be used. However, the sample must have a square cross section and a span of three times the specimen depth. Typical dimensions are 0.15-m by 0.15-m (6-in. by 6-in.) cross section and 0.30-m (18-in.) span. After molding, specimens are kept in the mold for the first 24 ± 8 hours, then removed from the mold and cured at 23 ± 1.7°C (73.4 ± 3°F), either in saturated-lime water or in a moist cabinet with a relative humidity of 95% or higher until testing. The specimen is then turned on its side and centered in the third-point loading apparatus, as illustrated in Figure 7.33. The load is continuously applied at a specified rate until rupture. If fracture initiates in the tension surface within the middle third of the span length, the flexure strength (modulus of rupture) is calculated as

$$R = \frac{Mc}{I} = \frac{PL}{bd^2} \tag{7.5}$$

where

R = flexure strength, MPa (psi),
M = maximum bending moment = $PL/6$, N.mm (lb.in.),
c = d/2, mm (in.),
I = moment of inertia = $bh^3/12$, mm^4 (in.^{4}),
P = maximum applied load, which is distributed evenly (1/2 to each) over the two loading points, N (lb),
L = span length, mm (in.),
b = average width of specimen, mm (in.), and
d = average depth of specimen, mm (in.).

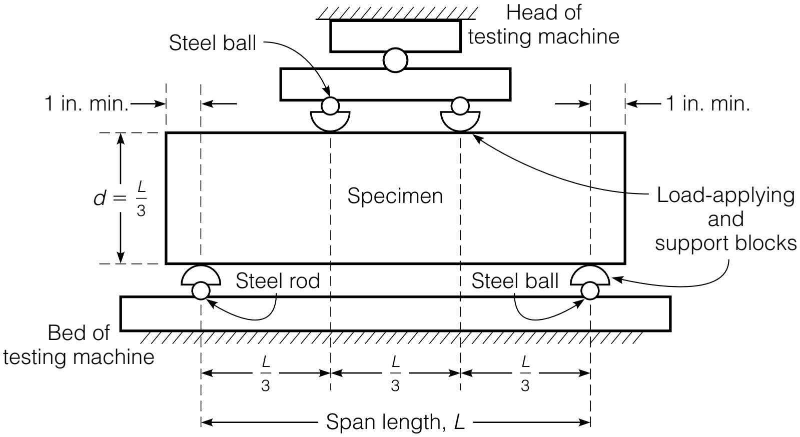

FIGURE 7.33 Apparatus for flexure test of concrete by third-point loading method (ASTM C78). Copyright ASTM. reprinted with permission.

Note that third-point loading ensures a constant bending moment without any shear force applied in the middle third of the specimen. Thus, Equation 7.5 is valid as long as fracture occurs in the middle third of the specimen. If fracture occurs slightly outside the middle third, the results can still be used with some corrections. Otherwise the results are discarded.

For normal-weight concrete, the flexure strength can be approximated as

$$R = (0.62 \text{ to } 0.83)\sqrt{f'_c} \tag{7.6a}$$

$$R = (7.5 \text{ to } 10)\sqrt{f'_c} \tag{7.6b}$$

Equation 7.6a is used for SI units, where both R and f'_c are in MPa, whereas Equation 7.6b is used for U.S. customary units, where both R and f' are in psi.

7.5.4 Rebound Hammer Test

The rebound hammer test, also known as the Schmidt hammer test, is a nondestructive test performed on hardened concrete to determine the hardness of the surface (Figure 7.34). The hardness of the surface can be correlated, to some extent, with the concrete strength. The rebound hammer is commonly used to get an indication of the concrete strength. The device is about 0.3 m (1 ft) long and encloses a mass and a spring. The spring-loaded mass is released to hit the surface of the concrete. The mass rebounds, and the amount of rebound is read on a scale attached to the device. The larger the rebound, the harder is the concrete surface and, therefore, the greater is the strength. The device usually comes with graphs prepared by the manufacturer to relate

FIGURE 7.34 Rebound hammer for nondestructive evaluation of hardened concrete.

rebound to strength. The test can also be used to check uniformity of the concrete surface.

The test is very simple to run and is standardized by ASTM C805. To perform the test, the hammer must be perpendicular to a clean, smooth concrete surface. In some cases, it would be hard to satisfy this condition. Therefore, correlations, usually provided by the manufacturer, can be used to relate the strength to the amount of rebound at different angles. Rebound hammer results are also affected by several other factors, such as local vibrations, the existence of coarse aggregate particles at the surface, and the existence of voids near the surface. To reduce the effect of these factors, it is desirable to average 10 to 12 readings from different points in the test area.

7.5.5 Penetration Resistance Test

The penetration resistance test, also known as the Windsor Probe test, is standardized by ASTM C803. The instrument (Figure 7.35) is a gunlike device that shoots probes into the concrete surface in order to determine its strength. The amount of penetration of the probe in the concrete is inversely related to the strength of concrete. The test is almost nondestructive since it creates small holes in the concrete surface.

