

Standard Practice for Selecting Proportions for Structural Lightweight Concrete (ACI 211.2-98)

Reported by ACI Committee 211

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This standard describes, with examples, two methods for proportioning and adjusting proportions of structural grade concrete containing lightweight aggregates. The weight (pycnometer) method uses a specific gravity factor determined by a displacement pycnometer test on the aggregates (Method 1). The weight method also employs the specific gravity factor to estimate the weight per yd^3 of the fresh concrete. The damp, loose volume method uses the cement content-strength relationship for the design of all lightweight and sand lightweight concrete (Method 2). Examples are given for systematic calculation of batch weights; effective displaced volumes; and adjustment to compensate for changes in aggregate moisture content; aggregate proportions; cement content; slump, air content, or both

Keywords: absorption; **adsorption**; air content; air entrainment; cement content; coarse aggregate; fine aggregate; fineness modulus; grading; lightweight aggregate; **mixture proportioning**; moisture; slump test; specific gravity factor.

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CHAPTER 1—INTRODUCTION

1.1—Purpose

The purpose of this standard is to provide generally applicable methods for selecting and adjusting mixture proportions for structural lightweight concrete. These methods are also applicable to concrete containing a combination of lightweight and normalweight aggregate.

1.2—Scope

Discussion in this standard is limited to structural grade, lightweight aggregates, and structural lightweight-aggregate concrete. Structural lightweight-aggregate concrete is defined as concrete which: (a) is made with lightweight aggregates conforming to ASTM C 330, (b) has a compressive strength in excess of 2500 psi (17.2 MPa) at 28 days of age when tested in accordance with methods stated in ASTM C 330, and (c) has an equilibrium weight not exceeding 115 lb/ft³ (1842 kg/m³) as determined by ASTM C 567. Concrete in which a portion of the lightweight aggregate is replaced by normalweight aggregate is within the scope of this standard. When normalweight fine aggregate is used, it should conform to the requirements of ASTM C 33. The use of pozzolanic and chemical admixtures is not covered in this standard.

CHAPTER 2—FACTORS AFFECTING PROPORTIONING OF LIGHTWEIGHT AGGREGATE CONCRETE

2.1—Aggregates (absorption and moisture content)

2.1.1 The principal factors necessitating modification of proportioning and control procedures for lightweight-aggregate concrete, compared with normalweight concrete, are the greater absorptions and the higher rates of absorption of most lightweight aggregates.

2.1.2 Damp aggregates are preferable to dry aggregates at time of mixing, as they tend to absorb less water during mixing and therefore reduce the possibility of loss of slump as the concrete is being mixed, transported, and placed. Damp aggregates have less tendency to segregate in storage. Absorbed water is accounted for in the mixture-proportioning procedure.

2.1.3 When concrete is made with lightweight aggregates that have low initial moisture contents (usually less than 8 to 10%) and relatively high rates of absorption, it may be desirable to mix the aggregates with one-half to two-thirds of the mixing water for a short period before adding cement, admixtures, and air-entraining admixture to minimize slump loss. The supplier of the particular aggregate should be consulted regarding the necessity for such predampening and for mixing procedure.

2.1.4 Concrete made with saturated lightweight aggregates may be more vulnerable to freezing and thawing than concrete made with damp or dry lightweight aggregates, unless the concrete is allowed to lose its excess moisture after curing, before such exposure, and has developed adequate strength to resist freezing.

2.1.5 When producing trial batches in the laboratory using the specific gravity method, the specific gravity of the lightweight aggregate should be determined at the moisture content anticipated before use.

2.1.6 For most concrete mixture proportions to be practical, aggregate proportions should be listed at a moisture condition readily attainable in the laboratory and in the field. In structural lightweight concrete, the main problem is accounting properly for the moisture in (absorbed), and on (adsorbed), the lightweight aggregate particles as well as for the effects of absorption for a specific application. Traditionally, concrete technologists have assumed, for aggregate moisture content correction purposes, that aggregates are in one of the four conditions at the time of use. These four conditions are shown in Fig. 2.1.

