Guide for Structural Lightweight-Aggregate Concrete

Reported by ACI Committee 213

John P. Ries, Chair — G. Michael Robinson, Secretary

David J. Akers	Ralph D. Gruber	Bruce W. Ramme
Michael J. Boyle	Jiri G. Grygar	Steven K. Rowe
Theodore W. Bremner	Edward S. Kluckowski	Shelley R. Sheetz
Ronald G. Burg	Mervyn J. Kowalsky	Peter G. Snow
David A. Crocker	Michael L. Leming	Jeffrey F. Speck
Calvin L. Dodl	W. Calvin McCall	William X. Sypher
Per Fidjestol	Avi A. Mor	Alexander M. Vaysburd
Dean M. Golden	Dipak T. Parekh	Ming-Hong Zhang

Special thanks goes to the following associate members for their contribution to the revision of this document: Kevin Cavanaugh, Shawn P. Gross, Thomas A. Holm, Henry J. Kolbeck, David A. Marshall, Hesham Marzouk, Karl F. Meyer, Jessica S. Moore, Tarun R. Naik, Robert D. Thomas, Victor H. Villarreal, Jody R. Wall, and Dean J. White, II.

The guide summarizes the present state of technology. It presents and interprets the data on lightweight-aggregate concrete from many laboratory studies, accumulated experience resulting from successful use, and the performance of structural lightweight-aggregate concrete in service.

This guide includes a definition of lightweight-aggregate concrete for structural purposes, and discusses, in condensed fashion, the production methods for and inherent properties of structural lightweight aggregates. Other chapters follow on current practices for proportioning, mixing, transporting, and placing; properties of hardened concrete; and the design of structural concrete with reference to ACI 318.

Keywords: abrasion resistance; aggregate; bond; contact zone; durability; fire resistance; internal curing; lightweight aggregate; lightweight concrete; mixture proportion; shear; shrinkage; specified density concrete; strength; thermal conductivity.

FOREWORD

This guide covers the unique characteristics and performance of structural lightweight-aggregate concrete. General historical information is provided along with detailed information on lightweight aggregates and proportioning, mixing, and placing of concrete containing these aggregates. The physical properties of the structural lightweight aggregate along with design information and applications are also included.

Structural lightweight concrete has many and varied applications, including multistory building frames and floors, curtain walls, shell roofs, folded plates, bridges, prestressed or precast elements of all types, marine structures, and others. In many cases, the architectural expression of form combined with functional design can be achieved more readily with structural lightweight concrete than with any other medium. Many architects, engineers, and contractors recognize the inherent economies and advantages offered by this material, as evidenced by the many impressive lightweight concrete structures found today throughout the world.

CONTENTS

Chapter 1—Introduction, p. 213R-2

1.1—Objectives

ACI 213R-03 supersedes ACI 213R-87 (Reapproved 1999) and became effective September 26, 2003.

1.2—Historical background
1.3—Terminology
1.4—Economy of lightweight concrete

Chapter 2—Structural lightweight aggregates, p. 213R-5
2.1—Internal structure of lightweight aggregates
2.2—Production of lightweight aggregates
2.3—Aggregate properties

Chapter 3—Proportioning, mixing, and handling, p. 213R-8
3.1—Scope
3.2—Mixture proportioning criteria
3.3—Materials
3.4—Proportioning and adjusting mixtures
3.5—Mixing and delivery
3.6—Placing
3.7—Pumping lightweight concrete
3.8—Laboratory and field control

Chapter 4—Physical and mechanical properties of structural lightweight-aggregate concrete, p. 213R-12
4.1—Scope
4.2—Method of presenting data
4.3—Compressive strength
4.4—Density of lightweight concrete
4.5—Specified-density concrete
4.6—Modulus of elasticity
4.7—Poisson's ratio
4.8—Creep
4.9—Drying shrinkage
4.10—Splitting tensile strength
4.11—Modulus of rupture
4.12—Bond strength
4.13—Ultimate strength factors
4.14—Durability
4.15—Absorption
4.16—Alkali-aggregate reaction
4.17—Thermal expansion
4.18—Heat flow properties
4.19—Fire endurance
4.20—Abrasion resistance

Chapter 5—Design of structural lightweight-aggregate concrete, p. 213R-24
5.1—Scope
5.2—General considerations
5.3—Modulus of elasticity
5.4—Tensile strength
5.5—Shear and diagonal tension
5.6—Development length
5.7—Deflection
5.8—Columns
5.9—Prestressed lightweight concrete
5.10—Thermal design considerations
5.11—Seismic design
5.12—Fatigue
5.13—Specifications

Chapter 6—High-performance lightweight concrete, p. 213R-30
6.1—Scope and historical developments
6.2—Structural efficiency of lightweight concrete
6.3—Applications of high-performance lightweight concrete
6.4—Reduced transportation cost
6.5—Enhanced hydration due to internal curing

Chapter 7—References, p. 213R-35
7.1—Referenced standards and reports
7.2—Cited references
7.3—Other references

CHAPTER 1—INTRODUCTION

1.1—Objectives

The objectives of this guide are to provide information and guidelines for designing and using lightweight concrete. By using such guidelines and construction practices, the structures can be designed and performance predicted with the same confidence and reliability as normalweight concrete and other building materials.

1.2—Historical background

The first known use of lightweight concrete dates back over 2000 years. There are several lightweight concrete structures in the Mediterranean region, but the three most notable structures were built during the early Roman Empire and include the Port of Cosa, the Pantheon Dome, and the Coliseum.

The Port of Cosa, built in about 273 B.C., used lightweight concrete made from natural volcanic materials. These early builders learned that expanded aggregates were better suited for marine facilities than the locally available beach sand and gravel. They went 25 mi. (40 km) to the northeast to quarry volcanic aggregates at the Volcine complex for use in the harbor at Cosa (Bremner, Holm, and Stepanova 1994). This harbor is on the west coast of Italy and consists of a series of four piers (~ 13 ft [4 m] cubes) extending out into the sea. For two millennia they have withstood the forces of nature with only surface abrasion. They became obsolete only because of siltation of the harbor.

The Pantheon, finished in 27 B.C., incorporates concrete varying in density from the bottom to the top of the dome. Roman engineers had sufficient confidence in lightweight concrete to build a dome whose diameter of 142 ft (43.3 m) was not exceeded for almost two millenniums. The structure is in excellent condition and is still being used to this day for spiritual purposes (Bremner, Holm, and Stepanova 1994).

