concrete INFORMATION
PCA

Structural Lightweight Concrete

Structural lightweight concrete is defined as concrete with a 28-day compressive strength in excess of 2,500 psi and an air-dry unit weight of 115 lb. per cubic foot or less. Structural lightweight is not the same as very lightweight concrete, which has a unit weight range of 15 to 90 lb. per cubic foot, a compressive strength seldom in excess of 1,000 psi, and is used primarily for insulating purposes.*

Structural lightweight concrete became possible in 1917 when Stephen J. Hayde discovered a way to produce expanded shale lightweight aggregate. He found that certain types of shale, clay, and slate, when exposed to high temperatures in a rotary kiln, expand and produce a sound, hard, lightweight aggregate.

Structural lightweight aggregates usually are classified according to production process because the various processes produce aggregates with somewhat different physical properties. Shale, clay, and slate are expanded in the rotary kiln or on a sintering grate. Blast-furnace slag is expanded by treating it with water while in a molten state. Sintered fly ash is produced by pelletizing fly ash and burning on a sintering grate.

PRODUCTION PROCESSES

Rotary Kiln

Shales and slates are crushed and screened before feeding into the upper end of an inclined rotary kiln, whereas clay is usually extruded or pelletized before burning. The material travels slowly to the hot zone where the temperature of the material reaches 1,800 to 2,200 deg.F. At these temperatures the material is in a plastic state, and gases released within the material expand it to form a lightweight cellular structure. Following expansion, the material is discharged and cooled at a controlled rate. In some operations the material then is crushed, screened, and stockpiled. It generally is stocked in three sizes: fine, smaller than No. 4 (3/16 in.); medium coarse, 3/8 in. to No. 8 (3/32 in.); and structural coarse, 3/4 in. to No. 4. The crushed product tends to be sharp or angular in shape, with a porous surface texture.

A variation of this method produces expanded shale aggregates with relatively smooth surfaces, referred to as "presized" or "coated" aggregates. Suitable raw material is crushed and screened into separate sizes or pelletized by extrusion. Only one size is fed into the kiln and expanded at a time. The material then is cooled and stored. Crushing these aggregates later usually is unnecessary as various sizes are combined to produce the required gradation.

Sintering

Suitable raw material is crushed and screened. It then is mixed with a small amount of fuel, such as finely ground coal or coke, and spread evenly over a traveling grate. The grate passes under an ignition hood where the fuel is ignited. The fuel continues to burn as the grate moves over blowers. As the material becomes plastic at these high temperatures, gases forming within the mass are entrapped, creating a cellular structure. The clinker formed is allowed to cool; it then is crushed and screened for use. The crushed particles generally are sharp and angular in shape, with a porous surface texture.

In a variation of this process, clay or pulverized shale is mixed with finely ground fuel and moisture; or fly ash, which usually contains sufficient carbon for fuel, is mixed with moisture. The material then is pelletized or extruded, and sintered. The finished product tends to be round or cylindrical in shape.

Water Treatment

Expanded slag is produced by applying controlled amounts of water to molten blast-furnace slag. This is done either by the machine process, in which the molten slag is agitated in a machine with a controlled amount of water, or by the water jet process, in which jets of water under high pressure are forced into the molten mass. In new processes now in use, the slag may be expanded by steam generated when a thin layer of molten material is poured on a moist porous base, or expanded and pelletized by throwing the molten slag with a limited amount of water through the air from a rapidly rotating ribbed drum. The pelletizing process results in spherical-shaped particles of coarse aggregate, with some

*See *Special Types of Concrete,* IS183T, Portland Cement Association.

crushing required to produce the finer sizes. The other expanded slags are also crushed and screened to the required aggregate sizes.

PROPERTIES OF LIGHTWEIGHT AGGREGATES

In general, those aggregate characteristics that influence properties of normal-weight concrete also influence properties of structural lightweight concrete. For lightweight aggregates, more consideration is given to such factors as the bulk unit weight, absorption, and particle shape, size, and surface texture. These factors influence the strength, durability, workability, finishability, control, and economy of structural lightweight concrete.

Requirements for lightweight aggregates for use in structural concrete are outlined in ASTM C330, Specification for Lightweight Aggregates for Structural Concrete. Although both natural and processed aggregates are included in this specification, the following discussion is limited to the types produced by rotary kiln, sintering, or water treatment processes.

Unit Weight

Lightweight aggregates have unit weights significantly lower than normal-weight aggregates. They range from 35 to 70 lb. per cubic foot, depending on the type of aggregate and its specific gravity, gradation, and particle shape. The unit weight of normal-weight aggregates varies from 90 to 110 lb. per cubic foot. The unit weights of rounded and angular aggregates with the same specific gravity may differ considerably.

ASTM C330 limits the dry, loose unit weight of lightweight aggregate for structural concrete to a maximum of 70 lb. per cubic foot for fine aggregate, 55 lb. per cubic foot for coarse aggregate, and 65 lb. per cubic foot for combined fine and coarse aggregate. These low unit weights account for the low unit weight of structural lightweight concrete.

Variations in the unit weight of a lightweight aggregate from a single source may affect the unit weight and strength of the concrete. Successive shipments of the aggregate should not differ by more than 10 percent from that of the original sample submitted for acceptance.

Absorption

Normal-weight aggregates usually absorb 1 to 2 percent water by weight of dry aggregate. They usually contain some interior moisture at the time of batching and absorb very little additional water during the mixing operation. The amount of mixing water required can be adjusted readily to compensate for absorption in normal-weight concrete.

In contrast, lightweight aggregates may absorb 5 to 20 percent water by weight of dry material, depending on the pore structure of the aggregate, based on a 24-hour absorption test. This can amount to as much as 250 lb. of water per cubic yard of concrete if total absorption is reached. However, total absorption normally does not occur during mixing and before placement. During mixing, allowance should be made for the aggregates' water demand so that the mixture does not stiffen and become unworkable during the interval between mixing and placement. Prewetted *but not saturated* aggregates are generally used to control the uniformity of lightweight mixtures. The uniformity of the concrete depends on the uniformity of the moisture content of the aggregates. Prewetting, usually at the aggregate supplier's plant, should be done at least 24 hours before mixing to allow time for moisture to distribute itself uniformly throughout the aggregate. During outdoor storage in stock piles, the moisture content will rarely, if ever, exceed two-thirds of the 24-hour absorption. Uniformity of absorption is more important than the amount of absorption in batching lightweight aggregate concrete.

