Chapter 4

Proportioning Structural Lightweight Concrete

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Expanded Shale, Clay & Slate Institute (ESCSI)
2225 E. Murray Holladay Rd, Suite 102
Salt Lake City, Utah 84117
(801) 272-7070 Fax: (801) 272-3377
info@escsi.org www.escsi.org

CHAPTER 4

4.0 Introduction
4.1 Factors Affecting Proportioning of Lightweight Concrete
Absorption characteristics
"Saturated" Surface Dry
Stockpile Moisture content
Full Saturation
Aggregate Grading
Air Entrainment
4.2 Methods of Proportioning
4.3 Absolute Volume Method
4.4 Damp Loose Volumetric Method
4.5 Adjusting Mixture Proportions
4.6 Controlling Proportions in the Field
4.7 Meeting Project Specifications
4.8 Specified Density Concrete
4.9 Lightweight, Non-Structural "Fill" Concrete
4.10 Polymer Modified Lightweight Concrete
4.11 Shrinkage Compensated Cement / Lightweight Concrete
4.12 Fiber Reinforced Lightweight Concrete
4.13 Insulating Grade Lightweight Aggregate and Insulating Concretes

Appendix 4A ACI 211.2-04 "*Standard Practice for Selecting Proportions for Structural Lightweight Concrete.*" (Under revision by 211.2 to be supplied later)
Appendix 4B Procedure for determination of density factor of structural lightweight aggregate
Appendix 4C ESCSI Schematic Volume Computation Sheets.
Appendix 4D Supporting references contained in 4.10 and 4.11

CHAPTER 4 PROPORTIONING STRUCTURAL LIGHTWEIGHT CONCRETE

4.0 Introduction

This chapter provides generally applicable methods for selecting and adjusting mixture proportions for structural lightweight concrete. In keeping with section 5.1.2 of ASTM C94-04, these methods are also applicable to concretes containing a combination of lightweight and normalweight aggregate. This chapter builds on the information and procedures of ACI 211.2-04 "*Guide for Selecting Proportions for Structural Lightweight Concrete"* Appendix 4A, and to enhance clarity, numerous additions derived from the paper "*Moisture Dynamics in Lightweight Aggregate and Concrete"* Chapter 3-Appendix 3F, and other documents were added throughout this chapter.

Additionally, as this chapter was designed to parallel ACI 211.2, and be a stand alone document, a considerable amount of basic aggregate technology developed in Chapter 3 is repeated here. Discussion in this chapter is limited to structural lightweight aggregates, and structural lightweight concretes.

ACI 213 defines structural lightweight concrete as: *Structural lightweight-aggregate concrete made with structural lightweight aggregate as defined in ASTM C 330.* The concrete has a minimum 28-day compressive strength of 2500 psi (17 MPa), an equilibrium density between 70 and 120 lb/ft^3 (1120 and 1920 kg/m^3), and consists entirely of lightweight aggregate or a combination of lightweight and normal-density aggregate.

These definitions are not specifications. Project specifications vary. While lightweight concrete with an equilibrium density of 70 to 105 lb/ft^3 (1120 to 1680 kg/m^3) is infrequently used, most lightweight concrete has an equilibrium density of 105 to 120 lb/ft^3 (1680 to 1920 kg/m^3). Because lightweight concrete is often project-specific, contacting the aggregate supplier before project design is advised to ensure an economical mixture and to establish the available range of density and strength.

When normalweight aggregate is used, it should conform to the requirements of ASTM C 33.

4.1 Factors Affecting the Proportioning of Lightweight Concrete

The principal factor that requires modification to mixture proportioning for lightweight concrete, compared to normalweight concrete, is the higher rate and magnitude of absorption of the lightweight aggregate.

To fully understand the role of absorbed water in the aggregate of fresh concrete mixture and the enhancement of hydration, it is essential to use terms that unambiguously define the amount and location of the water. As with all densities of hardened concrete, absorbed water is useful for extended internal curing and the reduction of autogenous and plastic shrinkage. For precise determination of the w/cm ratio, it is essential to evaluate the amount of water on the surface of the aggregate (adsorbed water) as this water contributes to the "net" mixing water.

When proportioning concrete use caution when using the expression "saturated" lightweight aggregates, to avoid the lack of precision existing in those cases where the lightweight aggregate used, may only have a moderate degree of saturation.

Aggregates conditioned to a relatively high degree of saturation are essential at time of mixing, as they significantly limit the amount of water absorbed during mixing and therefore reduce the possibility of slump loss as the concrete is being mixed, transported, and placed. In addition, pre-wet aggregates have fewer tendencies to segregate in storage. Absorbed water is directly accounted for in the increase of the relative density of the lightweight aggregate in the mixture-proportioning procedure.

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 there should be a proper accounting for the moisture in (absorbed), and on the surface (adsorbed), of the lightweight aggregate particles.

The oven-dry density of an individual particle depends both on the density of the solid vitreous material and the pore volume within the particles, and generally increases when particle size decreases. After pulverizing in a jar mill over an extended period, the relative density of the poreless, solid ceramic material was determined to be 2.60 by methods similar to those used in measuring the relative density of cement, Fig. 4.1.

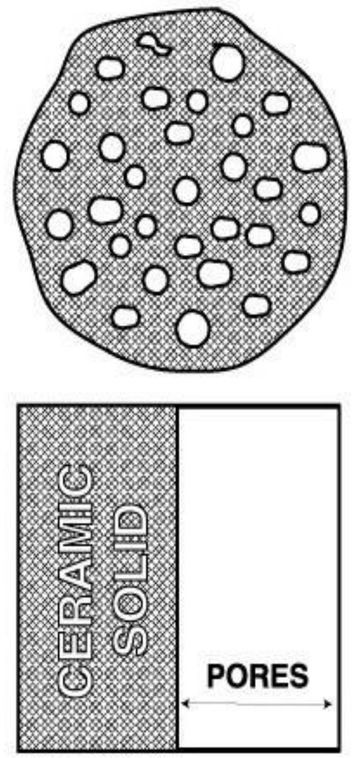


Figure 4.1. ***Schematic of Dry Structural Lightweight Aggregate***

Absorption Characteristics

Due to their cellular structure, lightweight aggregates absorb more water than their ordinary aggregate counterparts. Based upon a 24-hour absorption test conducted in accordance with the procedures of ASTM C 127 and ASTM C 128, structural-grade lightweight aggregates will absorb from 5 to more than 25 percent moisture by mass of dry aggregate. By contrast, ordinary aggregates generally absorb less than 2 percent of moisture. The important distinction in stockpile moisture content is that with lightweight aggregates the moisture is largely absorbed into the interior of the particles, whereas with ordinary aggregates it is primarily surface moisture. Recognition of this difference is essential in mixture proportioning, batching, and control. Rate of absorption is unique to each lightweight aggregate, and is dependent on the characteristics of pore size, continuity, and distribution, particularly for those pores close to the surface.

When the aggregate is used in concrete the internally absorbed water within the particle is not immediately available for chemical interaction with cement as mixing water, and as such, does not enter into water-cement ratio (W/Cm) calculations. However, it is extremely beneficial in maintaining longer periods of hydration (Internal Curing) essential to improvements in the aggregate/matrix contact zone. Internal curing will also bring about a significant reduction of permeability by extending the period in which additional products of hydration are formed in the pores and capillaries of the binder.

As can be seen in Fig. 4.2 the rate of absorption can be divided into four regions.

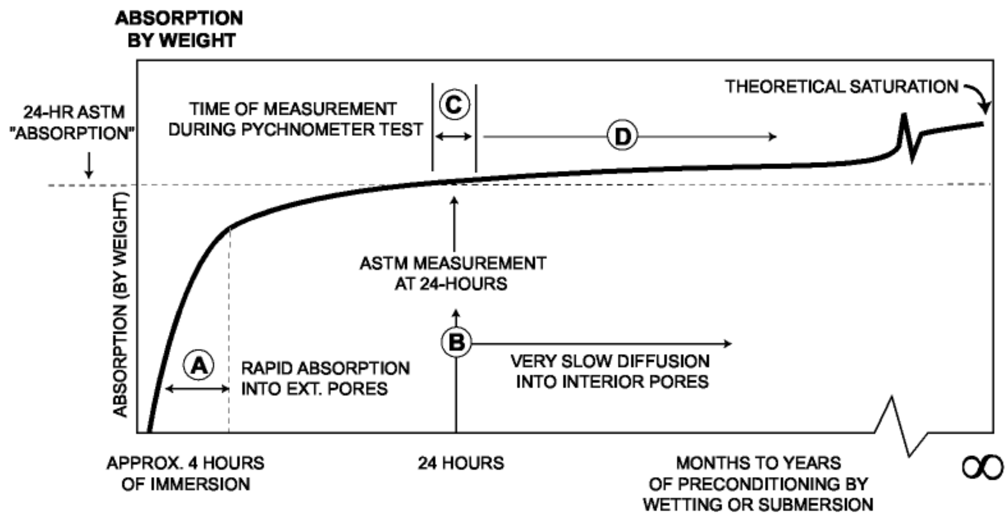


Figure 4.2. ***Absorption vs. Time for typical structural grade ESCS lightweight aggregate***

<u>Region A.</u> Rapid entry of water by capillary absorption by close to surface pores within the first few hours.
<u>Region B.</u> Very slow diffusion into interior pores.
<u>Region C.</u> When the moisture content is approximately equal to that obtained by ASTM procedure (24 hour immersion), then the slope of the line reflecting further absorption represents the very slow process of diffusion. This is the basis for providing accurate relative density values during the relatively short time used to conduct pycnometer tests at 24 hours.
<u>Region D.</u> Absorption developed over an extended period of time used to mix, transport, place, and prior to initial set (6-8 hours ±) will be very small, and therefore the W/Cm ratio will be ***<u>decreased</u>*** by an equivalent small amount. Consequently there will be a negligible influence on slump loss if aggregates are batched at a moisture content close to the 24 hour submerged value.

For illustrative purpose the water absorption with time for a medium absorptive lightweight aggregate is shown in Figs. 4.2, 4.3 and Table 4.1 and the resulting degree of pore saturation is shown schematically in Fig. 4.4.

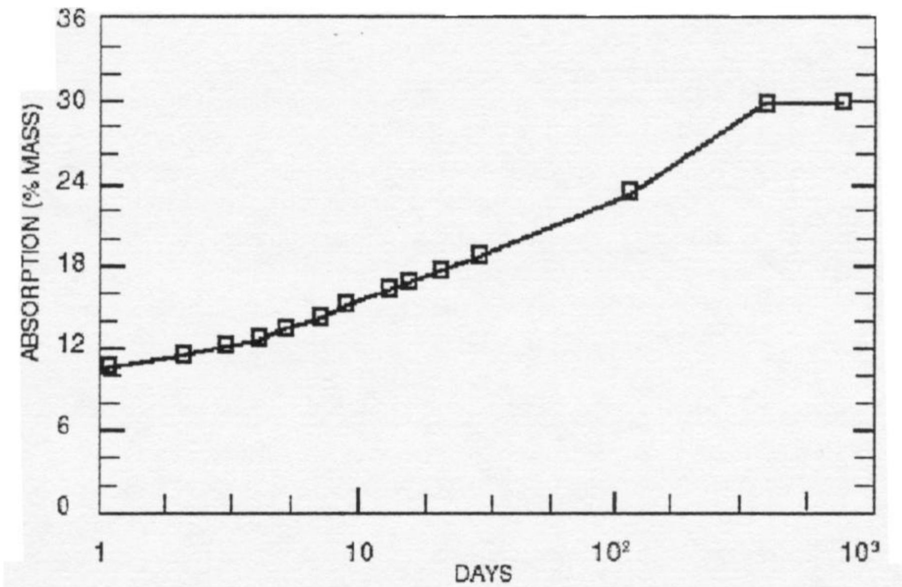
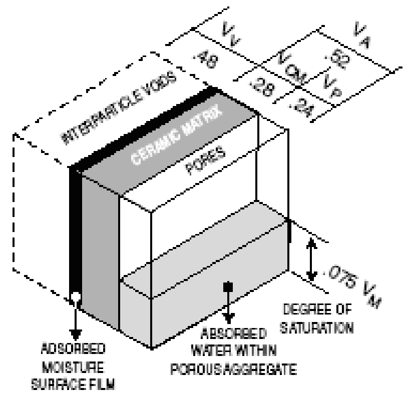


Figure 4.3 ***Water Absorption by Weight of Coarse Lightweight Aggregates during 2-years of Water Immersion***

Table 4.1. Aggregate Absorption and Degree of Saturation (Holm et. al. 2004)

Immersion Time	Water Absorption (% Mass)	Degree of Saturation	% of 24-Hour Soak	Relative Density Factor
0 mins	0	0	0	1.38
2 mins	5.76	.17	55	1.46
5 mins	6.15	.18	59	1.46
15 mins	6.75	.20	64	1.47
60 mins	7.74	.23	74	1.49
2 hours	8.32	.24	79	1.49
1 day	10.5	.31	100	1.52
3 days	12.11	.35	115	1.55
28 days	18.4	.54	175	1.63
4 months	23.4	.69	223	1.70
1 year	30	.88	285	1.79
2 years	30	.88	285	1.79



$$\text{Fractional Part of Lightweight Aggregate Paticle } (V_A) \text{ occupied by the solid ceramic Matrix} = \frac{RD_D}{RD_{CM}} \left[\frac{\text{Relative Dry Density}}{\text{Relative Density of the Solid Ceramic Matrix}}\right] = \frac{1.38}{2.60} = 0.53$$

Fractional Part of Lightweight Aggregate Particle Occupied by Pores = 1.00 - 0.53 = 0.47

$$V_{CM} \left[\text{Fractional Part of Bulk Volume occupied by the Solid Ceramic Matrix}\right] = V_A \times \left[\text{Fractional Part of Aggregate Particle } (V_A) \text{ occupied by the Solid Ceramic Matrix}\right] = 0.52 \times 0.53 = 0.28$$

$$\therefore \; V_P \left[\text{Fractional Part of Bulk Volume Occupied by Pores in Aggregate}\right] = 0.52 - 0.28 = 0.24$$

$$V_M \left[\text{Fractional Volume of Bulk Loose Sample Occupied by Moisture}\right] = \frac{\left[\text{Moisture Content by Weight}\right]\left[\text{Bulk Loose Dry Density of Sample}\right]}{1000 \left[\text{Density of Water}\right]} = \frac{0.105 \times 714}{1000} = .075$$

$$DS \left[\text{Degree of Saturation of the Pores Occupied by Moisture}\right] = \frac{0.075}{0.24} = 0.31 \, *$$

* "Saturated Surface Day" after 24-hour submersion for this illustrative sample represents water filling only 31% of the available pore space.

Figure 4.4. ***Schematic representation of volumes occupied By the ceramic matrix, the remaining pores and the degree of saturation of absorbed water of a particular Lightweight Aggregate.***

“Saturated” Surface Dry

“Standard Test Method for Density Relative Density, Specific Gravity and Absorption of Coarse Aggregate”, ASTM C 127 proposes that this method is not intended to be used for lightweight aggregates. Section 5.5 reports “The pores in lightweight aggregates are not necessarily filled with water after immersion for 24 hours. In fact the absorption potential for many aggregates is not satisfied after several days’ immersion in water. Therefore, this test method is not intended for use with lightweight aggregate”. ASTM C 128 “*Standard Test Method for Density, Relative Density (Specific Gravity) and Absorption of Fine Aggregate”,* has similar language. Both statements were based upon procedures associated with the proportioning of dry lightweight aggregate and do not reflect current practice of batching prewet lightweight aggregate. Indeed, it is common practice in many areas to establish lightweight concrete mix designs based upon W/Cm values associated with the relative densities of prewet lightweight aggregate that does not consider the absorbed water as net mixing water. This of course is also true when using normalweight aggregates but to a considerably smaller degree.

ASTM C 127 and C 128 procedure prescribe measuring the “saturated” particle density in a pycnometer and then determining the absorbed moisture content on the sample that had been immersed in water for 24 hours. Saturated particle density is inaccurately named in the case of Lightweight Aggregates; partially saturated after a 24-hour soak is more accurate. After a 24-hour immersion in water, the rate of moisture absorption into the lightweight aggregate will be so low that the partially saturated particle density will be essentially unchanged during the time necessary to take weight measurements in the pycnometer. After the moisture content is known, the oven-dry particle density may be directly computed. Fig. 4.5 illustrates typical ESCS lightweight aggregate.

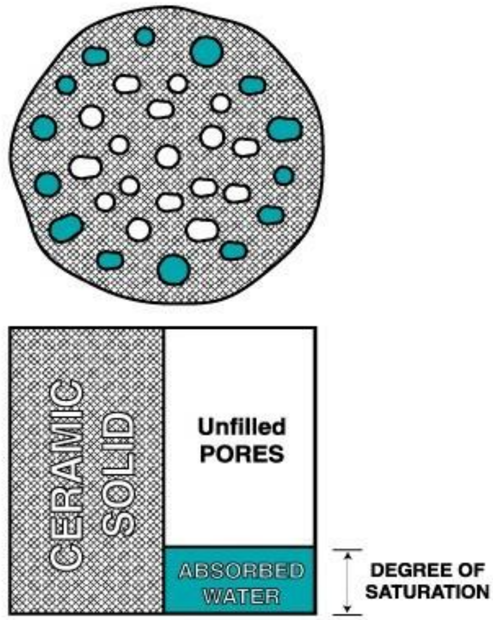


Figure 4.5 ***Schematic of "Saturated" Surface Dry as defined by ASTM C 127 and C 128 after 24-hour submersion***

Example: Assume the following measured physical properties of these particular lightweight aggregate using ASTM procedures are:

Relative Density, RD_{24} = 1.52
Moisture Absorption, M_{24} = 10.5%
Relative density solid, RD_{SOLIDS} = 2.6
Bulk Density, BD = 44.6 pcf (714 kg/m³)

with the 24-hour immersion in a pychometer, measuring a relative density of 1.52

and with an "absorption" of 10.5% by mass. The oven-dry particle density (PD_{OD}) may be back calculated to be as follows:

$$PD_{OD} = \frac{1.52}{(1+.105)} = 1.38$$

It follows then that the fractional volume of ceramic solids, $V_S = \frac{1.38}{2.60} = .53$

Fraction Volume of pores, $V_P = 1.00 - .53 = .47$
The degree of saturation (DS: the extent to which the pores are filled)

$$DS = \frac{.105x2.60x.53(volume of\ absorbed water)}{.47(Fractional volume of\ pores)} = .31$$

Following the prescribed ASTM procedures the degree of saturation for ESCS lightweight aggregate will generally be in the range of approximately 25 to 35% of the theoretical saturation. The use of the ASTM expression "saturated surface dry" is therefore, inappropriate for lightweight aggregate because it's theoretically inaccurate and analytically misleading.

Stockpile Moisture Content

From a practical perspective and considering the fact that most lightweight concrete is placed by pumping, the usual practice is to batch the lightweight aggregate at a moisture condition greater than the "Absorption Value" defined by ASTM C 127 procedures (24-hour immersion). In this condition the absorbed (internal) moisture content will be in excess of the 24 hour absorption value defined by ASTM. The degree of saturation necessary for adequate pumping characteristics, as determined by practical field experience, may be obtained from the ESCS supplier.

Example, assume for this hypothetical lightweight aggregate (Fig. 4.6) that experience has shown that the lightweight concrete will pump efficiently when the lightweight aggregate used has absorption of at least 17% by mass.

At that condition the $DS\ \text{(Degree of Saturation)} = \frac{.17(2.60x.53)}{.47} = .50.$

Due to the continuous pre-wetting, and because of the very slow further tendency to absorb water into the aggregate, there will invariably be a film of surface (adsorbed) water on the surface of the lightweight aggregate It is essential to evaluate this quantity of surface water for an accurate determination of the "net" mixing water that influences workability and determines the effective w/cm ratio.

Therefore, it is necessary to run the usual moisture test as follows. Measure the weight of the as-received surface moist sample (W_T). After towel drying, measure the weight of the surface dry sample (W_{TD}) and conduct the drying test.

Sample calculations:

Measured Weights (W) in grams

W_T **(Total sample) = 602g**

W_{TD} **(Towel dried) = 562g**

W_{OD} **(Oven dried) = 480g**

Moisture Content (M) in %

$$M_T \text{ (Total Sample)} = \frac{602 - 480}{480} x100 = 25.4\%$$

$$M_{AB} \text{ (Absorbed)} = \frac{562 - 480}{480} x100 = 17.1\%$$

$$M_S \text{ (Surface)} = \frac{602 - 562}{480} x100 = 8.3\%$$

Absorbed moisture content increases LWA relative density, which increased fresh density and enhances internal curing in the hardened concrete.

Surface moisture content is “free water” that must be added to “net” mixing water in the determination of W/Cm ratio and directly influences workability.

