Lightweight Concrete and Aggregates

Thomas A. Holm

Authorized Reprint from Standard Technical Publication 169C © Copyright 2001
ASTM INTERNATIONAL, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959

Lightweight Concrete and Aggregates

48

Thomas A. Holm[1]

PREFACE

Lightweight concrete and aggregates were first discussed by R. E. Davis and J. Kelly in the 1956 edition of *ASTM STP 169*. The *ASTM STP 169A* and *ASTM STP 169B* editions were authored by D. W. Lewis. The general presentation of this paper is similar to earlier chapters; however, additional information on elastic properties of lightweight aggregates, as well as strength making, durability, and placement characteristics of lightweight concrete is included to reflect the current state of the art. This edition also includes new discussions relative to the contact zone and internal curing as well as revisions to ASTM methods for calculating the equilibrium density of structural lightweight concrete adopted by ASTM since the publication of *ASTM STP 169B* in 1978.

CLASSIFICATION OF LIGHTWEIGHT AGGREGATES AND LIGHTWEIGHT AGGREGATE CONCRETES

ASTM Standards provide requirements for lightweight aggregates that are used in structural masonry units and insulating types of concrete. Structural and insulating lightweight aggregate concretes are broadly divided into three groups based upon their use and physical properties. Unit weight, thermal conductivity and compressive strength ranges normally associated with each class of concrete are summarized in (Table 1).

This chapter addresses concretes where weight reduction is achieved through the use of lightweight aggregates and does not include cellular or foam concrete, where lighter weight is developed primarily by inclusion of large amounts of air or gas through foaming-type agents. No-fines concretes with very large, unfilled interstitial voids produced with aggregate content deficient in fine aggregates are also excluded from this review, which restricts discussion to the predominant forms of lightweight aggregate concretes based upon inorganic lightweight aggregates.

STRUCTURAL-GRADE LIGHTWEIGHT AGGREGATE AND STRUCTURAL LIGHTWEIGHT AGGREGATE CONCRETE

Structural-grade lightweight concretes generally contain aggregates made from pyroprocessed shales, clays, slates, expanded slags, expanded fly ash, and those mined from natural porous volcanic sources. Minimum compressive strength of structural-grade lightweight aggregate concrete has, in effect, been jointly established by the ASTM Specification for Lightweight Aggregates for Structural Concrete (C 330) and the Standard Building Code for Reinforced Concrete (ACI 318) [*1*] which requires that: "Structural concrete made with lightweight aggregate; the air-dried unit weight at 28 days is usually in the range of 1440 to 1850 kg/m^3 (90 to 115 lb/ft^3) and the compressive strength is more than 17.2 MPa (2500 psi)." This is a definition, not a specification and project requirements may permit equilibrium unit weights up to 1900 kg/m^3 (120 lb/ft^3). Although structural concrete with equilibrium unit weights from 1450 to 1920 kg/m^3 (90 to 120 lb/ft^3) are often used, most lightweight aggregate concrete used in structures have equilibrium unit weights between 1600 to 1760 kg/m^3 (100 and 110 lb/ft^3).

Structural-grade lightweight aggregates are produced in manufacturing plants from raw materials including suitable shales, clays, slates, fly ashes, or blast furnace slags. Naturally occurring lightweight aggregates are mined from volcanic deposits that include pumice and scoria types. Pyroprocessing methods include the rotary kiln process (a long, slowly rotating, nearly horizontal cylinder lined with refractory materials similar to cement kilns); the sintering process wherein a bed of raw materials including fuel is carried by a traveling grate under ignition hoods; and the rapid agitation of molten slag with controlled amounts of air or water. No single description of raw material processing is all-inclusive and the reader is urged to consult local lightweight aggregate manufacturers for physical and mechanical properties of lightweight aggregates and the concrete made with them.

Increased usage of processed lightweight aggregates is evidence of environmentally sound planning, as these products utilize materials with limited structural applications in their natural state, thus minimizing construction industry demands on finite resources of natural sands, stones, and gravels.

ASTM C 330 requires fine lightweight aggregates used in the production of structural lightweight concrete to be properly graded, with 85 to 100% passing the 4.75 mm

---

[1] Vice president of Engineering, Solite Corporation, Richmond, VA 23261.

TABLE 1—Lightweight Aggregate (LWA) Concrete Classified According to Use and Physical Properties.[a]

Class of Lightweight Aggregate Concrete	Type of Lightweight Aggregate used in Concrete	Typical Range of Lightweight Concrete Unit Weight	Typical Range of Compressive Strength	Typical Range of Thermal Conductivities
Structural	Structural-grade LWA C 330	(1440 to 1840) 90 to 115 air dry	(>17) (>2500)	not specified in C 330
Structural/ Insulating	Either structural C 330 or insulating C 332 or a combination of C 330 and C 332	(800 to 1440) (50 to 90) air dry	(3.4 to 17) (500 to 2500)	C 332 from (0.22) (1.50) to (0.43) (3.00) oven dry
Insulating	Insulating-grade LWA C 332	(240 to 800) (15 to 50) oven dry	(0.7 to 3.4) 100 to 500	C 332 from (0.065) (0.45) to (0.22) (1.50) oven dry

[a] Unit weights are in (kg/m^3) (lb/ft^3), compressive strengths in (MPa) (psi), and thermal conductivity in (W/m · °K) (Btu · in./h · ft^2 · °F).

(3/16 in.) screen with a dry loose bulk density less than 1120 kg/m^3 (70 lb/ft^3). Four coarse aggregate gradations are provided for use in structural lightweight concrete with maximum dry loose bulk density limited to 880 kg/m^3 (55 lb/ft^3). Combined fine and coarse aggregate formulations must not exceed a maximum dry loose unit weight of 1040 kg/m^3 (65 lb/ft^3). Tests are conducted in accordance with ASTM Test Method for Unit Weight and Voids in Aggregate (C 29) using the shoveling procedure.

INSULATING-GRADE LIGHTWEIGHT AGGREGATES AND INSULATING LIGHTWEIGHT CONCRETES

Very light nonstructural concretes, employed primarily for high thermal resistance, incorporate low-density low-strength aggregates such as vermiculite and perlite. With low unit weights, seldom exceeding 800 kg/m^3 (50 lb/ft^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 0.69 to 6.89 MPa (100 to 500 psi).

ASTM Specification for Lightweight Aggregates for Insulating Concrete (C 332) limits thermal conductivity values for insulating concretes to a maximum of 0.22 W/m·K (1.50 Btu · in. · /h · ft^2 °F) for concrete having an oven-dry density of 800 kg/m^3 (50 lb/ft^3) or less, and to 0.43 W/m · K (3.0 Btu · in. · /h · ft^2 °F) for those weighing up to 1440 kg/m^3 (90 lb/ft^3). Lighter concretes are those made with Group I aggregates (perlites and vermiculite), while higher unit weights result from the use of Group II aggregates (expanded shales, 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 unit weight tests on the insulating concretes. Moisture content of insulating materials directly affects both the thermal conductivity and unit weight, but to varying degrees. A 1% increase in moisture content will increase unit weight 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.