Most concrete mixture proportions are reported with aggregates in either saturated surface-dry (SSD) condition or oven-dry (OD) condition. In the field, aggregates are usually in the air-dry (AD) or wet condition. Lightweight aggregate, however, usually presents a unique situation. Most structural lightweight-aggregate concrete mixture proportions are reported in the OD condition; however, in the field they are not SSD, but in a damp or wet condition. This condition is usually achieved by sprinkling, soaking, thermal quenching, or vacuum saturation. The result is sometimes referred to as the “as-is” condition (Fig. 2.2).

Table 2.1—Comparison of fineness modulus by weight and volume for typical lightweight aggregate

Sieve size, no.	Opening, in. (mm)	Percent retained by weight	Cumulative percent retained by weight	Bulk specific gravity, SSD basis	Percent retained by volume	Cumulative percent retained by volume
4	0.187 (4.75)	0	0	—	0	0
8	0.0937 (2.38)	22	22	1.55	26	26
16	0.0469 (1.19)	24	46	1.78	25	51
30	0.0234 (0.59)	19	65	1.90	19	70
50	0.0117 (0.30)	14	79	2.01	13	83
100	0.0059 (0.15)	12	91	2.16	10	93
Pan	—	9	100	2.40	7	100

Note: Fineness modulus (by weight) = 3.03; fineness modulus (by volume) = 3.23.

The main problem for the concrete technologist is to have an easy method of using field data to convert the oven-dry laboratory trial proportions to proportions in the “as-is” moisture condition.

2.2—Aggregates (gradation)

2.2.1 Grading of the fine and coarse aggregates and the proportions used have an important effect on the concrete. A well-graded aggregate will have a continuous distribution of particle sizes, producing a minimum void content and will require a minimum amount of cement paste to fill the voids. This will result in the most economical use of cement and will provide maximum strength with minimum volume change due to drying shrinkage.

2.2.2 In general, the largest total volume of aggregate in the concrete is achieved:

- (a) when the coarse aggregate is well graded from the largest to the smallest sizes;
- (b) when the particle is rounded to cubical in shape; and
- (c) when the surface texture is least porous.

Conversely, concrete containing coarse aggregates that tend to be angular in shape, more porous in surface texture, and possibly deficient in one or more particle sizes, will require a smaller volume of aggregates.

These same factors of grading, particle shape, and texture also affect the percentage of fine aggregate required with a minimum percentage of fine aggregate being associated with a rounded or cubical shape and smooth texture. It is common that when a well-graded, normalweight sand is used to replace lightweight fine aggregate, the proportion of coarse lightweight aggregate may be increased. The proportion of coarse aggregate should approach the maximum consistent with workability and placeability, unless tests indicated that a lesser proportion provides optimum characteristics.

In some cases, strength may be increased by reducing the nominal maximum size of the aggregate without increasing the cement content.

2.2.3 For normalweight aggregates, the bulk specific gravities of fractions retained on the different sieve sizes are nearly equal. Percentages retained on each size indicated by weight

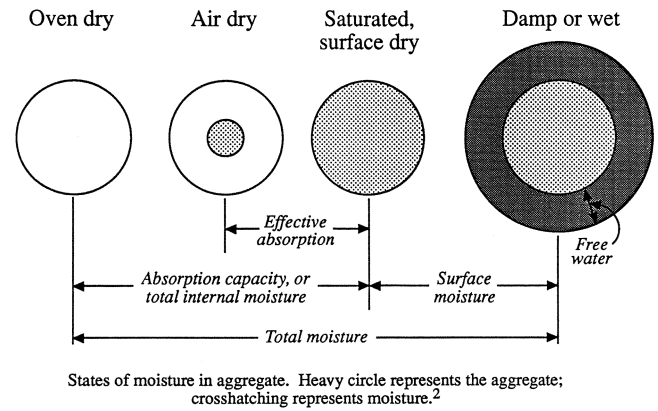


Fig. 2.1—States of moisture in aggregate.