The device is equipped with a special template with three holes, which is placed on the concrete surface. The test is performed in each of the holes. The average of the penetrations of the three probes through these holes is determined, using a scale and a special plate. Care should be exercised in handling the device to avoid injury. As a way of improving safety, the device cannot be operated without pushing hard on the concrete surface to prevent accidental shooting. The penetration resistance test is expected to provide better strength estimation than the rebound hammer, since the penetration resistance measurement is made not just at the surface but also in the depth of the sample.

FIGURE 7.35 Windsor probe test device.

7.5.6 Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity test (ASTM C597) measures the velocity of an ultrasonic wave passing through the concrete (Figure 7.36). In this test, the path length between transducers is divided by the travel time to determine the average velocity of wave propagation. Attempts have been made to correlate pulse velocity data with concrete strength parameters. No good correlations were found, since the relationship between pulse velocity and strength data is affected by a number of variables, such as age of concrete, aggregate–cement ratio, aggregate type, moisture condition, and location of reinforcement (Mehta and Moneiro 1993). This test is used to detect cracks, discontinuities, or internal deterioration in the structure of concrete.

7.5.7 Maturity Test

Maturity of a concrete mixture is defined as the degree of cement hydration, which varies as a function of both time and temperature. Therefore, it is assumed that, for a particular concrete mixture, strength is a function of maturity. Maturity meters (Figure 7.37) have been developed to provide an estimate of concrete strength by monitoring the temperature of concrete with time. This test (ASTM C1074) is performed on fresh concrete and continued for several days. The maturity meter must be calibrated for each concrete mix.

FIGURE 7.36 Ultrasonic pulse velocity apparatus (Courtesy of James Instrument Inc.).

FIGURE 7.37 Checking the maturity of fresh concrete using the maturity meter.

7.6 Alternatives to Conventional Concrete

There are several alternatives that increase the flexibility and applications of concrete. While a technical presentation of materials for each of these technologies is beyond the scope of this book, the engineer should be aware of some of the materials used to provide additional capabilities of concrete. Some of these alternatives include the following:

self-consolidating concrete
flowable fill
Shotcrete
lightweight concrete
high-strength concrete
shrinkage-compensating concrete
fiber-reinforced concrete
heavyweight concrete
polymers and concrete
high-performance concrete roller-compacted concrete

7.6.1 Self-Consolidating Concrete

Self-consolidating concrete (SCC), also known as self-compacting concrete, is a highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement, without any mechanical consolidation (NRMCA). Some of the advantages of using SCC are the following:

1. It can be placed at a faster rate, with no mechanical vibration and less screeding, resulting is savings in placement costs.
2. It improves and makes more uniform the architectural surface finish with little or no remedial surface work.
3. It improves ease of filling restricted sections and hard-to-reach areas. This allows the designer to create structural and architectural shapes not achievable with conventional concrete.
4. It improves consolidation around reinforcement and bond with reinforcement.
5. It improves pumpability.

Two important properties specific to self-consolidating concrete in its plastic state are its *flowability* and *stability*. The high flowability of SCC is achieved by using high-range water-reducing admixtures without adding extra mixing water. The stability, or resistance to segregation, is attained by increasing the amount of fines and/or by using admixtures that modify the viscosity of the mixture. Fines could be either cementitious materials or mineral fines.

The most common field test that has been used to measure the flowability and stability of SCC is a modified version of the slump test, discussed

FIGURE 7.38 Measuring the spread during the slump flow test.

earlier. In this slump flow test, the slump cone is completely filled, without consolidation. The cone is lifted, and the spread of the concrete is measured, as shown in Figure 7.38. The flowability is measured by the spread, or slump flow. The spread typically ranges from 455 to 810 mm (18 to 32 inches), depending on the requirements of the project. The resistance to segregation, or stability, is measured with the visual stability index (VSI). The VSI is established on the basis of whether bleed water is observed at the leading edge of the spreading concrete or aggregates pile at the center. VSI values range from 0 for "highly stable" to 3 for unacceptable stability.

During the slump flow test, the viscosity can be measured by the rate at which the concrete spreads. The time taken for the concrete to reach a spread diameter of 50 cm (20 inches) from the moment the sump cone is lifted up is measured. This is called the T_{50} (T_{20}) measurement and typically varies between 2 and 10 seconds for SCC. A T_{50} (T_{20}) value indicates a more viscous mix, which is more appropriate for concrete in applications with congested reinforcement or in deep sections. A lower T_{50} (T_{20}) value may be appropriate for concrete that has to travel long horizontal distances without much obstruction.

7.6.2 Flowable Fill

Flowable fill is a self-leveling and self-compacting, cementitious material with an unconfined compressive strength of 8.3 MPa (1200 psi) or less. Flowable fill is primarily used as a backfill material in lieu of compacted granular fill (Figure 7.39). Flowable fill is also commonly referred to as controlled low-strength material (CLSM), controlled density fill (CDF), flowable compacting fill, lean fill, unshrinkable fill, flow mortar, fly ash flow, and liquid dirt (NRMCA).