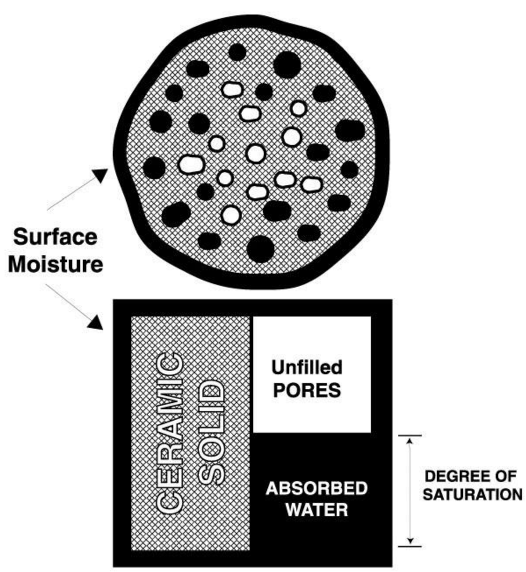


Figure 4.6 *Schematic of “Partially Saturated” Surface Wet (Moisture Condition of Stockpiled Lightweight Aggregate with Some Surface Water)*

Full Saturation

Lightweight aggregate exposed to moisture in production plants and/or stored in open stockpiles will contain a certain moisture content. Lightweight aggregates that are used alone in geotechnical, horticulture or asphalt applications are exposed to the weather, sprinkled or submerged, will continue to absorb water over time.

In the following LWA investigation, the effective particle density of a submerged LWA sample was measured throughout a two-year period to demonstrate long-term weight gain. Long-term absorption and relative density characteristics are also shown in Table 4.1, and Fig. 4.2 and Fig. 4.3. When moisture absorption-versus-time relationships are extrapolated or theoretical calculations used to estimate the total filling of all the lightweight aggregate pores, it can be shown that for this particular lightweight aggregate, the absorbed moisture content at total saturation ($M@_{TS}$) after an infinite immersion will approach 34% by mass with a totally saturated particle density of 1.85.

$$\text{Moisture content at total saturation } M@_{TS} = \frac{.47x1.0}{.53x2.6} = .34$$

$$\text{Relative density at total saturation } RD@_{TS} = (.53x2.6) + (.47x1.0) = 1.85$$

Complete filling of pores in a structural LWA is unlikely because the non-interconnected pores are enveloped by a very dense ceramic matrix. However, these calculations do reveal a conservative upper limit for the density in submerged design considerations.

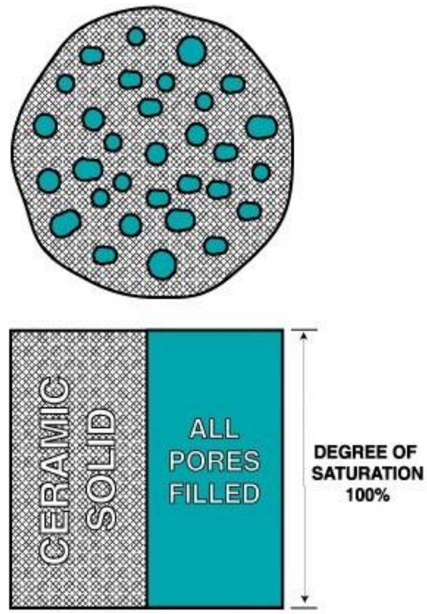


Figure 4.7 ***Schematic of Total Saturation (TS) Theoretically All Pores Filled***

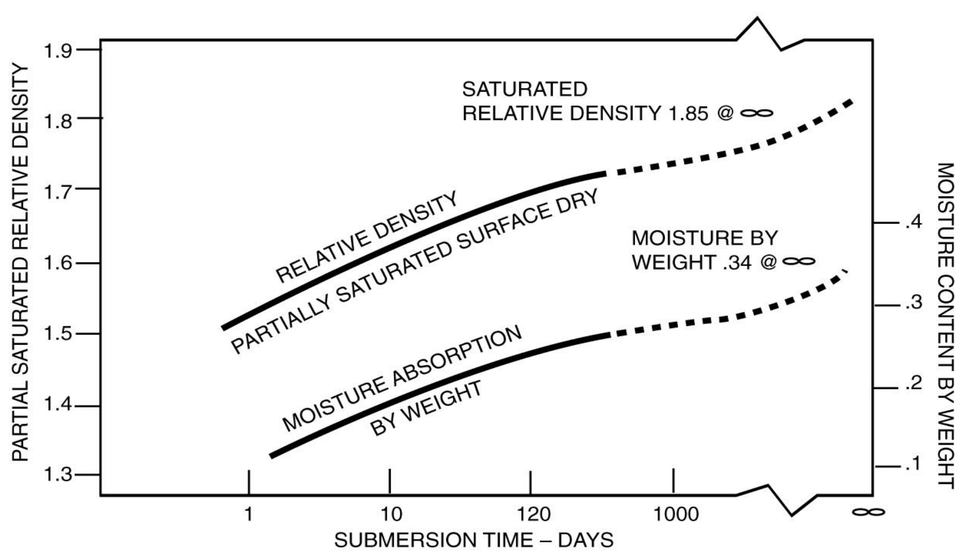


Figure 4.8. ***Moisture absorption (by weight) and relative density of lightweight aggregate versus time submersion***

Aggregate Grading

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.

In general, the largest total volume of aggregate in the concrete is achieved: when the coarse aggregate is well-graded from the largest to the smallest sizes and when the particle is rounded to cubical in shape.

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 rough texture. It is common that when 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 indicate 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.

The use of normal weight sand usually results in an increase in strength and modulus of elasticity. These increases, however, are made at the sacrifice of increased density. The mixture proportions selected, therefore, should consider these properties in conjunction with the corresponding effects on the overall economy of the structure.

Air entrainment

Air entrainment is strongly recommended in lightweight aggregate concrete. It reduces density, enhances workability, improves resistance to freezing and thawing cycles and deicer chemicals, decreases bleeding, and tends to obscure minor grading deficiencies. When severe exposure, at anytime of its service life, 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 4.0 percent and higher.

The volume of entrained air for lightweight aggregate concrete shall be according to the requirements of ACI 318.

The strength of high strength lightweight concrete may be reduced by high air contents. At normal air contents (4 to 6 percent), the reduction is small if slumps are 5 in. or less.

The volumetric method of measuring air, as described in ASTM C 173, is the most reliable method of measuring air in structural lightweight concrete and is thus recommended.

4.2 Methods of Proportioning

ACI 211.2 *"Standard Practice for Selecting Proportions for Structural Lightweight Concrete"* provides guidance for the two proportioning methods currently used in the USA. They are the Absolute Volume method and the Damp Loose Volume method. Because each LWA manufacturer has specific proportions and recommendations based on satisfactory production and long term field performance of their product, this manual offers principals that are appropriate to both methods. Interested parties should consult ACI 211.2 and the LWA manufacturer. Some general comments about the two methods follow.

Absolute Volume (Previously referred to as weight method-specific gravity pycnometer)-For several decades' Lightweight aggregate concrete has been proportioned the same way as normalweight concrete, by the absolute volume method using a relative density factor on the basis of a water-cementitious materials ratio relationship. This method requires the surface and absorbed moisture content of the batched lightweight aggregate to be determined. As with normalweight concrete the amount of surface water, which contributes to the "net" mixing water determines the water to cementitious material ratio.

Damp Loose Volume— Some manufacturers use this method with any combination of lightweight and normalweight aggregates. This method is based on proportioning graphs/charts using local materials that were developed over several years of field experience using this method. Lightweight concrete mixtures are proportioned on a cement and air content basis to produce the required consistency rather than on a water-cementitious ratio to strength basis.. Therefore, it is essential to contact the LWA supplier before using this method. In general this method develops trial mixture proportions based on damp, loose volumes converted to batch weights

4.3 Absolute Volume Method

Proportioning mixtures for the lightweight concrete involves determining the relative density factor of the lightweight aggregate, as discussed in Appendix A, from which the first estimate of the density of fresh lightweight concrete can be made. The absorbed moisture content of lightweight coarse aggregate should be measured by the method described in ASTM C 127.

As with normalweight concrete, 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 job specifications will dictate , density, and strength, and may dictate the maximum w/cm, type of admixtures, cement types, and placement methods.

Step 1: Estimation of mixing water—The quantity of water per unit volume of concrete required to produce a given slump is primarily dependent on the particle shape and grading of the fine aggregates, amount of entrained air, and inclusion of chemical admixtures. It is not significantly affected by the quantity of cementitious materials or the grading of the coarse aggregate. Table 4.2 provides estimates of required mixing water for concretes made with various nominal maximum sizes of aggregate, with and without air entrainment. Depending on aggregate texture and shape, mixing water requirements may be different from the tabulated values, but they are sufficiently accurate for the first estimate. Such differences in water demand are not necessarily reflected in strength since other compensating factors may be involved.

Table 4.2 — Approximate mixing water and air content requirements for different slumps and nominal maximum sizes of aggregates for concretes

Slump, in. (mm)	Mixing Water lb/yd^3 (kg/m^3) of concrete for indicated nominal maximum sizes of aggregates		
	3/8 in. (9.5 mm)	1/2 in. (12.7 mm)	3/4 in. (19.0 mm)
Air-entrained concrete			
1 to 2 (25 to 50)	305 (181)	295 (175)	280 (166)
3 to 4 (75 to 100)	340 (202)	325 (193)	305 (181)
5 to 6 (125 to 150)	355 (211)	335 (199)	315 (187)
Recommended average† total air content, percent, 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
Non Air-Entrained Concrete			
1 to 2 (25 to 50)	350 (208)	335 (199)	315 (187)
3 to 4 (75 to 100)	385 (228)	365 (217)	340 (202)
5 to 6 (125 to 150)	400 (237)	375 (222)	350 (208)
Approximate amount of entrapped air in non-air-entrained concrete, percent	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^o F (20 to 25^o C). They are maximum for reasonably well-shaped angular aggregates graded within limits of accepted specifications. The use of water-reducing chemical admixtures will reduce mixing water. The volume of the liquid admixtures is included as part of the total volume of the mixing water.

†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, 213, 345, 318, 301, 302 and 308. 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 must 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 percent 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, if may be desirable to calculate the needed air content by taking 9 percent of the actual mortar value.

Ref. ACI 211.2-98 (Re-approved 2004) Table 3.2.

Step 2: Selection of approximate water-cementitious ratio or minimum cementitious material content — The required w/cm is determined not only by strength requirements but also by such factors as durability and finishing properties. 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/cm should be kept low even though strength requirements may be met with a higher value. Table 4.3 gives limiting values.

Table 4.3 — Maximum permissible water-cementitious 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, sils, 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 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/cm* may be increased by 0.05.

Ref: ACI 211.2-98 (Re-approved 2004) Table 3.4

Step 3: Selection of Air Content: Table 4.2 suggests 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 reduction in density.

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 conditioned 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 201.2, 213, 302.1, and 345.

Step 4: Estimation of lightweight coarse aggregate content- In most areas the weight per cubic yard of lightweight aggregate used in commercial projects has been established based upon the usual methods of placing (pumping), the characteristics of the fine aggregate (grading and particle shape) and usual specification requirements for fresh and equilibrium densities. Generally, the nominal maximum size of aggregate should be the largest that is economically available and consistent with the dimensions of the structure.

Step 5: All prior volumes are summed, (V_W, V_{CM}, V_A, V_{CA})

Step 6: Calculation of fine aggregate content—At completion of Step 5, all ingredients of the concrete have been estimated except the fine aggregate. Its quantity is determined by computing the volume necessary for producing a cubic yard (meter), and then multiplying that volume by the relative density of the fine aggregate.

Step 7: After calculating the weight of the aggregate, it is necessary to complete the unit volume (yd^3, m^3). The weights of all constituents may be calculated.

Step 8: After summing all total weights the fresh density may be calculated.

Step 9: Meeting Fresh Density Specifications-Knowing the maximum fresh density permitted (for acceptance at delivery) by the project specification (ASTM C 138) and the estimated reduction in density due to drying the equilibrium density (for structural designs) may be calculated (ASTM C 567) to be less than the design density limitations.

Step 10: The Equilibrium Density (D_{EQ}) is then determined following the procedures of ASTM C 567.

The aggregate quantities to be weighed out for the concrete must allow for moisture in the aggregates. Since the aggregates will be moist, their dry weights should be increased by the percentage of water they contain, both absorbed and surface. The mixing water added to the batch must be reduced by an amount equal to the free moisture contributed by the aggregate (i.e., total moisture minus absorption).

Establishment of batch weights per unit volume of concrete can be best accomplished as shown in Table 4.4:

Table 4.4 Absolute Volume Proportioning Methodology

1	**a.** **b.**	Estimate free (net) water requirements. Compute absolute volume of water.	**(W_W)** **(V_W)**
2	**a.** **b.**	Based upon specification requirements (maximum, water/cementitious ratio, or minimum cement content compute weight of cementitious materials. Compute absolute volume of cementitious materials.	**(W_{CM})** **(V_{CM})**
3		Based upon specification requirements or durability exposure determine volume of air.	**(V_A)**
4	**a.** **b.**	Based upon current practice (usually related to density requirements for structural loads) establish weight of coarse lightweight aggregate. Compute absolute volume of coarse aggregate.	**(W_{CA})** **(V_{CA})**
5		Sum up absolute volumes of water **(V_W)** cementitious materials **(V_{CM})**, air **(V_A)** and coarse lightweight aggregate **(V_{CA})**.	
6		Calculate volume **(V_{FA})** and weight **(W_{FA})** of fine aggregate necessary to make one cubic meter (cubic yard). $V_{FA} = 27 – (V_W + V_{CM} + V_A + V_{CA})$ $(V_{FA} = 1.0 – (V_W + V_{CM} + V_A + V_{CA}))$ $W_{FA}= V_{FA} \times D_{FA} \times 62.4$ $(W_{FA}= V_{FA} \times D_{FA})$	**(V_{FA})** **(W_{FA})**
7		Compute total weight **(W_C)** for one cubic meter **(yd^3)**	**(W_C)**
8		Calculate fresh density **(D_F)** $D_F = W_W + W_C + W_A + W_{CA} + W_{FA} \div 27$ $(D_F = W_W + W_C + W_A + W_{CA} + W_{FA})$ Compare with specifications for maximum fresh density.	**(D_F)**
9		Following procedures of ASTM C 567 determine the calculated equilibrium density **(D_{EQ})** compare with maximum structural self load or code related fire rated slab requirements.	**(D_{EQ})**

Sample of Typical Mixture Proportioning

Absolute volume method:
The following is an illustration of the proportioning procedures where several of the specific mixture requirements are specified.

Specifications and Requirements:

- 3500 psi (24 MPa) specified compressive strength at 28 days
- 1200 psi (8 MPa) required over-design (per ACI 318, Section 5.3.2.2, no prior history)
- Required average strength of concrete 4700 psi (32 MPa)
- Lightweight aggregate: ASTM C 330
- Natural Sand ASTM C 33 5-0 mm (No. 4 – 0)
- Air-entraining admixture (AEΛ) for 6 $\pm$ 1 percent: ASTM C 260
- Water-reducing admixture (WRA) use permitted: ASTM C 494, Type A or D
- Slump 5 $\pm$ 1 in. (125 $\pm$ 25 mm) at pump discharge.

Background information:
From the lightweight aggregate manufacturer:

- Relative density factor – 1.55 at a 12% percent moisture content (Reference ACI 211.2, Appendix A).
- Suggested coarse aggregate factor (CAF) 850 lb/yd³ (504 kg/m³) at a 12% moisture content (stockpile condition)

From the sand supplier:

- Relative density = 2.62 (2620) fineness modulus = 2.80

From the cement supplier:

- Relative density = 3.15 (3150)

Step 1: From the ready-mix supplier

- With local sand and midrange water reducer, pump mixtures require approximately 300 lb/cy (178 kg/m³) of net water.

Step 2: Typical w/cm ratios recommended for exposure conditions of .45 require cementitious materials 300/.45=667 lbs/cy (178/.45=396 kg/m³)

Step 3: Based on Exposure condition – 6% air content

Step 4: Based upon current practice local aggregates and using in-place density requirements coarse LWA (W_{CA}) used is 850 lb/cy (504 kg/m³): V_{FA} is calculated:

$$V_{CA} = \frac{850}{1.55x624} = 8.79\,ft^3 \left(\frac{504}{1550} = .323m^3 \right)$$

Step 5: Sum up Volumes of V_W, V_{CM}, V_A, and V_{CA}

$$\sum V = 4.81 + 3.39 + 1.62 + 8.79 = 18.61 ft.^3$$
$$\left(\sum V = .178 + .125 + .060 + .325 = .688 m^3\right)$$

Step 6: Calculate volume (V_{FA}) and weight (W_{FA}) of the fine aggregate

$$V_{FA} = 27 - 18.61 = 8.39 \ ft.^3$$
$$(V_{FA} = 1.000 - .688 = .312 m^3)$$
$$W_{FA} = 8.39 x 2.62 x 624 = 1372 \ lb$$
$$(W_{FA} = .312 x 2620 = 817 \ kg)$$

Step 7: Compute total weight (W_C) of one yd^3, (m^3) of concrete

$$W_C = 300 + 667 + 850 + 1372 = 3189 \ lbs.$$
$$(W_C = 178 + 395 + 504 + 817 = 1894 \ kg)$$

Step 8: Calculate fresh density (D_F)

$$D_F = 3189 / 27 = 118.1 lb / yd^3$$
$$(D_F = 1894 kg / m^3)$$

Step 9: Calculate weight of oven dry concrete (W_{DC})

$$W_{DC} = (667 x 1.2) + (850 / 1.12) + (1372 / 1.02) = 2904 \text{ lb}$$
$$(\text{W}_{\text{DC}} = (395 x 1.2) + (504 / 1.12) + (817 / 1.02) = 1725 \text{ kg})$$

Step 10: Calculate equilibrium density (D_{EQ})

$$D_{EQ} 2904 / 27 + 3 = 110.6$$
$$(D_{EQ} = 1725 + 50 = 1775)$$

Results of the sample problem illustrating the absolute volume methods are summarized in Table 4.5.

Table 4.5 Sample Problem Illustrating the Absolute Volume Method.

Proportioning Step		in/lb		Metric	
		Weight (or Density)	Volume	Weight (or density)	Volume
1.	W_W weight of water V_W volume of water	300 ---	--- .4.81	178	--- .178
2.	W_{CM} weight of cementitious materials V_{CM} volume of cementitious materials 667/3.15 x 62.4 (395/3150)	667 ---	--- 3.39	395 ---	.125
3.	V_A volume of air (.06 x 27)	---	1.62	---	.060
4.	W_{CA} weight of coarse aggregate Volume of coarse aggregate	850 ---	--- 8.79	504	--- .325
5.	Sum of volumes ($V_W + V_{CM} + V_A + V_{CA}$)	---	18.61	---	.688
6.	V_{FA} volume of fine aggregate 27-18.61 (1.0-.688) W_{FA} weight of fine aggregate 8.39 x 2.62 x 62.4 (.312 x 2620)	 1372	8.39 ---	--- 817	.312 ---
7.	W_C sum of all weights	3189	---	1894	---
8.	D_F fresh density	118.1	---	1894	
9.	W_{DC} weight of over dry concrete 1.12 + 817/1.02/395 x 1.2 + 504 (1.12 + 1372/1.02/667 x 1.2 + 850)	2904		1725	
10.	D_{EQ} calculated equilibrium density 1725 + 50 (2904/27 + 3)	110.6		1775	

Metric weights (mass) or density kg/m³, volume m³
In. lb. weights or density lb/y³, volume ft³

4.4 Damp Loose Volumetric Method

(Sample damp loose volume proportioning problem and approval of text of Section 4.4 to be determined by ESCSI members using this procedure)

Some lightweight aggregate producers recommend trial mixture proportions based on damp, loose volumes converted to batch weights. This procedure is applicable to all combinations of lightweight aggregate and normal weight aggregate. The total volume of aggregates required, measured as the sum of the uncombined volumes on a damp, loose basis, will usually be from 30 to 34 ft^3/yd^3. It is recommended that the aggregate producer be consulted to obtain a closer approximation of cementitious material content and aggregate proportions required to achieve desired strength and density with the specific aggregate. When this information is not available, the only alternative is to make a sufficient number of trial mixtures with varying cementitious material contents to achieve a range of compressive strengths including the compressive strength desired.

It is usually more practical to establish proportions by a series of trial mixtures proportioned on a cement content basis with the water adjusted for the desired slump for the required degree of workability. Specimens from each acceptable trial mixture are tested at the specified ages to establish the cement content strength relationship in the series. From this information the cement content for the desired strength can be selected.

One procedure for estimating concrete trial mixture proportions in the absence of satisfactory historical data is to use, develop, or obtain from a lightweight aggregate producer a graph like Fig. 4.9 (a).