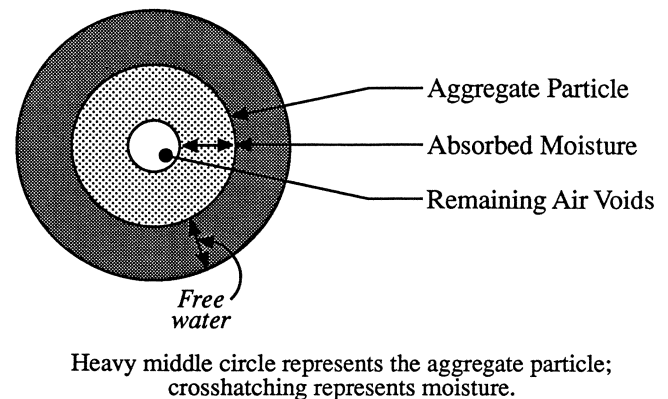


Fig. 2.2—“As-is” condition.

give a true indication of percentages by volume. The bulk specific gravity of the various size fractions of lightweight aggregate, however, usually increases as the particle size decreases. Some coarse aggregate particles may float on water, whereas material passing a No. 100 sieve (0.15 mm) may have a specific gravity approaching that of normalweight sand. It is the volume occupied by each fraction, and not the weight of material retained on each sieve, that determines the void content and paste content, and influences workability of the concrete. For a fine aggregate with a specific gravity of 1.89, the percentages retained on each sieve and fineness modulus, by weight and by volume, are computed for comparison in the example illustrated in Table 2.1.

A fineness modulus of 3.23 by volume in the example indicates a considerably coarser grading than that normally associated with the fineness modulus of 3.03 by weight. Therefore, lightweight aggregates require a larger percentage of material retained on the finer sieve sizes on a weight basis than do normalweight aggregates to provide an equal size distribution by volume.

2.2.4 As indicated in Section 1.2, concrete containing some normalweight aggregates, such as normalweight sand, is classified as lightweight concrete, provided the strength and unit weight requirements are met. The use of normalweight sand usually results in some increase in strength and modulus of elasticity. These increases, however, are made at the sacrifice of increased weight. The mixture proportions

selected, therefore, should consider these properties in conjunction with the corresponding effects on the overall economy of the structure.

2.3—Water-cementitious material ratio

2.3.1 Method 1—Lightweight-aggregate concrete may be proportioned by Method 1 (weight method, specific gravity pycnometer) on the basis of an approximate water-cementitious material ratio (w/cm) relationship when the absorption of the lightweight aggregate is known or determined, as described later in Appendix A. This method utilizes the fact that the sum of the weights per unit volume of all ingredients in a mixture is equal to the total weight of the same mixture. If the weight of the particular concrete per unit volume, which contains a particular aggregate, is known or can be estimated from the specific gravity factor of the aggregate, the weight of the lightweight aggregates in that volume of concrete can be determined.

2.3.2 Method 2—When trial mixtures are proportioned by procedures other than the weight method (Method 1—specific gravity pycnometer), the net water-cement ratio of most lightweight concrete mixtures cannot be established with sufficient accuracy to be used as a basis for mixture proportioning. This is due to the difficulty of determining how much of the total water is absorbed in the aggregate and thus is not available for reaction with the cement, versus the amount of water that is absorbed in open surface pores or cells of the aggregate particles, which usually remains there after surface drying and is available to react with the cement. The amount of free water in the surface pores or open cells varies according to the size and number of pores or open cells in the lightweight-aggregate particles. Lightweight-aggregate concrete mixtures are usually established by trial mixtures proportioned on a cement air content basis at the required consistency rather than on a water-cement ratio-strength basis when the weight method is not employed.