FIGURE 7.39 Filling a sink hole with flowable fill.

The flowable fill mix consists of cement, sand, and water typically mixed with fly ash, ground granulated blast furnace (GGBF) slag, and/or air generating admixtures. The type and proportions of ingredients used to make the flowable fill can largely change its properties to match its intended use.

One of the unique properties of flowable fill that makes it advantageous compared with compacted granular fill is its flowability. High flowability and self-leveling characteristics allow flowable fill to eliminate voids and access spaces that prove to be difficult or impossible with compacted granular fill.

When the flowable fill is placed in the cavity, its initial in-place volume is slightly reduced in the order of 10 mm per meter (1/8 inch per foot) of depth. This settlement is caused by the displacement of water and the release of entrapped air as a result of consolidation. Once the flowable fill is hardened, the settlement stops and the volume does not change.

Flowable fill can be proportioned to have a wide range of compressive strength. However, the most commonly used flowable fill mixtures are proportioned with consideration of possible excavation in future years and range in compressive strengths between 0.35 MPa and 1 MPa (50 and 150 psi). Flowable fill with a compressive strength less than 150 psi may be excavated manually, while at the same time having adequate bearing capacity to support external loads, such as the weight of a vehicle. Flowable fill exhibiting strengths between 150 and 300 psi will require mechanical equipment for excavation. If the strength exceeds 2 MPa (300 psi), the material is not considered excavatable.

Flowable fill has several advantages over compacted granular backfill. Flowable fill does not require compaction, which is a main concern with granular backfill. Flowable fill can also reach inaccessible locations, such as places around pipes, which are hard to reach with granular backfill. Flowable fill also has a greater bearing capacity than compacted granular fill and no noticeable settlement. It can even be placed in standing water. These advantages result in reduced in-place costs for labor and equipment, as well as time saving during construction.

Flowable fill is typically used as backfill for utility trenches, retaining walls, pipe bedding, and building excavation. It is also used as structural fill for poor soil conditions, mud jacking, floor and footing support, and bridge conversion. Other uses include pavement base, erosion control, and void filling. Flowable fill has been getting more common in recent years and is mostly available at local ready-mix producers.

7.6.3 Shotcrete

Shotcrete is mortar or small-aggregate concrete that is sprayed at high velocity onto a surface (see Figures 7.40 and 7.41). Shotcrete, also known as "gunite" and "sprayed concrete," is a relatively dry mixture that is consolidated by the impact force and can be placed on vertical or horizontal surfaces without sagging.

FIGURE 7.40 Constructing a swimming pool using shotcrete.

FIGURE 7.41 Shotcrete used in lining a tunnel.

Shotcrete is applied by either the dry or wet process. In the dry process, a premixed blend of cement and damp aggregate is propelled through a hose by compressed air to a nozzle, while the water is added at the nozzle. In the wet process, all ingredients are premixed and pumped through a hose to the nozzle and forced to the surface using compressed air. In either case, the nozzle should be held perpendicular to the surface to reduce the rebound of coarse aggregates off the surface. The nozzle is held about 0.5 to 1.5 m (1.5 to 5 ft) away from the surface.

Supplementary cementitious materials, such as fly ash and silica fume, can be used in shotcrete to improve workability, chemical resistance, and durability. Accelerating admixtures can also be used to reduce the time of initial set and to allow buildup of thicker layers of shotcrete in a single pass. Steel fibers may also be used to improve flexural strength, ductility, and toughness (Kosmatka et al. 2002).

7.6.4 Lightweight Concrete

Students competing in the annual ASCE concrete canoe competition frequently produce concrete with a unit weight less than water. The *ACI Guide* *for the Structural Lightweight Aggregate Concrete* requires a 28-day compressive strength of 17 MPa (2500 psi) and an air-dried unit weight of less than 1850 kg/m^3 (115 lb/ft^3) for structural lightweight concrete. The use of lightweight concrete in a structure is usually predicated on the overall cost of the structure; the concrete may cost more, but the reduced dead weight can reduce structural and foundation costs.

The mix proportions for lightweight concrete must compensate for the absorptive nature of the aggregates. Generally, lightweight aggregates are highly absorptive and can continue to absorb water for an extended period of time (Figures 7.42 and 7.43). This makes the determination of a water–cementitious materials ratio problematical. In addition, the lightweight aggregates tend to segregate by floating to the surface. A minimum slump mix, with air entraining, is used to mitigate this effect.

Nonstructural applications of very lightweight concrete have also been developed. Concrete made with styrofoam "aggregates" has been used for insulation in some building construction.