The dome contains intricate recesses formed with wooden formwork to reduce the dead load, and the imprint of the grain of the wood can still be seen. The excellent cast surfaces that are visible to the observer show clearly that these early builders had successfully mastered the art of casting concrete made with lightweight aggregates. Vitruvius took special interest in building construction and commented on what was unusual. The fact that he did not single out lightweight concrete for comment might simply imply that these early builders were fully familiar with this material (Morgan 1960).

The Coliseum, built in 75 to 80 A.D., is a gigantic amphitheater with a seating capacity of 50,000 spectators. The foundations were cast with lightweight concrete using crushed volcanic lava. The walls were made using porous, crushed-brick aggregate. The vaults and spaces between the walls were constructed using porous-tufa cut stone. After the fall of the Roman Empire, lightweight concrete use was limited until the 20th century when a new type of manufactured, expanded shale, lightweight aggregate became available for commercial use.

Stephen J. Hayde, a brick manufacturer and ceramic engineer, invented the rotary kiln process of expanding shale, clay, and slate. When clay bricks are manufactured, it is important to heat the preformed clay slowly so that evolved gases have an opportunity to diffuse out of the clay. If they are heated too rapidly, a "bloater" is formed that does not meet the dimensional uniformity essential for a successfully fired brick. These rejected bricks were recognized by Hayde as an ideal material for making a special concrete. When reduced to appropriate aggregate size and grading, these bloated bricks could be used to produce a lightweight concrete with mechanical properties similar to regular concrete. After almost a decade of experimentation, in 1918 he patented the process of making these aggregates by heating small particles of shale, clay, or slate in a rotary kiln. A particle size was discovered that, with limited crushing, produced an aggregate grading suitable for making lightweight concrete (ESCSI 1971).

Commercial production of expanded slag began in 1928, and in 1948 the first structural-quality, sintered-shale, lightweight aggregate was produced using shale in eastern Pennsylvania.

One of the earliest uses of reinforced lightweight concrete was in the construction of ships and barges around 1918. The U.S. Emergency Fleet Building Corporation found that, for concrete to be effective in ship construction, the concrete would need a maximum density of about 110 lb/ft^3 (1760 kg/m^3) and a compressive strength of approximately 4000 psi (28 MPa). Concrete was obtained with a compressive strength of approximately 5000 psi (34 MPa) and a unit weight of 110 lb/ft^3 (1760 kg/m^3) or less using rotary-kiln-produced expanded shale and clay aggregate.

Considerable impetus was given to the development of lightweight concrete in the late 1940s when a National Housing Agency survey was conducted on the potential use of lightweight concrete for home construction. This led to an extensive study of concrete made with lightweight aggregates. Sponsored by the Housing and Home Finance Agency, parallel studies were conducted simultaneously in the laboratories of the National Bureau of Standards (Kluge, Sparks, and Tuma 1949) and the U.S. Bureau of Reclamation (Price and Cordon 1949) to determine properties of concrete made with a broad range of lightweight aggregate types. These studies and earlier works focused attention on the potential structural use of some lightweight-aggregate concrete and initiated a renewed interest in lightweight members for building frames, bridge decks, and precast products in the early 1950s. Following the collapse of the original Tacoma Narrows Bridge, the replacement suspension structure design used lightweight concrete in the deck to incorporate additional roadway lanes without the necessity of replacing the original piers.

During the 1950s, many multistory structures were designed from the foundations up, taking advantage of reduced dead weight using lightweight concrete. Examples are the 42-story Prudential Life Building in Chicago, which used lightweight concrete floors, and the 18-story Statler Hilton Hotel in Dallas, designed with a lightweight concrete frame and flat plate floors.

These structural applications stimulated more-concentrated research into the properties of lightweight concrete. In energy-related floating structures, great efficiencies are achieved when a lightweight material is used. A reduction of 25% in mass in reinforced normalweight concrete will result in a 50% reduction in load when submerged. Because of this, the oil and gas industry recognized that lightweight concrete could be used to good advantage in its floating structures as well as structures built in a graving dock and then floated to the production site and bottom-founded. To provide the technical data necessary to construct huge offshore concrete structures, a consortium of oil companies and contractors was formed to evaluate lightweight aggregate candidates suitable for making high-strength lightweight concrete that would meet their design requirements. The evaluations started in the early 1980s, with the results made available in 1992. As a result of this research, design information became readily available and has enabled lightweight concrete to be used for new and novel applications where high strength and high durability are desirable (Hoff 1992).

1.3—Terminology

Aggregate, insulating—*Nonstructural aggregate meeting the requirements of ASTM C 332*. This includes Group I aggregate, Perlite with a bulk density between 7.5 and 12 lb/ft^3 (120 and 192 kg/m^3), Vermiculite with a bulk density between 5.5 and 10 lb/ft^3 (88 and 160 kg/m^3), and group II aggregate that meets the requirements of ASTM C 330 and ASTM C 331. (See **aggregate**, **structural-lightweight**, and **aggregate**, **masonry-lightweight**.)

Aggregate, lightweight—See **aggregate**, **structural lightweight**; **aggregate**, **masonry lightweight**; or **aggregate, insulating**.

Aggregate, masonry-lightweight (MLWA)—*Aggregate meeting the requirements of ASTM C 331 with bulk density less than 70 lb/ft^3 (1120 kg/m^3) for fine aggregate and less than 55 lb/ft^3 (880 kg/m^3) for coarse aggregate*. This includes aggregates prepared by expanding, pelletizing, or sintering products such as blast-furnace slag, clay, diatomite, fly ash, shale, or slate; aggregates prepared by processing natural materials such as pumice, scoria, or tuff; and aggregates derived from and products of coal or coke combustion.

Aggregate, structural lightweight (SLA)—*Structural aggregate meeting the requirements of ASTM C 330 with bulk density less than 70 lb/ft^3 (1120 kg/m^3) for fine aggregate and less than 55 lb/ft^3 (880 kg/m^3) for coarse aggregate*. This includes aggregates prepared by expanding, pelletizing, or sintering products such as blast-furnace slag, clay, fly ash, shale or slate, and aggregates prepared by processing natural materials such as pumice, scoria or tuff.

Aggregate, low-density—See **aggregate**, **structural lightweight**.

Concrete, all lightweight—Concrete in which both the coarse- and fine-aggregate components are lightweight aggregates. (Deprecated term—use preferred term; **concrete**, **lightweight**; **concrete**, **structural lightweight**; or **concrete**, **specified-density**.)

Concrete, high-strength lightweight—Structural lightweight concrete with a 28-day compressive strength of 6000 psi (40 MPa) or greater.

Concrete, lightweight—See **concrete**, **structural lightweight** or **specified density**.