Whenever possible, prewetting, batching, and mixing should be done in accordance with the lightweight aggregate producer's recommendations.

Particle Shape, Surface Texture, and Size

The shape, surface texture, and size of lightweight aggregate particles can influence the cost, workability, finishability, and density of the concrete. The maximum size of coarse aggregate seldom exceeds ¾ in. Most aggregates used for structural lightweight concrete tend toward cubical or rounded shapes. However, some lightweight aggregates are angular and have rough-textured surfaces. Aggregates with these characteristics require a greater percentage of fines to provide additional mortar for proper workability.

Gradation

Gradation of lightweight aggregates should conform to the requirements of ASTM C330. Well-graded aggregates have a minimum void content and require a minimum of cement paste to fill the voids.

Bulk Specific Gravity

Bulk specific gravity for lightweight aggregates is generally between 1.0 and 2.4. The bulk specific gravity for any particular aggregate will usually increase as the maximum particle size decreases. However, with present ASTM test methods, it may be difficult to determine accurately the bulk specific gravity of many lightweight aggregates. The mix design method for structural lightweight concrete does not utilize the bulk specific gravity, but is based on an approach involving the concept of "specific gravity factors," which takes into account the actual moisture condition of the aggregate at the time of mixing.

PLASTIC STATE OF LIGHTWEIGHT CONCRETE

Unit Weight

Unit weight of structural lightweight concrete in the plastic state may range from 95 to 120 lb. per cubic foot. Variations in unit weight are due to differences in composition, absorption, air content, natural sand content, and bulk specific gravity of the aggregates. Concrete made with dry lightweight aggregates will have lower fresh unit weight than concrete made with initially damp aggregates, but weights at later ages after normal drying tend to equalize.

Workability and Finishability

Lightweight concrete mixtures can be proportioned to have the same workability, finishability, and general appearance as a properly proportioned normal-weight concrete mixture. Sufficient cement paste must be present to coat each particle, and coarse aggregate particles should not separate from the mortar. Enough fine aggregate is needed to keep the fresh concrete cohesive. If aggregate is deficient in minus No. 30 sieve material, finishability may be improved by using a portion of natural sand, by increasing cement content, or by using satisfactory mineral fines. Since entrained air improves the workability of lightweight concrete, it should be used regardless of exposure.

Slump

Due to lighter aggregate weight, lightweight concrete does not slump as much as normal-weight concrete with the same workability. Air-entrained lightweight concrete with a slump of 2 to 3 in. can be placed under conditions that would require a slump of 3 to 5 in. for normal-weight concrete. It is seldom necessary to exceed slumps of 4 in. for normal placement of lightweight concrete. With higher slumps, the large aggregate particles tend to float to the top, making finishing difficult.

Entrained Air

Entrained air ensures resistance to freezing and thawing cycles and de-icer applications. It also improves workability, reduces the amount of bleeding and segregation, and may compensate for minor grading deficiencies in the aggregates. Thus entrained air is recommended in all lightweight concrete, whether or not freeze-thaw resistance is a factor.

The amount of entrained air in structural lightweight concrete should be sufficient to provide good workability of the plastic concrete and adequate freeze-thaw resistance of the hardened concrete. Air content is generally between 4½ and 9 percent, depending on maximum size of aggregate.

Vibration

Vibration can be used effectively to consolidate either lightweight or normal-weight concrete. Frequencies in excess of 7,000 vpm, about the same as those commonly used for normal-weight concrete, are recommended. The length of time for proper consolidation varies, depending on the mix characteristics. Excessive vibration causes segregation by forcing large aggregate particles to the surface.

Internal vibration is recommended for all slabs thicker than 8 in. and for thinner slabs that contain reinforcing steel or conduit. The vibrator head should be completely immersed during vibration; for thick slabs it will be possible to insert the vibrator vertically, while for thinner slabs it should be dragged through the concrete at an angle or even horizontally, and at a constant velocity.

Placing, Finishing, and Curing

Lightweight concrete is generally easier to handle and place than normal-weight concrete. A slump of 2 to 4 in. produces best results in finishing lightweight concrete. Greater slumps may cause segregation, delay finishing operations, and result in rough, uneven surfaces.

On flat surfaces, a high-frequency vibrating screed is effective for finishing. Finishing operations should be started earlier than for comparable normal-weight concrete, but finishing *too* early may be harmful. A minimum amount of floating and troweling should be done; aluminum or magnesium finishing tools are preferred.

The same curing practices should be used for lightweight concrete as for normal-weight concrete.

HARDENED STATE OF LIGHTWEIGHT CONCRETE

Compressive Strength

Lightweight concrete with 28-day compressive strengths of 3,000 to 5,000 psi generally can be produced with cement contents of 400 to 750 lb. per cubic yard, depending on the particular lightweight aggregate being used. Certain lightweight aggregates can be used to make concretes with strengths in excess of 7,000 psi, with cement contents up to 940 lb. per cubic yard. The rate of strength development for lightweight concrete is approximately the same as for normal-weight concrete.

Sometimes concretes made with certain types of lightweight aggregates show a strength ceiling beyond which an increase in cement will produce no noticeable increase in strength. Strength ceiling is mainly influenced by the coarse aggregate, and may be increased by reducing the maximum size of aggregate.

Tensile and Flexural Strength

Moist-cured specimens of lightweight and normal-weight concretes of equal compressive strength have approximately equal tensile and flexural strengths.

A convenient relative measure of the tensile strength is the splitting tensile strength determined by ASTM C496, Method of Test for Splitting Tensile Strength of Cylindrical Concrete Specimens. The splitting tensile strength of air-dried lightweight concrete generally is less than that of moist-cured lightweight concrete and varies from about 70 to 100 percent of that of normal-weight concrete of equal compressive strength. Replacement of lightweight fines by natural sand usually increases tensile strength. The results of splitting tensile strength tests on air-dried lightweight concrete may be used as a reliable measure of the unit shear capacity of lightweight concrete beams and slabs.