7.6.5 Heavyweight Concrete

Biological shielding used for nuclear power plants, medical units, and atomic research and test facilities requires massive walls to contain radiation. Concrete is an excellent shielding material. For biological shields, the mass of

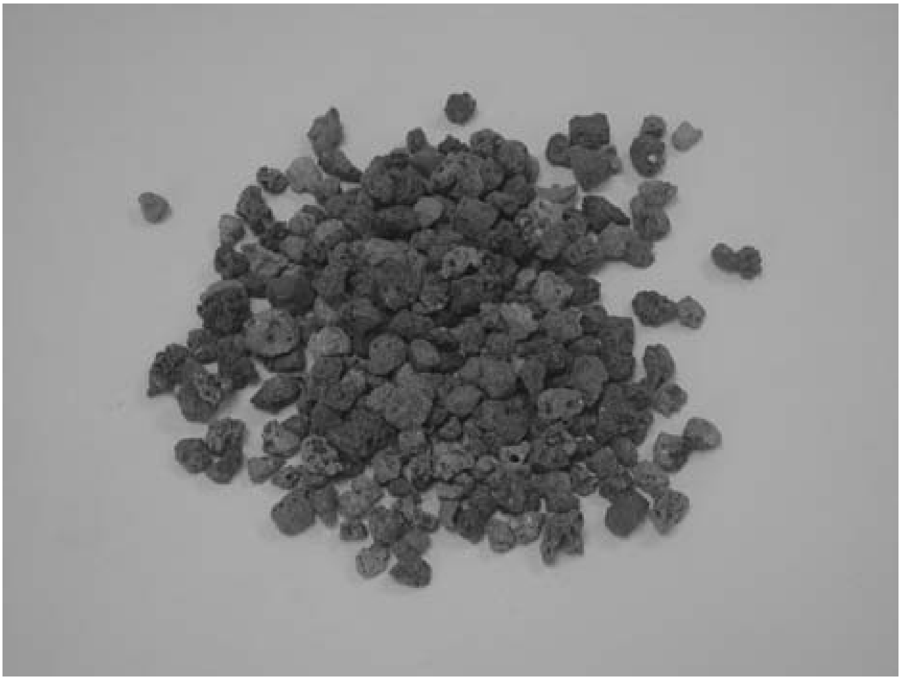

FIGURE 7.42 Aggregate used for lightweight concrete.

FIGURE 7.43 ASCE students at Arizona State University making a concrete canoe using lightweight concrete.

the concrete can be increased with the use of heavyweight aggregates. The aggregates can be either natural or manufactured. Natural heavyweight aggregates include barite, magnetite, hematite, geothite, illmenite, and ferrophosphorus. The specific gravity of these aggregates range from 3.4 to 6.5. Steel, with a specific gravity of 7.8, can be used as aggregate for heavyweight concrete (Figure 7.44). However, the specific gravity of the aggregates makes workability and segregation of heavyweight concrete problematical. Using a higher proportion of sand improves the workability. The workability problem can be avoided by preplacing aggregate, then filling the voids between aggregate particles with grout of cement, sand, water, and admixtures. ASTM C637, *Specifications for Aggregates for Radiation Shielding Concrete* and ASTM C637, *Nomenclature of Constituents of Aggregates for Radiation Shielding Concrete* provide further information on heavyweight concrete practices.

7.6.6 High-Strength Concrete

Concrete made with normal-weight aggregate and having compressive strengths greater than 40 MPa (6000 psi) is considered to be high-strength concrete. Producing a concrete with more than 40 MPa compressive strength requires care in the proportioning of the components and in quality control

FIGURE 7.44 Steel used as aggregate for heavy weight concrete.

during construction. The microstructure of concrete with a compressive strength greater than 40 MPa is considerably different from that of conventional concrete. In particular, the porosity of the cement paste and the transition zone between the cement paste and the aggregate are the controlling factors for developing high strength. This porosity is controlled by the water–cementitious materials ratio. The development of superplasticizers has permitted the development of high-strength concrete that is workable and flowable at low water–cementitious materials ratios. In addition, high-strength concrete has excellent durability due to its tight pore structure. In the United States, high-strength concrete is used primarily for skyscrapers. The high-strength and corresponding high elastic modulus allow for reduced structural element size.

7.6.7 Shrinkage-Compensating Concrete

Normal concrete shrinks at early ages, especially if it is not properly cured, as discussed earlier in this chapter. The addition of alumina powders to the cement can cause the concrete to expand at early ages. Shrinkage-compensating cement is marketed as Type K cement. Expansive properties can be used to advantage by restraining the concrete, either by reinforcing or by other means, at early ages. As the restrained concrete tries to expand, compressive stresses are developed. These compressive stresses reduce the tensile stresses developed by drying shrinkage, and the chance of the concrete cracking due to drying shrinkage is reduced. Details on the design and use of shrinkage-compensating concrete are available in ACI Committee 223 report *Recommendations for the Use of Shrinkage-Compensating Cements*.

7.6.8 Polymers and Concrete

Polymers can be used in several ways in the production of concrete. The polymer can be used as the sole binding agent to produce *polymer concrete*. Polymers can be mixed with the plastic concrete to produce *polymer–portland cement concrete*. Polymers can be applied to hardened concrete to produce *polymer-impregnated concrete*.