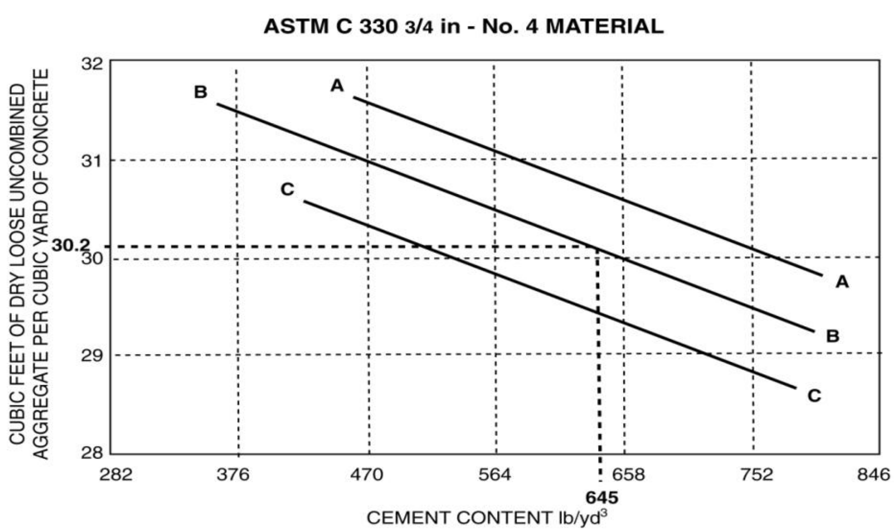


Figure 4.9 (a) Design *chart for uncombined aggregates for lightweight concrete.*

This graph was developed by batching several mixtures of varying cement contents, similar air contents, (4 to 6 percent), and a constant slump of 5 ± 1 in. (125 ± 25 mm), then plotting the volumes of dry loose uncombined materials (¾ in. – No. 4 – 0 (5-0 mm) natural concrete sand) for those mixtures having good workability and proper yield. This method is similar to the one used to develop the original coarse aggregate factor (CAF) values used in conjunction with the fineness modulus (FM) to estimate normal weight concrete mixtures.

The graph was also developed to minimize or eliminate the need for "extra" trial mixtures to establish approximate proportions of materials needed to determine: proper yield, workability, combining losses, and strength. This enables the technologist to proceed directly with three trial mixtures, or perhaps one mixture, for verification of specific materials for specific mixture design criteria. After trial mixture proportions selected with this method are tested, it will become apparent that the line B-B in Fig. 4.9(a) can move in the direction of either line A-A or line C-C at the same slope. The movement of the line B-B in either direction is caused by changes in the aggregate grading, changing from one aggregate size to another, adjustments for texture or workability, or for pump or conventional placement, (i.e., if a change was made to go from ASTM C 330 ¾ in. (19-5 mm) – No. 4 to 3/8 in. – No. 8, (9.5-2.38 mm) the Line B-B would shift downward toward Line C-C due to a reduction in voids, causing a reduction in combining loss). The slope of Line B-B (and therefore Lines A-A and C-C) relates the volume of aggregate to the volume of cement. For example, decreasing the cement content from 658 to 564 lb/yd^3 (390-355 kg/m^3) on Fig. 4.9(a), Line B-B, increases the design volume from 30 to 30.5 ft^3/yd^3 (1.11 to 1.13 m^3/m^3).

An additional advantage of this development procedure is that when the test specimens from the trial mixtures are tested, a strength-versus-cement content curve (or range) for historical information can be plotted similar to Fig. 4.9(b).

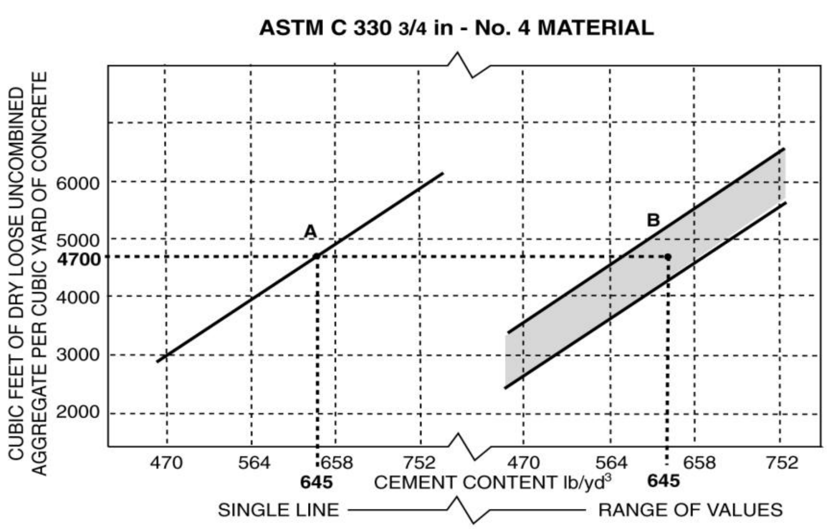


Fig. 4.9(b)—*Strength versus cement content*.

4.5 Adjusting Mixture Proportions

General

In proportioning normalweight concrete (ACI 211.1), the volume displaced or absolute volume occupied by each ingredient of the mixture (except entrained air) is calculated as the weight in lb of that ingredient divided by the product of 62.4 lb/ft³ and the specific gravity of that ingredient. Total volume of the mixture is the sum of the displaced or absolute volume of each ingredient thus calculated plus the volume of entrained and entrapped air determined by direct test.

Changes in lightweight aggregate moisture content, grading, or relative density as well as usual job site variation in entrained air suggest frequent checks of the fresh concrete to facilitate adjustments necessary for consistent concrete characteristics. Standardized field tests for slump ASTM C 143, fresh density ASTM C 138, and entrained-air content ASTM C 173 are used to verify conformance of field concretes with the project specification. Sampling should be conducted in accordance with ASTM Practice Sampling Freshly Mixed Concrete (C 172). ASTM Test Method for Density of Structural Lightweight Concrete (C 567) describes methods for calculating the in-service, equilibrium density of structural lightweight concrete. When variations in fresh density exceed ± 3 lb/ft³ an adjustment in batch weights may be required to restore specified concrete properties. To avoid adverse effects on durability, strength, and workability, air content should not vary more than ± 1.5% from target values.

Both field mixtures and laboratory mixtures may require adjustment from time to time to compensate for some unintentional change in the characteristics of the concrete or to make a planned change in the characteristics. Adjustment may be required, for example, to compensate for a change in moisture content of the aggregates; it may be desired to proportion a mixture for greater or lesser cement content, or use of chemical admixtures; or other cementitious material, or perhaps, a change in slump or air content may be necessary. Sometimes adjustments are needed for pumping. These adjustments can be made with considerable confidence based on either a first trial mixture or on previous field or laboratory mixtures with similar aggregates. Small mixtures of perhaps 1.0 to 2.0 ft^3 total volume that are made and adjusted in the laboratory will require some further adjustments when extrapolated to field mixtures of possibly 100 to 300 times the laboratory volume. It is recommended that tests of fresh density, air content, and slump be made on the initial field mixtures, and any necessary adjustments be made on the field batch quantities.

Guides for adjusting mixtures—When it is desirable to change the amount of cementitious material, the volume of air, or the percentage of fine aggregate in a mixture, or when it is desirable to change the slump of the concrete, it is necessary to offset such changes with adjustments in one or more other factors if yield and other characteristics of the concrete are to remain constant. The following paragraphs indicate some of the compensating adjustments, show the usual direction of adjustments necessary, and give a rough approximation of the amount of the adjustments per yd^3 (m^3) of concrete. However, note that the numerical values given are intended for guidance only, that they are approximations, and that more accurate values obtained by observation and experience with particular materials should be used whenever possible.

Proportion of fine aggregate—An increase in the percentage of fine to total aggregates generally requires an increase in water content. For each percent increase in fine aggregate, increase water by approximately 3 lb/yd^3 (1.8 kg/m^3). An increase in water content will require an increase in cement content to maintain strength. For each 3 lb/yd^3 (1.8 kg/m^3) increase in water, increase cement by approximately 1 percent. Coarse and fine aggregate weights should be adjusted as necessary to obtain desired proportions of each, and to maintain required total effective displaced volume.

Air content—An increase in air content will be accompanied by an increase in slump unless water is reduced to compensate. For each percent increase in air content, water should be decreased by approximately 5 lb/yd^3 (3.0 kg/m^3) An increase in air content may be accompanied by a decrease in strength unless compensated for by additional cement (see Table 4.2). Fine aggregate weight should be adjusted as necessary to maintain required total effective displaced volume.

Slump—An increase in slump may be obtained by increasing water content. For each desired 1 in. increase in slump, water should be increased approximately 10 lb/yd^3 (5.9 kg/m^3) when initial slump is about 3 in (75 mm); it is somewhat less when initial slump is higher. Increase in water content will be accompanied by a decrease in strength unless compensated for by an increase in cement content. For each 10 lb/yd^3 (5.9 kg/m^3) increase in water, increase cement content approximately 3 percent. Adjustment should be made in fine aggregate weight as necessary to maintain required total effective displaced volume.

Adjustment for changes in aggregate moisture condition—Procedure to adjust for changes in moisture content of aggregates is as follows:

a. Maintain constant the weight of cement and the effective displaced volumes of cement and air.

b. Calculate new weights of both coarse and fine aggregates, using the appropriate value for total moisture content, so that oven-dry weights of both coarse and fine aggregates remain constant.

c. Calculate effective displaced volumes of both coarse and fine aggregates using weights of the aggregates in the appropriate moisture condition or the relative density factor corresponding to that moisture condition.

d. Calculate the required effective displaced volume of added water as the difference between the required 27 ft^3 (1 m^3) and the total of the effective displaced volumes of the cement, air, and coarse and fine aggregates.

e. Calculate required weight of added water as 62.4 lb/ft^3 (1,000 kg/m^3) multiplied by the required effective displaced volume of added water determined in (d).

4.6 Controlling Proportions in the Field

Proportions that have been established for given conditions may require adjustment from time to time to maintain the planned proportions in the field. Knowledge that proportions are remaining essentially constant, or that they may vary beyond acceptable limits, can be obtained by conducting tests for fresh density of concrete (ASTM C 138), air content (ASTM C 173), and slump (ASTM C 143). These tests should be made not only at such uniform frequency as may be specified (a given number of tests per stated quantity of concrete, per stated time period, or per stated section of structure, etc.), but should also be made when observation indicates some change in the ingredients of the concrete or in the physical characteristics of the concrete. These tests should be made, for example, when moisture contents of the aggregates may have changed appreciably, when the concrete shows change in slump or workability characteristics, or when there is an appreciable change in added water requirements.

A change in fresh density of concrete, with batch weights and air content remaining constant, shows that the batch is over-yielding (with lower density) or under-yielding (with higher density). The over-yielding batch will have lower than planned cement content, and the under-yielding batch will have a higher than planned cement content (Fig. 4.10).

A change in the aggregate relative density factor may be the result of: (a) a change in the moisture content of the aggregate; or (b) a basic change in aggregate density. If a moisture test indicates moisture changes, the mixture should be adjusted. If the basic aggregate density has changed, determination of new moisture content, relative density factor relationships are indicated (Aggregate density changes may be a result of changes in raw material and/or its processing). A change in slump may indicate: (a) a change in air content; (b) a change in moisture content of aggregate without corresponding change in batching; or (c) a change in aggregate grading or density. Each of these factors is also indicated by the fresh density test.

Controlling concrete mixtures in the field also requires recognizing possible changes due to variations in ambient temperature of ingredients, length of mixing and agitating time, and other causes. Discussion of such factors is beyond the scope of this reference manual.

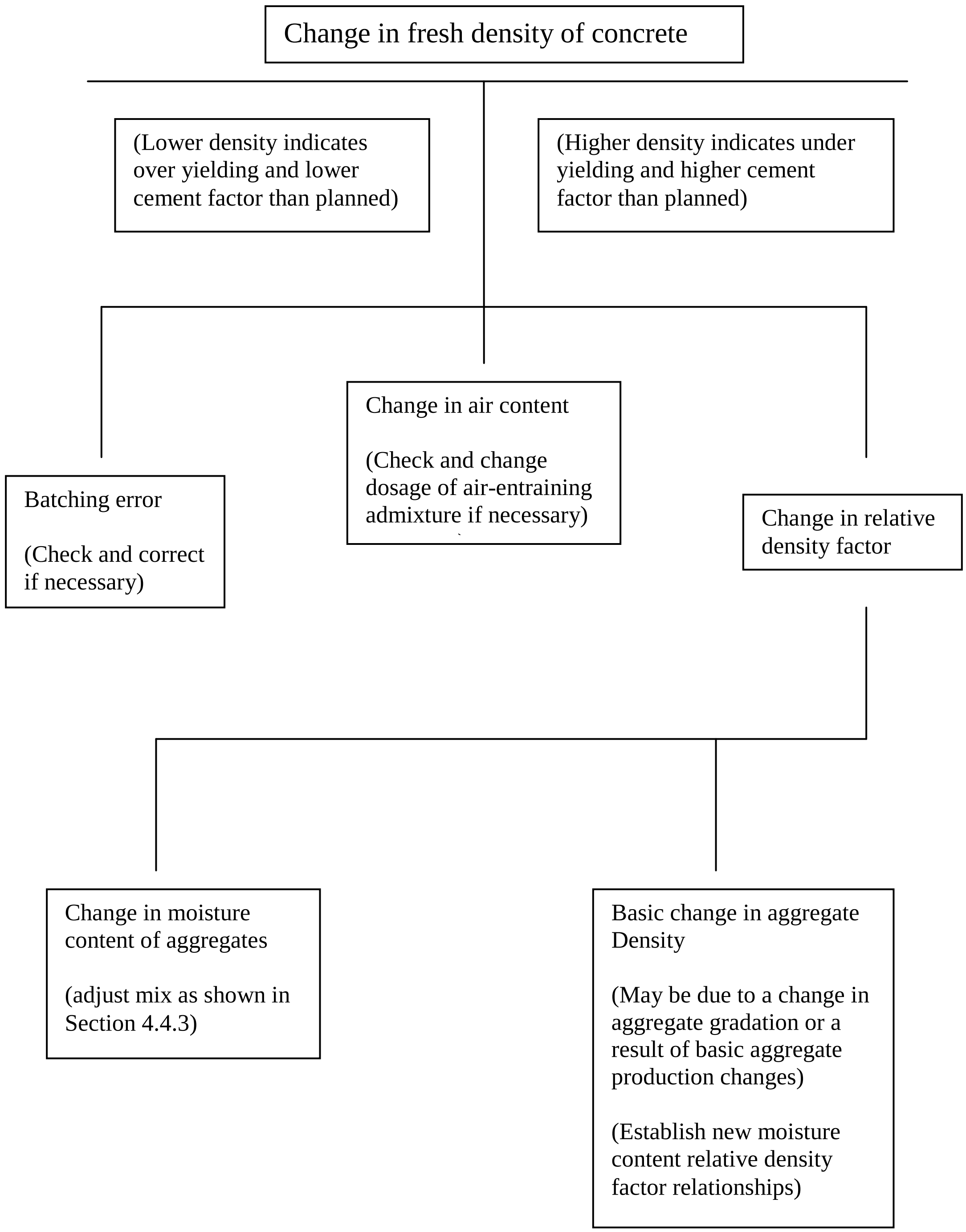


Figure 4.10 ***Controlling proportions***

4.7 Meeting Project Specifications

Although there are numerous structural applications of all lightweight concretes (coarse and fine lightweight aggregate), usual commercial practice in North America is to design lightweight concrete where part or all of the fine aggregates used is natural sand. Long-span bridges using concrete with three-way blends (coarse and fine lightweight aggregates and small supplemental natural sand volumes) have provided long-term durability and structural efficiency by increasing the density/strength ratios. Normalweight sand replacement will typically increase unit weight from about 5 to 10 lb/ft^3 (80 to more than 160 kg/m^3). Using increasing amounts of cement to obtain high strengths above 5,000 psi (35 MPa) concrete will increase equilibrium density from 2 to 6 lb/ft^3 (32 to 96 kg/m^3) using ASTM C 567.

The fresh density of lightweight aggregate concretes is a function of mixture proportions, air contents, water demand, and the relative density and moisture content of the lightweight aggregate. Decrease in density of exposed concrete is due to moisture loss that, in turn, is a function of ambient conditions and surface area/volume ratio of the concrete element. Design professionals should specify a maximum fresh density for lightweight concrete, as limits for acceptability should be controlled at time of placement.

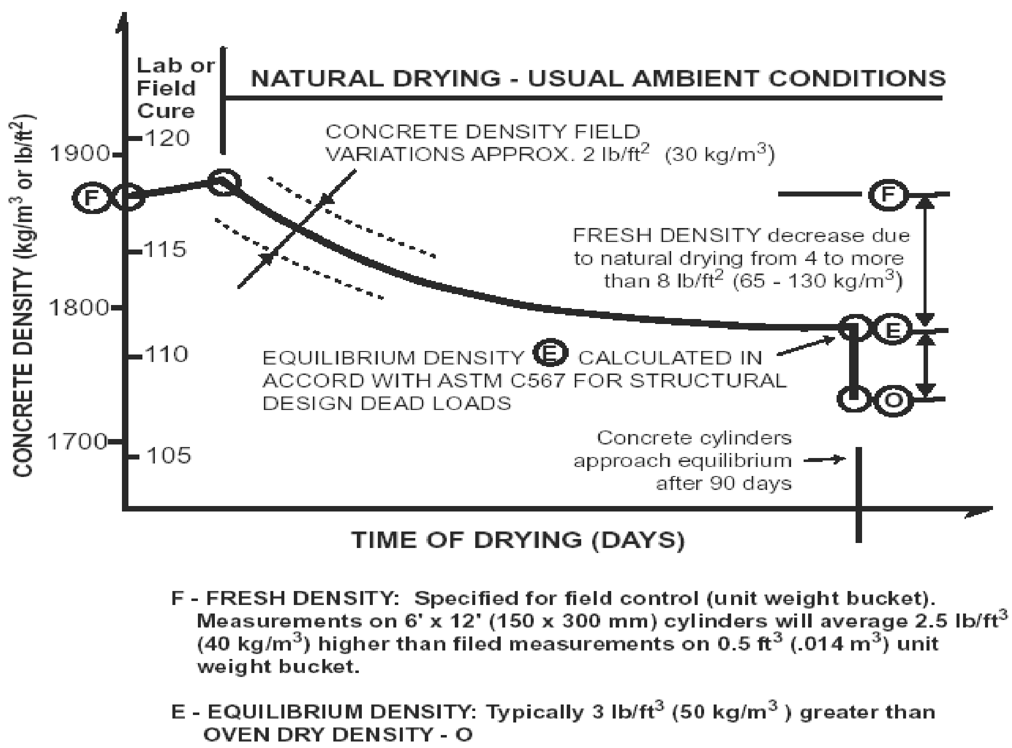


Figure 4.11 ***Concrete density versus time of drying for structural Lightweight concrete ACI 213R-03, ASTM 169 D***

Unless otherwise specified the dead loads used for design should be based upon the calculated equilibrium density that, for most conditions and structural members, may be assumed to be reached after 90 days. Extensive tests reported in ACI 213, Structural Lightweight Concrete, conducted during North American durability studies demonstrated that despite wide initial variations of aggregate moisture content, equilibrium density was found to be about 50 kg/m³ (3.1 lb/ft³) above oven-dry density. When weights and moisture contents of all the constituents of the batch of concrete are known, an approximate calculated equilibrium density may be determined.

4.8 Specified Density Concrete

The use of specified density concrete is based on engineer's decisions to improve structural efficiency by optimizing concrete density. Specified density concrete is defined as concrete with a range of density less than what is generally associated with normalweight concrete 145-155 lb/ft³ (2320-2480 kg/m³), and greater than the code defined maximum density for lightweight concrete 115 lb/ft³ (1840 kg/m³). Specified density concrete is achieved by replacing part of the ordinary normalweight aggregate (Relative Density typically greater than > 2.60) with either coarse or fine lightweight aggregate (Relative Density typically lower than<1.60). Specified density concrete has been used on bridges, marine structures, precast elements and consumer products in North America, Europe and several other parts of the word. For further information see Section 6.2.

4.9 Lightweight, Non-Structural "Fill" Concrete

Quite frequently ready-mix concrete and their lightweight aggregate suppliers are called upon by design professionals and contractors to supply lightweight, non-structural fill concrete. There are numerous possibilities for this very efficient concrete that from a density standpoint, falls somewhere between a structural concrete and an insulating concrete. Compressive strengths of 2500 psi for floor fill and 500 psi for roof fill are typical. For strength development of these non-structural concretes see Fig. 4.12. Typical mixture proportions are shown in Table 4.6.

Table 4.6 Mixture Proportions for Typical "Floor Fill" and "Roof Fill" Non-Structural Lightweight Concretes

Mixture No.	1	2	3
Cement (lb)	520	450	410
Water (lb)	360	340	340
Fine LWA (3/8-0) (lb)	1770	1730	1680
Total Weight (lb)	2650	2530	2430
Air %	13	19	19
Slump (in)	5.0	6.0	6.0
Compressive Strength (psi)			
@ 2 days	635	355	320
@ 7 days	1100	605	525
@ 28 days (3 x 6)	2170	1030	930
@ 28 days (6 x 12)	2090	940	870
Density (lb/ft^3)			
Fresh	98	90	90
@ 2 days	97	89	87
@ 7 days	96	87	87
@ 28 days	94	85	85
Oven Dry (Calculated)	82	78	74
Equilibrium (Calculated)	85	81	77

The results of this particular investigation could undoubtedly be improved using pozzolans, higher volumes of air entraining admixtures and lower density lightweight aggregates. The intention of providing these results is only to set up a template for further investigations.