Flexural strength is determined by ASTM C78, Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). Most authorities do not consider the modulus of rupture of lightweight concrete undergoing drying a reliable measure of its flexural strength because of the sensitivity of the test to the moisture condition of the specimen.

Modulus of Elasticity

Structural lightweight concrete has a modulus of elasticity between 1,400,000 and 3,000,000 psi, depending on the compressive strength, type of lightweight aggregate, and sand content. Normal-weight sand often is used with lightweight aggregate to increase the modulus of elasticity. Generally, the modulus of elasticity of lightweight concrete is 20 to 50 percent lower than that of normal-weight concrete of equal strength.

An approximate relationship that can be used to estimate the modulus of elasticity of structural lightweight concrete, E_c, in pounds per square inch, is

$$E_c = Cw^{1.5}\sqrt{f'_c} \text{ psi}$$

in which w is the air-dry unit weight of the concrete in pounds per cubic foot, f'_c is the compressive strength in pounds per square inch as determined from 6x12-in. cylinders, and C is a factor dependent upon the value of f'_c. Values of C corresponding to different values of f'_c are given in Fig. 1. This empirical formula is reasonably reliable for structural lightweight concretes with compressive strengths of 2,500 to 7,000 psi. For important work where the modulus of elasticity is a critical factor, it should be determined by tests of the concrete in question.

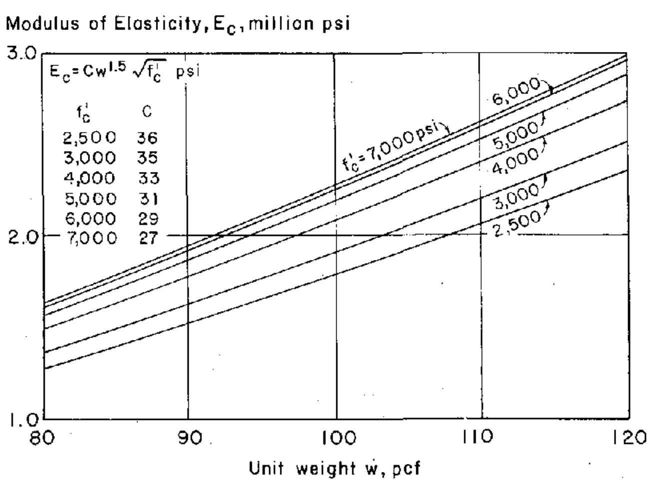

Fig. 1. Modulus of elasticity as a function of strength and air-dry unit weight of concrete.

Poisson's Ratio

Poisson's ratio is approximately the same for lightweight and normal-weight concretes. This value is generally between 0.15 and 0.25, depending upon the aggregate, moisture condition, and age of the concrete. A value of 0.2 is usually assumed for design purposes.

Bond to Reinforcing Steel

Strength of bond between concrete and deformed steel reinforcement is principally a function of the compressive strength of concrete or of its splitting tensile strength. Bond strength tests of some lightweight concretes yield bond strength values ranging from equal to 20 percent less than those of normal-weight concrete of equal compressive strength. ACI 318, Building Code Requirements for Reinforced Concrete, provides allowable design relationships amongst hardened concrete properties.

Drying Shrinkage

Drying shrinkage of lightweight concrete made and cured at normal temperatures ranges from about slightly less to 30 percent more than that of some normal-weight concretes. High-strength lightweight concrete (7,000 to 9,000 psi) has about the same shrinkage as comparable normal-weight concrete. Atmospheric steam-cured lightweight concrete has a lower drying shrinkage than normally cured lightweight concrete. Drying shrinkage of concretes made with some lightweight aggregates may be reduced by partial or full replacement of lightweight fines with a good grade of natural sand.

Creep

Creep of lightweight concrete ranges from about the same to 50 percent more than that of some normal-weight concretes. Creep is dependent upon magnitude of stress, strength of concrete, age at loading, time after loading, method of curing, and moisture condition of the concrete. Higher-strength lightweight concretes show 20 to 40 percent less creep than lower-strength lightweight concretes when loaded at the same age. Partial or full replacement of lightweight fines with natural sand fines may effectively reduce creep. Creep of atmospheric steam-cured lightweight concrete is about 25 to 40 percent less than that of moist-cured lightweight concrete. When precise knowledge of creep is required and data are not available, tests should be performed on the concrete in question.

Freeze-Thaw Resistance

The resistance of lightweight concrete to the action of freezing and thawing is dependent upon the same factors that affect freeze-thaw resistance of normal-weight concrete—entrained air, cement content, total water content, and moisture condition of the aggregate.

Use of intentionally entrained air increases the freeze-thaw resistance of concrete made with lightweight aggregates, especially if the aggregates are in a soaked condition at the time of mixing. Resistance to freezing and thawing of many air-entrained lightweight concretes is equal to or greater than that of many air-entrained normal-weight concretes. The amount of intentionally entrained air required for adequate durability of lightweight concrete is about the same as that required for normal-weight concrete.

The effect of cement content and total water content on durability of lightweight concrete is approximately the same as for normal-weight concrete—increasing the cement content and decreasing the total water content improve durability.

Structural lightweight concrete to be subjected to a severe environment involving freezing and thawing should have a specified compressive strength of about 3,750 psi and should contain an adequate amount of entrained air. Tests have indicated that the freeze-thaw resistance of structural lightweight concrete of compressive strengths less than 5,000 psi may be increased by partial or full replacement of fine aggregates with normal-weight sand.

Moisture condition of lightweight aggregates at the time of mixing has a significant effect on freeze-thaw resistance of concrete. Non-air-entrained concrete made with air-dried aggregates usually is more resistant to freezing and thawing than concrete made with soaked aggregates. Vacuum-treated lightweight aggregates, when used in concrete subject to a freezing environment, must be allowed an extended air-drying period prior to freezing weather. The influence of moisture condition of aggregate is not as pronounced for air-entrained concretes.

To evaluate freeze-thaw resistance of lightweight aggregates, laboratory freeze-thaw tests of concrete should be used, supplemented by field performance records. This is the same procedure as that generally used for evaluating normal-weight aggregates.

Resistance to De-Icer Scaling

Concrete made with lightweight aggregates can be made resistant to the effects of de-icer chemicals by the use of entrained air, low water-cement ratio, and adequate curing followed by several weeks of air drying prior to application of de-icers.