2.4—Air entrainment

2.4.1 Air entrainment is recommended in most lightweight-aggregate concrete as it is in most normalweight concrete (ACI 201.2R and 213R). It enhances workability, improves resistance to freezing-and-thawing cycles and deicer chemicals, decreases bleeding, and tends to obscure minor grading deficiencies. When severe exposure is not anticipated, its use may be waived, but the beneficial effects of air entrainment on concrete workability and cohesiveness are desirable and can be achieved at air contents of not less than 4.0%. Entrained air also lowers the unit weight of the concrete by several percentage points.

2.4.2 The amount of entrained air recommended for lightweight-aggregate concrete that may be subjected to freezing-and-thawing or to deicer salts is 4 to 6% air when maximum aggregate size is 3/4 in. (19.0 mm), and 4.5 to 7.5% when maximum aggregate size is 3/8 in. (9.5 mm).

2.4.3 The strength of lightweight concrete may be reduced by high air contents. At normal air contents (4 to 6%), the reduction is small if slumps are 5 in. (125 mm) or less and cement contents are used as recommended.

2.4.4 The volumetric method of measuring air, as described in ASTM C 173/C 173M, is the most reliable method of measuring air in either air-entrained concrete or non-air-entrained, structural lightweight concrete and is recommended.

CHAPTER 3—ESTIMATING FIRST TRIAL MIXTURE PROPORTIONS

3.1—General

The best approach to making a first trial mixture of lightweight concrete, which has given properties and uses a particular aggregate from a lightweight-aggregate source, is to use proportions previously established for a similar concrete using aggregate from the same aggregate source. Such proportions may be obtained from the aggregate supplier and may be the result of either laboratory mixtures or of actual mixtures supplied to jobs. These mixtures may then be adjusted as necessary to change the properties or proportions using the methods described in [Chapter 4](#).

Chapter 3 provides a guide to proportioning a first trial mixture where such prior information is not available, following which, the adjustment procedures of Chapter 4 may be used. Trial mixtures can be proportioned by either:

1. *Method 1 (weight method, specific gravity pycnometer)*—Lightweight coarse aggregate and normalweight fine aggregate; or

2. *Method 2 (volumetric method)*—All lightweight and combinations of lightweight and normalweight aggregates.

Method 1 (the weight method) is described in detail in Section 3.2, and the volumetric method is described in [Section 3.3](#).

3.2—Method 1: Weight method (specific gravity pycnometer)

For use with lightweight coarse aggregate and normalweight fine aggregate.

3.2.1 This procedure is applicable to sand-lightweight concrete comprised of lightweight coarse aggregate and normalweight fine aggregate. Estimating the required batch weights for the lightweight concrete involves determining the specific gravity factor of lightweight coarse aggregate, as discussed in Appendix A, from which the first estimate of the weight of fresh lightweight concrete can be made. Additionally, the absorption of lightweight coarse aggregate may be measured by the method described in ASTM C 127 or by the spin-dry procedure discussed in Appendix B, which permits the calculation of effective mixing water.

3.2.2 The proportioning follows the sequence of straightforward steps that, in effect, fit the characteristics of the available materials into a mixture suitable for the work. The question of suitability is frequently not left to the individual who selects the proportions. The job specifications may dictate some or all of the following:

1. Minimum cement or cementitious materials content;
2. Air content;
3. Slump;
4. Nominal maximum size of aggregate;
5. Strength;



Table 3.1—Recommended slumps for various types of construction

Types of construction	Slump, in. (mm)*	
	Maximum†	Minimum†
Beams and reinforced walls	4 (100)	1 (25)
Building columns	4 (100)	1 (25)
Floor slabs	3 (75)	1 (25)

*Slump may be increased when chemical admixtures are used, provided that the admixture-treated concrete has the same or lower w/c or w/cm and does not exhibit segregation potential or excessive bleeding.