Polymer concrete is a mixture of aggregates and a polymer binder. There are a wide variety of polymers that can be mixed with aggregates to make polymer concrete. Some of these can be used to make rapid-setting concrete that can be put in service in under an hour after placement. Others are formulated for high strength; 140 MPa (20,000 psi) is possible. Some have good resistance to chemical attack. A common characteristic is that most polymer concretes are expensive, limiting their application to situations in which their unique characteristics make polymer concrete a cost-effective alternative to conventional concrete.

Polymer–portland cement concrete incorporates a polymer into the production of the portland cement concrete. The polymer is generally an elastomeric emulsion, such as latex.

7.6.9 Fiber-Reinforced Concrete

The brittle nature of concrete is due to the rapid propagation of microcracking under applied stress. However, with fiber-reinforced concrete, failure takes place due to fiber pull-out or debonding. Unlike plain concrete, fiber-reinforced concrete can sustain load after initial cracking. This effectively improves the toughness of the material. In addition, the flexural strength of the concrete is improved by up to 30%. For further information on the design and applications of fiber-reinforced concrete, consult the *ACI Guide for Specifying, Mixing, Placing and Finishing Steel Fiber Reinforced Concrete*.

Fibers are available in a variety of sizes, shapes, and materials (Figure 7.45). The fibers can be made of steel, plastic, glass, and natural materials. Steel fibers are the most common. The shape of fibers is generally described by the aspect ratio, length/diameter. Steel fibers generally have diameters from 0.25 mm to 0.9 mm (0.01 in. to 0.035 in.) with aspect ratios of 30 to 150. Glass fiber elements' diameters range from 0.013 mm to 1.3 mm (0.005 in. to 0.05 in.).

FIGURE 7.45 Fibers used for fiber-reinforced concrete

The addition of fibers to concrete reduces the workability. The extent of reduction depends on the aspect ratio of the fibers and the volume concentration. Generally, due to construction problems, fibers are limited to a maximum of 2% by volume of the mix. Admixtures can be used to restore some of the workability to the mix.

Since the addition of fibers does not greatly increase the strength of concrete, its use in structural members is limited. In beams, columns, suspended floors, etc., conventional reinforcing must be used to carry the total tensile load. Fiber-reinforced concrete has been successfully used for floor slabs, pavements, slope stabilization, and tunnel linings.

7.6.10 Roller-Compacted Concrete

Based on the unique requirements for mass concrete used for dam construction, roller-compacted concrete (RCC) was developed. This material uses a relatively low cement factor, relaxed gradation requirements, and a water content selected for construction considerations rather than strength. RCC is a no-slump concrete that is transported, placed, and compacted with equipment used for earth and rockfill dam construction. The RCC is hauled by dump trucks, spread with bulldozers, and compacted with vibration compactors. Japanese experience using RCC in construction found several advantages:

1. The mix is economical, because of the low cement content.
2. Formwork is minimal, because of the layer construction method.
3. The low cement factor limits the heat of hydration, reducing the need for external cooling of the structure.
4. The placement costs are lower than those for conventional concrete methods, due to the use of high-capacity equipment and rapid placement rates.
5. The construction period is shorter than that for conventional concrete.

In addition, experience in the United States has demonstrated that RCC in-place material costs are about one-third those of conventional concrete. The two primary applications of RCC have been for the construction of dams and large paved areas, such as military tank parking aprons.

7.6.11 High-Performance Concrete

While the current specifications for concrete have provided a material that performs reasonably well, there is concern that the emphasis on strength in the mix design process has led to concrete that is inadequate in other performance characteristics. This has led to an interest in developing specifications and design methods for what has been termed *high-performance concrete* (HPC). The American Concrete Institute (ACI) defines HPC as concrete that meets special performance and uniformity requirements, which cannot always be obtained using conventional ingredients, normal mixing procedures, and typical curing practices. These requirements may include the following enhancements:

ease of placement and compaction
long-term mechanical properties
early-age strength
toughness
volume stability
extended life in severe environments

These enhanced characteristics may be accomplished by altering the aggregate gradation, including special admixtures, and improving mixing and placement practices. Currently, a compressive strength in the order of 70 to 175 MPa (10,000 to 25,000 psi) can be obtained. As the need for HPC is better understood and embraced by the engineering community, there will probably be a transition in concrete specification from the current prescriptive method to the performance-based or performance-related specifications. A Strategic Highway Research Program (SHRP) study (Zia et al. 1991) defined HPC as

maximum water–cementitious materials ratio of 0.35;
minimum durability factor of 80%, as determined by ASTM C 666, Procedure A; and
minimum strength criteria of either:

a. 21 MPa (3000 psi) within 4 hours after placement (Very Early Strength, VES),
b. 34 MPa (5000 psi) within 24 hours (High Early Strength, HES), or
c. 69 MPa (10,000 psi) within 28 days (Very High Strength, VHS).