One such application is the fill concrete on roof structures where the slope to drain requires concrete thicknesses of from as much as 12 inches feathered out to less than 1/2 at the drain. This highly functional concrete is best served by structural lightweight aggregate grading from 3/8 to 0 with a high air content. The effect of the high air content is two-fold. Obviously, there is a considerable weight reduction when air contents are in the range of 15 to 25%. Secondly, and less obvious, there is a significant reduction in the mixing water required to place this type of concrete despite it containing a high surface area fine aggregate. This is due to the untold millions of air bubbles that provide a ball bearing mechanism to create plasticity to the mix in lieu of the water of convenience generally necessary to provide adequate workability of the concrete for placing. The reduction in the water content in this mixture is significant in that these concretes do not usually require venting. This formation reaches an equilibrium moisture condition with ambient air in a relatively short period of time. As an example of this rapid decline in moisture content versus time consider Fig. 4.13 which shows three different high air, all fine lightweight aggregate mixes which were proportioned with air contents of from approximately 9 to just under 20%. Note that the most rapid decline in moisture content is in the first 7 to 10 days which is always a time element required before any roofing membrane could be placed on the concrete. Placing a roofing membrane that seals in moisture from the top and having little access for the moisture content to escape downwards is one source of roofing problems. The moisture may rise under the membrane at a later date, particularly in the first hot summer day with vapor pressure causing the development of bubbles under the roofing membrane. As shown in Fig. 4.13, a plot of the density versus time, these concretes tend to lose significant amounts of the free, uncombined water and reach equilibrium rather quickly. Unlike insulating concrete that use highly absorbent very low density aggregates (perlite, vermiculite) the water requirements of lightweight fill concrete using structural grade aggregates are low.

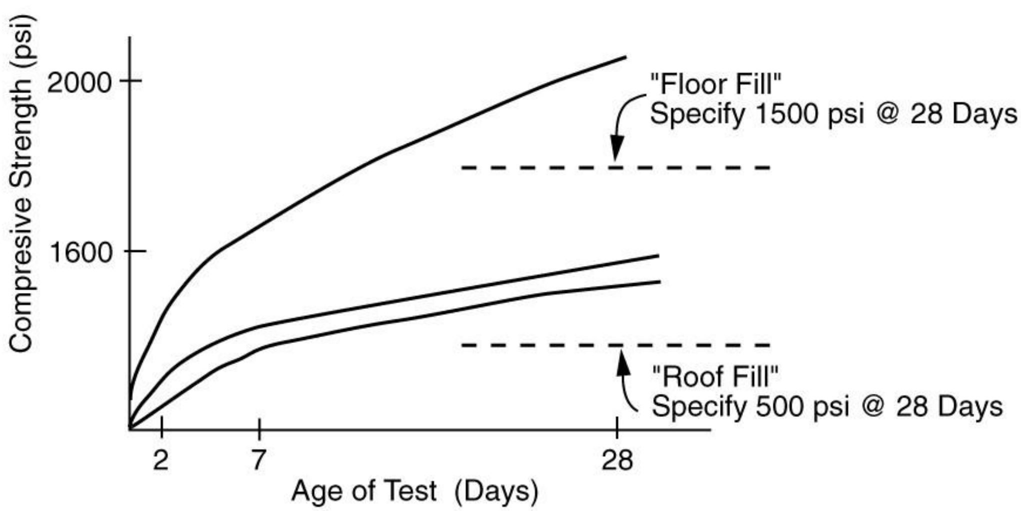


Figure 4.12 ***Compressive strength of fill concrete as a function of time.***

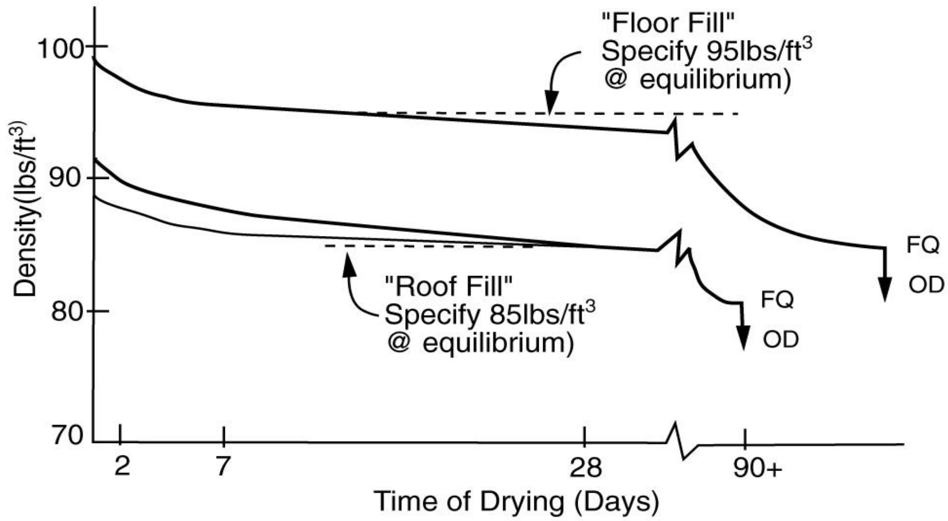


Figure 4.13 ***Density of concrete as a function of drying time.***

Water used in the production of fill concrete can be simplistically grouped into three areas; the first being that water required for the hydration of cement which is routinely taken as a fraction of the weight of cement, somewhere in the order of approximately 20 by weight. The second fraction of water required for workability is uncombined chemically, lost to the atmosphere and forms the capillaries through which additional water can migrate. This water loss of the concrete is a function of the ambient environment, the thickness of the concrete and the degree of curing. This type of concrete reaches an equilibrium density in approximately 60 to 90 days.

The third is water that is held physically (not chemically). This water will not leave the concrete except under accelerated high temperature drying. This may be seen in the last part of the curve where concretes after reaching equilibrium were oven dried.

Strength requirements for fill concretes vary according to the application. When used as a slope to drain on roofs the only strength necessary is that required to provide a sound substraight for the roofing membrane and for usual construction loads on the roof. In general, a strength of approximately 500 psi is required. As shown Fig. 4.12 the strengths of these fill concretes vary anywhere from 900 psi to over 2000 psi depending on the mixture formulations, cement and air contents.

Thermal resistance of these low density fill concretes is intermediate between the usual structural lightweight concretes and the very low density non-structural concretes and may be calculated by the equation which compares thermal conductivity versus density. This equation developed by Valore in ACI paper, February 1980, has been shown to be accurate for all ranges of lightweight concretes.

$$k_c = 0.5e^{0.02d} \text{ (inch pound unit)}$$
$$k_c = 0.072e^{0.00012d} \text{ (SI units)}$$
$$\text{where } d = \text{oven-dry density in lb/ft}^3 \text{ (kg/m}^3\text{)}$$

A major advantage of this semi-insulating, fill concrete is that it is extremely practical, as it can be batched by regular ready mixed concrete procedures (there is no bagging and filling of ready-mix trucks by hand). The concrete dries to an equilibrium density quickly, and has sufficient strength that often allows walking on the next day. Additionally, moderate structural and thermal insulating properties are also provided.

4.10 Polymer Modified Lightweight Concrete

There has been considerable research and development but minimal applications of polymer modified lightweight concretes. A comprehensive report on “Polymer Concrete for Structural Applications”, was commissioned by the U.S. Army Construction Engineering Research Laboratory and reported by Valore (1974) and Valore and Naus (1975), Haynes and Eckroth (1979) and others as listed in Appendix 4E.

The U.S. Army comprehensive report provided information on the following properties of polymer modified lightweight concrete:

- Proportioning
- Compressive strength tested at various ages and temperatures
- Modulus of Elasticity
- Compressive Strength Ceiling
- Splitting Tensile Strength
- Bond to Hardened Concrete
- Water absorption after 5 hour boil
- Effect of Density on Strength and Stiffening
- Economic Considerations
- Linear Thermal Expansion

In the report by Haynes and Eckroth (1979) the lightweight aggregate particle was filled with polymer. The reduction in densities when compared to normalweight was essential in the conceptual design of a massive floating platform and an enormous cold water pipe, 60 feet in diameter and 2,000 feet deep. This was acquired for the design of an ocean thermal energy conversion (OTEC) that would use temperature difference of cold ocean water to drive a turbine to generate electricity. An extensive laboratory developed physical property information which is contained in the report.

4.11 Shrinkage Compensated Cement / Lightweight Concrete

Bridge decks and other structures sensitive to cracking have been constructed with lightweight concretes containing expansive cement. A report published in the "Ohio Paver" November 1989 indicated that the Ohio Turnpike Commission had utilized the combination of Haydite lightweight aggregate and the Type K cement in 16 of its reconstructed bridge decks.

Aroni and Pocivka reported the results of a comprehensive testing program "*Effect of Expanded Shale Aggregate on Properties of Expansive Cement Concrete"* 1967. They reported "the shrinkage characteristics of expansive cement concrete are improved by the presence of internal water in the pores of lightweight aggregate".

In the results of tests on various physical properties by lightweight aggregate manufacturers conducted by the University of West Virginia and is referenced in Appendix 4D.

4.12 Fiber Reinforced Lightweight Concrete

A considerable volume of research into the use of steel and polymer fibers to structurally reinforce lightweight concrete has resulted in only a modest amount of practical applications. Comprehensive testing by Balaqura et al (1993) at Rutgers University and Craig (1979) at N.J. Institute of Technology are included in the ESCSI "*Fiber Reinforce Lightweight Concrete"* file and are listed in Appendix 4D.

4.13 Insulating-Grade Lightweight Aggregates and Insulating Lightweight Concretes

Insulating concrete is very light and non-structural concrete that is used primarily for high thermal resistance and incorporate low-density low-strength aggregates such as vermiculite and perlite. With low densities, seldom exceeding 50 lb/ft^3 (800 kg/m^3), thermal resistance is high, these concretes are not intended to be exposed to the weather and generally have a compressive strength range from about 100 to 500 psi (0.69 to 6.89 MPa). See also ACI 523.1 "*Guide for Cast-in-Place Low Density Concrete"* and ACI 523.3 "*Guide for Cellular Concretes Above 50 pcf and for Aggregate Concrete Above 50 pcf with Compressive Strengths less than 2500 psi".*

ASTM *Specification for Lightweight Aggregates for Insulating Concrete* (C 332) limits thermal conductivity values for insulating concretes to maximum of 1.50 Btu • in. • /h • ft² ºF (0.22 W/m • K) for concrete having an oven-dry density of 50 lb/ft³ (800 kg/m³) or less, and to 3.0 Btu • in. • /h • ft² ºF (0.43 W/m • K) for those weighing up to 90 lb/ft³ (1440 kg/m³). Lighter concretes are those made with Group I aggregates (perlite and vermiculite), while higher densities result from the use of Group II aggregates (expanded shale's, expanded slags and natural lightweight aggregates).

Thermal conductivity values may be determined in accordance with ASTM *Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box* (C 236) and ASTM *Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot Plate Apparatus* (C 177). Oven-dried specimens are used for both thermal conductivity and density tests on the insulating concretes. Moisture content of insulating materials directly affects both the thermal conductivity and density, but to varying degrees. A 1% increase in moisture content will increase density by an equivalent 1% but may increase thermal conductivity by as much as 5 to 9% [2]. Use of oven-dried specimens provides an arbitrary basis for comparison but clearly does not duplicate in-service applications. The controlled test conditions serve to permit classification of materials and to provide a standardized reference environment.

Reverse Mixtures

"Reverse" lightweight concrete mixtures (also termed "inverted" mixtures) are compositions in which the fine aggregate used is lightweight aggregate (as opposed to the usual practice of using natural sand) and the coarse aggregate is normalweight (as opposed to the usual lightweight aggregate) These concretes have been successfully used in various parts of the United States for several decades. The primary application of this type of proportioning is for structural lightweight concrete slabs supported by metal deck on fire rated steel framed structures.

In 1967 Leonard Hobbs reported the results of a number of differing contractors of LWA/NWA to produce high strength concretes. Included in this series of tests was a mixture containing 13.08 cf of ridgelite fine aggregate and 733 pcf of a 3/8 maximum top size pea gravel that resulted in an equilibrium density under 110 pcf with 28 day compressive strength exceeding 7000 psi (see tables 4.7 and 4.8).

Table 4.7 Results of Tests Conducted on "Reverse" Lightweight Concrete Mixtures

PROPORTIONS FOR ONE CUBIC YARD OF CONCRETE	Mix No. 1 (control mix)	Mix No. 2	Mix No. 3	Mix No. 4	Mix No. 5
Cement, Perm, Type 2	8.80 sx.	8.78 sx.	8.80 sx.	8.78 sx.	8.67 sx.
W.C. Sand, S.S.D.	1,212 lbs.	-----	-----	-----	1,200 lbs.
Ridgelite Sand, Dry	------	12.92 cu. ft.	13.08 cu. ft.	12.97 cu. ft.	-----
Pea Gravel, S.S.D.	1,507 lbs.	1,503 lbs.	733 lbs.	-----	-----
Rocklite 3/8 inch, Dry	------	-----	8.08 cu. ft.	15.85 cu. ft.	16.42 cu. ft.
Total Water	44.2 gal	50.7 gal.	52.1 gal.	54.7 gal.	49.2 gal.
Slump	4.0 in.	3.7 in.	4.2 in.	4.7 in.	5.5 in.
Air Content (Rollamtr)	2.5%	3.1%	2.8%	3.1%	2.5%
UNIT WEIGHTS pcf	Average of three 6" x 12" cylinders except for "Plastic"				
Plastic (1/2 cu. ft.)	145.0	125.2	111.7	96.8	116.3
One Day	147.3	127.2	113.0	98.2	116.8
6-Days	146.2	125.7	111.0	96.4	116.1
14-Days	145.8	125.1	110.4	95.5	114.8
21-Days	145.5	124.9	110.1	95.2	114.3
28-Days	145.3	124.7	109.8	94.8	114.1
28-Day Compressive Strenths, psi, Average of 3:	6013 6137 6332 <6161>	7641 7694 7782 <7606>	6880 7128 7252 <7087>	6550 6572 6650 <6591>	No Results
28-Day Compressive Strengths, psi Average of 4:	6367 6456 6827 6933 <6646>	7676 7853 8065 8171 <7941>	7145 7170 7192 7358 <7216>	6226 6579 6668 6686 <6540>	6579 6729 6880 6915 <6776>

(1) Cured in laboratory air at approximately 50% humidity except for Mix No. 5 which was moist cured at 100% humidity for the first 6 days.

(2) Cured in the moist room at 100% humidity for the full 28 days.

Table 4.8 Aggregate Physical Properties Use in "Reverse" Mixture Tests

	W.C. SAND	RIDGELITE SAND	PEA GRAVEL	ROCKLITE 3/8"
SIEVE SIZE	**SIEVE ANALYSIS, Percent Passing by Weight**			
1/2	----	----	----	----
3/8	----	----	100	96
1/4	100	----	33	4
No. 4	97	100	7	1
No. 8	84	94	3	----
No. 16	67	67	----	----
No. 30	42	44	----	----
No. 50	16	21	----	----
No. 100	4	7	----	----
Dry Loose Unit Weight	96 pcf	49 pcf	90 pcf	43 pcf
Specific Gravity	2.66 SSD	1.41 Dry	2.66 SSD	1.23 Dry
Percent Solids	58	56	54	57

Source of Materials:

Cement: Permaente, Type 2 from Kaiser Cement and Gypsum Corp.
W.C. Sand: Con Rock's plant at Irwindale
Pea Gravel: Con Rock's plant at Irwindale
Ridgelite Sand: Ceramic Concrete Aggregates plant at Frazier Park
Rocklite 3/8 inch: Ceramic Concrete Aggregates plant at Ventura

These strengths and densities would exceed the requirements of usual Underwriters Laboratories criteria. However, for reasons not fully understood UL is reluctant to certify these mixtures without yet still another test in their own laboratory.

The Underwriters Laboratory Fire Resistance Directory – Fire Resistance Hourly Ratings for Beams, Floors and Roofs includes mixture information, (note that many designs, for example D840 specify unit weight, but not aggregate sizes and compositions, e.g.

Density	**Form Units**	**Thickness**
107-113	All depths	3 ¼ in.
107-120	All depths	3 ½ in
107-116	2 and 3 in. deep only	¾ in

Also mentioned are strength, 3000 psi, air content 4 to 7 percent and manufacturing process rotary kiln or sintered method – but not the mixture composition.

In order to overcome this objection, Big River Industries and the Utelite Corporation partnered and funded a major testing program, "*Heat Transmission Test Results for Comparing Fire Endurance of Traditional Blend and Reverse Blend Lightweight Aggregate Concrete"* that was reported by Van Geem (1991).

This report addressed the situation in where "Manufacturers are now manufacturing lightweight concrete using reverse blends, which are normalweight coarse material and lightweight fines. It is known however, that the primary factor controlling fire endurance for lightweight concrete is unit weight. Generally the lighter the unit weight the greater the fire endurance of the concrete. Therefore, it is anticipated that the endurance of a reverse blend lightweight concrete will be equivalent to the fire endurance of a conventional blend lightweight concrete of the same unit weight".

The finding of the investigation was:

1. Reverse blend concretes tested have similar or slightly less steady-state heat transmission than conventional blend concretes with similar unit weights in this test program. Results are for specimen mean temperatures of approximately 300 and 1000ºF.
2. Conventional and reverse blend materials of the same unit weight have similar responses to heat transmission during transient temperature conditions. Results are for transient temperatures from ambient to 300ºF and 300º to 1000ºF.
3. Based on these test results, it is predicted that the fire endurance of the reverse blend concretes subjected to an ASTM E119 time-temperature curve will be either similar or slightly longer than the conventional blend concretes of the same unit weight. This prediction is based on the ASTM E119 criteria for the unexposed surface temperature and the particular concrete blends tested in this program.

Table 4.9 Thermal Conductivity Test Results for Concrete Specimens

Specimen Source and Type	Specimens Tested	Average Specimen Unit Wt., ** pcf	Average Specimen Thickness in.	Test Date	Test Duration*** days	Thermal Conductivity k, Btu•in/hr•sq-ft.•°F
Utelite Conv. Blend	2A & 2B	111	1.99	7/19/91	2	5.9
Utelite Conv. Blend	2A & 2B	111	1.99	7/22/91	3	7.2
Utelite Reverse Blend	1A & 1B	111	1.9845	7/26/91	2	5.8
Utelite Reverse Blend	1A & 1B	111	1.9845	7/29/91	3	6.4
Big River Reverse Blend	B & C	96	2.006	8/2/91	2	4.1
Big River Reverse Blend	B & C	96	2.006	8/5/91	3	4.6
Big River Conv. Blend	1 & 2	92	1.998	8/9/91	2	4.9
Big River Conv. Blend	1 & 2	92	1.998	8/12/91	3	5.1

***Measured in accordance with ASTM Designation: C177 using a guarded hot plate.**
****Oven dry unit weight before testing**
*****Includes time before steady-state equilibrium is achieved.**

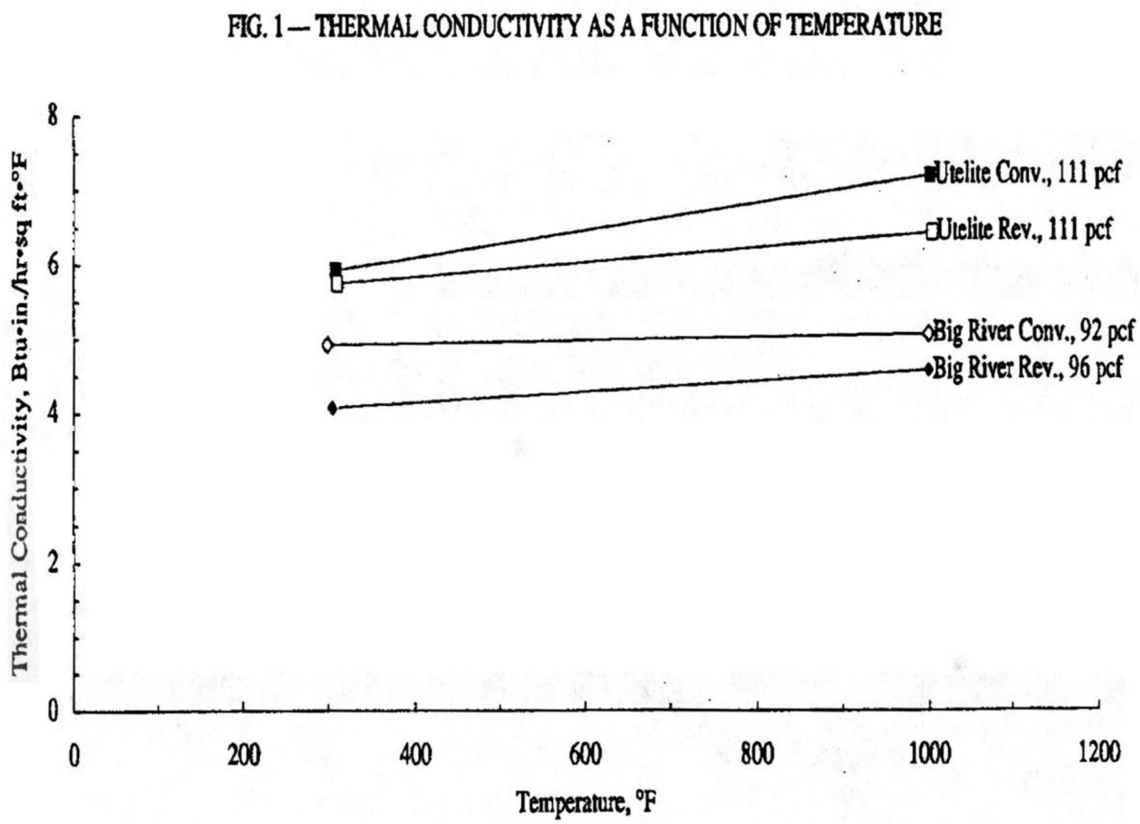


Figure 4.14 ***Thermal Conductivity as a Function of Temperature***

4A

ACI 211.2-04 “Standard Practice for Selecting Proportions for Structural Lightweight Concrete”

ACI 211.2-98
(Reapproved 2004)

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

Reported by ACI Committee 211

Jay R. Prestera, Secretary
Michael Boyle, Chair
David A. Crocker, Chair, Subcommittee B

Edward A. Abdun-Nur, Stanley G. Barton*, Leonard W. Bell, George R. U. Berg, Stanley J. Blas, Jr., Peggy M. Carrasquillo, Ramon L. Carrasquillo, Martyn T. Conrey, James E. Cook, Russell A. Cook*, William A. Cordon, Wayne J. Costa, Kenneth W. Day, Calvin L. Dodl*, Donald E. Graham, George W. Hollon*, William W. Hotaling, Jr., Robert S. Jenkins, Paul Klieger, Frank J. Lahm, Stanley H. Lee, Gary R. Mass, Richard C. Meininger, Richard W. Narva, Leo P. Nicholson, James E. Oliverson, James S. Pierce, Sandor Popovics, Steven A. Ragan, Harry C. Robinson, Jere H. Rose, James A. Scherocman, James M. Shilstone, Sr., George B. Southworth, Alfred B. Spamer, Paul R. Stodola*, Michael A. Taylor, Stanley J. Virgalitte*, William H. Voelker, Jack W. Weber, Dean J. White, II, Milton H. Wills, Jr., Francis C. Wilson, Robert L. Yuan

*Members of Subcommittee B who prepared this standard.