Thermal Characteristics

Thermal expansion. The coefficient of thermal expansion for structural lightweight concrete varies from 3.6 to 6 $\times 10^{-6}$ in./in./F., depending on the aggregate type and amount of natural sand. The ranges for normal-weight concretes are 3.5 to 7 $\times 10^{-6}$ in./in./F., depending upon the mineralogical type of aggregate (siliceous or calcareous).

Thermal conductivity. Since thermal conductivity varies inversely with unit weight, lightweight concrete has better thermal insulation properties than normal-weight concrete. The thermal conductivity, k, of structural lightweight concrete is usually between 2.3 to 4.3 Btu/hr. (sq.ft.) (F./in. thickness) for oven-dry concretes weighing 80 to 110 pcf. For normally dry lightweight concrete, corresponding values of k range from 2.7 to 5.2. The normally dry unit weight of concrete is attained after moisture equilibrium is achieved with normal ambient weather conditions. The corresponding k value for oven-dry normal-weight concrete is generally between 9 and 12 Btu/hr. (sq.ft.) (F./in. thickness), depending upon the unit weight of the concrete. The lower thermal conductivity of structural lightweight concrete contributes to a somewhat higher fire endurance than is obtained from normal-weight concrete.

Abrasion Resistance

The compressive strength of concrete is the most important single factor related to abrasion resistance. However, because of the porous structure of lightweight aggregates, the resistance of each thin wall or shell to load and/or impact may be low compared to the point load and impact resistance offered by concrete made with solid particles of similar composition. Therefore, the abrasion resistance of all-lightweight-aggregate concretes may not be sufficient for steel-wheeled or exceptionally heavy industrial traffic. As the severity of wear becomes less, the abrasion resistance should be as satisfactory as that of normal-weight concrete. The use of natural sand in lightweight concrete improves resistance to abrasion.

Use of Normal-Weight Fine Aggregates

Principally for economy, normal-weight fine aggregates often are used to replace, partially or completely, the lightweight fine aggregates in lightweight concrete mixtures. As previously discussed, partial or complete replacement of lightweight fines with a good normal-weight sand generally improves such properties as strength, workability, finishability, durability, and modulus of elasticity, and generally decreases the water required for a given slump. However, it also has a detrimental effect on such properties as unit weight (increases from 10 to 18 pcf), thermal insulation, and fire resistance. By the judicious use of a good natural sand, these factors may be balanced to achieve the desired performance and economy.

PROPORTIONING

The principles for proportioning normal-weight concrete mixtures apply also to lightweight concrete mixtures, but their application is generally different. Conventional procedures may be used with good results for those mixtures containing lightweight aggregates characterized by rounded particle shape, coated or sealed surfaces, and relatively low values of absorption.

Because of the variations in total absorption and rate of absorption of most lightweight aggregates, the water-cement ratio cannot be established accurately enough to be used as a basis for mix proportioning. Thus, lightweight aggregate mixtures are best established by a series of trial mixes proportioned on a cement-content basis for the required degree of workability. Specimens from each trial batch are tested at desired ages to establish relationships between strength and cement content. From these relationships, the cement content for the required strength can be determined.

Lightweight structural concrete for use in a watertight structure should be designed for a specified compressive strength of at least 3,750 psi for fresh water exposure or 4,250 psi for sea water exposure. When the concrete will be exposed to soils and groundwaters containing injurious sulfate concentrations, the concrete should be designed for a specified strength of at least 4,000 psi.

Estimating Mix Proportions

The best approach to making a first trial mix is to use proportions previously established for similar concrete made with aggregates from the same source. Such proportions may be obtained either from laboratory mixes or from actual mixes supplied to jobs. Producers furnishing lightweight aggregates for structural concrete can supply data on mix proportions for various strength and exposure conditions. Their estimates of cement content and other mix proportions for given conditions are very useful as a starting point in making trial mixes.

Water content. The maximum size of lightweight aggregate used in concrete is usually ¾ in. or smaller. Typical normal-weight concrete mixes with ¾-in. maximum-size aggregate require total water contents of about 310 to 360 lb. per cubic yard. Because of the higher absorption of lightweight aggregates, between 290 and 500 lb. of water may be required for making a cubic yard of lightweight concrete. Replacement of lightweight fines with normal-weight sand reduces the water requirement to a narrower range. For air-entrained lightweight concrete, the amount of water required is usually less by 2 to 3 percent for each 1 percent of entrained air.

Cement content. The wide range in lightweight aggregate characteristics is reflected in a wide range in cement contents to produce a given strength. Table 1 gives an approximation of the cement contents for establishing trial mix proportions to obtain a given strength.

Table 1. Approximate Relationship Between Strength and Cement Content*

Compressive strength, psi	Cement content, lb. per cu.yd.
2,500	425 to 700
3,000	475 to 750
4,000	550 to 850
5,000	650 to 950

*Adapted from ACI 211.2-69, Recommended Practice for Selecting Proportions for Structural Lightweight Concrete.

Proportion of fine to coarse aggregate. Lightweight concrete mixes require higher percentages of fines than normal-weight concrete because of differences between the bulk specific gravities of fine and coarse lightweight aggregate particles, and also because most lightweight aggregates are angular in shape and have rough surface textures. Workable mixes of lightweight concrete require 40 to 60 percent of fines *by bulk volume*. Mixes with coated lightweight aggregates require less fines since these aggregates are more nearly similar to normal-weight aggregates in shape and surface texture. With natural sand replacement of lightweight fines, the proportion of fine to coarse aggregate is reduced and rarely exceeds 40 percent of the total bulk volume of aggregates.

Experience has shown that generally between 28 and 32 cu.ft. of dry, loose lightweight aggregates (fine and coarse measured separately) is required to produce a cubic yard of concrete. The total volume of aggregates and the proportion of fine to coarse aggregate, which depend on gradation, shape, size, and surface texture of the aggregate particles, have a great influence on the workability and finishability of fresh concrete. In general, a smaller total volume of aggregates and a lower percentage of fine aggregate will be required if the aggregates are well graded, ranging from rounded to cubical in shape and with a smooth surface texture than if they are poorly graded, angular in shape, and porous.