Concrete, low-density—See **concrete, lightweight**.

Concrete, normalweight—Concrete having a density of 140 to 155 lb/ft^3 (2240 to 2480 kg/m^3) made with ordinary aggregates (sand, gravel, crushed stone).

Concrete, sand lightweight—Concrete with coarse lightweight aggregate and normalweight fine aggregate. (Deprecated term—use preferred term; **concrete**, **structural lightweight**; **concrete**, **lightweight**; or **concrete, specified-density**.)

Concrete, specified density (SDC)—Structural concrete having a specified equilibrium density between 50 to 140 lb/ft^3 (800 to 2240 kg/m^3) or greater than 155 lb/ft^3 (2480 kg/m^3) (see **concrete, normalweight**). SDC may consist as one type of aggregate or of a combination of lightweight or normal-density aggregate. This concrete is project specific and should include a detailed mixture testing program and aggregate supplier involvement before design.

Concrete, structural lightweight aggregate—See **concrete, structural lightweight**.

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

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

Contact zone—The transitional layer of material connecting aggregate particles with the enveloping continuous mortar matrix.

Curing, internal—Internal curing refers to the process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water. The internal water is made available by the pore system in structural lightweight aggregate that absorbs and releases water.

Density, equilibrium—As defined in ASTM 567, it is the density reached by structural lightweight concrete (low density) after exposure to relative humidity of 50 ± 5% and a temperature of 73.5 ± 3.5 °F (23 ± 2 °C) for a period of time sufficient to reach a density that changes less than 0.5% in a period of 28 days.

Density, oven-dry—As defined in ASTM C 567, the density reached by structural lightweight concrete after being placed in a drying oven at 230 ± 9 °F (110 ± 5 °C) for a period of time sufficient to reach a density that changes less than 0.5% in a period of 24 h. The oven-dry density test is to be performed at the age specified.

Lightweight — The generic name of a group of aggregates having a relative density lower than normal-density aggregates. (See **aggregate**, **lightweight**). The generic name of concrete or concrete products having lower densities than normalweight concrete products. (See **concrete**, **structural lightweight**, and **concrete**, **lightweight**).

1.4—Economy of lightweight concrete

The use of lightweight concrete is usually predicated on the reduction of project cost, improved functionality, or a combination of both. Estimating the total cost of a project is necessary when considering lightweight concrete because the cost per cubic yard (cubic meter) is usually higher than a comparable unit of ordinary concrete. The following example is a typical comparison of unit cost between lightweight and normalweight concrete on a bridge project.

For example, assume the in-place cost of a typical short-span bridge may vary from 50 to 200 \$/ft^2 (540 to 2150 \$/m^2).

If the average thickness of the deck was 8 in. (200 mm) then one cubic yard (cubic meter) of concrete would yield approximately 40 ft^2/yd^3 (5 m^2/m^3).

The increased cost of using lightweight concrete with a cost of 20 \$/yd^3 (26 \$/m^3) over normalweight concrete would be 20 \$/yd^3/40 ft^2/yd^3 = 0.50 \$/ft^2 (5 \$/m^2), or generally less than a 1% increase.

This increase would easily be offset by any of the following economies, or more importantly, by significant increases in bridge, building, or marine structure functionality:

- The reduction in foundation loads may result in smaller footings, fewer piles, smaller pile caps, and less reinforcing;
- Reduced dead loads may result in smaller supporting members (decks, beams, girder, and piers), resulting in a major reduction in cost;
- Reduced dead load will mean reduced inertial seismic forces;
- In bridge rehabilitation, the new deck may be wider or an additional traffic lane may be added without structural or foundation modification;
- On bridge deck replacements or overlays, the deck may be thicker to allow more cover over reinforcing or to provide better drainage without adding additional dead load to the structure;
- With precast-prestress use, longer or larger elements can be manufactured without increasing overall mass. This may result in fewer columns or pier elements in a

Table 1.1—Analysis of shipping costs of concrete products*

	Project Example No. 1	Project Example No. 2
Shipping cost per truck load	$1100	$1339
Number of loads required		
Normalweight	431	87
Lightweight	287	66
Reduction in truck loads:	144	21
Transportation savings		
Shipping cost per load	$1100	$1339
Reduction in truck loads	× 144	× 21
Transportation savings:	$158,400	$28,119
Profit impact		
Transportation savings	$158,400	$28,119
Less: premium cost of lightweight concrete	17,245	3799
Transportation cost savings by using lightweight concrete	$141,155	$24,320

*Courtesy of Big River Industries, Inc.

system that is easier to lift or erect, and fewer joints or more elements per load when transporting. There are several documented cases where the savings in shipping costs far exceeded the increased cost of using lightweight concrete. At some precast plants, each element's shipping cost is evaluated by computer to determine the optimum concrete density;

- In marine applications, increased allowable topside loads and the reduced draft resulting from the use of lightweight concrete may permit easier movement out of dry docks and through shallow shipping channels; and
- Due to the greater fire resistance of lightweight concrete, as reported in ACI 216.1, the thickness of slabs may be reduced, resulting in significantly less concrete volumes.

Lightweight concrete is often used to enhance the architectural expression or construction of a structure. In building construction, this usually applies to cantilevered floors, expressive roof design, taller buildings, or additional floors added to existing structures. With bridges, this may allow a wider bridge deck (additional lanes) being placed on existing structural supports. Improved constructibility may result in cantilever bridge construction where lightweight concrete is used on one side of a pier and normalweight concrete used on the other to provide weight balance while accommodating a longer span on the lightweight side of the pier. The use of lightweight concrete may also be necessary when better insulating qualities are needed in thermally sensitive applications like hot water, petroleum storage or building insulation.

1.4.1 *Transportation costs*—In situations where transportation costs are directly related to the weight of concrete products, there can be significant economies developed through the use of lightweight concrete. The range of products includes large structural members (girders, beams, walls, hollow-core panels, double tees) to smaller consumer products (precast stair steps, fireplace logs, wall board, imitation stone). Two trucking studies conducted at a U.S. precast plant are shown in Table 1.1. These studies demonstrated that the transportation cost savings were seven times more than the additional cost of lightweight aggregate. Savings vary with the size and mass of the product and are most significant for the smaller consumer-type products. For example, one manufacturer of wallboard has shipped products to all 48 mainland states from one manufacturing facility. Less trucks in congested cities is not only environmentally friendly but also generates fewer public complaints. The potential for lower costs is possible when shipping by rail or barge but is most often realized in trucking where highway loadings are posted. The example given in Table 1.1 is a typical analysis of cost for shipping prestressed double-tee members to projects in the late 1990s.