†May be increased 1 in. for methods of consolidation other than vibration.

6. Unit weight;

7. Type of placement (such as pump, bucket, belt conveyor); and

8. Other requirements (such as strength overdesign, admixtures, and special types of cement and aggregate).

Regardless of whether the concrete characteristics are prescribed by the specifications or are left to the individual selecting the proportions, establishment of batch weights per unit volume of concrete can be best accomplished in the following sequence:

Step 1: Choice of slump—If slump is not specified, a value appropriate for the work can be selected from Table 3.1. The slump ranges shown apply when vibration is used to consolidate the concrete. Mixtures of the stiffest consistency that can be placed efficiently should be used.

Step 2: Choice of nominal maximum size of lightweight aggregate—The largest nominal maximum size of well-graded aggregates has fewer voids than smaller sizes. Hence, concrete with large-sized aggregates require less mortar per unit volume of concrete. Generally, the nominal maximum size of aggregate should be the largest that is economically available and consistent with the dimensions of the structure. In no event should the nominal maximum size exceed one-fifth of the narrowest dimension between sides of forms, one-third the depth of slabs, nor three-quarters of the minimum clear spacing between individual reinforcing bars, bundles of bars, or pretensioning strands. These limitations are sometimes waived by the engineer if workability and methods of consolidation are such that the concrete can be placed without honeycombing or voids. When high-strength concrete is desired, better results may be obtained with reduced nominal maximum sizes of aggregate because these can produce higher strengths at a given w/c or w/cm .

Step 3: Estimation of mixing water and air content—The quantity of water per unit volume of concrete required to produce a given slump is dependent on the nominal maximum size, particle shape and grading of the aggregates, amount of entrained air, and inclusion of chemical admixtures. It is not greatly affected by the quantity of cement or cementitious materials. Table 3.2 provides estimates of required mixing water for concrete made with various nominal maximum sizes of aggregate, with and without air entrainment. Depending on aggregate texture and shape, mixing water requirements may be somewhat above or below the tabulated values, but they are sufficiently accurate for the first estimate. Such differences in water demand are

Table 3.2—Approximate mixing water and air content requirements for different slumps and nominal maximum sizes of aggregates*

Aggregate size	3/8 in. (9.5 mm)	1/2 in. (12.7 mm)	3/4 in. (19.0 mm)
Air-entrained concrete			
	Water, lb/yd ³ (kg/m ³) of concrete		
Slump, 1 to 2 in. (25 to 50 mm)	305 (181)	295 (175)	280 (166)
Slump, 3 to 4 in. (75 to 100 mm)	340 (202)	325 (193)	305 (181)
Slump, 5 to 6 in. (125 to 150 mm)	355 (211)	335 (199)	315 (187)
	Recommended average† total air content, %, for level of exposure		
Mild exposure	4.5	4.0	4.0
Moderate exposure	6.0	5.5	5.0
Extreme exposure‡	7.5	7.0	6.0
Nonair-entrained concrete			
	Water, lb/yd ³ (kg/m ³) of concrete		
Slump, 1 to 2 in. (25 to 50 mm)	350 (208)	335 (199)	315 (187)
Slump, 3 to 4 in. (75 to 100 mm)	385 (228)	365 (217)	340 (202)
Slump, 5 to 6 in. (125 to 150 mm)	400 (237)	375 (222)	350 (208)
	Approximate amount of entrapped air in nonair-entrained concrete, %		
	3	2.5	2

*Quantities of mixing water given for air-entrained concrete are based on typical total contents requirements as shown for "moderate exposure" in the table above. These quantities of mixing water are for use in computing cement or cementitious materials content for trial batches at 68 to 77 °F (20 to 25 °C). They are maximum for reasonably well-shaped angular aggregates graded within limits of accepted specifications. The use of water-reducing chemical admixtures (ASTM C 494) may also reduce mixing water by 5% or more. The volume of the liquid admixtures is included as part of the total volume of the mixing water. The slump values of 7 to 11 in. (175 to 275 mm) are only obtained through the use of water-reducing chemical admixture; they are for concrete containing nominal maximum size aggregate not longer than 1 in. (25 mm).