STRUCTURAL/INSULATING LIGHTWEIGHT AGGREGATE CONCRETES

Widespread industrial applications that call for "fill" concretes require modest compressive strengths with densities intermediate between the structural- and insulating-grade concretes. These concretes may be produced with high air mixes with structural-grade lightweight aggregate, with sanded insulating lightweight aggregate mixes, or with formulations incorporating both structural- and insulating-grade lightweight aggregates. Compressive strengths from 3.4 to 17 MPa (500 to 2500 psi) are not uncommon with thermal resistance less than concretes containing only insulating-grade lightweight aggregate.

LIGHTWEIGHT AGGREGATE PROPERTIES

Internal Structure of Lightweight Aggregates

Lightweight aggregates develop low particle specific gravity because of the cellular pore system. Cellular structure within the particles is normally developed at high temperatures by formation of gases due to the reaction of heat on certain raw material constituents coincident with incipient fusion causing gas expansion to be trapped in the viscous, pyroplastic mass. Strong, durable lightweight aggregates are produced when small-size, well-distributed, noninterconnected pores are enveloped in a continuous, crack free, vitreous phase [*3*] (Fig. 1).

PARTICLE SHAPE AND SURFACE TEXTURE

Depending on the source and the method of production, lightweight aggregates exhibit considerable differences in

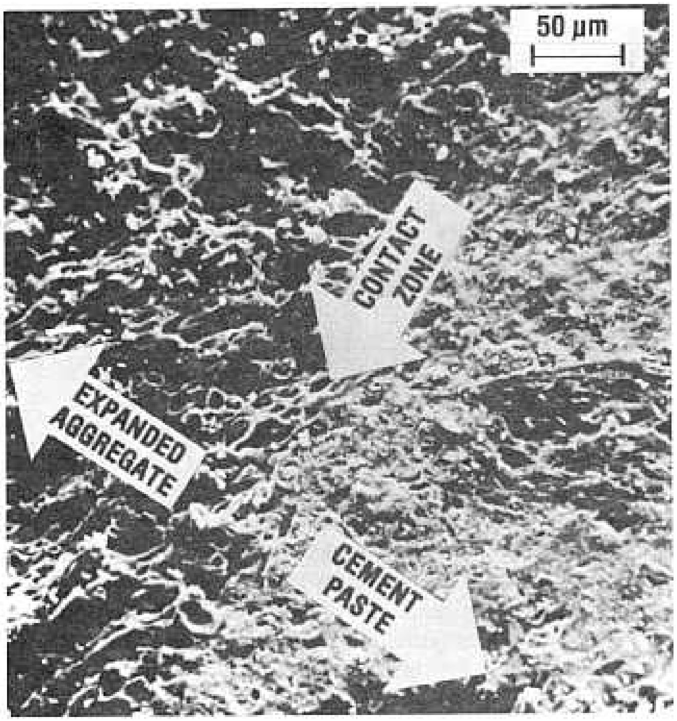


FIG. 1—Contact zone—structural lightweight concrete from 30-year-old bridge deck, W.P. Lane Memorial Bridge over the Chesapeake Bay, Annapolis, Maryland: compression strength 24 MPa (3500 psi); density 1680 kg/m³ (105 lb/ft³).

particle shape and texture. Shapes may be cubical, rounded, angular, or irregular. Textures may range from fine pore, relatively smooth skins to highly irregular surfaces with large exposed pores. Particle shape and surface texture directly influence workability, coarse-to-fine aggregate ratio, cement content requirements, and water demand in concrete mixes, as well as other physical properties.

SPECIFIC GRAVITY

The specific gravity of an aggregate is the ratio between the mass of a quantity of the material and the volume occupied by the individual particles contained in that sample. This volume includes the pores within the particles but does not include the voids between the particles. In general, the volume of the particles is determined from the volume displaced submerged in water when penetration of water into the particles during the test is limited by previous saturation. Specific gravity of individual particles depends both on the specific gravity of the poreless vitreous material and the pore volume within the particles, and generally increases when particle size decreases. The specific gravity of the pore-free vitreous material may be determined by pulverizing the lightweight aggregate in a jar mill and then following procedures used for determination of the specific gravity of cement in the ASTM Test Method for Density of Hydraulic Cement (C 188).

BULK UNIT WEIGHT OF LIGHTWEIGHT AGGREGATES

Aggregate bulk unit weight is defined as the ratio of the mass of a given quantity of material and the total volume occupied by it. This volume includes the voids between as well as within the particles. Unit weight is a function of particle shape, density, size, gradation, and moisture content, as well as the method of packing the material (loose, vibrated, rodded) and varies not only for different materials, but for different sizes and gradations of a particular material. Table 2 summarizes the maximum unit weights for lightweight aggregates listed in ASTM C 330, ASTM Specification for Lightweight Aggregates for Concrete Masonry Units (C 331), and ASTM C 332. Minimum unit weights for perlite and vermiculite are also provided to limit over-expanded, weak particles that would break down in mixing.

Density of insulating concrete is usually determined in an over-dry condition, using oven-dry weight and dimensions of specimens associated with to those subjected to either thermal conductivity or compressive strength tests. Density of insulating concretes made with perlite or vermiculite aggregates or cellular concretes may range from 240 to 800 kg/m³ (15 to 50 lb/ft³), while those made with other types of lightweight aggregates are usually in the range of 800 to 1440 kg/m³ (50 to 90 lb/ft³).

TOTAL POROSITY

Void content (within particle pores and between particles' voids) can be determined from measured values of particle specific gravity and bulk unit weight. If, for example, measurements on a sample of lightweight coarse aggregate are:

1. bulk dry loose unit weight, 770 kg/m³ (48 lb/ft³);
2. particle specific gravity, 1400 kg/m³; and
3. specific gravity of poreless vitreous material, 2500 kg/m³;

TABLE 2—Requirements of ASTM C 330, C 331, and C 332 for Dry Loose Unit Weight of Lightweight Aggregates.

Aggregate Size and Group	Maximum Unit Weight, kg/m³ (lb/ft³)	Minimum Unit Weight, kg/m³ (lb/ft³)
ASTM C 330 AND C 331		
fine aggregate	(1120) (70)	
coarse aggregate	(880) (55)	
combined fine and coarse aggregate	(1040) (65)	
ASTM C 332		
Group 1		
Perlite	(196) (12)	(120) (7.5)
Vermiculite	(160) (10)	(88) (5.5)
Group 2		
fine aggregate	(1120) (70)	
coarse aggregate	(880) (55)	
combined fine and coarse aggregate	(1040) (65)	

then the fractional pore volume of an individual particle is

$$\frac{2500 - 1400}{2500} = 0.44$$

and the fractional interstitial void volume (between particles) is

$$\frac{1400 - 770}{1400} = 0.45$$

For this example, total porosity (pores and voids) would then equal

$$[0.45 + (0.44 \times 0.55)] = 0.69$$

GRADATION

Gradation requirements are generally similar to those provided for normal-weight aggregate with the exception that lightweight aggregate particle size distribution permits a higher weight through smaller sieves. This modification recognizes the increase in specific gravity typical for the smaller particles of most lightweight aggregates, and that while standards are established by weights passing each sieve size, ideal formulations are developed through volumetric considerations.