Entrained air. Most lightweight concretes contain 2 to 4 percent entrapped air, but since this has negligible effect on workability and durability, additional entrained air is desirable. Lightweight concrete subject to freezing and thawing or de-icer applications should contain no less than 6 ±1½ percent total (entrapped plus entrained) air when maximum aggregate size is ¾ in. and 7½ ±1½ percent when maximum aggregate size is 3/8 in. Even when freeze-thaw resistance is not required, entrained air is recommended to provide workability. Optimum air content for workability is generally between 4 and 8 percent for lightweight concrete. The volumetric method of measuring air, as described in Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method (ASTM C173, CSA A23.2.18), is recommended.

Trial Mixes

Unless reliable data are available, based on experience with the same proportions and materials as will be used on the job, use trial mixes to determine the relationship of strength to cement content. Trial mixes should be made with at least three different cement contents. Each mix should have the desired degree of workability and sufficient entrained air to ensure durability and workability.

Each trial batch should produce at least 1½ cu.ft. of concrete. This amount will allow determinations of air content and unit weight and the molding of at least four or five 6x12-in. compression test specimens. After strength tests have been made, results are plotted to relate strength and cement content, and the cement content that produces the required strength is determined. Based on the mix proportions of the trial mixes, the mix proportions for the selected cement content can be estimated accurately.

Small trial batches of 1½ cu.ft. that are made and adjusted in the laboratory may require some further adjustments when extrapolated to field mixes.

The design and adjustment procedure for an all-lightweight concrete mixture is shown in the following example. If part or all of the lightweight fine aggregate is replaced by normal-weight sand, it is recommended that the adjustments be based on an original mix that incorporates normal-weight sand, with adjustments to the natural sand fraction being based either (1) on saturated-surface-dry weight and bulk specific gravity, saturated-surface-dry basis (ASTM C128), or (2) on aggregate in moisture condition as used and a corresponding specific gravity factor. It should be noted that full replacement of lightweight fines will reduce the water demand by 10 to 15 percent. It will also improve workability and permit a reduction in volume percentage of fines of up to 10 percent of the total volume of aggregates.

Example. The problem is to design an all-lightweight-aggregate concrete mix for 4,000 psi strength at 28 days. The concrete should be air entrained and have a slump of about 4 in. Use Type I or Normal portland cement with an air-entraining admixture. Dry, loose unit weights of coarse and fine aggregates are 45 and 60 lb. per cubic foot, respectively. The moisture contents of the aggregates at time of mixing are 5 and 8 percent for coarse and fine aggregate, respectively.

Step 1. Determine the specific gravities of the coarse and the fine aggregate according to the pycnometer method (see Appendix) for different moisture conditions ranging from 0 (oven dry) to the maximum expected moisture content. For lightweight aggregates, the relationship of aggregate weight to displaced volume as determined by pycnometer is termed a "specific gravity factor." It is a function of the moisture content of the aggregates. Specific gravity factors are used in a variation of the absolute volume method of mix proportioning to calculate the effective volumes displaced by the lightweight aggregates in concrete.

Step 2. Estimate quantities. From Table 1, the cement content may be expected to range from 550 to 850 lb. per cubic yard. Accordingly, trial mixes with approximate cement contents of 600, 700, and 800 lb. per cubic yard will be made. Since the total dry-loose volume of aggregate required per cubic yard of concrete averages about 30 cu.ft., this value is used for estimating purposes. For the first trial, equal volumes of fine and coarse aggregate are used. The amount of air-entraining admixture to be used to entrain about 6 percent air should be based on the admixture producer's recommendations.

Step 3. Calculate the loose weights of the damp coarse and fine aggregate required per cubic yard. These will be: 15 × 45 × 1.05 = 709 lb. of coarse aggregate and 15 × 60 × 1.08 = 972 lb. of fine aggregate.

Step 4. Calculate the displaced volumes of the damp aggregates, using the specific gravity factors corresponding to the actual moisture condition. Assume that the specific gravity factors have been determined as 1.37 and 1.95 for coarse and fine aggregates, respectively. (Steps 4 through 6 are shown in Columns 1 and 2 of Table 2.) Pycnometer specific gravity factors obtained after 10-minute immersion of aggregates are normally used for mix 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 mix proportions should be determined on the basis of the 10-minute specific gravity factor. However, in order to provide guidance in determining the additional amount of water required to compensate for the anticipated loss of yield, the mix proportions should be recalculated using specific gravity factors corresponding to a longer immersion time.

Step 5. Calculate the displaced volumes of cement and air.

Step 6. The required volume of water is calculated as the difference between 27 cu.ft. and the total of the displaced volumes of cement, air, and aggregates. The weight of water required is the required volume of water multiplied by 62.4 lb. per cubic foot.

Step 7. Calculate the weights of materials required for the 1½-cu.ft. trial batch, by dividing the weights from Column 1 by $\frac{27}{1.5} = 18$ (Column 3).

Table 2. Initial Batch Proportions and Trial Batch Adjustments

	1	2	3	4	5	6	7	8	9
	Estimated batch proportions (damp aggregates)		Weights for 1.5 cu.ft. trial batch, lb.	Correction for 1.5 cu.ft., lb.	Correction for 1 cu.yd., lb.	Corrected batch proportions (damp aggregates)		Adjusted batch proportions (damp aggregates)	
	Weight, lb.	Displaced vol., cu.ft.				Weight, lb.	Displaced vol., cu.ft.	Weight, lb.	Displaced vol., cu.ft.
Cement	600	$\frac{600}{62.4 \times 3.15} = 3.05$	33.3			600	3.05	0.92 × 600 = 552	0.92 × 3.05 = 2.81
Air		27 × 0.06 = 1.62					1.62		1.62
Coarse aggregate	709	$\frac{709}{62.4 \times 1.37} = 8.29$	39.4	+3.9	+70	709 + 70 = 779	$\frac{779}{62.4 \times 1.37} = 9.11$	0.92 × 779 = 717	0.92 × 9.11 = 8.38
Fine aggregate	972	$\frac{972}{62.4 \times 1.95} = 7.99$	54.0			972	7.99	0.92 × 972 = 894	0.92 × 7.99 = 7.35
Water	6.05 × 62.4 = 378	27.00 − 20.95 = 6.05	21.0	+4.8	+86	378 + 86 = 464	$\frac{464}{62.4} = 7.44$	0.92 × 464 = 427	0.92 × 7.44 = 6.84
Total		27.00					29.21		27.00

Step 8. Mix the materials and examine the mixture for workability, slump, air content, and unit weight. If the mixture is satisfactory, no correction will be necessary, and cylinders for compression tests may be cast. If a correction in the amount of aggregate or of added water is required, the mix proportions will have to be adjusted as listed in Steps 9 through 12.