CHAPTER 2—STRUCTURAL LIGHTWEIGHT AGGREGATES

2.1—Internal structure of lightweight aggregates

Lightweight aggregates have a low-particle relative density because of the cellular pore system. The cellular structure within the particles is normally developed by heating certain raw materials to incipient fusion; at this temperature, gases are evolved within the pyroplastic mass, causing expansion, which is retained upon cooling. Strong, durable, lightweight aggregates contain a uniformly distributed system of pores that have a size range of approximately 5 to 300 μm, developed in a continuous, relatively crack-free, high-strength vitreous phase. Pores close to the surface are readily permeable and fill with water within the first few hours of exposure to moisture. Interior pores, however, fill extremely slowly, with many months of submersion required to approach saturation. A small fraction of interior pores are essentially noninterconnected and remain unfilled after years of immersion.

2.2—Production of lightweight aggregates

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. Pyroprocessing methods include the rotary kiln process (a long, slowly rotating, slightly inclined 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 an ignition hood; 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.

The increased usage of processed lightweight aggregates is evidence of environmentally sound planning, as these products require less trucking and use of materials that have limited structural applications in their natural state, thus minimizing construction industry demands on finite resources of natural sands, stones, and gravels.

Table 2.1—Bulk-density requirements of ASTM C 330 and C 331 for dry, loose, lightweight aggregates

Aggregate size and group	Maximum density, lb/ft^3 (kg/m^3)
ASTM C 330 and C 331	
-fine aggregate	70 (1120)
-coarse aggregate	55 (880)
-combined fine and coarse aggregate	65 (1040)

2.3—Aggregate properties

Each of the properties of lightweight aggregates may have some bearing on the properties of the fresh and hardened concrete. It should be recognized, however, that properties of lightweight concrete, in common with those of normalweight concrete, are greatly influenced by the quality of the cementitous matrix. Specific properties of aggregates that may affect the properties of the concrete are listed in Sections 2.3.1 through 2.3.8.

2.3.1 *Particle shape and surface texture*—Lightweight aggregates from different sources, or produced by different methods, may differ considerably in particle shape and texture. Shape may be cubical and reasonably regular, essentially rounded, or angular and irregular. Surface textures may range from relatively smooth with small exposed pores to irregular with small to large exposed pores. Particle shape and surface texture of both fine and coarse aggregates influence proportioning of mixtures in such factors as workability, pumpability, fine-to-coarse aggregate ratio, binder content, and water requirement. These effects are analogous to those obtained with normalweight aggregates with such diverse particle shapes as exhibited by rounded gravel, crushed limestone, traprock, or manufactured sand.

2.3.2 *Relative density*—Due to their cellular structure, the relative density of lightweight-aggregate particles are lower than that of normalweight aggregates. The lightweight particle relative density of lightweight aggregate also varies with particle size, being highest for the fine particles and lowest for the coarse particles, with the magnitude of the differences depending on the processing methods. The practical range of coarse lightweight aggregate relative densities, corrected to the dry condition, are from almost 1/3 to 2/3 that for normalweight aggregates. Particle densities below this range may require more cement to achieve the required strength and may thereby fail to meet the density requirements of the concrete.

2.3.3 *Bulk density*—The bulk density of lightweight aggregate is significantly lower, due to the cellular structure, than that of normalweight aggregates. For the same grading and particle shape, the bulk density of an aggregate is essentially proportional to particle relative densities. Aggregates of the same particle density, however, may have markedly different bulk densities because of different percentages of voids in the dry-loose or dry-rodded volumes of aggregates of different particle shapes. The situation is analogous to that of rounded gravel and crushed stone, where differences may be as much as 10 lb/ft^3 (160 kg/m^3), for the same particle density and grading, in the dry-rodded condition. Rounded and angular lightweight aggregates of the same particle density may differ by 5 lb/ft^3 (80 kg/m^3) or more in the dry-loose condition, but the same mass of either will occupy the same volume in concrete. This should be considered in assessing the workability when using different aggregates. Table 2.1 summarizes the maximum densities for the lightweight aggregates listed in ASTM C 330 and C 331.

2.3.4 *Strength of lightweight aggregates*—The strength of aggregate particles varies with type and source and is measurable only in a qualitative way. Some particles may be strong and hard and others weak and friable. For compressive strengths up to approximately 5000 psi (35 MPa), there is no reliable correlation between aggregate strength and concrete strength.

2.3.4.1 *Strength ceiling*—The concept of "strength ceiling" may be useful in indicating the maximum compressive and tensile strength attainable in concrete made with a given lightweight aggregate using a reasonable quantity of cement. A mixture is near its strength ceiling when similar mixtures containing the same aggregates and with higher cement contents have only slightly higher strengths. It is the point of diminishing returns, beyond which an increase in cement content does not produce a commensurate increase in strength. The strength ceiling for some lightweight aggregates may be quite high, approaching that of some normalweight aggregates.

The strength ceiling is influenced predominantly by the coarse aggregate. The strength ceiling can be increased appreciably by reducing the maximum size of the coarse aggregate for most lightweight aggregates. This effect is more apparent for the weaker and more friable aggregates. In one case, the strength attained in the laboratory for concrete containing 3/4 in. (19 mm) maximum size of a specific lightweight aggregate was 5000 psi (35 MPa); for the same cement content, the strength was increased to 6100 and 7600 psi (42 and 52 MPa) when the maximum size of the aggregate was reduced to 1/2 and 3/8 in. (13 and 10 mm), respectively, whereas concrete unit weights were concurrently increased by 3 and 5 lb/ft^3 (48 and 80 kg/m^3).

Meyer and Kahn (2002) reported that, for a given lightweight aggregate, the tensile strength may not increase in a manner comparable to the increase in compressive strength. Increases in tensile strength occur at a lower rate relative to increases in compressive strength. This becomes more pronounced as compressive strength increases beyond 5000 psi.