An exception to the procedures of ASTM Method for Sieve Analysis of Fine and Coarse Aggregates (C 136) requires reduction of the weight of fine aggregate sample tested according to the lightweight aggregate's unit weight, and sieving time not to exceed 5 min.

Producers of structural lightweight aggregate normally stock materials in several standard size formulations of coarse, intermediate, and fine aggregate. By combining size fractions or by replacing some or all of the fine fraction with a normal-weight sand, a wide range of concrete unit weights may be obtained. The aggregate producer is the best source of information for the proper aggregate combinations to meet fresh unit weight specifications and equilibrium unit weights for dead load design considerations.

Normal-weight sand replacement will typically increase unit weight from about 80 to more than 160 kg/m^3 (5 to 10 lb/ft^3). Using increasing amounts of cement to obtain high strengths above 35 MPa (5000 psi) concrete will increase air dry density from 32 to 96 kg/m^3 (2 to 6 lb/ft^3).

ABSORPTION CHARACTERISTICS

Due to their cellular structure, lightweight aggregates absorb more water than their normal-weight aggregate counterparts. Based upon a 24-h absorption test, conducted in accordance with the procedures of ASTM Test Method for Specific Gravity and Absorption of Coarse Aggregate (C 127) and ASTM Test Method for Specific Gravity and Absorption of Fine Aggregate (C 128), structural-grade lightweight aggregates will absorb from 5 to more than 25% by weight of dry aggregate. By contrast, normal-weight aggregates generally absorb less than 2% of moisture. The important difference in measurements of stockpile moisture contents is that with lightweight aggregates the moisture is largely absorbed into the interior of the particles whereas in normal-weight aggregates it is primarily surface adsorption. Recognition of this essential difference is important in mix proportioning, batching, and control. Rate of absorption of lightweight aggregates is dependent on the characteristics of pore size, connection, and distribution, particularly those close to the surface. Internally absorbed water within the particle is not immediately available for chemical interaction with cement as mixing water, but extremely beneficial in maintaining longer periods of curing essential to improvements in the aggregate/matrix contact zone. Internal curing will also bring about reduction of permeability by extending the period in which additional products of hydration are formed in the pores and capillaries of the binder.

MODULUS OF ELASTICITY OF LIGHTWEIGHT AGGREGATE PARTICLES

The modulus of elasticity of concrete is a function of the moduli of its constituents. Concrete may be considered as a two-phase material consisting of coarse aggregate inclusions within a continuous "mortar" fraction that includes cement, water, entrained air, and fine aggregate. Dynamic measurements made on aggregates alone have shown a relationship corresponding to the function: $E = 0.008\ \rho^2$, where E is the dynamic modulus of elasticity of the particle in MPa and ρ is the dry mean specific gravity in kg/m^3 [*4*] (Fig. 2). Dynamic moduli for usual expanded aggregates have a range of 10 to 16 GPa (1.45 to 2.3 × 10^6 psi), whereas the range for strong ordinary aggregates

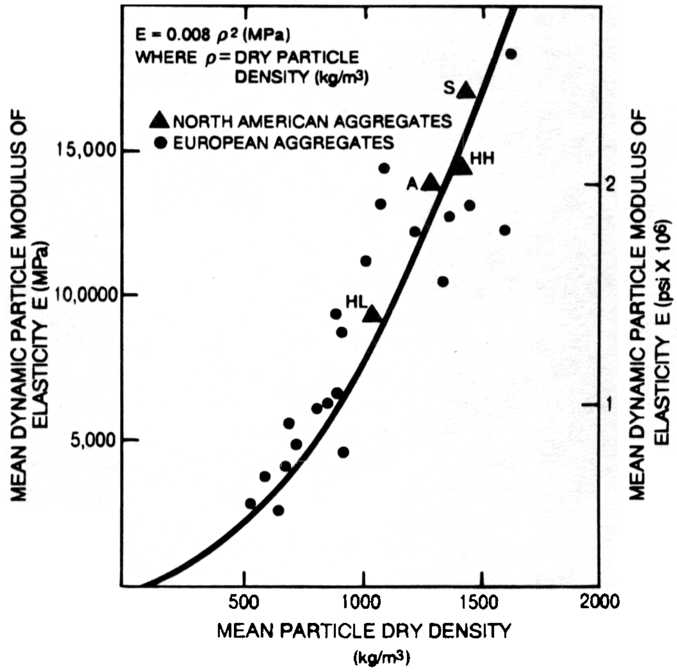


FIG. 2—Relationship between mean particle density and the mean dynamic modulus of elasticity for the particles of lightweight aggregate [*12*].

is approximately 30 GPa (4.35 × 10^6 psi) to 100 GPa (14.5 × 10^6 psi).

PROPERTIES AND PRODUCTION OF LIGHTWEIGHT AGGREGATE CONCRETE

Comprehensive reports detailing the properties of lightweight concretes and lightweight aggregates have been published by Shideler [*5*], Reichard [*6*], Holm [*7*], Carlson [*8*], and Valore [*9,10*]. The first three deal with structural-grade concretes, Carlson reported on lightweight aggregate for concrete masonry units, and Valore covered both structural and insulating concretes. In most instances, test procedures for measuring properties of lightweight concretes were the same as commonly used for normal-weight concretes. In limited cases, special test procedures particularly suited to measure lightweight concrete characteristics were developed.

PROPORTIONING

In general, proportioning rules and techniques used for ordinary concrete mixes apply to lightweight concrete with added attention given to concrete unit weight and the influence of the water absorption characteristics of the lightweight aggregate [*11*]. Most structural-grade lightweight concretes are proportioned by absolute volume methods in which the fresh concrete produced is considered equal to the sum of the absolute volumes of cement, aggregates, net water, and entrained air. Proportioning by this method requires the determination of absorbed and adsorbed moisture contents and the as-used specific gravity of the separate sizes of aggregates. A widely used alternative to the absolute volume procedures is to proportion lightweight concrete mixes by the damp loose volume method [*11*].

Specifications for structural-grade lightweight concrete usually require minimum values for compressive and tensile splitting strength, maximum limitations on slump, specified ranges of air content, and, finally, a limitation on maximum fresh unit weight. Reduction of concretes' high density leads to improved structural efficiency and is, therefore, an important consideration in proportioning lightweight concrete mixtures. While this property depends primarily on the specific gravity of the lightweight aggregates, it is also influenced to a lesser degree by cement, water, and air contents, and proportions of coarse-to-fine aggregate.