Thus, high-performance concrete is characterized by special performance, both short-term and long-term, and uniformity in behavior (Nawy 1996). Such requirements cannot always be achieved by using only conventional materials or applying conventional practices. Since concrete is the most widely used construction material worldwide, new concrete construction has to utilize the currently available new technology in order to eliminate costly future rehabilitation.

Revolutionary new construction materials and modifications and improvements in the behavior of traditional materials have been developed in the last three decades. These developments have been considerably facilitated by increased knowledge of the molecular structure of materials, studies of long-term failures, development of more powerful instrumentation and monitoring techniques, and the need for stronger and better performing materials, suitable for larger structures, longer spans, and more ductility.

In spite of the current advances of the concrete technology and the development of high-performance concretes, it is expected that the concrete industry will continue improving through the development of new components and admixtures, microstructural studies, blended cement compositions, better material selection and proportioning techniques, and more efficient placement techniques.

SUMMARY

The design of durable portland cement concrete materials is the direct responsibility of civil engineers. Selection of the proper proportions of portland cement, water, aggregates, and admixtures, along with good construction practices, dictates the quality of concrete used in structural applications. Using the volumetric mix design method presented in this chapter will lead to concrete with the required strength and durability. However, the proper design of portland cement concrete is irrelevant unless proper construction procedures are followed, including the appropriate mixing, transporting, placing, and curing of the concrete. To ensure that these processes produce concrete with the desired properties, a variety of quality control tests are performed by civil engineers, including slump tests, air content tests, and strength-gain-with-time tests.

While the vast majority of concrete projects are constructed with conventional materials, there are a variety of important alternative concrete formulations available for specialty applications. These alternatives are introduced in this chapter; however, the technology associated with these alternatives is relatively complex, and further study is required in order to fully understand the behavior of these materials.

QUESTIONS AND PROBLEMS

7.1 The design engineer specifies a concrete strength of 5500 psi. Determine the required average compressive strength for
  a. a new plant where s is unknown
  b. a plant where $s = 500$ psi for 22 test results
  c. a plant with extensive history of producing concrete with $s = 400$ psi
  d. a plant with extensive history of producing concrete with $s = 600$ psi

7.2 A project specifies a concrete strength of 24.1 MPa. Materials engineers will design the mix for a strength higher than that to account for variabilities.
  a. Calculate the required average compressive strength of the mix design if the mixing plant has a standard deviation of $s = 3.8$ MPa.
  b. Using the ACI code equation, estimate what would be the modulus of elasticity of this concrete at the *required* compressive strength.

7.3 A project specifies a concrete strength of at least 3000 psi. Materials engineers will design the mix for a strength higher than that. Calculate the required average compressive strength of the mix design if the standard deviation is $s = 350$ psi. Estimate the modulus of elasticity of the concrete at the required average compressive strength (the calculated strength, not the given strength).

7.4 What is your recommendation for the maximum nominal size of coarse aggregate for the following situation?
A continuously reinforced concrete pavement cross section contains a layer of No. 6 reinforcing bars at 6-inch centers, such that the steel is just above mid-depth of a 10-inch thick slab. Cover over the top of the steel is therefore about 4 inches.

7.5 A concrete mix with a 3-inch slump, w/c ratio of 0.50, and sand with a fineness modulus of 2.4 contains 1700 lb of coarse aggregate. Compute the required weight of coarse aggregate per cubic yard. To adjust the mix so as to increase the compressive strength, the water-to-cement ratio is reduced to 0.45. Will the quantity of coarse aggregate increase, decrease, or stay the same? Explain your answer.

7.6 You are working on a concrete mix design that requires each cubic yard of concrete to have 0.45 water-to–cementitious materials ratio, 1963 lb/yd^3 of dry gravel, 4% air content, and 565 lb/ft^3 of cement. The available gravel has a specific gravity of $G_{\text{gravel}} = 2.7$, a moisture content of 1.6%, and absorption of 2.4%. The available sand has a specific gravity of $G_{\text{sand}} = 2.5$, a moisture content of 4.8%, and absorption of 1.5%. For each cubic yard of concrete needed on the job, calculate the weights of cement, moist gravel, moist sand, and water that should be added to the batch. Summarize and total the mix design when finished (don't include air entrainer in summary).

7.7 Design the concrete mix according to the following conditions:

Design Environment
Building frame
Required design strength = 27.6 MPa
Minimum dimension = 150 mm
Minimum space between rebar = 40 mm
Minimum cover over rebar = 40 mm
Statistical data indicate a standard deviation of compressive strength of 2.1 MPa is expected (more than 30 samples).
Only air entrainer is allowed.