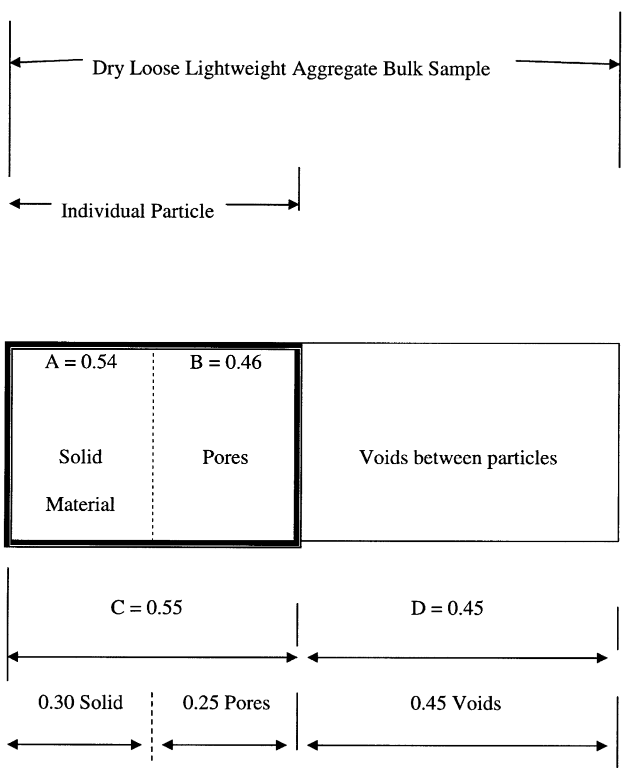
2.3.5 *Total porosity*—Proportioning concrete mixtures and making field adjustments of lightweight concrete require a comprehensive understanding of porosity absorbtion and the degree of saturation of lightweight-aggregate particles. The degree of saturation (the fractional part of the pores filled with water) can be evaluated from pychnometer measurements, which determine the relative density at various levels of absorbtion, thus permitting proportioning by the absolute volume procedure. Normally, pores are defined as the air space inside an individual aggregate particle and voids are defined as the interstitial space between aggregate particles. Total porosity (within the particle and between the particles) can be determined from measured values of particle relative density and bulk density.

For example, if measurements on a sample of lightweight coarse aggregate are:

- Bulk density, dry, loose 48 lb/ft^3 (770 kg/m^3), BD = 0.77 (ACI 211.2; ASTM 138);
- Dry-particle relative density 87 lb/ft^3 (1400 kg/m^3) RD = 1.4 (ACI 211.2; ASTM 138); and
- Relative density of the solid particle material without pores 162 lb/ft^3 (2600 kg/m^3) RD = 2.6 (ACI 211.1; ASTM 138).

Note: The particle relative density of the solids (ceramic material without pores) used in this example, 162 lb/ft^3 (2600 kg/m^3), RD = 2.6, was the average value determined by the following procedure: small samples of three different expanded aggregates were ground separately in a jar ball mill for 24 h. After each sample was reduced, it was then tested in accordance with ASTM C 150 to determine the relative density of the ground lightweight aggregate. According to Weber and Reinhardt (1995), the pore structure of expanded aggregates reveals that a small percentage of pores are less than 10 m and exist unbroken within the less than 200 sieve (75 μm) sized particles. The relative densities of the vitreous structure are typically in excess of 162 lb/ft^3 (2600 kg/m^3). The true particle porosity may be slightly greater than that determined by the following calculations. When very small pores are encapsulated by a strong, relatively crack-free vitreous structure, however, the pores are not active in any moisture dynamics.

Using the values given previously, the following results:



Then the total porosity (pores and voids) equals:

0.45 (voids) + (0.46 (pores) × 0.55 (particles) = 0.70, where A = the fractional solid volume (without pores) of the vitreous material of an individual particle, equals 1.4/2.6 = 0.54; B = the subsequent fractional volume of pore (within the particle), equals 1.00 – 0.54 = 0.46; C = for this example, the fractional volume of particles equals 0.77/1.4 = 0.55; and D = the fractional volume of interstitial voids (between particles) = 1.00 – 0.55 = 0.45.

2.3.6 *Grading*—Grading requirements for lightweight aggregates deviate from those of normalweight aggregates (ASTM C 33) by requiring a larger mass of the lightweight aggregates to pass through the finer sieve sizes. This modification in grading (ASTM C 330) recognizes the increase in density with decreasing particle size of lightweight expanded aggregates. This modification yields the same volumetric distribution of aggregates retained on a series of sieves for both lightweight and normalweight aggregates.

Producers of lightweight aggregate normally stock materials in several standard sizes such as coarse, intermediate, and fine aggregate. By combining size fractions or replacing some or all of the fine fraction with a normalweight sand, a wide range of concrete densities can be obtained. The aggregate producer is the best source of information for the proper aggregate combinations to meet fresh concrete density specifications and equilibrium density for dead-load design considerations.

Normalweight sand replacement will typically increase the equilibrium concrete density from about 5 to 10 lb/ft^3 (80 to 160 kg/m^3). Using increasing amounts of cement to obtain high-strength concrete may increase the density from 2 to 6 lb/ft^3 (32 to 96 kg/m^3). With modern concrete technology, however, it will seldom be necessary to significantly increase cement content to obtain the reduced water-cementitious material ratios *(w/cm)* needed to obtain the specified strength because this can be done using water-reducing or high-range water-reducing admixtures.

2.3.7 *Moisture content and absorption*—Lightweight aggregates, due to their cellular structure, are capable of absorbing more water than normalweight aggregates. Based on a standard ASTM C 127 absorption test expressed at 24 h, lightweight aggregates generally absorb from 5 to 25% by mass of dry aggregate, depending on the aggregate pore system.

In contrast, most normalweight aggregates will absorb less than 2% of moisture. The moisture content in a normalweight aggregate stockpile, however, may be as high as 5 to 10% or more. The important difference is that the moisture content with lightweight aggregates is absorbed into the interior of the particles as well as on the surface, while in normalweight aggregates, it is largely surface moisture. These differences become important as discussed in the following sections on mixture proportioning, batching, and control.

The rate of absorption in lightweight aggregates is a factor that also has a bearing on mixture proportioning, handling, and control of concrete, and depends on the aggregate pore characteristics. The water, that is internally absorbed in the lightweight aggregate, is not immediately available to the cement and should not be counted as mixing water. Nearly all moisture in the natural sand, on the other hand, may be surface moisture and, therefore, part of the mixing water.

2.3.8 *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

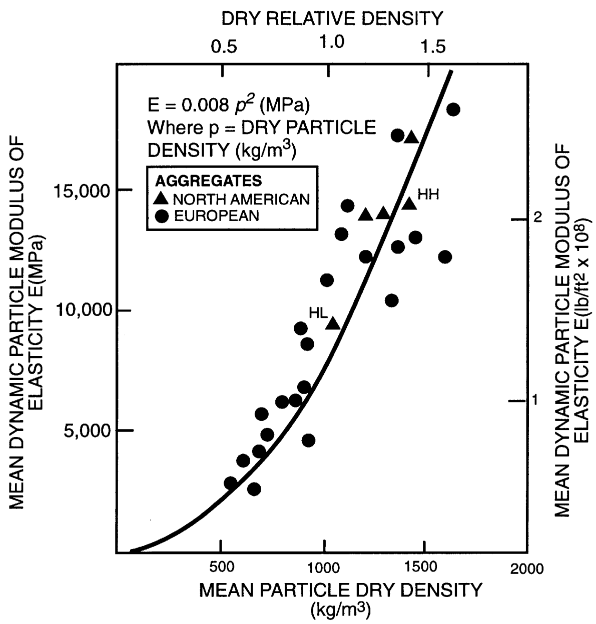


Fig. 2.1—Relationship between mean particle density and the mean dynamic modulus of elasticity for the particles of lightweight aggregates (Bremner and Holm 1986).