When lightweight aggregates contain levels of absorbed moisture greater than that developed after a one-day immersion, the rate of further absorption will be very low and for all practical purposes lightweight concrete may be batched, placed, and finished with the same facility as their normal-weight concrete counterparts. Under these conditions water/cement (w/c) ratios, while not normally specified, may be established with precision comparable to concretes containing normal-weight aggregates. Water absorbed within the lightweight aggregate prior to mixing is not available for calculating the volume of cement paste at the time of setting. This absorbed water is available, however, for continued cement hydration after external curing has ended. The general practice is to proportion the mix for a particular lightweight aggregate on the basis of a cement content at a given slump.

As with normal-weight concrete, air entrainment in lightweight concrete significantly improves durability and resistance to scaling. In concretes made with angular lightweight aggregates, it is also an effective means of improving workability of otherwise harsh mixtures. With moderate air contents, bleeding and segregation are reduced and mixing water requirements lowered while maintaining optimum workability. Because of the elastic compatibility of the lightweight aggregate and cementitious binder phases, strength reduction penalties due to high air contents will be lower for structural lightweight concrete than for normal-weight concretes [*12*]. Recommended ranges of total air content of usual structural lightweight concretes are shown in Table 3.

Air content of lightweight aggregate concretes is determined in accordance with the procedures of ASTM Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method (C 173). Volumetric measurements assure reliable results while pressure meters will provide erratic data due to the influence of aggregate porosity.

Air contents higher than are required for durability considerations are frequently developed for high thermal resistance, or for lowering unit weight of semi-structural "fill" concrete, with reduced compressive strength as a natural consequence. Use of water reducers, retarders, and superplasticizers will result in improved lightweight concrete characteristics in a manner similar to that of normal-weight concretes, however, superplasticizers, while effective, will increase the density of lightweight as well as other concretes.

MIXING, PLACING, FINISHING, AND CURING

When properly proportioned, structural lightweight concrete can be delivered and placed with the same facility as ordinary concretes. The most important consideration in handling any type of concrete is to avoid separation of coarse aggregate from the mortar fraction. Basic principles required to secure a well-placed lightweight concrete include:

(a) well-proportioned, workable mixes that use a minimum amount of free water;
(b) equipment capable of expeditiously moving the concrete;
(c) proper consolidation in the forms; and
(d) quality workmanship in finishing.

TABLE 3—Total Air Content for Lightweight Concretes.

Maximum Size of Aggregate	Air Content, % by volume
(20 mm) (3/4 in.)	4 to 8
(10 mm) (3/8 in.)	5 to 9

Well-proportioned structural lightweight concretes can be placed and screeded with less physical effort than that required for ordinary concrete. Excessive vibratation should be avoided, as this practice serves to drive the heavier mortar fraction down from the surface where it is required for finishing. On completion of final finishing, curing operations similar to ordinary concrete should begin as soon as possible. Lightweight concretes batched with aggregates having high absorptions carry their own internal water supply for curing within the aggregate and as a result are more forgiving to poor curing practices or unfavorable ambient conditions. This "internal curing" water is transferred from the lightweight aggregate to the mortar phase as evaporation takes place on the concrete surface, thus maintaining continuous moisture balance by replacing moisture essential for an extended continuous hydration period determined by ambient conditions and the as-batched lightweight aggregate moisture content.

Lightweight aggregates may absorb part of the mixing water when exposed to increased pumping pressures. To avoid loss of workability, it is essential to raise the presoak absorption level of lightweight aggregates prior to pumping. Presoaking is best accomplished at the aggregate production plant where uniform moisture content is achieved by applying water from spray bars directly to the aggregate moving on belts. This moisture content can be maintained and supplemented at the concrete plant by stockpile hose and sprinkler systems.

Presoaking will significantly reduce the lightweight aggregates' rate of absorption, minimizing water transfer from the mortar fraction that, in turn, causes slump loss during pumping. Higher moisture contents developed during presoaking will result in increased specific gravity that, in turn, develops higher fresh concrete unit weight. Higher water content due to presoaking will eventually diffuse out of the concrete, developing a longer period of internal curing as well as a larger differential between fresh and equilibrium unit weight than that associated with lightweight concretes placed with lower moisture contents. Aggregate suppliers should be consulted for mix design recommendations necessary for consistent pumpability.

LABORATORY AND FIELD CONTROL

Changes in lightweight aggregate moisture content, gradation, or specific gravity 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 consistency, fresh unit weight, and entrained-air content should be employed to verify conformance of field concretes with design mixes and the project specification. Sampling should be conducted in accordance with ASTM Practice for Sampling Freshly Mixed Concrete (C 172) and ASTM Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method (C 173). The ASTM Test Method for Unit Weight of Structural Lightweight Concrete (C 567) describes methods for calculating the in-service, equilibrium unit weight of structural lightweight concrete. In general, when variations in fresh density exceed ±2%, 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 specified values.

DENSITY OF STRUCTURAL LIGHTWEIGHT CONCRETE

Although there are numerous structural applications of all lightweight concretes (coarse and fine lightweight aggregate), usual commercial practice in North America is to design sanded lightweight concretes where part or all of the fine aggregates used is natural sand. Long-span bridges using concretes with three-way blends (coarse and fine lightweight aggregates and small supplemental natural sand volumes) have provided long-term durability and structural efficiency (density/strength ratios) [*14*]. Earliest research reports [*5,6,15,16*] compared all lightweight concretes with "reference" normal-weight concrete while later studies reported in Refs *13,17–19* supplemented the early findings with data based upon sanded lightweight concretes.

The fresh unit weight of lightweight aggregate concretes is a function of mix proportions, air contents, water demand, and the specific gravity 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 member. Design professionals should specify a maximum fresh density for lightweight concrete, as limits of acceptability should be controlled at time of placement.

Dead loads used for design should be based upon equilibrium density that, for most conditions and members, may be assumed to be reached after 90 days. Extensive tests conducted during North American durability studies demonstrated that despite wide initial variations of aggregate moisture content, equilibrium density was found to be 50 kg/m³ (3.1 lb/ft³) above oven-dry density (Fig. 3). European recommendations for in-service density are similar [*4*].