†Additional recommendations for air content and necessary tolerances on air content for control in the field are given in a number of ACI documents, including ACI 201.2R, 345R, 318, 301, and 302.1R. ASTM C 94 for ready-mixed concrete also gives air content limits. The requirements in other documents may not always agree exactly, so in proportioning concrete, consideration should be given to selecting an air content that will meet the needs of the job and also meet the applicable specifications.

‡These values are based on the criteria that 9% air is needed in the mortar phase of the concrete. If the mortar volume will be substantially different from that determined in this recommended practice, it may be desirable to calculate the needed air content by taking 9% of the actual mortar value.

not necessarily reflected in strength because other compensating factors may be involved.

Table 3.2 indicates the approximate amount of entrapped air to be expected in non-air-entrained concrete, and shows the recommended levels of average air content for concrete in which air is to be purposely entrained for durability, workability, and reduced in weight.

When trial batches are used to establish strength relationships or verify strength-producing capability of a mixture, the least-favorable combination of mixing water and air content should be used. That is, the air content should be the maximum permitted or likely to occur, and the concrete should be gaged to the highest permissible slump. This will avoid developing an overly optimistic estimate of strength on the assumption that average rather than extreme conditions will prevail in the field. For additional information on air content recommendations, see ACI 201.2R, 213R, 302.1R, and 345R.

Step 4: Selection of approximate w/c —The required w/c or w/cm is determined not only by strength requirements but also by such factors as durability and finishing properties. Because different aggregates and cements generally produce

Table 3.3—Relationships between w/c and compressive strength of concrete*

Compressive strength at 28 days, psi (MPa)	Approximate water-cement ratio, by weight	
	Nonair-entrained concrete	Air-entrained concrete
6000 (41.4)	0.41	—
5000 (34.5)	0.48	0.40
4000 (27.6)	0.57	0.48
3000 (20.7)	0.68	0.59
2000 (13.8)	0.82	0.74

*Values are estimated average strengths for concrete containing not more than 2% air for non-air-entrained concrete and 6% total air content for air-entrained concrete. For a constant w/c or w/cm , the strength of concrete is reduced as the air content is increased. Twenty-eight-day strength values may be conservative and may change when various cementitious materials are used. The rate at which the 28-day strength is developed may also change.

Strength is based on 6 x 12 in. (150 x 300 mm) cylinders moist cured for 28 days in accordance with the sections on "Initial Curing" and "Curing of Cylinders for Checking the Adequacy of Laboratory Mixture Proportions for Strength or as the Basis for Acceptance or for Quality Control" of ASTM C 31 of *Making and Curing Concrete Specimens in the Field*. These are cylinders moist cured at $73.4 \pm 3^\circ\text{F}$ ($23 \pm 2^\circ\text{C}$) before testing.

The relationship in this table assumes a nominal maximum aggregate size of about 3/4 to 1 in. (19 to 25 mm). For a given source of aggregate, strength produced at a given w/c or w/cm will increase as nominal maximum size of aggregate decreases. See Section 2.3.

Table 3.4—Maximum permissible water-cement ratios for concrete in severe exposures*

Type of structure	Structure wet continuously or frequently; exposed to freezing and thawing [†]	Structure exposed to sea water or sulfates
Thin sections (railings, curbs, sills, ledges, ornamental work) and sections with less than 1 in. (25 mm) cover over steel	0.45	0.40 [‡]
All other structures	0.50	0.45 [‡]

*Based on ACI 201.2R.

[†]Concrete should also be air entrained.