Committee that voted on reapproval, 2004

Frank A. Kozeliski, Chair
Ed T. McGuire, Secretary
G. Michael Robinson, Chair, Subcommittee B

William L. Barringer, Muhammed P. A. Basheer, Casimir Bognacki, Michael J. Boyle, Marshall L. Brown, Ramon L. Carrasquillo, James E. Cook, John F. Cook, Raymond A. Cook, David A. Crocker, D. Gene Daniel, Francois de Larrard, Donald E. Dixon, Calvin L. Dodl, Darrell F. Elliot, Michael R. Gardner, John T. Guthrie, G. Terry Harris, Sr., Richard D. Hill, David L. Hollingsworth, Said Iravani, Tarif M. Jaber, Robert S. Jenkins, Gary Knight, Colin L. Lobo, Howard P. Lux, Gary R. Mass, Jan Olek, H. Celik Ozyildirim, Dipak T. Parekh, James S. Pierce, Steven A. Ragan, Royce J. Rhoads, John P. Ries, Shelley R. Sheetz, James M. Shilstone, Sr., Ava Shypula, Jeffrey F. Speck, William X. Sypher, Stanley J. Virgalitte, Woodward L. Vogt, Michael A. Whisonant, Dean J. White, II, Richard M. Wing

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.

ACI 211.2-98 (Repproved 2004) supersedes ACI 211.2-91 and became effective March 1, 1998.

CONTENTS

Chapter 1—Introduction, p. 211.2-2
1.1—Purpose
1.2—Scope

Chapter 2—Factors affecting proportioning of lightweight-aggregate concrete, p. 211.2-2
2.1—Aggregates (absorption and moisture content)
2.2—Aggregates (gradation)
2.3—Water-cementitious material ratio
2.4—Air entrainment

Chapter 3—Estimating first trial mixture proportions, p. 211.2-4
3.1—General
3.2—Method 1: Weight method (specific gravity pycnometer)
3.3—Method 2: Volumetric method (damp, loose volume)

Chapter 4—Adjusting mixture proportions, p. 211.2-16
4.1—General
4.2—Method 1: Weight method (specific gravity pycnometer)
4.3—Method 2: Volumetric method (damp, loose volume)
4.4—Adjustment procedures
4.5—Controlling proportions in the field

Chapter 5—References, p. 211.2-18
5.1—Referenced standards and reports

Appendix A—Determination of specific gravity factors of structural lightweight aggregate, p. 211.2-19

Appendix B—Determination of structural lightweight coarse aggregate absorption, p. 211.2-20

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/ft^3 (1842 kg/m^3) 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

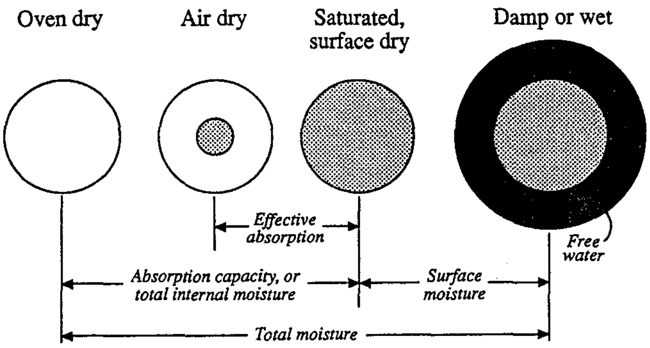
(c) when the surface texture is least porous.

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.

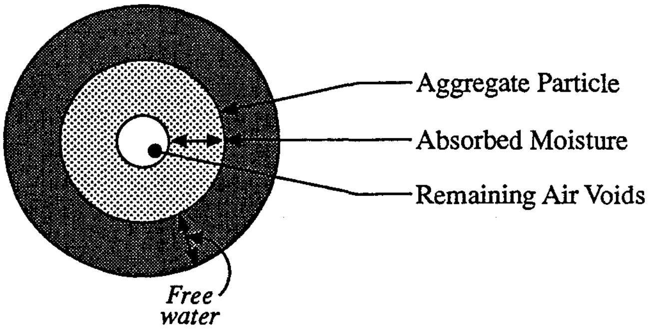
In some cases, strength may be increased by reducing the nominal maximum size of the aggregate without increasing the cement content.

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 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.



States of moisture in aggregate. Heavy circle represents the aggregate; crosshatching represents moisture.[2]

Fig. 2.1—States of moisture in aggregate.



Heavy middle circle represents the aggregate particle; crosshatching represents moisture.

Fig. 2.2—"As-is" condition.

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. (25 mm) 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 not necessarily reflected in strength because other compensating factors may be involved.

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.

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 ± 3 °F (23 ± 2 °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 dry weights should be increased by the percentage of water they contain, both absorbed and surface. The mixing water added to the bath must be reduced by an amount equal to the free moisture contributed by the aggregate (such as total moisture minus absorption).

3.2.3 *Sample computations—Method 1: weight method (specific gravity pycnometer)*—A sample problem in inch-pound units (Example A—inch-pound units) will be used to illustrate application of the proportioning procedures. The following conditions are assumed:

3.2.3.1 Type I non-air-entrained cement will be used.

3.2.3.2 Lightweight coarse aggregate and normalweight fine aggregate are of satisfactory quality and are graded within limits of generally accepted specifications, such as ASTM C 330 and C 33.

3.2.3.3 The coarse aggregate has a specific gravity factor of 1.50 and an absorption of 11.0%.

3.2.3.4 The fine aggregate has an absorption of 1.0%, and a fineness modulus of 2.80.

Lightweight concrete is required for a floor slab of a multistory structure subjected to freezing and thawing during construction. Structural design considerations require a 28-day compressive strength of 3500 psi. On the basis of information in Table 3.1 and previous experience, under the conditions of placement to be used, a slump of 3 to 4 in. should be used and that the available 3/4 in.to No. 4 lightweight coarse aggregate will be suitable.

The oven-dry loose weight of coarse aggregate is found to be 47 lb/ft^3. Employing the sequence outlined in Section 3.2.2, the quantities of ingredients per yd^3 of concrete are calculated as follows:

Step 1—As indicated previously, the desired slump is 3 to 4 in.

Step 2—The locally available lightweight aggregate, graded from 3/4 in. to No. 4, has been indicated as suitable.

Step 3—Because the structure will be exposed to severe weathering during construction, air-entrained concrete will be used. The approximate amount of mixing water to produce a 3 to 4 in. slump in air-entrained concrete with 3/4 in. nominal maximum-size aggregate is found from Table 3.2 to be 305 lb/yd^3. Estimated total air content is shown as 6.0%.

Step 4—From Table 3.3, the *w/c* needed to produce a strength of 3500 psi in air-entrained concrete is found to be approximately 0.54. In consideration of the severe exposure during construction, the maximum permissible *w/c* or *w/cm* from Table 3.4 is 0.50.

Step 5—From the information derived in Steps 3 and 4, the required cement content is found to be 305/0.50 = 610 lb/yd^3.

Step 6—The quantity of lightweight coarse aggregate is estimated from Table 3.5. For a fine aggregate having fineness modulus of 2.80 and 3/4 in. nominal maximum size of coarse aggregate, the table indicates that 0.70 yd^3 of coarse aggregate, on a dry-loose basis, may be used in each yd^3 of concrete. Therefore, for a unit volume, the coarse aggregate will be 1 × 0.70 = 0.70 yd^3. Because it weighs 47 lb/ft^3, the dry weight of coarse aggregate is 0.70 × 47 × 27 = 888 lb. Because the coarse aggregate has an absorption of 11.0%, the saturated weight is 1.11 × 888 = 986 lb.

Table 3.6—First estimate of weight of fresh lightweight concrete comprised of lightweight coarse aggregate and normalweight fine aggregate

Specific gravity factor	First estimate of lightweight concrete weight, lb/yd^3(kg/m^3)* — Air-entrained concrete 4%	6%	8%
1.00	2690 (1596)	2630 (1561)	2560 (1519)
1.20	2830 (1680)	2770 (1644)	2710 (1608)
1.40	2980 (1769)	2910 (1727)	2850 (1691)
1.60	3120 (1852)	3050 (1810)	2990 (1775)
1.80	3260 (1935)	3200 (1899)	3130 (1858)
2.00	3410 (2024)	3340 (1982)	3270 (1941)

*Values for concrete of medium richness (550 lb of cement per yd^3 [326 kg/m^3]) and medium slump with water requirements based on values for 3 to 4 in. (75 to 100 mm) slump in Table 3.2. If desired, the estimated weight may be refined as follows, if necessary information is available: for each 10 lb (5.9 kg) difference in mixing water from Table 3.2, correct the weight per yd^3 15 lb in the opposite direction (8.9 kg per m^3); for each 100 lb (59.3 kg^3) difference in cement content from 550 lb (326 kg), correct the weight per yd^3 15 lb in the same direction (8.9 kg per m^3).

Step 7—With the quantities of water, cement, and coarse aggregate established, the remaining material comprising the yd^3 of concrete must consist of sand and the total air used. The required sand is determined on the weight basis by difference. From Table 3.6, the weight of a yd^3 of air-entrained concrete made with lightweight aggregate having a specific gravity factor of 1.50 is estimated to be 2980 lb. (For a first trial batch, exact adjustments of this value for usual differences in slump, cement factor, and aggregate specific-gravity factor are not critical.) Weights already known are

	Per yd^3
Water (net mixing)	305 lb
Cement	610 lb
Coarse aggregate	986 lb (saturated)
Total	1901 lb

The saturated surface dry (SSD) weight of sand, therefore, is estimated to be 2980 – 1901 = 1079 lb. Oven-dry weight of sand is 1079/1.01 = 1068 lb.

Step 8—For the laboratory trial batch, it is convenient to scale the weights down to produce at least 1.0 ft^3 of concrete. The batch weights for a 1.0 ft^3 batch are calculated as follows

Cement	610/27 =	22.59 lb
Fine aggregate (SSD)	1079/27 =	39.96 lb
Coarse aggregate (SSD)	986/27 =	36.52 lb
Water (net mixing)	305/27 =	11.30 lb
Total		110.37 lb

Tests indicate total moisture content of 15.0% for the lightweight coarse aggregate and 6.0% for the fine aggregate. Absorbed water does not become part of the mixing water and must be excluded from the adjustment of added water. Thus, surface water contributed by the lightweight coarse aggregate amounts to 15.0 – 11.0 = 4.0% and by the fine aggregate 6.0 – 1.0 = 5.0%. The adjustments to the aggregates for this free moisture are calculated as follows

Fine aggregate (39.96/1.01) × 1.06 = 41.94 lb
Coarse aggregate (36.52/1.11) × 1.15 = 37.84 lb

The adjustment of the added water to account for the moisture added with the aggregates is as follows

Water from fine aggregate = 41.96 – 39.96 = 1.98 lb
Water from coarse aggregate = 37.84 – 36.52 = 1.32 lb

Therefore, water to be added to the batch is

$$11.30 - 1.98 - 1.32 = 8.00 \text{ lb}$$

The weights to be used for the 1.0 ft^3 trial batch are

Cement	22.59 lb
Fine aggregate (wet)	41.94 lb
Coarse aggregate (wet)	37.84 lb
Water (added)	8.00 lb
Total	110.37 lb

Step 9—Although the calculated quantity of water to be added was 8.00 lb, the amount actually used in an attempt to obtain the desired 3 to 4 in. slump was 8.64 lb. The as-mixed batch, therefore, consists of

Cement	22.59 lb
Fine aggregate (wet)	41.94 lb
Coarse aggregate (wet)	37.84 lb
Water (added)	8.64 lb
Total	111.01 lb

The concrete mixture is judged to be satisfactory as to workability and finishing properties; however, the concrete had a measured slump of only 2 in. and a unit weight of 108.0 lb/yd^3. To provide the proper yield for future trial batches, the following adjustments are made.

Because the yield of the trial batch was 111.01/108.0 = 1.028 ft^3 and the mixing water actually used was 8.64 (added) + 1.98 (from fine aggregate) + 1.32 (from coarse aggregate) = 11.94 lb, the mixing water required for 1 yd^3 of concrete with the same 2 in. slump as the trial batch should be approximately

$$(11.94/1.028) \times 27 = 314 \text{ lb}$$

As indicated in Section 4.4.2.3, this amount must be increased by about 15 lb/yd^3 to raise the slump from the measured 2 in. to the desired 3 to 4 in. range, bringing the net mixing water to 329 lb. With the increased mixing water, additional cement will be required to maintain the desired *w/c* of 0.50. The new cement content per yd^3 becomes

$$329/0.50 = 658 \text{ lb}$$

Because workability was found to be satisfactory, the quantity of lightweight coarse aggregate per unit volume of concrete will be maintained the same as in the trial batch. The amount of coarse aggregate per yd^3 becomes

$$(37.84/1.028) \times 27 = 994 \text{ lb (wet)}$$

which is

$$994/1.15 = 864 \text{ lb (dry)}$$

or

$$864 \times 1.11 = 959 \text{ lb (SSD)}$$

The new estimate for the weight (Fig. 4.1) of a unit volume of concrete is 108.0 × 27 = 2916 lb/yd^3. Therefore, the amount of fine aggregate per yd^3 required is

$$2916 - (329 + 658 + 959) = 970 \text{ lb (SSD)}$$

or

$$970/1.01 = 960 \text{ lb (dry)}$$

The adjusted batch weights per yd^3 are

Cement	658 lb
Fine aggregate (dry)	960 lb
Coarse aggregate (dry)	864 lb
Water (total*)	434 lb
Total	2916 lb

or on a SSD condition

Cement	658 lb
Fine aggregate (SSD)	970 lb
Coarse aggregate (SSD)	959 lb
Water (net mixing)	329 lb
Total	2916 lb

A verification laboratory trial batch of concrete using the adjusted weights should be made to determine if the desired properties have been achieved.

3.2.6 *Sample computations—Method 1: weight method (specific gravity pycnometer)*—A second sample problem in inch-pound units. (Example B—inch-pound units) will be used to illustrate application of the proportioning procedures where several of the specific mixture requirements are specified. Examples B and D (volumetric method—damp, loose volume method, Section 3.3.4) are similar for direct comparison of both methods.

Requirements

- 3500 psi specified compressive strength at 28 days;
- 1200 psi required over-design (per ACI 318, Section 5.3.2.2, no prior history);
- Required average strength of concrete f'_{cr} : 4700 psi;
- Lightweight aggregate: ASTM C 330, 3/4 in. to No. 4;
- Concrete sand: ASTM C 33, No. 4 to 0;

- Air-entraining admixture (AEA) for 6 ± 1%: ASTM C 260;
- Water-reducing admixture (WRA) use permitted: ASTM C 494, Type A or D; and
- Slump: 4 ± 1 in.; conventional placement.

Background information

From the lightweight-aggregate manufacturer:

- Specific gravity factor—1.48 at a 15% moisture content (ACI 211.2, Appendix A); and
- Suggested coarse aggregate factor (CAF) is 870 lb/yd^3 at a 15% moisture content ("as-is" condition).

From the sand supplier:

- Specific gravity = 2.60, fineness modulus = 2.80.

From the cement supplier:

- Specific gravity = 3.14;

General information

- Moisture content at time of use = 15%; and
- Unit weight of water = 62.4 lb/ft^3.

Proportioning design

Step 1: Establish *w/c* required for 4700 psi air-entrained concrete = 0.42 (Table 3.4, interpolated value).

Step 2: Establish water required per yd^3 (SSD basis), 3 to 4 in. slump, air-entrained, 3/4 in. aggregate = 305 lb less 11% for WRA = 271 lb (Table 3.2).

Step 3: Calculate cement content = 271 lb/0.42 = 645 lb.

Step 4: Calculate air content = 27.00 ft^3/yd^3 × 0.06 = 1.62 ft^3.

Step 5: Calculate lightweight aggregate absolute volume 870 lb/1.48 × 62.4 lb/ft^3 = 9.42 ft^3.

Step 6: Calculate absolute volume of sand by totaling absolute volumes of all other materials and subtracting from 27 ft^3.

Item A: Cement absolute volume = 645/3.14 × 6.24 = 3.29 ft^3

Item B: Water absolute volume = 271 lb/1 × 62.4 = 4.34 ft^3

Item C: Air volume (from Step 4) = 1.62 ft^3

Item D: Lightweight aggregate absolute volume (from Step 5) = 9.42 ft^3

Total of absolute volumes + volume of air 18.67 ft^3

Item E: Sand absolute volume = 27.00 – 18.67 = 8.33 ft^3

Sand weight = 8.33 × 2.60 × 62.4 = 1351 lb

Step 7: Calculate theoretical plastic unit weight by adding all batch weights and dividing by 27.

Weights: 1 yd^3

Cement	645 lb
LWA (as is)	870 lb
Sand (dry)	1351 lb
Water (total)	271 lb
Total	**3137 lb/yd^3**
	or 116.2 lb/ft^3 plastic

Mixtures must be monitored and adjusted in the field to maintain yield.

3.25 *Sample computations—Method 1: weight method (specific gravity pycnometer)*—A sample problem in SI units (Example A—SI units) will be used to illustrate application of the proportioning procedures. The following conditions are assumed:

3.2.5.1 Type I non-air-entrained cement will be used.

3.2.5.2 Lightweight coarse aggregate and normalweight fine aggregate are of satisfactory quality and are graded within limits of generally accepted specifications, such as ASTM C 330 and C 33.

3.2.5.3 The coarse aggregate has a specific gravity factor of 1.50 and an absorption of 11.0%.

3.2.5.4 The fine aggregate has an absorption of 1.0%, and a fineness modulus of 2.80.

Lightweight concrete is required for a floor slab of a multistory structure subjected to freezing and thawing during construction. Structural design considerations require a 28-day compressive strength of 24 MPa. On the basis of information in Table 3.1 and previous experience, under the conditions of placement to be used, a slump of 75 to 100 mm should be used, and the available 19 to 5 mm lightweight coarse aggregate will be suitable.

The oven-dry loose weight of coarse aggregate is found to be 47 lb/ft^3. Employing the sequence outlined in Section 3.2.2, the quantities of ingredients per yd^3 of concrete are calculated as follows:

Step 1—As indicated previously, the desired slump is 75 to 100 mm.

Step 2—The locally available lightweight aggregate, graded from 19 to 5 mm, has been indicated as suitable.

Step 3—Because the structure will be exposed to severe weathering during construction, air-entrained concrete will be used. The approximate amount of mixing water to produce a 75 to 100 mm slump in air-entrained concrete with 19 mm nominal maximum-size aggregate is found from Table 3.2 to be 181 kg/m^3. Estimated total air content is shown as 6.0%.

Step 4—From Table 3.3, the *w/c* needed to produce a strength of 24 MPa in air-entrained concrete is found to be approximately 0.54. In consideration of the severe exposure during construction, the maximum permissible *w/c* or *w/cm* from Table 3.4 is 0.50.

Step 5—From the information derived in Steps 3 and 4, the required cement content is found to be 181/0.50 = 362 kg/m^3.