Available Materials
Air entrainer: Manufacture specification 6.3 ml/1% air/100 kg cement.
Coarse aggregate: 19 mm maximum size, river gravel (rounded)
Bulk oven-dry specific gravity = 2.55, Absorption = 0.3%
Oven-dry rodded density = 1761 kg/m^3
Moisture content = 2.5%
Fine aggregate: Natural sand

Bulk oven-dry specific gravity = 2.659, Absorption = 0.5%
Moisture content = 2%
Fineness modulus = 2.47

7.8. Design the concrete mix according to the following conditions.

Design Environment
Pavement slab, Bozeman, Montana (cold climate)
Required design strength = 3000 psi
Slab thickness = 12 in.
Statistical data indicate a standard deviation of compressive strength of 250 psi is expected (more than 30 samples).
Only air entrainer is allowed.

Available Materials
Air entrainer: Manufacture specification is 0.15 fl oz/1% air/100 lb cement.
Coarse aggregate: 2 in. maximum size, crushed gravel (angular)
Bulk oven-dry specific gravity = 2.573, Absorption = 0.1%
Oven-dry rodded density = 120 pcf
Moisture content = 1%
Fine aggregate: Natural sand
Bulk oven-dry specific gravity = 2.54, Absorption = 0.2%
Moisture content = 3.67%
Fineness modulus = 2.68

7.9 The design of a concrete mix requires 1173 kg/m^3 of gravel in dry condition, 582 kg/m^3 of sand in dry condition, and 157 kg/m^3 of free water. The gravel available at the job site has a moisture content of 0.8% and absorption of 1.5%, and the available sand has a moisture content of 1.1% and absorption of 1.3%. What are the masses of gravel, sand, and water per cubic meter that should be used at the job site?

7.10 Design a non-air-entrained concrete mix for a small job with a maximum gravel size of 25 mm (1 in.). Show the results as follows:
a. masses of components to produce 2000 kg (4400 lb) of concrete.
b. volumes of components to produce 1 m^3 (36 ft^3) of concrete.

7.11 Design a non-air-entrained concrete mix for a small job with a maximum gravel size of $^3/_4$ in. Show the results as follows:
a. weights of components to produce 5000 lb of concrete.
b. volumes of components to produce 1 yd^3 of concrete.

7.12 Why is it necessary to measure the air content of concrete at the job site rather than at the batch plant? Name one of the methods used to measure the air content of concrete.

7.13 What do we mean by curing concrete? What would happen if concrete is not cured?

7.14 Discuss five different methods of concrete curing.

7.15 Discuss the change in volume of concrete at early ages.

7.16 Discuss the creep response of concrete structures. Provide examples of the effect of creep on concrete structures.

7.17. On one graph, draw a sketch showing the typical relationship between the stress and strain of concrete specimens with high and low water–cementitious materials ratios. Label all axes and curves. Comment on the effect of increasing the water–cementitious materials ratio on the stress–strain response.

7.18 Using Figure 7.29,

a. Determine the ultimate stress at each water–cementitious materials ratio.

b. Determine the secant modulus at 40% of the ultimate stress at each water–cementitious materials ratio.

c. Plot the relationship between the secant moduli and the ultimate stresses.

d. Plot the relationship between the moduli and the ultimate stresses on the same graph of part (c), using the relation of the ACI Building Code (Equation 7.3).

e. Compare the two relations and comment on any discrepancies.

7.19 A normal-weight concrete has an average compressive strength of 4500 psi. What is the estimated modulus of elasticity?

7.20 Discuss the significance of the compressive strength test on concrete. Draw a graph to show the relationship between compressive strength and water–cementitious materials ratio for different curing times (Label all axes and curves).

7.21 What is the standard size of PCC specimens to be tested for compressive strength? If a smaller size is used, which size is expected to provide higher compressive strengths? Why? Which size provides strengths close to that of an actual concrete structure?

7.22 A short plain concrete column with dimensions of 12 in. × 12 in. × 36 in. is to be constructed. If the compressive strength of the concrete is 5000 psi, what is the maximum load that can be applied to this column using a factor of safety of 1.2?

7.23 What is the purpose of performing the flexure test on concrete? How are the results of this test related to the compressive strength test results?

7.24 What are the advantages of using a third-point loading flexure test over a center-point loading flexure test? Draw a shear force diagram and a bending moment diagram for each case to support your answer.

7.25 Consider a standard flexural strength specimen of length L, width a, and depth a. Assume third point loading where the load at failure from the test machine is P, which is distributed evenly (1/2 to each) over the two loading points. Derive the equation for calculating the modulus of rupture of the beam in terms of P, L, and a.

7.26 The flexure strength test was performed on a concrete beam having a cross section of 0.15 m by 0.15 m and a span of 0.45 m. If the load at failure was 35.7 kN, calculate the flexure strength of the concrete.

7.27 A normal-weight concrete has an average compressive strength of 20 MPa. What is the estimated flexure strength?

7.28 Discuss two nondestructive tests to be performed on hardened concrete. Show the basic principles behind the tests and how they are performed.