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 $E = 0.008p^2$, where E is the dynamic modulus of elasticity of the particle, in MPa, and p is the dry mean particle density, in k/m^3 (Fig. 2.1).

Dynamic moduli for typical expanded aggregates have a range of 1.45 to 2.3 × 10^6 psi (10 to 16 GPa), whereas the range for strong normalweight aggregates is approximately 4.35 to 14.5 × 10^6 psi (30 to 100 GPa) (Muller-Rochholz 1979).

CHAPTER 3—PROPORTIONING, MIXING, AND HANDLING

3.1—Scope

The proportioning of lightweight concrete mixtures is determined by economical combinations of the constituents that typically include portland cement; aggregate; water; chemical admixtures, mineral admixtures, or both; in a way that the optimum combination of properties is developed in both the fresh and hardened concrete. A prerequisite to the selection of mixture proportions is a knowledge of the properties of the constituent materials and their compliance with pertinent ASTM specifications.

Based on a knowledge of the properties of the constituents and their interrelated effects on the concrete, lightweight concrete can be proportioned to have the properties specified for the finished structure.

This chapter discusses:

- Criteria on which concrete mixture proportions are based;
- The materials that make up the concrete mixture; and
- The methods by which these are proportioned.

Mixing, delivery, placing, finishing, and curing also will be discussed, particularly where these procedures differ from those associated with normalweight concrete. The chapter concludes with a brief discussion on laboratory and field quality control.

3.2—Mixture proportioning criteria

Chapter 4 indicates a broad range of values for many physical properties of lightweight concrete. Specific values depend on the properties of the particular aggregates being used and on other conditions. In proportioning a lightweight-concrete mixture, the engineer is concerned with obtaining predictable values of specific properties for a particular application.

Specifications for lightweight concrete usually require minimum permissible values for compressive and tensile strength, maximum values for slump, and both minimum and maximum values for air content. For lightweight concrete, a limitation is always placed on the maximum value for fresh and equilibrium density.

From a construction standpoint, the workability of fresh concrete should also be considered. In proportioning lightweight concrete mixtures, these properties may be optimized. Some properties are interdependent, and improvement in one property, such as workability, may affect other properties such as density or strength. The final criterion to be met is overall performance in the structure as specified by the architect/engineer.

3.2.1 *Specified physical properties*

3.2.1.1 *Compressive strength*—Compressive strength is further discussed in Chapter 4. The various types of lightweight aggregates available will not always produce similar compressive strengths for concrete of a given cement content and slump.

Compressive strength of structural concrete is specified according to design requirements of a structure. Normally, strengths specified will range from 3000 to 5000 psi (21 to 35 MPa) and less frequently up to 7000 psi (48 MPa) or higher. Although some lightweight aggregates are capable of producing very high strengths consistently, it should not be expected that concrete made with every lightweight aggregate classified as "structural" can consistently attain the higher strength values.

3.2.1.2 *Density*—From the load-resisting considerations of structural members, reduced density of lightweight concrete can lead to improved economy of structures despite an increased unit cost of concrete. Therefore, density is a very important consideration in the proportioning of lightweight-concrete mixtures. While this property depends primarily on aggregate density and the proportions of lightweight and normalweight aggregate, it is also influenced by the cement, water, and air contents. Within limits, concrete density can be maintained by adjusting proportions of lightweight and normalweight aggregates. For example, if the cement content is increased to provide additional compressive strength, the unit weight of the concrete will be increased. On the other hand, complete replacement of the lightweight-aggregate fines with normalweight sand could increase the concrete density by approximately 10 lb/ft^3 (160 kg/m^3) or more at the same strength level. This should also be considered in the overall economy of lightweight concrete.

If the concrete producer has several different sources of lightweight aggregate available, the optimum balance of cost and concrete performance may require a detailed investigation. Only by comparing concrete of the same compressive strength and of the same equilibrium density can the fundamental differences of concrete made with different aggregates be properly evaluated. In some areas, only a single source of lightweight aggregate is economically available. In this case, the concrete producer needs only to determine the density of concrete that satisfies the economy and specified physical properties of the structure.

3.2.1.3 *Modulus of elasticity*—Although values for E_c are not always specified, this information is usually available for concrete made with specific lightweight aggregates. This property is further discussed in detail in Chapters 4 and 5.

3.2.1.4 *Slump*—Slump should be the lowest value consistent with the ability to satisfactorily place, consolidate, and finish the concrete and should be measured at the point of discharge.

3.2.1.5 *Entrained-air content*—Air entrainment in lightweight concrete, as in normalweight concrete, is required for resistance to freezing and thawing, as shown in ACI 201.2R, Table 1.1. In concrete made with some lightweight aggregates, it is also an effective means of improving workability. Because entrained air reduces the mixing water requirement while maintaining the same slump, as well as reducing bleeding and segregation, it is normal practice to use air entrainment in lightweight concrete regardless of its exposure to freezing and thawing.

Recommended ranges of total air contents for lightweight concrete are shown in Table 3.1

Attempts to use a large proportion of normalweight aggregate in lightweight concrete to reduce costs and then to use a high air content to meet density requirements are counterproductive. Such a practice usually becomes self-defeating because compressive strength is thereby lowered for each increment of air beyond the recommended ranges. The cement content should then be increased to meet strength requirements. Although the percentages of entrained air required for workability and freezing-and-thawing resistance reduce the density of the concrete, it is not recommended that air contents be increased beyond the upper limits given in Table 3.1 simply to meet density requirements. Adjustment of proportions of aggregates, principally by limiting the normalweight aggregate constituent, is the most reliable, and usually the more economical, way to meet specified density requirements. Nonstructural or insulating concrete may use higher air contents to lower density.

3.2.2 *Workability*—Workability is an important property of freshly mixed lightweight concrete. The slump test is the most widely used method to measure workability. Similar to normalweight concrete, properly proportioned, lightweight concrete mixtures will have acceptable finishing characteristics.