Step 9. Assume that more coarse aggregate may be used without harming workability or finishability, and that more water is required to obtain the desired slump. The amounts of coarse aggregate and water added to the 1½-cu.ft. trial batch were 3.9 and 4.8, respectively (Column 4).

Step 10. The total correction per cubic yard will be 3.9 X 18 = 70 lb. coarse aggregate and 4.8 X 18 = 86 lb. water (Column 5).

Step 11. Calculate the corrected batch proportions (Columns 6 and 7).

Step 12. Multiply the weights and displaced volumes of materials from Step 11 by $\frac{27.00}{29.21} = 0.92$ to adjust the quantities to a yield of 27 cu.ft.

The adjusted quantities are for damp aggregates (Columns 8 and 9). For future adjustments of batch proportions, it is necessary to convert the batch weights of materials to dry weights. The dry weights will serve as basis for the calculation of adjustments for change in aggregate moisture conditions, cement content, proportions of aggregates, slump, or air content, in order to maintain a yield of 27 cu.ft.

The procedure to convert batch weights for damp aggregates to batch weights for dry aggregates is detailed in the following steps and shown in Table 3.

Adjustments for dry state (Table 3)

Step 13. From the batch proportions for damp aggregates (Column 1), calculate the dry weights of coarse and fine aggregates (Column 3). Maintain constant the weight of cement.

Step 14. Calculate the displaced volumes of dry aggregates (Column 4), using the specific gravity factors for the dry state. Assume that the specific gravity factors for the dry state have been determined as 1.34 and 1.99 for coarse and fine aggregates, respectively.

Step 15. Maintaining constant the displaced volumes of cement and air, calculate the required displaced volume of added water (Column 4). From this, calculate the required weight of added water (Column 3).

Subsequent shipments of aggregates may have different moisture contents. It will be necessary, therefore, to adjust the batch weights of materials to maintain a yield of 27 cu.ft. This is done by adjusting the weights of aggregates from the dry condition to the new moisture conditions.

Assume that the new moisture conditions are 2 and 4 percent for coarse and fine aggregates, respectively. To calculate the adjusted weights, the specific gravity factors for the dry state and the new moisture conditions will be required. Assume that the specific gravity factors have been determined as 1.35 and 1.97 for the new moisture condition, for coarse and fine aggregates, respectively.

Adjustments for new moisture conditions (Table 3)

Step 16. Maintain constant the weight of cement and the displaced volumes of cement and air.

Step 17. Calculate the weights of aggregates for the new moisture conditions (Column 5).

Step 18. Calculate the displaced volumes of aggregates (Column 6), using the specific gravity factors of 1.35 and 1.97 for the new moisture conditions.

Step 19. Calculate the required displaced volume of added water (Column 6). From this, calculate the required weight of added water (Column 5).

Adjustment for change in cement content. Two more trial mixes should be made with approximate cement contents of 700 and 800 lb. per cubic yard. Much of the trial-and-error work can be simplified by using the proportions obtained from the first trial mix. The mix proportions will

Table 3. Adjustments for Changes in Aggregate Moisture Conditions

	1	2	3	4	5	6
	Batch proportions (damp aggregates)		Converted batch proportions (dry aggregates)		Adjusted batch proportions (aggregates in new moisture condition)	
	Weight, lb.	Displaced vol., cu.ft.	Weight, lb.	Displaced vol., cu.ft.	Weight, lb.	Displaced vol., cu.ft.
Cement	552	2.81	552	2.81	552	2.81
Air		1.62		1.62		1.62
Coarse aggregate	717	8.38	$\frac{717}{1.05} = 683$	$\frac{683}{62.4 \times 1.34} = 8.17$	683 X 1.02 = 697	$\frac{697}{62.4 \times 1.35} = 8.27$
Fine aggregate	894	7.35	$\frac{894}{1.08} = 828$	$\frac{828}{62.4 \times 1.99} = 6.67$	828 X 1.04 = 861	$\frac{861}{62.4 \times 1.97} = 7.00$
Water	427	6.84	7.73 X 62.4 = 482	27.00 − 19.27 = 7.73	7.30 X 62.4 = 456	27.00 − 19.70 = 7.30
Total		27.00		27.00		27.00

have to be adjusted to compensate for the increase in cement content by a corresponding decrease in fine aggregate content. The procedure is explained in the following steps and shown in Table 4.

Step 20. Maintain constant the weights and volumes displaced by dry coarse aggregate, air, and water, shown in Columns 3 and 4 of Table 3. Transfer these values to Columns 1 and 2 of Table 4.

Step 21. Calculate the volume displaced by new cement content (Column 4).

Step 22. Calculate the required displaced volume of dry fine aggregate as the difference between 27 cu.ft. and the total of the displaced volumes of cement, air, coarse aggregate, and water (Column 4).

Step 23. Calculate the required weight of dry fine aggregate from the displaced volume determined in Step 22, using the value of its specific gravity factor for the dry state (Column 3).

Step 24. Convert the weight of dry fine aggregate to the weight at the original moisture condition (Column 5). Calculate the displaced volume of damp fine aggregate (Column 6).

Step 25. Calculate the required volume of added water (Column 6). From this, calculate the required weight of added water (Column 5).

Adjustments for changes in proportion of fine aggregate, slump, or air content. Minor changes in proportion of fine to total aggregate, in slump, or in air content sometimes may be desired. These changes will necessitate corresponding adjustments in mix proportions to maintain yield and other characteristics constant. The following rules of thumb may be used as a guide:

1. For each 1 percent increase (or decrease) in the percentage of fine aggregate to total aggregate, increase (or decrease) water by approximately 3 lb. and cement content by 1 percent per cubic yard.
2. For each 1 in. increase (or decrease) in slump, increase (or decrease) water by approximately 10 lb. and cement content by 3 percent per cubic yard. Somewhat more water and correspondingly more cement will be required when the initial slump is less than 3 in.
3. For each 1 percent increase (or decrease) in air content, decrease (or increase) water by approximately 5 lb. per cubic yard and increase (or decrease) cement content by 2 percent per cubic yard. The adjustment in cement content may be smaller in lean mixes.