[‡]If sulfate-resisting cement (Type II or Type V of ASTM C 150) is used, permissible w/c or w/cm may be increased by 0.05.

different strengths at the same w/c or w/cm , it is highly desirable to have or develop the relationship between strength and w/c or w/cm for the materials actually to be used. In the absence of such data, approximate and relatively conservative values for concrete containing Type I portland cement can be taken from Table 3.3. With typical materials, the tabulated w/c or w/cm should produce the strengths shown, based on 28 day tests of specimens cured under standard laboratory conditions. The average strength selected must exceed the specified strength by a sufficient margin to keep the number of low tests within specified limits. For severe conditions of exposure, the w/c or w/cm should be kept low even though strength requirements may be met with a higher value. Table 3.4 gives limiting values.

Step 5: Calculation of cement content—The amount of cement per unit volume of concrete is determined in Steps 3 and 4. The required cement is equal to the estimated mixing water content (Step 3) divided by the w/c (Step 4). If, however, the specification includes a separate minimum limit on cement in addition to requirements for strength and durability, the mixture must be based on whichever criterion leads to the larger amount of cement. The use of other cementitious materials or chemical admixtures will affect

Table 3.5—Volume of coarse aggregate per unit of volume of concrete*

Maximum size of aggregate, in. (mm)	Volume of oven-dry loose coarse aggregates* per unit volume of concrete for different fineness moduli of sand			
	2.40	2.60	2.80	3.00
3/8 (9.5)	0.58	0.56	0.54	0.52
1/2 (12.7)	0.67	0.65	0.63	0.61
3/4 (19.0)	0.74	0.72	0.70	0.68

*Volumes are based on aggregates in oven-dry loose condition as described in ASTM C 29/C 29M for unit weight of aggregate. These volumes are selected from empirical relationships to produce concrete with a degree of workability suitable for usual reinforced construction. For more workable concrete, such as may sometimes be required when placement is to be by pumping, they may be reduced up to 10%.

properties of both the fresh and hardened concrete. The use of various combinations of cementitious material, use of chemical admixtures, or both, is beyond the scope of this document, but may be found in ACI 212.1R, 212.2R, 226.1R, and 226.3R.

Step 6: Estimation of lightweight coarse aggregate content—Aggregates of essentially the same nominal maximum size and grading will produce concrete of satisfactory workability when a given volume of coarse aggregate, on a dry, loose basis, is used per unit volume of concrete. Appropriate values for this aggregate volume are given in Table 3.5. For equal workability, the volume of coarse aggregate in a unit volume of concrete depends only on its nominal maximum size and fineness modulus of the normal-weight fine aggregate. Differences in the amount of mortar required for workability with different aggregates, due to differences in particle shape and grading, are compensated for automatically by differences in dry loose unit weight.

The volume of aggregate, in ft^3 (m^3), on an oven-dry loose basis, for a unit volume of concrete is equal to the value from Table 3.5 multiplied by 27 for a yd^3 (1 for a m^3). This volume is converted to dry weight of coarse aggregate required in a unit volume of concrete by multiplying it by the oven-dry loose weight per ft^3 (m^3) of the lightweight coarse aggregate.

Step 7: Estimation of fine aggregate content—At completion of Step 6, all ingredients of the concrete have been estimated except the fine aggregate. Its quantity is determined by difference.

If the weight of the concrete per unit volume is estimated from experience, the required weight of fine aggregate is the difference between the weight of fresh concrete and the total weight of the other ingredients.

Often the unit weight of concrete is known with reasonable accuracy from previous experience with the materials. In the absence of such information, Table 3.6 can be used to make a first estimate based on the specific gravity factor of the lightweight coarse aggregate and the air content of the concrete. Even if the estimate of concrete weight per yd^3 (m^3) is approximate, mixture proportions will be sufficiently accurate to permit easy adjustment on the basis of trial batches, as will be shown in the examples.

The aggregate quantities to be weighed out for the concrete must allow for moisture in the aggregates. Generally, the aggregates will be moist and their weight should be increased by the percentage of water they