When weights and moisture contents of all the constituants of the batch of concrete are known, an approximate calculated equilibrium density may be determined according to ASTM C 567 from the following equation

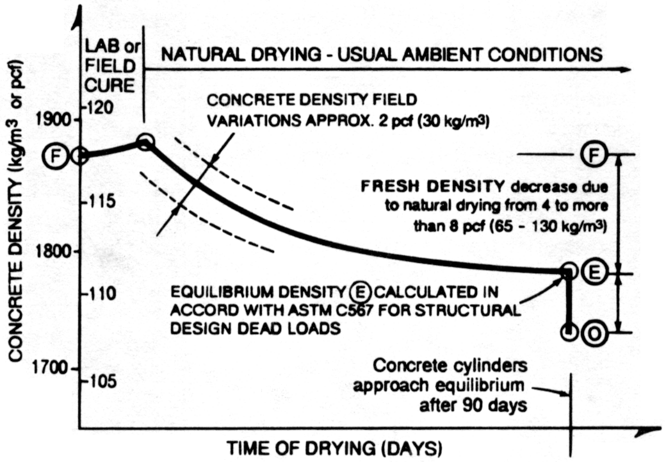
$$E = O + 50\ \text{kg/m}^3\ (E = O + 3\ \text{lb/ft}^3) \qquad (1)$$

where

$O = A + 1.2W$,
E = calculated equilibrium unit weight, kg/m³ (lb/ft³);
O = approximate oven-dry weight, kg/m³ (lb/ft³);
A = weight of dry aggregates in batch, kg (lb);
W = weight of cement in batch, kg (lb); and
1.2 = weight of hydrated water of hydration (estimated at 20% by weight of cement).

COMPRESSIVE STRENGTH

Compressive strength test procedures for structural lightweight aggregate concretes are similar to those for



Ⓕ **FRESH DENSITY**: Specified for field control (unit weight bucket). Measurements on 6" X 12" (150 X 300 mm) cylinders will average 2.5 pcf (40kg/m³) higher than field measurements on .5 pcf (.014 kg/m³) unit weight bucket.
Ⓔ **EQUILIBRIUM DENSITY**: Typically 3 pcf (50 kg/m³) greater than **OVEN DRY** Ⓞ

FIG. 3—Concrete density versus time of drying for structural lightweight concrete.

normal-weight concretes with the exception of the 21-day laboratory air 23°C (73.4°F) and 50% relative humidity drying period required by the procedures of ASTM Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (C 496) and ASTM C 567. While most structural-grade lightweight aggregates are capable of producing concretes with compressive strengths in excess of 35 MPa (5000 psi), a limited number of lightweight aggregates can be used in concretes that develop cylinder strengths from 48–69 MPa (7000 to 10 000 psi).

While compressive strengths of 21 to 35 MPa (3000 to 5000 psi) are common for cast-in-place structural lightweight concretes, 41 MPa (7000 psi) strengths are presently being specified for offshore applications. Light weight aggregate concrete will demonstrate a strength "ceiling" where further additions of cementitious materials will not significantly raise the maximum attainable strength. Strength ceilings that differ for each lightweight aggregate source are the result of pore size and distribution as well as the strength characteristics of the pore-free vitreous material surrounding the pores. The strength ceiling of a particular lightweight aggregate may be considerably increased by reduction of the top size in a particular grading formulation.

Compressive strength tests of lightweight insulating concrete having oven-dry unit weights not exceeding 800 kg/m³ (50 lb/ft³) are conducted in accordance with ASTM Test Method for Compressive Strength of Lightweight Insulating Concrete (C 495) on 75 × 150 mm (3 × 6 in.) cylinders. Twenty-five days after molding, the specimens are oven-dried at 60 ± 2.8°C (140 ± 5°F) for three days, cooled to room temperature, and tested for compressive strength at 28 days.

ASTM Methods of Securing, Preparing, and Testing Specimens from Hardened Lightweight Insulating Concrete for Compressive Strength (C 513) provides procedures for the determination of the compressive strength of cube specimens from hardened, field lightweight insulating concretes.

TENSILE STRENGTH

Shear, torsion, anchorage, bond strengths, and crack resistance are related to tensile strength that is, in turn, dependent upon tensile strength of the coarse aggregate and mortar phases and the degree to which the two phases are securely bonded. Traditionally, tensile strength has been defined as a function of compressive strength, but this is known to be only a first approximation that does not reflect aggregate particle strength, surface characteristics, nor the concrete's moisture content and distribution. The splitting tensile strength, as determined by ASTM C 496, is used throughout North America as a simple, practical design criteria that is known to be a more reliable indicator of tensile-related properties than beam flexural tests. Splitting tests are conducted by applying diametrically opposite compressive line loads to a concrete cylinder laid horizontally in a testing machine. A minimum tensile splitting strength of 2.0 MPa (290 psi) is a requirement for structural-grade lightweight aggregates conforming to the requirements of ASTM C 330.

Tests have shown that diagonal tensile strengths of beams and slabs correlate closely with the concrete splitting strengths [*20,21*]. As tensile splitting results vary for different combinations of materials, the specifier should consult with the aggregate suppliers for laboratory-developed splitting strength data. Special tensile strength test data should be developed prior to the start of unusual projects where development of early-age tensile-related handling forces occur as in precast or tilt-up members.

Tensile strength tests on structural lightweight concrete specimens that undergo some drying correlate better with the behavior of concrete in actual structures. Moisture loss progressing slowly into the interior of concrete members will result in the development of outer envelope tensile stresses that balance the compressive stresses in the still-moist interior zones. ASTM C 496 requires a seven-day moist and 21-day laboratory air drying at 23°C (73.4°F) and 50% relative humidity prior to conducting splitting tests. Structural-lightweight-concrete splitting tensile strengths vary from approximately 75 to 100% of normal-weight concretes of equal compressive strength. Replacing lightweight fine aggregate with normal-weight fines will normally increase tensile strength.

ELASTIC PROPERTIES

The modulus of elasticity of concrete is a function of the modulus of each constituent (binder matrix, expanded and normal density aggregates) and their relative mix proportion. The elastic modulus of normal-density concretes is higher because the moduli of the natural aggregate particles (and parent rock formations) are greater than the moduli of lightweight aggregate particles. For practical design conditions, the modulus of elasticity of concretes with densities between 1400 to 2500 kg/m³ (90 to 155 lb/

ft^3) and within normal strength ranges may be assumed to follow the formula [*1*,*4*]

$$E = 33\,p^{1.5}\sqrt{f_c} \qquad E = 0.04\,\sqrt{p^3 f_c} \tag{2}$$

where

E = denotes the secant modulus in psi (MPa),
p = the density in kg/m^3 (lb/ft^3), and
f_c = the compressive strength in MPa (psi) of a 150 by 300 mm (6 by 12 in.) cylinder (100 mm cube).

This or any other formula should be considered as only a first approximation, as the modulus is significantly affected (±25%) by moisture, aggregate type, and other variables. The formula clearly overestimates the modulus for high-strength lightweight concretes where limiting values are determined by the modulus of the lightweight aggregate. When design conditions require accurate elastic modulus data, laboratory tests should be conducted on specific concretes proposed for the project according to procedures of ASTM Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression (C 469).

Tests to determine Poisson's ratio by the static method for lightweight and sand-and-gravel concrete gave values that varied between 0.15 and 0.25 and averaged 0.20. Dynamic tests yielded slightly higher values [*6*]. A value of 0.20 may be assumed for design purposes for both types of concretes.

SHRINKAGE

As with ordinary concretes, shrinkage of structural lightweight concretes is principally determined by

(*a*) shrinkage characteristics of the cement paste fraction,
(*b*) internal restraint provided by the aggregate fraction,
(*c*) the relative absolute volume fractions occupied by the shrinkage medium (cement paste fraction) and the restraining skeletal structure (aggregate fraction), and
(*d*) humidity and temperature environments.