To calculate the adjustments, use the mix proportions that are based on dry aggregates. Maintaining the coarse aggregate constant, the quantities of cement, air, or water are increased or decreased according to the rules of thumb given above. These adjustments may result in an increase or a decrease in the total displaced volume. To maintain the original volume, the proportion of fine aggregate should be decreased or increased accordingly.

Example. Assume that the proportions given in Columns 3 and 4 of Table 4 should be adjusted to decrease the slump by 2 in. and increase air content by 2 percent.

From rule of thumb 2:

Decrease in slump of 2 in. will require 2 X 10 = 20 lb. decrease in water, and 2 X0.03 X 700 = 42 lb. decrease in cement per cubic yard.

From rule of thumb 3:

Two percent increase in air content will require 2 X 5 = 10 lb. decrease in water and 2 X 0.02 X 700 = 28 lb. increase in cement per cubic yard.

The total decrease in water will be 20 + 10 = 30 lb., and the total decrease in cement will be 42 − 28 = 14 lb.; the increase in air content will be 0.02 X 27.00 = 0.54 cu.ft.

Calculation of the adjustments is shown in Table 5. Columns 1 and 2 are the proportions given in Columns 3 and 4 of Table 4.

Adjustment of fine aggregate in Columns 3 and 4 is according to Steps 22, 23, and 24, and adjustment of fine aggregate and water in Columns 5 and 6 is according to Step 25.

Table 4. Adjustment of Proportions for Change in Cement Content

	1	2	3	4	5	6
	Values from Col. 3 and 4 of Table 3		Adjusted proportions (dry aggregates)		Converted proportions (damp aggregates)	
	Weight, lb.	Displaced vol., cu.ft.	Weight, lb.	Displaced vol., cu.ft.	Weight, lb.	Displaced vol., cu.ft.
Cement	552	2.81	700	$\frac{700}{62.4 \times 3.15} = 3.56$	700	3.56
Air		1.62		1.62		1.62
Coarse aggregate	683	8.17	683	8.17	683 X 1.05 = 717	$\frac{717}{62.4 \times 1.37} = 8.39$
Fine aggregate	828	6.67	5.92 X 62.4 X 1.99 = 735	27.00 − 21.08 = 5.92	735 X 1.08 = 794	$\frac{794}{62.4 \times 1.95} = 6.53$
Water	482	7.73	482	7.73	6.90 X 62.4 = 431	27.00 − 20.10 = 6.90
Total		27.00		27.00		27.00

Table 5. Adjustment of Proportions for Change in Air Content and Slump

	1	2	3	4	5	6
	Values from Col. 3 and 4 of Table 4		Adjusted proportions (dry aggregates)		Converted proportions (damp aggregates)	
	Weight, lb.	Displaced vol., cu.ft.	Weight, lb.	Displaced vol., cu.ft.	Weight, lb.	Displaced vol., cu.ft.
Cement	700	3.56	700 − 14 = 686	$\frac{686}{62.4 \times 3.15} = 3.49$	686	3.49
Air		1.62		1.62 + 0.54 = 2.16		2.16
Coarse aggregate	683	8.17	683	8.17	683 X 1.05 = 717	$\frac{717}{62.4 \times 1.37} = 8.39$
Fine aggregate	735	5.92	5.94 X 62.4 X 1.99 = 738	27.00 − 21.06 = 5.94	738 X 1.08 = 797	$\frac{797}{62.4 \times 1.95} = 6.55$
Water	482	7.73	482 − 30 = 452	$\frac{452}{62.4} = 7.24$	6.41 X 62.4 = 400	27.00 − 20.59 = 6.41
Total		27.00		27.00		27.00

FIELD OPERATIONS AND CONTROL

Stockpiling

Lightweight aggregates require the same care in stockpiling as do normal-weight aggregates. If clamshell buckets are used in stockpiling, they should not discharge lightweight aggregates from substantial heights. Prewetting limits or prevents loss of fine aggregates and minimizes segregation.

Moisture Control

The uniformity and quality of lightweight concrete are dependent on the uniformity of moisture content of aggregates. If moisture varies in aggregates at the time of batching, slump, yield, and uniformity may be difficult to control. The absorptive properties of some lightweight aggregates may require prewetting to as uniform a moisture content as possible or premixing of the aggregates with water. Prewetted aggregates should remain in the stockpiles for a minimum of 12 hours before use to prevent excessive variations in moisture content. The moisture content of aggregates should be known and aggregate batch weights should be adjusted to compensate for changes in absorbed water.

To compensate for water absorption by the aggregate, sufficient water should be added to the mix at the batch plant to produce the required slump at the jobsite. If the quantity of water added to the mix produces less than the required slump, additional water may be added at the jobsite to satisfy slump requirements.

Properly prewetted aggregates absorb less mixing water and reduce the possibility of loss in slump during mixing, transporting, and placing. Because absorption characteristics of lightweight aggregates differ, the aggregate producer's recommendations concerning the method and extent of prewetting should be followed.

Mixing

A universally applicable mixing procedure cannot be established because of differences in aggregate characteristics. Recommended mixing procedures of aggregate producers should be followed, if available. It may be necessary to make trials using different procedures to determine the best method for any given set of conditions.

Lightweight concrete may be batched and mixed in the same way as normal-weight concrete when the aggregates have less than 10 percent total absorption by weight (as determined by ASTM C127) or absorb less than 2 percent by weight in the first hour after immersion in water, based on aggregates tested at the minimum moisture content likely to occur at the batch plant. Aggregates usually are prewetted to obtain this minimum moisture condition.

It is generally recommended that mixing be done in two stages if the aggregates do not meet the above limits. In the first mixing stage, the mixer should be charged with about two-thirds of the total mixing water and all of the aggregates. The air-entraining or other admixture, if any, cement, and remaining water to bring the mix to the desired slump are added in the second mixing stage.