7.29 Discuss the concept of concrete maturity meters.

7.30 Discuss four alternatives that increase the use and application of conventional concrete.

7.31 What is self-consolidating concrete? How are its properties achieved? How are these properties measured?

7.32 What is flowable fill? Discuss its ingredients and its advantages.

7.33 Discuss the concept of high-performance concrete. Discuss some of its properties that make it preferred over conventional concrete.

7.34 Comparing PCC with mild steel, answer the following questions:

a. Which one is stronger?
b. Which one has a higher modulus or stiffness?
c. Which one is more brittle?
d. What is the range of compressive strength for a typical PCC?
e. What is the compressive strength for a high-strength concrete?
f. What would be a reasonable range for PCC modulus?

7.35 In a ready-mix plant, cylindrical samples are prepared and tested periodically to detect any mix problem and to ensure that the compressive strength is higher than the lower specification limit. The minimum target value was set at 4000 psi. The following compressive strength data were collected.

Sample No.	Compressive Strength (psi)	Sample No.	Compressive Strength (psi)
1	4914	14	5772
2	4732	15	4270
3	5670	16	5096
4	4310	17	4670
5	6110	18	5174
6	4316	19	5434
7	5240	20	3692
8	4950	21	4510
9	5230	22	3680
10	4190	23	4100
11	5770	24	3680
12	4524	25	3910
13	4056		

a. Calculate the mean, standard deviation, and the coefficient of variation of the data.
b. Using a spreadsheet program, create a control chart for these data showing the target value and the lower specification limit. Is the plant production meeting the specification requirement? If not, comment on possible reasons. Comment on the data scatter.

7.7 References

American Concrete Institute. Specifications for Structural Concrete. ACI Committee 301 Report, ACI 301–99. Farmington Hills, MI: American Concrete Institute, 1999.

American Concrete Institute. *Guide for Concrete Floor and Slab Construction*. ACI Committee 302 Report, ACI 302.1R-96. Farmington Hills, MI: American Concrete Institute, 1996.

American Concrete Institute. *Hot-Weather Concreting*. ACI Committee 305 Report, ACI 305R-99. Farmington Hills, MI: American Concrete Institute, 1999.

American Concrete Institute. *Cold-Weather Concreting*. ACI Committee 306 Report, ACI 306R-88. Farmington Hills, MI: American Concrete Institute, 1997.

American Concrete Institute. *Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete*. ACI Committee 211 Report, ACI 211.1–91. Farmington Hills, MI: American Concrete Institute, 1991.

American Concrete Institute. *Standard Practice for Curing Concrete*. ACI Committee 308 Report, ACI 308–92. Farmington Hills, MI: American Concrete Institute, 1997.

American Concrete Institute. *Building Code Requirements for Reinforced Concrete*. ACI Committee 318 Report, ACI 318–99. Farmington Hills, MI: American Concrete Institute, 1999.

Hognestad, E., N. W. Hanson, and D. McHenry. *Concrete Stress Distribution in Ultimate Strength Design*. Development Department Bulletin DX006. Skokie, IL: Portland Cement Association, 1955.

Kosmatka, S. H., B. Kerkhoff, and W. C. Panarese. *Design and Control of Concrete Mixtures*. 14th ed. Skokie, IL: Portland Cement Association, 2002.

Mehta, P. K. and P. J. M. Monteiro. *Concrete Structure, Properties, and Materials*. 2nd ed. Upper Saddle River, NJ: Prentice Hall, 1993.

National Ready Mixed Concrete Association (NRMCA). Concrete in Practice, CIP 37, "Self Consolidating Concrete." Silver Springs, MD: NRMCA, www.nrmca.org

National Ready Mixed Concrete Association (NRMCA). "Flowable Fill Materials." Silver Spring, MD: NRMCA, www.nrmca.org

Nawy, E. G. *Fundamentals of High Strength High Performance Concrete*, Concrete Design and Construction Series. Harlow, UK: Longman Group Limited, 1996.

Neville, A. M. *Properties of Concrete.* 3d ed. London: Pitman Books Ltd, 1981.

Portland Cement Association. *Concrete for Small Jobs.* IS174 T, 1988. Skokie, IL: Portland Cement Association, http://www.portcement.org/pdf_files/IS174

Powers, T. C., L. E. Copeland, J. C. Hayes and H. M. Mann. Permeability of portland cement paste. *Journal of American Concrete Institute* 51 (11) 285–298, Nov 1954.

Shah, S. P. and G. Winter. Inelastic Behavior and Fracture of Concrete. *Symposium on Causes, Mechanism, and Control of Cracking in Concrete.* American Concrete Institute Special Publication no. 20. Farmington Hills, MI: American Concrete Institute, 1968.

Zia, P., M.L. Leming, and S.H. Ahmad. *High Performance Concretes: A State-of-the-Art Report.* SHRP-C/FR-91-103, Washington, DC: Strategic Highway Research Program, National Research Council, 1991. http://www.tfhrc.gov/structur/hpc/hpc2/exec.htm