Water-cementitious material ratio—The *w/cm* can be determined for lightweight concrete proportioned using the specific gravity factor as described in ACI 211.2, Method 1.

Table 3.1—Recommended air content for lightweight concrete

Maximum size of aggregate	Air content percent by volume
3/4 in. (19 mm)	4.5 to 7.5
3/8 in. (10 mm)	6 to 9

When lightweight aggregates are adequately prewetted,* there will be a minimal amount of water absorbed during mixing and placing. This allows the net *w/cm* to be computed with an accuracy similar to that associated with normalweight concrete.

3.3—Materials

Lightweight concrete is composed of cement, aggregates, water, and chemical and mineral admixtures similar to normalweight concrete. Admixtures are added to entrain air, reduce mixing water requirements, and modify the setting time or other property of the concrete. Laboratory tests should be conducted on all the ingredients, and trial batches of the concrete mixtures proportions be performed with the actual materials proposed for use.

3.3.1 *Cementitous and pozzolanic material*—These materials should meet ASTM C 150, C 595, C 618, or C 1157.

3.3.2 *Lightweight aggregates*—For structural concrete, lightweight aggregate should meet the requirements of ASTM C 330. Because of differences in particle strength, the cement contents necessary to produce a specific concrete strength will vary with aggregates from different sources. This is particularly significant for concrete strengths above 5000 psi (35 MPa). Mixture proportions recommended by lightweight-aggregate producers generally provide appropriate cement content and other proportions that should be used as a basis for trial batches.

3.3.3 *Normalweight aggregates*—Normalweight aggregates used in lightweight concrete should conform to the provisions of ASTM C 33.

3.3.4 *Admixtures*—Admixtures should conform to appropriate ASTM specifications, and guidance for use of admixtures may be obtained from ACI 212.3R, 232.2R, 233R, and 234R.

3.4—Proportioning and adjusting mixtures

Proportions for concrete should be selected to make the most economical use of available materials to produce concrete of the required physical properties. Basic relationships have been established that provide guidance in developing optimum combinations of materials. Final proportions, however, should be established by laboratory trial mixtures, which are then adjusted to provide practical field batches, in accordance with ACI 211.2.

The principles and procedures for proportioning normalweight concrete, such as the absolute volume method, may

*Note: The time required to reach adequate prewetting will vary with each aggregate and the method of wetting used. The thermal and vacuum saturation method may provide adequate prewetting quickly. The sprinkling or soaking method may take several days to reach an adequate prewetted condition from a dry condition. Therefore, it is essential to contact the aggregate supplier on the prewetting method and length of time required. The percent moisture content achieved at an adequate prewetted condition is normally greater than what would be reached after 24 h submersion.

be applied in many cases to lightweight concrete. The local aggregate producers should be consulted for the particular recommended procedures.

3.4.1 *Absolute volume method*—In using the absolute volume method, the volume of fresh concrete produced by any combination of materials is considered equal to the sum of the absolute volumes of cementitous materials, aggregate, net water, and entrained air. Proportioning by this method requires the determination of water absorption and the particle relative density factor of the separate sizes of aggregates in an as-batched moisture condition. The principle involved is that the mortar volume consists of the total of the volumes of cement, fine aggregate, net water, and entrained air. This mortar volume should be sufficient to fill the voids in a volume of rodded coarse aggregate plus sufficient additional volume to provide satisfactory workability. This recommended practice is set forth in ACI 211.1 and represents the most widely used method of proportioning for normalweight concrete mixtures.

The density factor method, trial mixture basis, is described with examples in ACI 211.1. Displaced volumes are calculated for the cement, air, and net water (total water less amount of water absorbed by the aggregate). The remaining volume is then assigned to the coarse and fine aggregates. This factor may be used in calculations as though it were the apparent particle relative density and should be determined at the moisture content of the aggregate being batched.

3.4.2 *Volumetric method*—The volumetric method is described with examples in ACI 211.1. It consists of making a trial mixture using estimated volumes of cementitous materials, coarse and fine aggregates, and sufficient added water to produce the required slump. The resultant mixture is observed for workability and finishability characteristics. Tests are made for slump, air content, and fresh density. Calculations are made for yield (the total batch mass divided by the fresh density) and for actual quantities of materials per unit volume of concrete. Necessary adjustments are calculated and further trial mixtures made until satisfactory proportions are attained. Information on the dry-loose bulk densities of aggregates, the moisture contents of the aggregates, the optimum ratio of coarse-to-fine aggregates, and an estimate of the required cementitous material to provide the strength desired can be provided by the aggregate supplier.

3.5—Mixing and delivery

The fundamental principles of ASTM C 94 apply to lightweight concrete as they do to normalweight concrete. Aggregates with relatively low or high water absorption need to be handled according to the procedures that have been established by the aggregate supplier or the ready-mixed concrete producer. The absorptive nature of the lightweight aggregate requires prewetting to be as uniform a moisture content as possible before adding the other ingredients of the concrete. The proportioned volume of the concrete is then maintained, and slump loss during transport is minimized.

3.6—Placing

There is little or no difference in the techniques required for placing lightweight concrete from those used in properly placing normalweight concrete. ACI 304.5R discusses in detail the proper and improper methods of placing concrete. The most important consideration in handling and placing concrete is to avoid segregation of the coarse aggregate from the mortar matrix. The basic principles required for a good lightweight concrete placement are:

- A workable mixture using a minimum water content;
- Equipment capable of expeditiously handling and placing the concrete;
- Proper consolidation; and
- Good workmanship.

A well-proportioned lightweight concrete mixture can generally be placed, screeded, and floated with less effort than that required for normalweight concrete. Overvibration or overworking of lightweight concrete should be avoided. Overmanipulation only serves to drive the heavier mortar away from the surface where it is required for finishing and to bring the lower-density coarse aggregate to the surface. Upward movement of coarse lightweight aggregate may also occur in mixtures where the slump exceeds the recommendations provided in this chapter.

3.6.1 *Finishing floors*—Satisfactory floor surfaces are achieved with properly proportioned quality materials, skilled supervision, and good workmanship. The quality of the finishing will be in direct proportion to the efforts expended to ensure that proper principles are observed throughout the finishing process. Finishing techniques for lightweight concrete floors are described in ACI 302.1R.

3.6.1.1 *Slump*—Slump is an important factor in achieving a good floor surface with lightweight concrete and generally should be limited to a maximum of 5 in. (125 mm). A lower slump of about 3 in. (75 mm) imparts sufficient workability and also maintains cohesiveness and body, thereby preventing the lower-density coarse particles from working to the surface. This is the reverse of normalweight concrete where segregation results in an excess of mortar at the surface. In addition to surface segregation, a slump in excess of 5 in. (125 mm) may cause unnecessary finishing delays.