Step 6—The quantity of lightweight coarse aggregate is estimated from Table 3.5. For a fine aggregate having fineness modulus of 2.80 and 19 mm nominal maximum size of coarse aggregate, the table indicates that 0.70 m^3 of coarse aggregate, on a dry-loose basis, may be used in each m^3 of concrete. Therefore, for a unit volume, the coarse aggregate will be 1 × 0.70 = 0.70 m^3. Because it weighs 753 kg/m^3, the dry weight of coarse aggregate is 0.70 × 753 = 527 kg. Because the coarse aggregate has an absorption of 11.0%, the saturated weight is 1.11 × 527 = 585 lb.

Step 7—With the quantities of water, cement, and coarse aggregate established, the remaining material comprising the m^3 of concrete must consist of sand and the total air used. The required sand is determined on the weight basis by difference. From Table 3.6, the weight of a m^3 of air-entrained concrete made with lightweight aggregate having a specific gravity factor of 1.50 is estimated to be 1768 kg. (For a first trial batch, exact adjustments of this value for usual differences in slump, cement factor, and aggregate specific-gravity factor are not critical.) Weights already known are

	Per m^3
Water (net mixing)	181 kg
Cement	362 kg
Coarse aggregate	585 kg (saturated)
Total	1128 kg

Therefore, the saturated surface dry (SSD) weight of sand is estimated to be 1768 – 1128 = 640 kg. Oven-dry weight of sand is 640/1.01 = 634 kg.

Step 8—For the laboratory trial batch, it is convenient to scale the weights down to produce at least 0.028 m^3 of concrete. The batch weights for a 0.028 m^3 batch are calculated as follows

Cement	362 × 0.028 =	10.14 kg
Fine aggregate (SSD)	640 × 0.028 =	17.92 kg
Coarse aggregate (SSD)	585 × 0.028 =	16.38 kg
Water (net mixing)	181 × 0.028 =	5.07 kg
Total		49.51 kg

Tests indicate total moisture content of 15.0% for the lightweight coarse aggregate and 6.0% for the fine aggregate. Absorbed water does not become part of the mixing water and must be excluded from the adjustment of added water. Thus, surface water contributed by the lightweight coarse aggregate amounts to 15.0 – 11.0 = 4.0% and by the fine aggregate 6.0 – 1.0 = 5.0%. The adjustments to the aggregates for this free moisture are calculated as follows

Fine aggregate (17.92/1.01) × 1.06 = 18.81 kg
Coarse aggregate (16.38/1.11) × 1.15 = 16.97 lb

The adjustment of the added water to account for the moisture added with the aggregates is as follows

Water from fine aggregate = 18.81 – 17.92 = 0.89 kg
Water from coarse aggregate = 16.97 – 16.38 = 0.59 kg

Therefore, water to be added to the batch is

$$5.07 - (0.89 + 0.59) = 3.59 \text{ kg}$$

The weights to be used for the 0.028 m^3 trial batch are

Cement	10.14 kg
Fine aggregate (wet)	18.81 kg
Coarse aggregate (wet)	16.97 kg
Water (added)	3.59 kg
Total	49.51 kg

Step 9—Although the calculated quantity of water to be added was 3.59 kg, the amount actually used in an attempt to obtain the desired 50 mm slump was 3.88 kg. Therefore, the as-mixed batch consists of:

Cement	10.14 kg
Fine aggregate (wet)	18.81 kg
Coarse aggregate (wet)	16.97 kg
Water (added)	3.88 kg
Total	49.80 kg

The concrete mixture is judged to be satisfactory as to workability and finishing properties; however, the concrete had a measured slump of only 50 mm and a unit weight of 1730 kg/m^3. To provide the proper yield for future trial batches, the following adjustments are made.

Because the yield of the trial batch was 49.80/1730 = 0.0288 m^3 and the mixing water actually used was 3.88 (added) + 0.89 (from fine aggregate) + 0.59 (from coarse aggregate) = 5.36 kg, the mixing water required for 1 m^3 of concrete with the same 50 mm slump as the trial batch should be approximately

$$(5.36/0.0288) = 186 \text{ kg}$$

As indicated in Section 4.4.2.3, this amount must be increased by about 9 kg/m^3 to raise the slump from the measured 50 mm to the desired 75 to 100 mm range, bringing the net mixing water to 195 kg. With the increased mixing water, additional cement will be required to maintain the desired *w/c* of 0.50. The new cement content per m^3 becomes

$$195/0.50 = 390 \text{ kg/m}^3$$

Because workability was found to be satisfactory, the quantity of lightweight coarse aggregate per unit volume of concrete will be maintained the same as in the trial batch. The amount of coarse aggregate per m^3 becomes

$$(16.97/0.0288) = 589 \text{ kg (wet)}$$

which is

$$589/1.15 = 512 \text{ kg (dry)}$$

or

$$512 \times 1.11 = 569 \text{ kg (SSD)}$$

The new estimate for the weight (Fig. 4.1) of a unit volume of concrete is 1730 kg/m^3. Therefore, the amount of fine aggregate per yd^3 required is

$$1730 - (195 + 390 + 569) = 576 \text{ kg (SSD)}$$

or

$$576/1.01 = 570 \text{ kg (dry)}$$

The adjusted batch weights per m^3 are

Cement	390 kg
Fine aggregate (dry)	570 kg
Coarse aggregate (dry)	512 kg
Water (total*)	258 kg
Total	1730 kg

or on a SSD condition

Cement	390 kg
Fine aggregate (SSD)	576 kg
Coarse aggregate (SSD)	568 kg
Water (net mixing)	196 kg
Total	1730 kg

A verification laboratory trial batch of concrete using the adjusted weights should be made to determine if the desired properties have been achieved.

3.2.6 *Sample computations—Method 1: weight method (specific gravity pycnometer)*—A second sample problem in SI units. (Example B-SI units) will be used to illustrate application of the proportioning procedures where several of the specific mixture requirements are specified. Examples B and D (volumetric method—damp, loose volume method, Section 3.3.4) are similar for direct comparison of both methods.

Requirements

- 24 MPa specified compressive strength at 28 days;
- 8 MPa required over-design (per ACI 318, Section 5.3.2.2, no prior history);
- Required average strength of concrete f'_{cr} : 32 MPa;
- Lightweight aggregate: ASTM C 330, 19 to 5 mm;
- Concrete sand: ASTM C 33, 5 to 0 mm;
- Air-entraining admixture (AEA) for 6 ± 1%: ASTM C 260;
- Water-reducing admixture (WRA) use permitted: ASTM C 494, Type A or D; and
- Slump: 100 ± 25 mm.; conventional placement.

Background information

From the lightweight-aggregate manufacturer:

- Specific gravity factor—1.48 at a 15% moisture content (ACI 211.2, Appendix A); and
- Suggested coarse aggregate factor (CAF) is 516 kg/m^3 at a 15% moisture content ("as-is" condition).

From the sand supplier:

- Specific gravity = 2.60, fineness modulus = 2.80.

From the cement supplier:

- Specific gravity = 3.14.

General information:

- Moisture content at time of use = 15%; and
- Unit weight of water = 1000 kg/m^3.

Proportioning design

Step 1: Establish *w/c* required for 32 MPa air-entrained concrete = 0.42 (Table 3.4, interpolated value).

Step 2: Establish water required per yd^3 (SSD basis), 75 to 100 mm slump, air-entrained, 19 mm aggregate = 181 kg less 11% for WRA = 161 kg (Table 3.2).

Step 3: Calculate cement content = 161 kg/0.42 = 383 kg.

Step 4: Calculate air content = 0.06 m^3.

Step 5: Calculate lightweight aggregate absolute volume 516/(1.48 × 1000) = 03.49 m^3.

Step 6: Calculate absolute volume of sand by totaling absolute volumes of all other materials and subtracting from 1 m^3.

Item A: Cement absolute volume = 383/(3.14 × 1000) = 0.122 m^3

Item B: Water absolute volume = 161/(1.00 × 1000) = 0.161 m^3

Item C: Air volume (from Step 4) = 0.060 m^3

Item D: Lightweight aggregate absolute volume (from Step 5) = 0.349 m^3

Total of absolute volumes + volume of air = 0.692 m^3

Item E: Sand absolute volume = 1.000 – 0.692 = 0.308 m^3

Sand weight = 0.308 × 2.60 × 1000 = 800 kg

Step 7: Calculate theoretical plastic unit weight by adding all batch weights.

Weights: 1 m^3

Cement	383 kg
LWA (as is)	516 kg
Sand (dry)	800 kg
Water (total)	161 kg
Total	**1860 kg/m^3**

Mixtures must be monitored and adjusted in the field to maintain yield.

3.3—Method 2: Volumetric method (damp, loose volume)

For use with all lightweight aggregate or a combination of lightweight and normalweight aggregates.

3.3.1 Some lightweight aggregate producers recommend trial mixture proportions based on damp, loose volumes converted to batch weights. This procedure is applicable to all lightweight or to sand lightweight concrete comprised of various combinations of lightweight aggregate and normal-weight aggregate. The total volume of aggregates required, measured as the sum of the uncombined volumes on a damp, loose basis, will usually be from 28 to 34 ft^3/yd^3 (1.04 to 1.26 m^3/m^3). Of this amount, the loose volume of the fine aggregate may be from 40 to 60% of the total loose volume. Both the total loose volume of aggregate required and the proportions of fine and coarse aggregates are dependent on several variables; these variables relate to both the nature of the aggregates and to the properties of the concrete to be produced. Estimating the required batch weights for the lightweight concrete involves estimating cement content to produce a required compressive strength level. The aggregate producer should be consulted to obtain a closer approximation of cement content and aggregate propor-

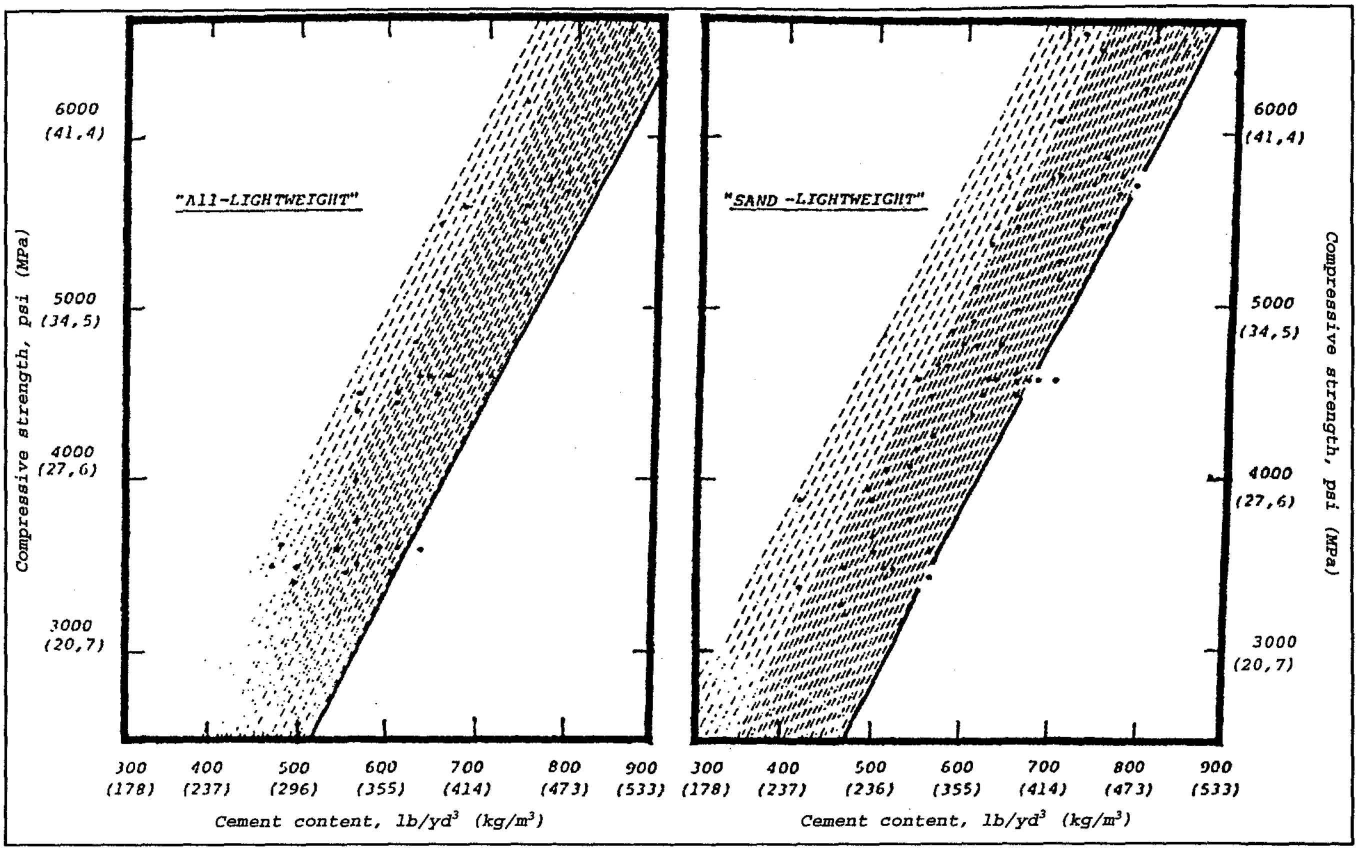


Fig. 3.1—Relationship of compressive strength and cement content of field concrete for lightweight fine aggregate and coarse aggregate, or lightweight coarse aggregate and normalweight fine aggregate (data points represent actual project strength results using a number of cement and aggregate sources).

tions required to achieve desired strength and unit weight with the specific aggregate. When this information is not available, the only alternative is to make a sufficient number of trial mixtures with varying cement contents to achieve a range of compressive strengths, including the compressive strength desired.

3.3.2 *Estimation of cement content*—The cement content-strength relationship is similar for a given source of lightweight aggregate but varies widely between sources. Therefore, the aggregate producer should be consulted for a close approximation of cement content necessary to achieve the desired strength. When this information is not available, the cement content can be estimated from the data in Fig. 3.1

3.3.3 *Sample computations*—A sample problem (Example C) will be used to illustrate application of the proportioning procedure. Assume that a sand lightweight concrete with 4000 psi (27.6 MPa) compressive strength weighing no more than 105 lb/ft^3 (1682 kg/m^3), air dry (as in ASTM C 567), is required and will be placed by bucket at a 4 in. (100 mm) slump. The damp, loose unit weights for the coarse and fine lightweight aggregates have been determined as 47 and 55 lb/ft^3 (753 and 881 kg/m^3). The normalweight fine aggregate has been determined to weigh 100 or 102 lb/ft^3 (1602 or 1634 kg/m^3) in a SSD condition with 2% absorption.

Bulking caused by moisture on the aggregate surface, while of little significance with coarse aggregate, must be taken into account with fine aggregate when using the damp, loose volume method. This is accomplished by increasing the volume of lightweight fine aggregate, usually in the range of 2 to 3%, depending on the typical condition of the aggregate as shipped. Normalweight fine aggregates can vary appreciably from different sources in the same general area and are best handled on the basis of dry, loose volumes plus moisture. The local lightweight-aggregate producer has been consulted and has recommended 580 lb (344 kg) of cement per yd^3 (m^3)with 17 ft^3 (0.63 m^3) if coarse lightweight aggregate, 5 ft^3 (0.18 m^3) of lightweight fine aggregate, and 9-1/2 ft^3 (0.35 m^3) if normalweight fine aggregates per yd^3 (m^3). A trial batch of 1 ft^3 (0.028 m^3) will be made. The tabulated computations are as follows

	First trial batch weights, damp, loose, lb	Adjusted weights, yd^3 damp, loose, lb
Cement	$\frac{580}{27} = 21.5$	$\frac{27}{1.011} \times 21.5 = 574$
Coarse lightweight aggregate	$\frac{17 \times 47}{27} = 29.6$	$\frac{27}{1.011} \times 29.6 = 791$
Fine lightweight aggregate	$\frac{5 \times 55}{27} = 10.2$	$\frac{27}{1.011} \times 10.2 = 272$
Fine normalweight aggregate	$\frac{9.5 \times 102}{27} = 35.9$	$\frac{27}{1.011} \times 35.9 = 959$

Added water (4-in. slump)	11.2	$\frac{27}{1.011} \times 11.2 = 299$
Total weight	108.4	2895

Fresh unit weight, ASTM C 138 = 107.2 lb/ft³

Yield: 108.4 lb/ft³/107.2 lb/ft³ = 1.011 lb/ft³

Air content, ASTM C 173 = 6.3%

A trial batch of 0.028 m³ will next be made using metric units. The tabulated computations are as follows

	First trial batch weights, damp, loose, kg	Adjusted weights, m³ damp, loose, kg
Cement	$344 \times 0.028 = 9.63$	$\frac{9.63}{0.0282} = 341$
Coarse lightweight aggregate	$0.028 \times 0.63 \times 753 = 13.28$	$\frac{13.28}{0.0282} = 471$
Fine lightweight aggregate	$0.028 \times 0.18 \times 881 = 4.44$	$\frac{4.44}{0.0282} = 157$
Fine normalweight aggregate	$0.028 \times 0.35 \times 1634 = 16.01$	$\frac{16.01}{0.0282} = 568$
Added water (100 mm slump)	5.08	$\frac{5.08}{0.0282} = 180$
Total weight	48.44	1717

Fresh unit weight, ASTM C 138 = 1717 kg/m³

Yield: 48.44 kg/107.2 kg/m³ = 0.0282 kg/m³

Air content, ASTM C 173 = 6.3%

3.3.4 *Sample computations*—A second sample problem (Example D) will be used to illustrate application of the proportioning procedure where several of the specific mixture requirements are specified. Also the derivation of the volumetric, damp loose method is discussed and utilized in preparing a laboratory trial mixture and the method's subsequent use in field moisture adjustment. Examples B (weight method—specific gravity pycnometer, Section 3.2.4) and D are similar for direct comparison of both methods.

Because of the variations in the amount and rate of absorption of most lightweight aggregates, the true *w/c* cannot always be determined accurately enough to be of practical value. It is usually more practical to establish proportions by a series of trial mixtures proportioned on a cement content basis (water held constant for the desired slump) for the required degree of workability. Specimens from each acceptable trial mixture are tested at the specified ages to establish the cement content strength relationship in the series. From this information the cement content for the desired strength can be selected. (Acceptable trial mixtures are those with the properties of workability, yield, slump, strength, and air content similar to those desired in the target mixture.)

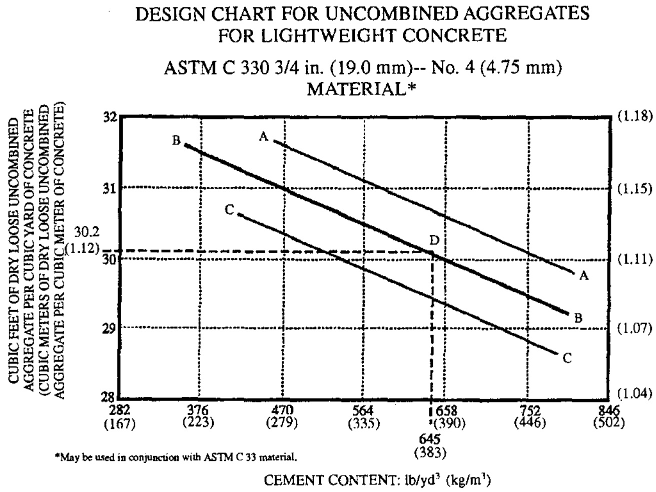


Fig. 3.2—Design chart for uncombined aggregates for lightweight concrete.

The usual approach to estimating concrete trial mixtures is to use proportions from previously established mixtures having the same materials sources and other similar properties. Producers supplying lightweight aggregate for structural lightweight concrete can usually supply data on mixture proportions for various applications. Their information is usually quite useful as a starting point in estimating trial mixtures for specific materials. Trial mixtures should be prepared in the absence of previously established data, with the same materials as will be used on the project. Trial mixtures should be made with at least three different cement contents and should have the desired degree of workability and adequate entrained air to ensure the durability and workability of the concrete for the intended application.

One procedure for estimating concrete trial mixture proportions in the absence of satisfactory historical data is to use, develop, or obtain from a lightweight aggregate producer a graph like Fig. 3.2.

This graph was developed by batching several mixtures of varying cement contents, similar air contents, (4 to 6%), and a constant slump of 5 ± 1 in. (125 ± 25 mm), then plotting the volumes of dry loose uncombined materials (3/4 in. to No. 4 [19 to 5 mm] lightweight aggregate and No. 4 to 0 [5 to 0 mm] natural concrete sand) for those mixtures having good workability and proper yield. This method is similar to the one used to develop the original coarse aggregate factor values used in conjunction with the fineness modulus to estimate normalweight concrete mixtures.