Aggregate characteristics influence cementitious binder quantities (the shrinking fraction) necessary to produce a required strength at a given slump. Particle strength, shape, and gradation influence water demand and directly determine the fractional volume and quality of the cement paste necessary to meet specified strength levels. Once that interaction has been established, it is the rigidity of the aggregate fraction that restrains shrinkage of the cement paste. When structural lightweight aggregate concretes are proportioned with cementitious binder amounts similar to that required for normal aggregate concretes, the shrinkage of lightweight concrete is generally, but not always, slightly greater than that of ordinary concrete due to the lower aggregate stiffness. The time rate of shrinkage strain development in structural lightweight concrete is slower, and the time required to reach a plateau of equilibrium is longer when the as-batched, lightweight-aggregate absorbed moisture is high. Maximum shrinkage strains of high-strength lightweight concretes are slightly greater than high-strength normal-weight concretes containing similar binder content [*22*].

ASTM C 330 limits shrinkage of structural lightweight concretes to less than 0.07% after 28 days of drying in a curing cabinet maintained at 37.8°C (100°F) at a relative humidity of 32%. Concrete mixtures used in the specimen prisms are prepared with a cement content of 335 kg/m^3 (564 lb/yd^3) with water contents necessary to produce a slump of 50 to 100 mm (2 to 4 in.) and air content of 6 ± 1%. Specimens are removed from the molds at one day, and moisture cured until seven days at which time the accelerated drying is initiated.

Shrinkage of block concrete is limited to 0.10% when determined in accordance with procedures outlined in ASTM C 331. The ASTM Test Method for Length Change of Hardened Hydraulic Cement Mortar and Concrete (C 157) is followed using fixed proportions of one part cement to six parts aggregate by dry loose volumes, with sufficient water to produce a slump of 50 to 76 mm (2 to 3 in.). Initial length measurements are made after seven days moist storage with final shrinkage measurements at the age of 100 days after storage in laboratory air at 23°C (73.4°F) and 50% relative humidity.

CREEP

Time-related increases in concrete strain due to sustained stress can be measured according to procedures of ASTM Test Method for Creep of Concrete in Compression (C 512). Creep and shrinkage characteristics on any concrete type are principally influenced by aggregate characteristics, water and cement content (paste volume fraction), age at time of loading, type of curing, and applied stress-to-strength ratio. Other second-level variables also influence creep and shrinkage but to a lesser degree. As creep and shrinkage strains will cause increase in long-time deflections, loss of prestress, reduction in stress concentration, and changes in camber, it is essential for design engineers to have an accurate assessment of these time-related characteristics as a necessary design input. ACI Committee 213 [*11*] demonstrates wide envelopes of one-year specific creep values for low-strength all-lightweight, normally cured concretes. Test results for higher-strength, steam-cured sanded-lightweight concretes have a range of values that narrows significantly and closely envelopes the performance of the normal-weight "reference" concrete. These values are principally based upon the results of the comprehensive testing program of Shideler [*5*]. Long-term investigations by Troxell [*23*] on normal-weight concretes report similar wide envelopes of results for differing natural aggregate types so comparisons with "reference" concretes should be based upon data specific to the concretes considered.

Additional large-scale creep testing programs are reported in Refs 7 and *19*, and Valore [*10*] has provided a comprehensive report that also includes European data on structural as well as insulating-grade lightweight concretes.

DURABILITY

Numerous accelerated freeze/thaw testing programs conducted on structural lightweight concrete in North

America [*24,25*] and in Europe [*4*] researching the influence of entrained-air volume, cement content, aggregate moisture content, specimen drying times, and testing environment have arrived at similar conclusions: air-entrained lightweight concretes proportioned with high-quality binder provide satisfactory durability results when tested under usual laboratory freeze/thaw programs. Observations of the resistance to deterioration in the presence of deicing salts on mature bridges indicate similar performance between structural lightweight and normal-weight concretes [*3*]. Comprehensive investigations into the long-term weathering performance of bridge decks [*26*] and marine structures [*27*] exposed for many years to severe environments support the findings of laboratory investigations and suggest that properly proportioned and placed lightweight concretes perform equal to or better than normal-weight concretes.

Core samples taken from hulls of 70-year-old lightweight concrete ships as well as 30- to 40-year-old lightweight concrete bridges have demonstrated concretes with high integrity contact zone between aggregate and the matrix with low levels of microcracking. Explanation of this proven record of high resistance to weathering and corrosion is due to several physical and chemical mechanisms including superior contact zone resistance to microcracking developed by significantly higher aggregate/matrix adhesion as well as internal stress reduction due to elastic matching of coarse aggregate and matrix phases. High ultimate strain capacity is also provided by concretes with a high strength/modulus ratios. The ratio at which the disruptive dilation of concrete starts is higher for lightweight concrete than for equal strength normal-weight concrete. A well-dispersed void system provided by the lightweight fine aggregates may also assist the air entrainment pore system and serve an absorption function by reducing salt concentration levels in the matrix phase [*27*].

Long-term pozzolanic action is provided when the silica-rich expanded aggregate combines with calcium hydroxide liberated during cement hydration. This will minimize leaching of soluble compounds and may also reduce the possibility of sulphate salt disruptive behavior [*28*].

It is widely recognized that while ASTM Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666) provides a useful comparative testing procedure, there remains an inadequate correlation between accelerated laboratory test results and the observed behavior of mature concretes exposed to natural freezing and thawing. The inadequate laboratory/field correlation observed for normal-weight concrete is compounded when interpreting results from laboratory tests on structural lightweight concretes prepared with aggregate moisture contents typical of commercial operations. A proposed modification to ASTM C 666 [*29*] suggests that a 14-day air-drying period prior to the first freezing cycle will improve correlation between laboratory test data and observed field performance. Durability characteristics of any concrete, both normal weight and lightweight, are primarily determined by the protective qualities of the cement paste matrix. It is imperative that permeability characteristics of the concrete matrix be of high quality in order to protect steel reinforcing from corrosion, which is clearly the dominant form of structural deterioration observed in current construction. The matrix protective quality of concretes proportioned for thermal resistance by using high-air and low-cement contents will be significantly reduced. Very low density, non-structural concretes will not provide resistance to the intrusion of chlorides, carbonation, etc., comparable to the long-term satisfactory performance demonstrated with high-quality, structural-grade lightweight concretes [*29*].