For truck mixers, the first stage should continue for ½ minute (5 to 10 revolutions) to 1½ minutes (15 to 30 revolutions) at top mixing speed, depending on the initial moisture content of the aggregates, or until the initial water demand of the aggregates is satisfied. The ingredients should be mixed for an additional 60 to 70 revolutions in the second stage. Immediately prior to discharge, the truck mixer should be rotated at top mixing speed for a minimum of 1 minute in order to minimize segregation.

For stationary mixers, initial mixing should continue for 30 seconds or until the initial water demand of the aggregates is satisfied. Then, after the remaining ingredients are added, mixing should continue for at least 1 minute in mixers with a capacity of 1 cu.yd. or less. Mixing time for larger mixers should be increased 15 seconds for each additional cubic yard of capacity or fraction thereof. Mixing time may be reduced if mixer performance tests conducted in accordance with ASTM C94 or CSA A23.1, Clause 12, show that the concrete as discharged is adequately uniform with the shorter mixing time.

Job Control

To ensure the uniformity of lightweight concrete, the cement content, slump, and volume of dry aggregate per cubic yard of concrete should be kept constant. Fresh unit weight, air content, and slump tests should be made frequently. The unit weight of freshly mixed lightweight concrete is correlated with the 28-day (design) air-dry unit weight and used as a basis for placement control and acceptance during construction.

A change in unit weight will reveal a discrepancy in yield. It will also indicate an error in batching, a change in air content, or a change in aggregate volume. A change in aggregate volume may be caused by a change in the specific gravity factor, which is a function of gradation, moisture content, and density of the aggregate.

A change in slump may be indicative of a change in air content, in moisture content of the aggregates, or in gradation or density.

Results of tests for unit weight, gradation, and moisture content generally reveal the cause of the change and indicate corrective measures. Variations in excess of ±2 percent in fresh unit weight generally will necessitate an adjustment in batch weights. Variations in air content should not exceed ±1.5 percent of a specified value to avoid adverse effects on compressive strength, workability, or durability.

Sampling and testing should be performed in accordance with the following ASTM or CSA standard methods:

a. ASTM C172 (CSA A23.2.21), Method of Sampling Fresh Concrete.

b. ASTM C143 (CSA A23.2.20), Test for Slump of Portland Cement Concrete.

c. ASTM C567, Test for Unit Weight of Structural Lightweight Concrete.

d. ASTM C173 (CSA A23.2.18), Test for Air Content of Freshly Mixed Concrete by the Volumetric Method.

e. ASTM C31 (CSA A23.2.14), Method of Making and Curing Concrete Compressive and Flexural Strength Test Specimens in the Field.

f. ASTM C39 (CSA A23.2.13), Test for Compressive Strength of Molded Concrete Cylinders.

Placing, Finishing, and Curing

The basic principles and techniques required to secure a satisfactory lightweight concrete job are similar to those applicable to normal-weight concrete:

1. The mix should be workable and utilize a minimum amount of water.

2. The equipment to place and consolidate the concrete should be adequate and properly used to ensure good quality workmanship.

Placing well-proportioned lightweight concrete generally requires less effort than normal-weight concrete. The concrete should generally be deposited in layers of 10 to 16 in. because of greater difficulty in eliminating entrapped air bubbles in lightweight concrete. Overvibration and overworking of the surface should be avoided, as they will tend to bring the lighter coarse aggregate to the surface and drive the heavier mortar away from the surface. Proper finishing of lightweight concrete floors can be obtained as follows:

1. Prevent segregation by providing a well-proportioned, cohesive mix, by keeping the slump as low as possible, limiting it to a maximum of 4 in., and by avoiding overvibration.

2. Use magnesium, aluminum, or other satisfactory tools that minimize surface tearing and pullouts. Vibrating screeds and jitterbugs may be used to advantage in depressing coarse particles and developing a good mortar surface for floating and trowelling.

3. Perform all finishing operations after free bleeding water has disappeared from the surface.

Ultimate performance of the concrete will be in proportion to the adequacy of curing. Curing should begin as quickly as possible after completion of the final finishing operation. The two methods commonly used in the field are water curing (ponding, sprinkling, or using wet coverings), and preventing loss of moisture from the exposed surfaces (covering with waterproof paper, plastic sheets, or sealing with liquid membrane-forming compounds). Generally, 7 days of curing are adequate for ambient air temperatures from 50 to 70 deg.F.; and 5 days for temperatures over 70 deg.F.

APPENDIX
DETERMINATION OF SPECIFIC GRAVITY FACTORS OF STRUCTURAL LIGHTWEIGHT CONCRETE

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

Pycnometer Method for Fine and Coarse Lightweight Aggregates

Apparatus.

(a) A pycnometer consisting of a narrow-mouth 2-qt. Mason jar with a spun-brass pycnometer top (Soiltest G-335, Humboldt H-3380, or equivalent).

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

(c) A water storage jar of about 5 gal. capacity, for maintaining water at room temperature.

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

Calibration of the pycnometer. The pycnometer is filled with water and agitated to remove any entrapped air. The filled pycnometer is then weighed and the weight (weight *B* in grams) is recorded.

Sampling procedure. Representative samples of about 2 to 3 cu.ft. of each size of aggregate should be obtained from the stockpile and put through a sample splitter or quartered until the correct size of 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 of the volume of the 2-qt. 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 105 to 110 deg.C. (221 to 230 deg.F.), 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 (percent of aggregate dry weight, 100 m.) is calculated.

The second aggregate sample is weighed (weight C in grams). The sample is then placed in the empty pycnometer and water is added until the jar is 3/4 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 again agitated 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 the 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 sample and water, is weighed (weight A in grams) after 5, 10, and 30 minutes of sample immersion to obtain complete data, and the weights at these times are recorded.

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.
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 specific gravity factors may be determined by the wholly equivalent weight-in-air-and-water procedures described in ASTM C127. 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

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

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ABSTRACT: Deals with concrete having 28-day compressive strength in excess of 2,500 psi and an air-dry unit weight of less than 115 lb. per cubic foot. Various methods of manufacturing lightweight aggregates are defined. Properties of these aggregates are discussed. The sheet outlines the properties of lightweight concrete in the plastic and hardened states. Procedures for mix design are detailed. Field operations and control are briefly discussed.

REFERENCE: *Structural Lightweight Concrete* (IS032.05T), Portland Cement Association, 1972. Reprinted in 1986.

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