The graph was also developed to minimize or eliminate the need for "extra" trial mixtures to establish approximate proportions of materials needed to determine: proper yield, workability, combining losses, and strength. This enables the technologist to proceed directly with three trial mixtures, or perhaps one mixture, for verification of specific materials for specific mixture design criteria. After trial mixture proportions selected with this method are tested, it will become

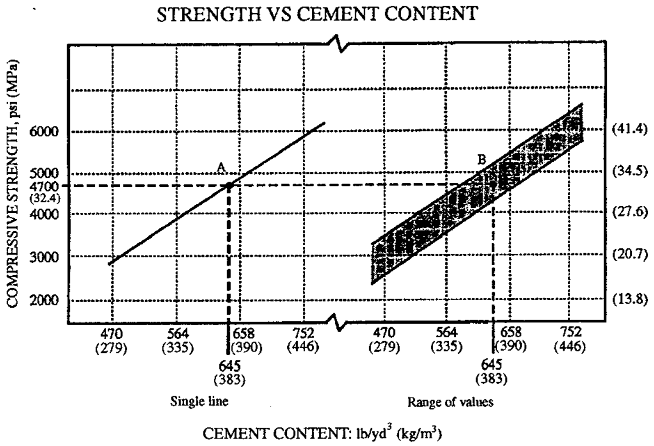


Fig. 3.3—Strength versus cement content.

apparent that the line B-B in Fig. 3.2 can move in the direction of either line A-A or line C-C at the same slope. The movement of the line B-B in either direction is caused by changes in the aggregate grading, changing from one aggregate size to another, adjustments for texture or workability, or for pump or conventional placement, (that is, if a change was made to go from ASTM C 330 3/4 in. to No. 4 [19 to 5 mm] to 3/8 in. to No. 8 [9.5 to 2.38 mm], the Line B-B would shift downward toward Line C-C due to a reduction in voids, causing a reduction in combining loss). The slope of Line B-B (and therefore Lines A-A and C-C) relates the volume of aggregate to the volume of cement. For example, decreasing the cement content from 658 to 564 lb/yd^3 (390 to 355 kg/m^3) on Fig. 3.2, Line B-B, increases the design volume from 30 to 30.5 ft^3/yd^3 (1.11 to 1.13 m^3/m^3).

An additional advantage of this development procedure is that when the test specimens from the trial mixtures are tested, a strength-versus-cement content curve (or range) for historical information can be plotted similar to Fig. 3.3.

Sample calculations (inch-pounds)

From the lightweight aggregate manufacturer:

- Oven-dry loose unit weight is 43 lb/ft^3, and the total water will be about 420 lb/yd^3.
- Forty-eight-hour laboratory soaked absorption is approximately 23%.
- Suggested coarse aggregate factor is 16.7 ft^3/yd^3.

From the sand supplier:

- Sand dry loose unit weight is approximately 100 lb/ft^3.

Step One: Estimate 1 yd^3 trial batch weights on an oven-dry basis.

- 645 lb cement from Fig. 3.3 (Point A)
- 718 lb 3/4-in. lightweight aggregate from background information: (16.7 ft^3/yd^3)(43 lb/ft^3) = 718 lb/yd^3
- 1350 lb concrete sand from Fig. 3.2: 30.2 ft^3/yd^3 – 16.7 ft^3/yd^3 = 13.50 ft^3/yd^3 and (13.50 ft^3) (100 lb/ft^3) = 1350 lb/yd^3
- 420 lb water from background information; can also be estimated from water Table 3.2 and adding the amount of water equal to the 48 h laboratory-soaked absorption.

3133 lb/yd^3(plastic) or 116.0 lb/ft^3 plastic

Step Two: Approximate air-dry weight.

(This is the plastic weight minus the oven-dry hydrated weight and corrected for the retained moisture.)

(645 lb cement) + [(0.20 water of hydration per ASTM C 567-91, Section 9.4) (645 lb cement)] is equal to the hydrated cement weight = 774 lb

plus the oven-dry lightweight aggregate weight = 718 lb
plus the oven-dry natural concrete sand weight = 1350 lb
equals the oven-dry weight 2842 lb/yd^3
or 105.3 lb/ft^3

The plastic unit weight minus the oven-dry hydrated weight is 116.0 lb/ft^3 – 105.3 lb/ft^3 = 10.7 lb/ft^3 and (10.7 lb/ft^3) (75% retained moisture factor per ASTM C 567-91, Section 9.7) = 8.0 lb/ft^3 and (8.0 lb/ft^3 retained moisture) + (105.3 lb/ft^3 oven-dry) = 113.3 lb/ft^3, which is the approximate air-dry weight.

Step Three: Convert oven-dry proportions to "as-is" proportions. Assume that the oven-dry concrete mixture design used previously is to be implemented in the field for a ready-mix concrete project and placed via truck chute. To minimize slump loss caused by absorption, the lightweight aggregate has been *sprinkled* for the past 48 h and the sprinkler has been turned off about 1 h before batch time to allow the aggregate's excess surface water to drain and the stockpile's overall moisture condition to stabilize.

The field technician's first activity is to obtain at least three representative loose unit weights of the wet or "as-is" (sprinkled or soaked) aggregate. The numerical values for the weights should have a narrow range (see ASTM C 330). A wide range could indicate variations in aggregate grading, moisture content, or careless loose unit weight measurement.

Loose unit field weights are

$$\frac{51\ \text{lb/ft}^3 + 52\ \text{lb/ft}^3 + 53\ \text{lb/ft}^3}{3} = 52\ \text{lb/ft}^3 \text{ ``as-is'' loose}$$

Multiply the "as-is" loose unit weight by the design coarse aggregate factor: (52 lb/ft^3) (16.7 ft^3/yd^3) = 868 lb/ft^3

From this information the field batch water, or added water, can be estimated

868 lb/yd^3 LWA ("as-is" loose)
– 718 lb/yd^3 LWA (dry loose)
150 lb/yd^3 Water IN, (absorbed) and ON, (adsorbed) the LWA

If the 48 h sprinkled field absorption is 18% then:

(718 lb/yd^3) (0.18 absorption) = 129 lb/yd^3 absorbed water and the free, surface, or adsorbed water is 150 lb/yd^3 – 129 lb/yd^3 = 21 lb/yd^3

Next, adjustments for sand surface moisture should be made; assume 3% surface moisture

$$1.000 + \frac{0.03}{1.000} + \frac{0.005}{1.000} = 1.035\text{, and}$$

(1350 lb/ft^3 oven-dry sand) (1.035 for the total moisture content) = 1397 lb/yd^3

The field batch water is

$420 lb/yd^3 - 150 lb/yd^3 = 270 lb/yd^3$ or

$420 lb/yd^3 - 129 lb/yd^3$ absorbed water $- 21 lb/yd^3$ surface water $= 270 lb/yd^3$, and

$270 lb/yd^3$ – sand moisture correction of $47 lb/yd^3 = 223 lb/yd^3$

This information provides the field mixture design as follows:

Field weights: 1 yd^3 – "as-is" basis
645 lb cement
870 lb 3/4-in. LWA ("as-is")
1397 lb sand (wet)
223 lb batch water
$3135 lb/yd^3$ or $116.1 lb/yd^3$ plastic

After batching, this mixture should be tested in the plastic state for yield, slump, and air content.

Appropriate corrections should be made if necessary to provide within tolerance concrete.

Mixtures must be adjusted in the field to maintain yield.

Sample calculations (metric units)

From the lightweight aggregate manufacturer:

- Oven-dry loose unit weight is 689 kg/m^3, and the total water will be about 249 kg/m^3.
- Forty-eight-hour laboratory soaked absorption is approximately 23%.
- Suggested coarse aggregate factor is 0.618 m^3/m^3.

From the sand supplier:

- Sand dry loose unit weight is approximately 100 lb/ft^3.

Step One: Estimate 1 yd^3 trial batch weights on an oven-dry basis.

- 338 kg cement from Fig. 3.3 (Point A)
- 426 kg 19 mm lightweight aggregate from background information: $(0.618)(689 kg/m^3) = 426 kg/m^3$
- 801 kg concrete sand from Fig. 3.2: $(1.118 - 0.618)1602 kg/m^3 = 801 kg/m^3$
- 249 kg water from background information; can also be estimated from water Table 3.2 and adding the amount of water equal to the 48 h laboratory-soaked absorption.

$1859 kg/m^3$(plastic)

Step Two: Approximate air-dry weight.

(This is the plastic weight minus the oven-dry hydrated weight and corrected for the retained moisture.)

(386 kg cement) + [(0.20 water of hydration per ASTM C 567, Section 9.4)(386 kg cement)] is equal to the hydrated cement weight = 463 kg

plus the oven-dry lightweight aggregate weight =	463 kg
plus the oven-dry natural concrete sand weight =	802 kg
equals the oven-dry weight	1690 kg/m^3

The plastic unit weight minus the oven-dry hydrated weight is $1859 kg/m^3 - 1690 kg/m^3 = 169 kg/m^3$ and $(169 kg/m^3)$ (75% retained moisture factor per ASTM C 567, Section 9.7) = 127 kg/m^3 and (127 kg/m^3 retained moisture) + (1690 kg/m^3 oven-dry) = 1817 kg/m^3, which is the approximate air-dry weight.

Step Three: Convert oven-dry proportions to "as-is" proportions. Assume that the oven-dry concrete mixture design used previously is to be implemented in the field for a ready-mix concrete project and placed via truck chute. To minimize slump loss caused by absorption, the lightweight aggregate has been sprinkled for the past 48 h and the sprinkler has been turned off about 1 h before batch time to allow the aggregate's excess surface water to drain and the stockpile's overall moisture condition to stabilize.

The field technician's first activity is to obtain at least three representative loose unit weights of the wet or "as-is" (sprinkled or soaked) aggregate. The numerical values for the weights should have a narrow range (see ASTM C 330). A wide range could indicate variations in aggregate grading, moisture content, or careless loose unit weight measurement.

Loose unit field weights are

$$\frac{817 kg/m^3 + 833 kg/m^3 + 849 kg/m^3}{3} = 833 kg/m^3$$

"as-is" loose

Multiply the "as-is" loose unit weight by the design coarse aggregate factor: $(833 kg/m^3)(0.618 m^3/m^3) = 515 kg/m^3$

From this information the field batch water, or added water, can be estimated

515 kg/m^3	LWA ("as-is" loose)
– 426 kg/m^3	LWA (dry loose)
89 kg/m^3	Water IN, (absorbed) and ON, (adsorbed) the LWA

If the 48 h sprinkled field absorption is 18% then:

$(426 kg/m^3)$ (0.18 absorption) = 77 kg/m^3 absorbed water and the free, surface, or adsorbed water is $89 kg/m^3 - 77 kg/m^3 = 12 kg/m^3$

Next, adjustments for sand surface moisture should be made; assume 3% surface moisture

$$1.000 + \frac{0.03}{1.000} + \frac{0.005}{1.000} = 1.035\text{, and}$$

(801 kg/m^3 oven-dry sand)(1.035 for the total moisture content) = 829 kg/m^3

The field batch water is

$249 kg/m^3 - 89 kg/m^3 = 160 kg/m^3$ or

$249 kg/m^3 - 77 kg/m^3$ absorbed water $- 12 kg/m^3$ surface water $= 160 kg/m^3$, and

$160 kg/m^3$ – sand moisture correction of $28 kg/m^3 = 132 kg/m^3$

This information provides the field mixture design as follows:

Field weights: 1 m^3 – "as-is" basis
383 kg cement
515 kg 19 mm LWA ("as-is")
829 kg sand (wet)
132 kg batch water
1859 kg/m^3

After batching, this mixture should be tested in the plastic state for yield, slump, and air content.

Appropriate corrections should be made if necessary to provide within tolerance concrete.

Mixtures must be adjusted in the field to maintain yield.

CHAPTER 4—ADJUSTING MIXTURE PROPORTIONS

4.1—General

In proportioning normalweight concrete (ACI 211.1), the volume displaced or absolute volume occupied by each ingredient of the mixture (except entrained air) is calculated as the weight in lb (kg) of that ingredient divided by the product of 62.4 lb/ft^3 (1000 kg/m^3) and the specific gravity of that ingredient. Total volume of the mixture is the sum of the displaced or absolute volume of each ingredient thus calculated plus the volume of entrained and entrapped air determined by direct test. Calculation of the absolute volume of cement, based on dry weight of cement in the mixture, and calculation of air as the percentage of air determined by test multiplied by total volume, are the same for both lightweight concrete and normalweight concrete mixtures. The volume displaced by normalweight aggregates is calculated on the basis of the SSD weights of aggregates and the bulk specific gravities (SSD basis) as determined by ASTM C 127 and C 128. Volume displaced by water in normalweight concrete mixtures is therefore on the basis of "net" mixture water. Net mixture water is the water added at the mixer plus any surface water on the aggregates or minus any water absorbed by aggregates that are less than saturated.

The effective volume displaced by lightweight aggregates in concrete is calculated on the basis of weights of aggregates with a known moisture content as used, and on a specific gravity factor that is a function of the moisture content of the aggregate, and that is determined in Appendix A. Effective displaced volume of water in lightweight concrete mixtures is then based on the actual water added at the mixer. The relationship of weight to displaced volume for lightweight aggregates, as determined by the method of Appendix A, is termed a specific gravity factor. It is the ratio of the weight of the aggregates as introduced into the mixer, to the effective volume displaced by the aggregates. The weight of aggregates as introduced into the mixer includes any moisture absorbed in the aggregate and any free water on the aggregates.

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

4.2.1 Specific gravity factors generally vary with moisture content of aggregates. For each aggregate type and gradation, therefore, it is necessary to determine by the method of Appendix A the specific gravity factors over the full range of moisture conditions likely to be encountered in service. The variation is usually approximately linear in the lower range of moisture contents, but may digress from linearity at higher moisture contents. Therefore, the full curve should be established and extrapolation should be avoided. (See example curve in Fig. A.1 of Appendix A.)

4.2.2 Indicated specific gravity factors of coarse aggregates generally increase slightly with time of immersion in the pycnometer because of continued aggregate absorption. The rate of increase becomes smaller with longer immersion periods. The increase with time of immersion generally is greatest when the aggregate is tested in the dry condition and will become smaller as the moisture content of the aggregate before immersion increases. Pycnometer specific gravity factors obtained after 10 min immersion of aggregates should normally be suitable for mixture proportioning and adjustment procedures. Where some loss of slump is anticipated in long-haul ready-mixed concrete operations due to continued absorption of water into the aggregates, additional water is required to offset the resultant loss of yield. The mixture proportions should be determined on the basis of the 10 min specific gravity factor. A calculation of the lower effective displaced volumes of aggregates, however, based on the longer time specific gravity factor, should provide guidance to the anticipated loss of yield to be compensated for by additional water.

4.2.3 *Trial batch adjustments*—Mixture proportions calculated by the weight method should be checked by means of trial batches prepared and tested in accordance with ASTM C 192 or by full-sized batches. Only sufficient water should be used to produce the required slump regardless of the amount assumed in selecting the trial proportions. The concrete should be checked for unit weight and yield (ASTM C 138) and for air content (ASTM C 173). It should also be carefully observed for proper workability, freedom from segregation, and finishing properties. Appropriate adjustments should be made in the proportions for subsequent batches in accordance with the following procedure.

4.2.3.1 Reestimate the required mixing water per unit volume of concrete by multiplying the net mixing water per unit volume of concrete by the net mixing water content of the trial batch by 27 for a yd^3 (for inch-pound units only) and dividing the product by the yield of the trial batch in ft^3 (m^3). If the slump of the trial batch is not correct, increase or decrease the reestimated amount of water by 10 lb/yd^3 (5.9 m^3) for each required increase or decrease of 1 in. (25 mm) in slump.

4.2.3.2 If the desired air content (for air-entrained concrete) was not achieved, re-estimate the admixture content and decrease or increase the mixing water content stated in Step 3 of Section 3.2.2 by 5 lb/yd^3 (3.0 kg/m^3)for each 1% by which the air content is to be increased from that of the previous trial batch.

4.2.3.3 Reestimate the weight per unit volume of fresh concrete by multiplying the unit weight in lb/ft^3 (kg/m^3) of the trial batch by 27 (for inch-pound units only) and decreasing or increasing the result by the anticipated percentage increase or decrease in air content of the adjusted batch from the first trial batch.

4.2.3.4 Calculate new batch weights starting with Step 5 of Section 3.2.2, modifying the volume of coarse aggregate from Table 3.5, if necessary, to provide proper workability.

4.3—Method 2: Volumetric method (damp, loose volume)

4.3.1 Trial batch adjustments to mixtures designed by the damp, loose volume method should be checked by means of trial batches prepared and tested in accordance with ASTM C 192 or full-sized batches. Only sufficient water should be used to produce the desired slump regardless of the amount assumed in the trial proportions. The concrete should be checked for unit weight and yield (ASTM C 138) and for air content (ASTM C 173). It should be carefully observed for workability and finishing properties. Appropriate adjustments should be made.

4.4—Adjustment procedures

4.4.1 Both field mixtures and laboratory mixtures may require adjustment from time to time to compensate for some unintentional change in the characteristics of the concrete or to make a planned change in the characteristics. Adjustment may be required, for example, to compensate for a change in moisture content of the aggregates; it may be desired to proportion a mixture for greater or lesser cement content, or use of chemical admixtures; or other cementitious material, or perhaps, a change in slump or air content may be necessary. These adjustments can be made with considerable confidence based on either a first trial mixture or on previous field or laboratory mixtures with similar aggregates. Small mixtures of perhaps 1.0 to 2.0 ft^3 (0.028 or 0.056 m^3) total volume that are made and adjusted in the laboratory will require some further adjustments when extrapolated to field mixtures of possibly 100 to 300 times the laboratory volume. Tests of fresh unit weight, air content, and slump should be made on the initial field mixtures, and any necessary adjustments should be made on the field batch quantities.

4.4.2 *Guides for adjusting mixtures*—When it is desirable to change the amount of cement, the volume of air, or the percentage of fine aggregate in a mixture, or when it is desirable to change the slump of the concrete, it is necessary to offset such changes with adjustments in one or more other factors if yield and other characteristics of the concrete are to remain constant. The following paragraphs indicate some of the compensating adjustments, show the usual direction of adjustments necessary, and give a rough approximation of the amount of the adjustments per yd^3 (m^3) of concrete. Note that the numerical values given are intended for guidance only, they are approximations, and more accurate values obtained by observation and experience with particular materials should be used whenever possible.

4.4.2.1 *Proportion of fine aggregate*—An increase in the percentage of fine to total aggregates generally requires an increase in water content. For each percent increase in fine aggregate, increase water by approximately 3 lb/yd^3 (1.8 kg/m^3). An increase in water content will require an increase in cement content to maintain strength. For each 3 lb/yd^3 (1.8 kg/m^3) increase in water, increase cement by approximately 1%. Coarse and fine aggregate weights should be adjusted as necessary to obtain desired proportions of each, and to maintain required total effective displaced volume.

4.4.2.2 *Air content*—An increase in air content will be accompanied by an increase in slump unless water is reduced to compensate. For each percent increase in air content, water should be decreased by approximately 5 lb/yd^3 (3.0 kg/m^3). An increase in air content may be accompanied by a decrease in strength unless compensated for by additional cement (see Section 2.4.3). Fine aggregate weight should be adjusted as necessary to maintain required total effective displaced volume.

4.4.2.3 *Slump*—An increase in slump may be obtained by increasing water content. For each desired 1 in. (25 mm) increase in slump, water should be increased approximately 10 lb/yd^3 (5.9 kg/m^3) when initial slump is about 3 in. (75 mm); it is somewhat less when initial slump is higher. Increase in water content will be accompanied by a decrease in strength unless compensated for by an increase in cement content. For each 10 lb/yd^3 (5.9 kg/m^3) increase in water, increase cement content approximately 3%. Adjustment should be made in fine aggregate weight as necessary to maintain required total effective displaced volume.

4.4.3 *Adjustment for changes in aggregate moisture condition*—Procedure to adjust for changes in moisture content of aggregates is as follows:

a. Maintain constant the weight of cement and the effective displaced volumes of cement and air.

b. Calculate new weights of both coarse and fine aggregates, using the appropriate value for total moisture content, so that oven-dry weights of both coarse and fine aggregates remain constant.

c. Calculate effective displaced volumes of both coarse and fine aggregates using weights of the aggregates in the appropriate moisture condition or the specific gravity factor corresponding to that moisture condition.

d. Calculate the required effective displaced volume of added water as the difference between the required 27 ft^3 (1 m^3) and the total of the effective displaced volumes of the cement, air, and coarse and fine aggregates.

e. Calculate required weight of added water as 62.4 lb/ft^3 (1000 kg/m^3) multiplied by the required effective displaced volume of added water determined in (d).

4.5—Controlling proportions in the field

Proportions that have been established for given conditions may require adjustment from time to time to maintain the planned proportions in the field. Knowledge that proportions are remaining essentially constant, or that they may vary beyond acceptable limits, can be obtained by conducting tests for fresh unit weight of concrete (ASTM C 138), air content (ASTM C 173), and slump (ASTM C 143). These tests should be made not only at such uniform frequency as may be specified (a given number of tests per stated quantity of concrete, per stated time period, or per stated section of structure), but should also be made when observation indicates some change in the ingredients of the concrete or in the physical characteristics of the concrete. These tests should be made, for example, when moisture contents of the aggregates may have changed appreciably, when the concrete shows change in slump or workability characteristics, or when there is an appreciable change in added water requirements.

A change in fresh unit weight of concrete, with batch weights and air content remaining constant, shows that the batch is overyielding (with lower unit weight) or underyielding (with higher unit weight) (Fig. 4.1). The overyielding batch will have lower than planned cement content, and the underyielding batch will have a higher than planned cement content.