For a number of years, field exposure testing programs have been conducted by the Canadian Department of Minerals, Energy and Technology (CANMET) on various types of concretes exposed to a cold marine environment at the Treat Island Severe Weather Exposure Station maintained by the U.S. Army Corps of Engineers at Eastport, Maine [*29*]. Concrete specimens placed on a mid-tide wharf experience alternating conditions of seawater immersion followed by cold air exposure at low tide. In typical winters, the specimens experience about 100 cycles of freezing and thawing. In 1978, a series of prisms were cast using commercial normal-weight aggregates with various cement types and including supplementary cementitious materials. Water-to-cement ratios of 0.40, 0.50, and 0.60 were used to produce 28-day compressive strengths of 30, 26 and 24 MPa (4350, 3770, and 3480 psi), respectively. In 1980, these mixes were essentially repeated with the exception being that the 40 mm (1½ in.) gravel aggregate was replaced with a 25 mm (1 in.) expanded-shale lightweight aggregate. Fine aggregates used in both 1978 and 1980 were commercially available natural sands. Cement contents for the semi-lightweight concrete mixtures were approximately 480, 360 and 240 kg/m^3 (800, 600, and 400 lb/yd^3) that produced compressive strengths of 36, 30 and 19 MPa (5220, 4350, and 2755 psi), respectively. All specimens continue to be evaluated annually for ultrasonic pulse velocity and resonant frequence as well as being rated visually. Ultrasonic pulse velocities are measured centrally along the long axis of the prisms. There were no significant differences between the structural lightweight concrete (eight years) and normal-weight concrete (ten years) after exposure to twice-daily seawater submersion and approximately 1000 cycles of freezing and thawing [*29*].

CHEMICAL REACTION

ACI Committee 201 on Durability of Concrete reports no documented instance of in-service distress caused by alkali reactions with lightweight aggregate. Mielenz [*30*] indicates that although the potential exists for alkali aggregate reaction with some natural lightweight aggregates and expanded perlite, the volume change may be accommodated without necessarily causing structural distress. Granulated blast furnace slag has been shown to be an effective inhibitor of such reactions [*31*], and the fine aggregate fractions of expanded shales, clays, and slates are known to be pozzolanic and may also serve to inhibit disruptive expansion. Bremner [*32*] reports that no evidence of alkali lightweight aggregate reaction was observed in tests conducted on 70-year-old marine and more than 30-year-old lightweight concrete bridge decks.

POPOUTS

Popouts may result from delayed disruptive expansions caused by the slow hydration of particles of hard-burned lime or magnesia, calcium sulfate, or unstable iron compounds. To test for the presence of these materials, concrete bars prepared by methods similar to those used for the shrinkage tests are cured and tested according to the procedures of ASTM Test Method for Autoclave Expansion of Portland Cement (C 151). No popouts are permitted by ASTM C 331 and C 330 since this disruptive expansion would cause unacceptable aesthetic blemishes on exposed concrete and masonry.

ABRASION RESISTANCE

Abrasion resistance of concrete depends on strength, hardness, and toughness characteristics of the cement paste and the aggregates, as well as on the bond between these two phases. Most lightweight aggregates suitable for structural concretes are composed of solidified glassy material comparable to quartz on the Moh scale of hardness. However, due to its porous system, the net resistance to wearing forces may be less than that of a solid particle of most natural aggregates. Structural-lightweight-concrete bridge decks that have been subjected to more than 100 million vehicle crossings including truck traffic show wearing performance similar to that of normal-weight concretes [*33*]. Limitations are necessary in certain commercial applications where steel-wheeled industrial vehicles are used, but such surfaces generally receive specially prepared surface treatments. Hoff [*34*] reports that specially developed testing procedures that measured ice abrasion of concrete exposed to arctic conditions demonstrated essentially similar performance for lightweight and normal-weight concretes.

BOND STRENGTH AND DEVELOPMENT LENGTH

Field performance has demonstrated satisfactory performance for lightweight concrete with respect to bond and development length. Because of the lower particle strength, lightweight concretes have somewhat lower bond splitting capacities than normal-weight concrete. Usual North American design practice (ACI 318 Standard Building Code for Reinforced Concrete) is to dispense with concepts of bond and require slightly longer embedment lengths for reinforcement in lightweight concretes than that required for normal-weight concrete.

FIRE RESISTANCE

When tested according to the procedures of ASTM Method for Fire Tests of Building Construction and Materials (E 119), structural lightweight aggregate concrete slabs, walls, and beams have demonstrated greater fire endurance periods than equivalent thickness members made with normal-weight aggregates (Fig. 4). Superior performance is due to a combination of lower thermal conductivity (lower temperature rise on unexposed surfaces), lower coefficient of thermal expansion (lower forces developed under restraint), and the inherent thermal stability developed by aggregates that have been exposed to temperatures greater than 1093°C (2000°F) during pyroprocessing.

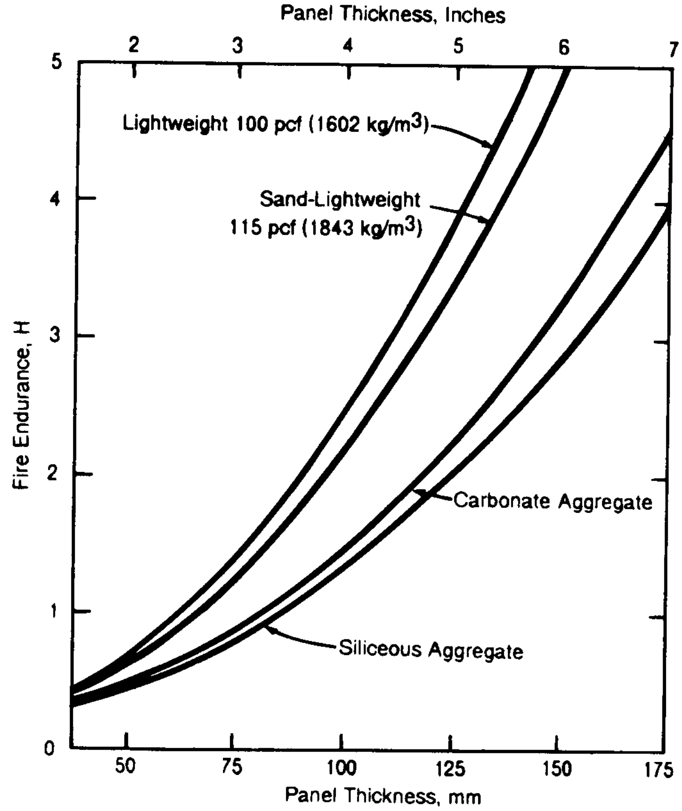


FIG. 4—Fire endurance (heat transmission) of concrete slabs as a function of thickness for naturally dried specimens [*11*].

Acknowledgments

The principal sources of information for this chapter include the *Guide for Structural Lightweight Aggregate Concrete* (ACI 213) [*11*], ACI 318 Building Code Requirements for Reinforced Concrete [*1*], the CEB-FIP Manual of Design and Technology: *Lightweight Aggregate Concrete* [*4*], and the *Handbook of Structural Concrete* [*7*]. References to specific building codes and national standards are incorporated because these recommendations have resulted in the satisfactory field service of structural lightweight concrete structures.

REFERENCES

[*1*] "Standard Building Code for Reinforced Concrete," ACI Committee 318, American Concrete Institute, Detroit, MI, 1989.