A change in the aggregate specific gravity factor may be the result of:

a. A change in the moisture content of the aggregate; or

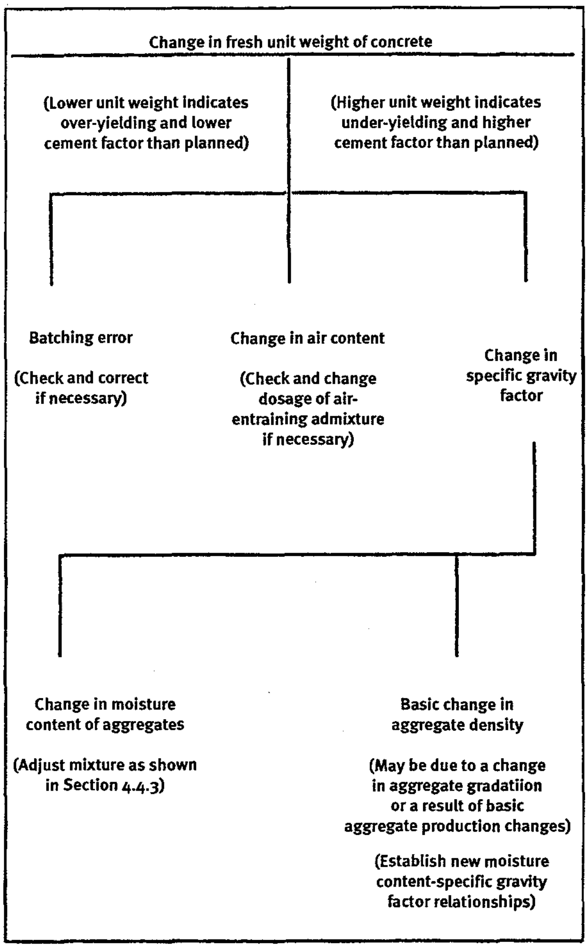


Fig. 4.1—Controlling proportions.

b. A basic change in aggregate density.

If a moisture test indicates moisture changes, the mixture should be adjusted, as shown in Section 4.4.3. If the basic aggregate density has changed, determination of new moisture content-specific gravity factor relationships are indicated (Aggregate density changes may be a result of changes in raw material, processing, or both). A change in slump may indicate:

a. A change in air content;

b. A change in moisture content of aggregate without corresponding change in batching; or

c. A change in aggregate gradation or density.

Each of these factors is also indicated by the fresh unit weight test.

Note: Controlling concrete mixtures in the field also requires recognizing possible changes due to variations in ambient temperature of ingredients, length of mixing and agitating time, and other causes. Discussion of such factors is beyond the scope of this standard.

Summary

The examples of the two methods of proportioning structural lightweight concrete mixtures are intended to provide guidance to the user. Each lightweight aggregate has its own particular characteristics that influence the mixture proportioning. Therefore, the user can only develop proficiency in proportioning and controlling structural lightweight concrete by practice. This proficiency is further increased with laboratory and field experience that can be gained from actual concrete production with each specific lightweight aggregate and selected mixture proportions.

CHAPTER 5—REFERENCES

5.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it desired to refer to the latest version.

American Concrete Institute (ACI)

201.2R	Guide to Durable Concrete
211.1	Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
212.1R	Admixtures for Concrete
212.2R	Guide for Use of Admixtures in Concrete
213R	Guide for Structural Lightweight-Aggregate Concrete
226.1R	Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete
226.3R	Use of Fly Ash in Concrete
301	Standard Specifications for Structural Concrete
302.1R	Guide for Concrete Floor and Slab Construction
318	Building Code Requirements for Structural Concrete
345	Standard Practice for Concrete Highway Bridge Deck Construction

ASTM International

C 29/C 29M	Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate
C 31/C 31M	Standard Practice for Making and Curing Concrete Test Specimens in the Field
C 33	Standard Specification for Concrete Aggregates
C 94/ C 94M	Standard Specification for Ready-Mixed Concrete
C 127	Standard Test Method for Density, Relative Density (Specific Gravity) and Absorption of Coarse Aggregate
C 128	Standard Test Method for Density, Relative Density (Specific Gravity) and Absorption of Fine Aggregate
C 138/ C 138M	Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
C 143/C 143M	Standard Test Method for Slump of Hydraulic Cement Concrete
C 150	Standard Specification for Portland Cement
C 173/C 173M	Standard Test Method for Air Content of Freshly Mixed Concrete by Volumetric Method
C 192/C 192M	Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

C 330	Standard Specification for Lightweight Aggregates for Structural Concrete
C 494/C 494M	Standard Specification for Chemical Admixtures for Concrete
C 566	Standard Test Method for Total Moisture Content of Aggregate by Drying
C 567	Standard Test Method for Determining Density of Structural Lightweight Concrete

These publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428

APPENDIX A—DETERMINATION OF SPECIFIC GRAVITY FACTORS OF STRUCTURALl LIGHTWEIGHT AGGREGATE

Methods presented herein describe procedures for determining the specific gravity factors of lightweight aggregates, either dry or moist.

Pycnometer method for fine and coarse lightweight aggregates:

a. A pycnometer consisting of a narrow-mouthed 2 qt (2 L) mason jar with a pycnometer top (Soiltest G-335, Humboldt H-3380, or equivalent).

b. A balance or scale having a capacity of at least 11 lb (5 kg) and a sensitivity of 0.035 oz. (1 g).

c. A water storage jar (about 5 gal. [20 L] capacity) for maintaining water at room temperature.

d. Isopropyl (rubbing) alcohol and a medicine dropper.

Calibration of pycnometer

The pycnometer is filled with water and agitated to remove any entrapped air and adding water to "top off" the jar. The filled pycnometer is dried and weighed and the weight (weight B in grams) is recorded. (A review of ASTM C 128 may be helpful regarding this method.)

Sampling procedure

Representative samples of about 2 to 3 ft^3 (0.057 to 0.085 m^3) of each size of aggregate should be obtained from the stockpile and put through a sample splitter or quartered until the correct size of the sample desired has been obtained. During this operation with damp aggregates, extreme care is necessary to prevent the aggregates from drying. The aggregate sample should occupy 1/2 to 2/3 the volume of the 2 qt (2 L) pycnometer.

Test procedure

Two representative samples should be obtained of each size of lightweight aggregate to be tested.

The first is weighed, placed in an oven at 221 to 230 °F (105 to 110 °C) and dried to constant weight. "Frying pan drying" to constant weight is an acceptable field expedient. The dry aggregate weight is recorded, and the aggregate moisture content (percentage of aggregate dry weight) is calculated.

The second aggregate sample is weighted (weight C in grams). The sample is then placed in the empty pycnometer and water is added until the jar is three-quarters full. The time of water addition should be noted.

The air entrapped between the aggregate particles is removed by rolling and shaking the jar. During agitation, the hole in the pycnometer top is covered with the operator's finger. The jar is then filled and agitated again to eliminate any additional entrapped air. If foam appears during the agitation and prevents the complete filling of the pycnometer with water at this stage, a minimum amount of isopropyl alcohol should be added with the medicine dropper to eliminate the foam. The water level in the pycnometer must be adjusted to full capacity and the exterior surfaces of the jar must be dried before weighing.

The pycnometer, thus filled with the sample and water, is weighed (weight A in grams) after 5, 10, and 30 min of sample immersion to obtain complete data, and the weights at these times are recorded after each "topping-off." Fig. A.1 shows a typical plot of such determinations. The variation is usually approximately linear in the lower range of moisture contents, but may digress from linearity at higher moisture contents. The full curve, therefore, should be established and extrapolation should be avoided.

Calculation

The pycnometer specific gravity factor S, after any particular immersion time, is calculated by the following formula.

$$S = \frac{C}{C + B - A}$$

where

A = weight of pycnometer charged with aggregate and then filled with water, g;
B = weight of pycnometer filled with water, g; and
C = weight of aggregate tested, moist or dry, g.

Buoyancy methods for coarse aggregates

If larger test samples of coarse aggregate than can be evaluated in the pycnometer are desired, coarse aggregate gravity factors may be determined by the wholly equivalent weight-in-air-and-water procedures described in ASTM C 127. The top of the container used for weighing the aggregates under water must be closed with a screen to prevent light particles from floating away from the sample.

Specific gravity factors by this method are calculated by the equation

$$\text{Specific gravity factor } S = \frac{C}{C - E}$$

where

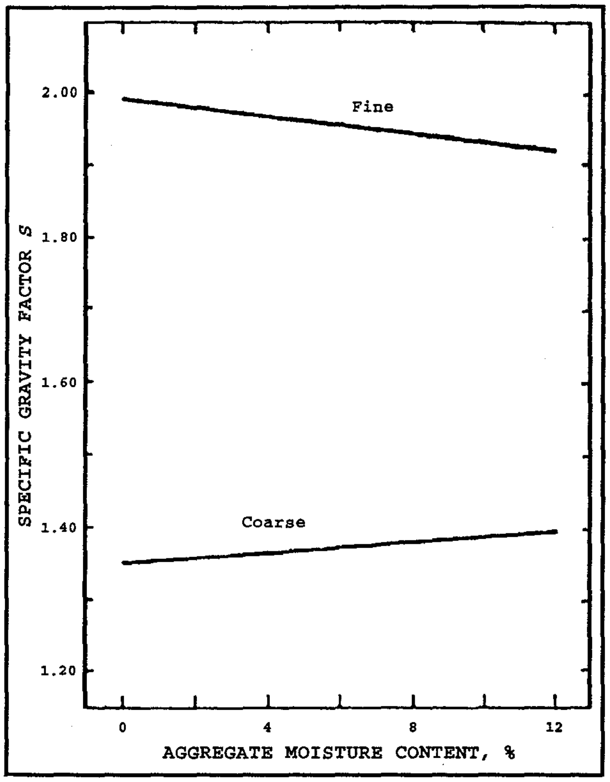


Fig. A.1—Example of relationship between pycnometer specific gravity factor and moisture content for lightweight aggregate.

C = same as above (the weight in air);
E = weight of coarse aggregate sample under water, g; and
S = specific gravity factor, equal (by the theory of the method) to the pycnometer specific gravity factor.

APPENDIX B—DETERMINATION OF STRUCTURAL LIGHTWEIGHT COARSE AGGREGATE ABSORPTION

The method presented hereafter describes a procedure for determining the absorption of lightweight coarse aggregate by spin-drying in a centrifuge to produce an SDD condition following 24 h of immersion in water.

Apparatus

a. A bench-top centrifuge with a speed control capable of spinning a 0.67 to 0.88 lb (300 to 400 g) sample of graded coarse aggregate at 500 rpm. A centrifuge similar to an International Model HN or a centrifugal extraction apparatus similar to a Soiltest Model AP 179-B are satisfactory.

b. A bowl or colander approximately 8-1/2 in. (216 mm) in diameter and 3-in. (75 mm) deep mounted on the axis of the centrifuge and fitted with a lid to prevent loss of the aggregate when spun. Centrifugal extractors are manufactured with such bowls; therefore, this requirement does not apply to them.

c. A balance having a capacity of at least 2.2 lb (1000 g) and a sensitivity of 0.0035 oz. (0.1 g).

Sampling procedure

Representative samples of about 44 to 66 lb (20 to 30 kg) of graded aggregate should be taken from the stockpile and reduced with a sample splitter or quartered until a 0.67 to 0.88 lb (300 to 400 g) sample is obtained. During this operation, definite precautions should be taken to prevent segregation of the coarser particles from those smaller in size. Two or more representative samples should be taken.

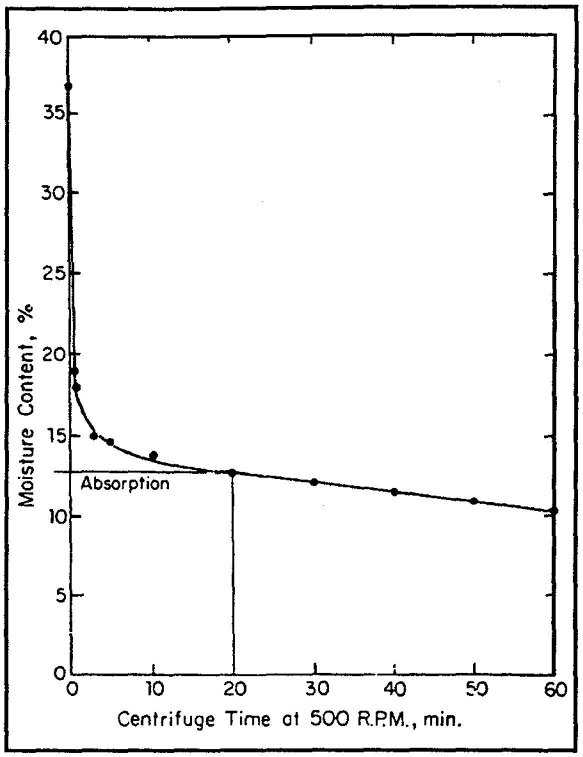


Fig. B.1—Typical relationship illustrating measurement of lightweight aggregate absorption.

Test procedure

Immerse the samples of graded, lightweight coarse aggregate for approximately 24 h in tap water at room temperature. After that period, decant the excess water and transfer the sample into the bowl or colander and secure the lid. Activate the centrifuge and spin the sample at 500 rpm for 20 min. Remove the sample and measure its SSD weight. Dry the sample to constant weight by any of the procedures described in ASTM C 566—electric or gas hot plate, electric heat lamps, or a ventilated oven capable of maintaining the temperature surrounding the sample at 221 to 239 °F (105 to 115 °C). Figure B.1 shows a typical plot of determining lightweight coarse aggregate absorption.

Calculation

After measuring the dry weight, the absorption of the lightweight coarse aggregate is calculated in the following manner

$$A, \% = 100\,(W - D)/D$$

where

W = saturated surface dry weight, g; and
D = dry weight, g.

A satisfactory test on two samples by the same technician should not differ by more than 0.67% in one test out of 20.

4B

Procedure for Determination of Density Factor of Structural Lightweight Aggregate

Procedure for Determination of Density Factors of Structural Lightweight Aggregate

Procedure for determining the density factors of lightweight aggregates containing absorbed water.

Pycnometer method for fine and coarse lightweight aggregates:

a. A pycnometer consisting of a narrow-mouthed 2-quart mason jar with a pycnometer top (Soil test G-335, Humboldt H-3380, or equivalent).
b. A balance or scale having a capacity of least 5 kg and a sensitivity of 1 g.
c. A water storage jar (about 5-gallon capacity) for maintaining water at room temperature.
d. Isopropyl (rubbing) alcohol and a medicine dropper.

Calibration of Pycnometer

The pycnometer is filled with water and agitated to remove any entrapped air. Water is added to "top off" the jar. The filled pycnometer is dried and weighed and the weight (weight *B* in grams) is recorded. (Regarding this method, a review of ASTM C 128 may be helpful).

Sampling Procedure

Representative samples of about 2 to 3 ft^3 (.06 to .09m^3) of each size aggregate should be obtained from the stockpile and put through a sample splitter or quartered until the correct size of the sample desired has been obtained. During this operation with damp aggregates, extreme care is necessary to prevent the aggregate from drying. The aggregate sample should occupy one-half to two-thirds the volume of the 1-quart pycnometer.

Test Procedure

Two representative samples should be obtained of each size of lightweight aggregate to be tested. The first is towel dried to remove surface (absorbed) water, weighed, placed in an oven at 105° C and dried to a constant weight. "Frying pan drying" to constant mass is an acceptable field expedient. The dry aggregate weight is recorded, and the aggregate moisture content (percentage of aggregate dry mass) is calculated.

The second aggregate sample is also towel dried, weighed (mass *C* in grams). The sample is then placed in the empty pycnometer and water is added until the jar is three-quarter full. The time of water addition should be noted.

The air entrapped between the aggregate particles is removed by rolling and shaking the jar. During agitation, the hole in the pycnometer tip is covered with the operator's finger. The jar is then filled and agitated again to eliminate any additional entrapped air. If foam appears during the agitation and prevents the complete filling of the pycnometer with water at this stage, a minimum amount of isopropyl alcohol should be added with a medicine dropper to eliminate the foam. The water level in the pycnometer must be adjusted to full capacity and the exterior surfaces of the jar must be dry before weighing.

The pycnometer, thus filled with the sample and water, is weighed (mass *A* in grams) after 5, 10, and 30 minutes of sample immersion to obtain complete date, and the weights at these times are recorded after each "topping off".

Calculation

The pycnometer relative density factor S, after any particular immersion time, is calculated by the following formula. In general the relative density and the absorbtion moisture content is reported after immersion for 24 hours.

$$S = C / (C + B - A)$$

Where:
A = mass of pycnometer charged with aggregate and then filled with water, *g*
B = mass of pycnometer filled with water, *g*
C = mass of moist aggregate tested, *g*

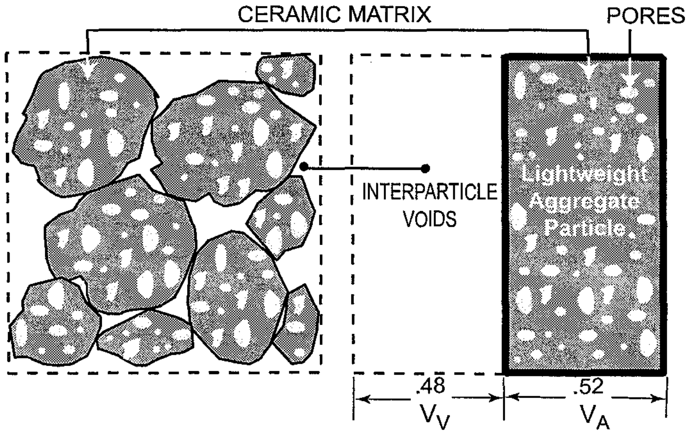
Relative Density Factor	Absorbed Moisture Percent by Dry Weight
1.34	0
1.50 @ 24 hours	12
1.61	20

Example of the measured relationship between pycnometer relative density and moisture content for lightweight aggregate.

Rationale:

Currently the only source of information on determining the relative density (specific gravity) factor for lightweight aggregate is ACI 211.2. This proposed appendix is a modified version of ACI 211.2. This information will be very useful to the users of this specification.

4C
ESCSI Schematic Volume Computation Sheets

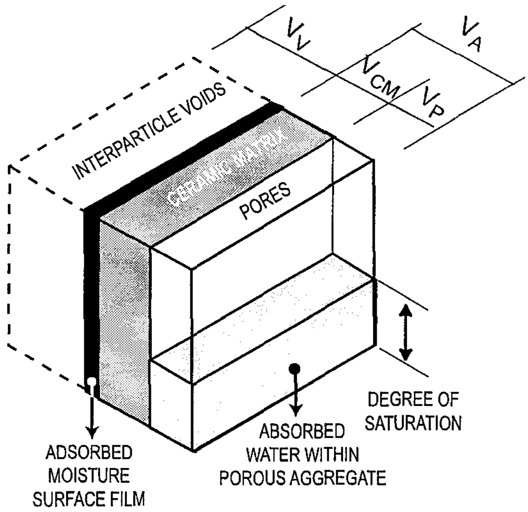


The following calculations are based on a hypothetical lightweight aggregate sample (illustrated above) that has a bulk loose dry density of 44.6 lb/ft³ (714 kg/m³) and a relative density (SSD pychnometer) of 1.50 after a 24-hour soak resulting in a moisture content of 8.5% by weight. The relative density of the ceramic matrix was measured to be 2.60.

$$RD_D \left[\text{Relative Density, Dry}\right] = \frac{RD_{24}}{(1 + M)} \left[\frac{\text{Pychnometer Relative Density after 24-Hour Soak}}{\text{Moisture Content by Weight after 24-hour Soak}}\right] = \underline{\qquad\qquad} =$$

$$V_A \left[\text{Fractional Part of Bulk Volume Occupied by Aggregate Particles}\right] = \frac{D_B}{RD_D} \left[\frac{\text{Measured Bulk Dry Loose Density}}{\text{Relative Density of Dry Particle}}\right] = \underline{\qquad} =$$

$$V_V \left[\text{Fractional Part of Bulk Volume Occupied by Voids between Particles}\right] = 1.0 - V_A =$$



Fractional Part of Lightweight Aggregate Paticle (V_A) occupied by the solid ceramic Matrix $= \dfrac{RD_D}{RD_{CM}}$ [Relative Dry Density / Relative Density of the Solid Ceramic Matrix] = ___ =

Fractional Part of Lightweight Aggregate Particle Occupied by Pores =

V_{CM} [Fractional Part of Bulk Volume occupied by the Solid Ceramic Matrix] = V_A x [Fractional Part of Aggregate Particle (V_A) occupied by the Solid Ceramic Matrix] =

∴ V_P [Fractional Part of Bulk Volume Occupied by Pores in Aggregate] =

V_M [Fractional Volume of Bulk Loose Sample Occupied by Moisture] = [Moisture Content by Weight] [Bulk Loose Dry Density of Sample] / 1000 [Density of Water] = ______ =

DS [Degree of Saturation of the Pores Occupied by Moisture] = ___ = *

* "Saturated Surface Day" after 24-hour submersion for this illustrative sample represents water filling only __ % of the available pore space.

4D

Supporting References Contained in 4.10 and 4.11 of this Chapter

Polymer Modified Lightweight Concrete

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