[*2*] Valore, R. C., Jr., "Calculation of U-Values of Hollow Concrete Masonry," *Journal*, American Concrete Institute, Detroit, MI, Feb. 1980.

[*3*] Holm, T. A., Bremner, T. W., and Newman, J. B., "Lightweight Aggregate Concrete Subject to Severe Weathering," *Concrete International*, June 1984.

[*4*] *Lightweight Aggregate Concrete*, CEB-FIP Manual of Design and Technology, Construction Press, Lancaster, UK, 1977.

[*5*] Shideler, J. J., "Lightweight Aggregate Concrete for Structural Use," *Journal*, American Concrete Institute, Oct. 1957; *Proceedings*, Vol. 54, pp. 298–328.

[*6*] Reichard, T. W., "Creep and Drying Shrinkage of Lightweight and Normal Weight Concretes," National Bureau of Standards, Monograph 74, U.S. Department of Commerce, Washington, DC, 4 March 1964.

[*7*] Holm, T. A., "Structural Lightweight Concrete," *Handbook of Structural Concrete*, Chapter 7, McGraw-Hill, New York, 1983.

[*8*] Carlson, C. C., "Lightweight Aggregates for Masonry Units," *Journal*, American Concrete Institute, Nov. 1956; *Proceedings*, Vol. 53, pp. 383–402.

[*9*] Valore, R. C., Jr., "Insulating Concretes," *Journal*, American Concrete Institute, Nov. 1956; *Proceedings*, Vol. 53, pp. 509–532.

[*10*] Valore, R. C., Jr., "North American Lightweight Concretes," *Concrete in Housing-Today and Tomorrow*, Warsaw, Poland, Sept. 1973.

[*11*] *Guide for Structural Lightweight Aggregate Concrete*, ACI Committee 213, American Concrete Institute, Detroit, MI, 1987.

[*12*] Bremner, T. W. and Holm, T. A., "Elastic Compatibility and the Behavior of Concrete," *Journal*, American Concrete Institute, March/April 1986.

[*13*] Hansen, J. A., "Replacement of Lightweight Aggregate Fines with Natural Sand in Structural Concrete," *ACI Journal Proceedings*, American Concrete Institute, Vol. 61, No. 7, July 1964.

[*14*] Holm, T. A. and Bremner, T. W., "70 Year Performance Record for High Strength Structural Lightweight Concrete," *Proceedings*, First Materials Engineering Congress, Materials Engineering Division, American Society of Civil Engineers, Denver, CO, Aug. 1990.

[*15*] Price, W. H. and Cordon, W. A., "Tests of Lightweight Aggregate Concrete Designed for Monolithic Construction," *Journal*, American Concrete Institute, April 1949; *Proceedings*, Vol. 45, pp. 581–600.

[*16*] Kluge, R. W., Spanks, M. M., and Tuma, E. C., "Lightweight Aggregate Concrete," *ACI Journal Proceedings*, American Concrete Institute, Vol. 45, No. 9, May 1949.

[*17*] Pfeifer, D. W., "Sand Replacement in Structural Lightweight Concrete-Splitting Tensile Strength," *ACI Journal Proceedings*, American Concrete Institute, Vol. 64, No. 7, July 1967.

[*18*] Pfeifer, D. W., "Sand Replacement in Structural Lightweight Concrete-Freezing and Thawing Tests," *ACI Journal Proceedings*, American Concrete Institute, Vol. 64, No. 11, Nov. 1967.

[*19*] Pfeifer, D. W., "Sand Replacement in Structural Lightweight Concrete-Creep and Shrinkage Studies," *ACI Journal Proceedings*, American Concrete Institute, Vol. 65, No. 2, Feb. 1968.

[*20*] Hansen, J. A., "Shear Strength of Reinforced Lightweight Concrete Beams," *ACI Journal Proceedings*, American Concrete Institute, Vol. 55, No. 3, Sept. 1958.

[*21*] Hansen, J. A., "Tensile Strength and Diagonal Tension Resistance of Structural Lightweight Concrete," *Journal*, American Concrete Institute, July 1961; *Proceedings*, Vol. 58, pp. 1–37.

[*22*] Holm, T. A., "Physical Properties of High Strength Lightweight Aggregate Concretes," *Proceedings*, Second International Congress of Lightweight Concrete, London, April 1980.

[*23*] Troxell, G. E., Raphael, J. M., and Davis, R. E., "Long Time Creep and Shrinkage Tests of Plain and Reinforced Concrete," *Proceedings*, Vol. 58, American Society for Testing and Materials, Philadelphia, 1958.

[*24*] Klieger, P. and Hansen, J. A., "Freezing and Thawing Tests of Lightweight Aggregate Concrete," *Journal*, American Concrete Institute, Jan. 1961.

[*25*] "Freeze-Thaw Durability of Structural Lightweight Concrete," Lightweight Concrete Information Sheet No. 13, Expanded Shale Clay & Slate Institute, Salt Lake City, 1970.

[*26*] Walsh, R. J., "Restoring Salt Damaged Bridges," *Civil Engineering*, May 1967.

[*27*] Holm, T. A., "Performance of Structural Lightweight Concrete in a Marine Environment," *Performance of Concrete in a Marine Environment*, ACI SP-65, American Concrete Institute, International Symposium, St. Andrews-By-The-Sea, Canada, Aug. 1980.

[*28*] Bremner, T. W., Holm, T. A., and deSouza, H., "Aggregate-Matrix Interaction in Concrete Subject to Severe Exposure," FIP-CPC International Symposium on Concrete Sea Structures in Arctic Regions, Calgary, Canada, 29 Aug. 1984.

[*29*] Holm, T. A. and Bremner, T. W., "The Durability of Structural Lightweight Concrete," *Durability of Concrete*, ACI SP-126, American Concrete Institute, Second International Conference, Montreal, Canada, Aug. 1991.

[*30*] Mielenz, R. C., "Chapter 33—Petrographic Examination," *Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM STP 169B*, American Society for Testing and Materials, Philadelphia, 1978.

[*31*] Pepper, L. and Mather, B., "Effectiveness of Mineral Admixtures in Preventing Excessive Expansion of Concrete Due to Alkali-Aggregate Reaction," *Proceedings*, American Society for Testing and Materials, Philadelphia, Vol. 59, 1959, pp. 1178–1202.

[*32*] Bremner, T. W., "Alkali-Aggregate Tests on Structural Lightweight Aggregate Concrete," unpublished private communication, Nov. 1991.

[*33*] "Criteria for Designing Lightweight Concrete Bridges," Federal Highway Administration Report No. FHWA/RD-85/045, Final Report, McLean, VA, Aug. 1985.

[*34*] Hoff, G. C., "High Strength Lightweight Aggregate Concrete for Arctic Applications," *Proceedings*, symposium on the Performance of Structural Lightweight Concrete, American Concrete Institute, Detroit, MI, Nov. 1991.