3.6.1.2 *Surface preparation*—Surface preparation before troweling is best accomplished with magnesium or aluminum screeds and floats, which minimize surface tearing and pullouts.

3.6.1.3 *Good practice*—A satisfactory finish on lightweight concrete floors can be obtained as follows:

a. Prevent segregation by:

1. Using a well-proportioned and cohesive mixture;
2. Requiring a slump as low as possible;
3. Avoiding over-vibration;

b. Time the placement operations properly;

c. Use magnesium, aluminum, or other satisfactory finishing tools;

d. Perform all finishing operations after free surface bleeding water has disappeared; and

e. Cure the concrete properly.

3.6.2 *Curing*—Upon completion of the finishing operation, curing of the concrete should begin as soon as possible. Ultimate performance of the concrete will be influenced by the extent of curing provided. ACI 302.1R and ACI 308.1 contain information on proper curing of concrete floor slabs.

Unlike traditional curing where moisture is applied to the surface of the concrete, internal curing occurs by the release of water absorbed within the pores of lightweight aggregate. Absorbed water does not enter the *w/cm* that is established at the time of set. As the pore system of the hydrating cement becomes increasingly smaller, water contained within the relatively larger pores of the lightweight aggregate particle is wicked into the matrix, thus providing an extended period of curing. The benefits of internal curing have been known for several decades where ordinary concrete incorporating lightweight aggregate with a high degree of absorbed water has performed extremely well in bridges, parking structures, and other exposed structures. Internal curing is beneficial for high-performance concrete mixtures containing supplementary cementitious materials, especially where the *w/cm* is less than 0.45. These low *w/cm* mixtures are relatively impervious and vulnerable to self-desiccation because external surface curing moisture is unable to penetrate.

3.7—Pumping lightweight concrete

3.7.1 *General considerations*—Unless the lightweight aggregates are satisfactorily prewetted, they may absorb mixing water and subsequently cause difficulty in pumping the concrete. For this reason, it is important to adequately condition the aggregate by fully prewetting before batching the concrete. The conditioning of the lightweight aggregate can be accomplished by any of the following:

- *Atmospheric*—Using a soaker hose or sprinkler system. The length of time required to adequately prewet a lightweight aggregate is dependent on the absorption characteristics of the aggregate. The lightweight aggregate supplier may be able to supply useful information. Uniform prewetting can be accomplished by several methods, including sprinkling, using a soaker hose, and by applying water to aggregate piles at either or both the aggregate plant or batch plants.
- *Thermal*—By immersion of partially cooled aggregate in water. It should be carefully controlled and is feasible only at the aggregate plant.
- *Vacuum*—By introducing dry aggregate into a vessel from which the air can be evacuated. The vessel is then filled with water and returned to atmospheric pressure. This should be performed only at the aggregate plant.

Prewetting minimizes the mixing water being absorbed by the aggregate, therefore minimizing the slump loss during pumping. This additional moisture also increases the density of the lightweight aggregate, which in turn increases the density of the fresh concrete. This increased density due to prewetting will eventually be lost to the atmosphere in drying and provides for extended internal curing.

3.7.2 *Proportioning pump mixtures*—When considering pumping lightweight concrete, some adjustments may be necessary to achieve the desired characteristics. The architect/engineer and contractor should be familiar with any mixture adjustments required before the decision is made as to the method of placement. The ready-mixed concrete producer and aggregate supplier should be consulted so that the best possible pump mixture can be determined. Pumping lightweight concrete is extensively covered in a report by the Expanded Shale, Clay, and Slate Institute (ESCSI) (1996).

When the project requirements call for pumping, the following general rules apply. These are based on the use of lightweight coarse aggregate and normalweight fine aggregate.

- Prewet lightweight aggregate to a moisture content recommended by the aggregate supplier;
- Maintain a 564 lb/yd^3 (335 kg/m^3) minimum cementitous content;
- Use selected liquid and mineral admixtures that will aid in pumping;
- To facilitate pumping, adjustments in the standard mixture proportion may result in a slight reduction in the volume of coarse aggregate, with a corresponding increase in the volume of fine aggregate;
- Cementitious content should be sufficient to accommodate a 4 to 6 in. (100 to 150 mm) slump at the point of placement;
- Use a well-graded natural sand with a good particle shape and a fineness modulus range of 2.2 to 2.7; and
- Use a properly combined coarse- and fine-aggregate grading. The grading should be made by absolute volume rather than by mass to account for differences in relative density of the various particle sizes.

Sometimes it is advisable to plan on various mixture designs as the height of a structure or distance from the pump to the point of discharge changes. Final evaluation of the concrete shall be made at the discharge end of the pumping system (ACI 304.5R).

3.7.3 *Pump and pump system*—Listed as follows are some of the key items pertinent to the pump and pumping system.

- Use the largest size line available, with a recommended minimum of 5 in. (125 mm) diameter without reducers;
- All lines should be clean, the same size, and “buttered” with grout at the start;
- Avoid rapid size reduction from the pump to line; and
- Reduce the operating pressure by:

1. Slowing down the rate of placement;
2. Using as much steel line and as little rubber line as possible;
3. Limiting the number of bends; and
4. Making sure the lines are gasketed and braced by a thrust block at turns.

A field trial should be conducted using the pump and mixture design intended for the project. Observers present should include representatives of the contractor, ready-mixed concrete producer, architect/engineer, pumping service, testing agency, and aggregate supplier. In the pump trial, the height and length to the delivery point of the concrete to be moved should be taken into account. Because most test locations will not allow the concrete to be pumped vertically as high as it would be during the project, the following rules of thumb can be applied for the horizontal runs with steel lines:

1.0 ft (0.3 m) vertical	=	4.0 ft (1.2 m) horizontal
1.0 ft (0.3 m) rubber hose	=	2.0 ft (0.6 m) of steel
1.0 ft (0.3 m) 90-degree bend	=	10.0 ft (3.0 m) of steel

3.8—Laboratory and field control

Changes in absorbed moisture or relative density of lightweight aggregates, which result from variations in initial moisture content or grading, and variations in entrained-air content suggest that frequent checks of the fresh concrete should be made at the job site to ensure consistent quality (ACI 211.1). Sampling should be in accordance with ASTM C 172. Tests normally required are: density of the fresh concrete (ASTM C 567); standard slump test (ASTM C 143); air content (ASTM C 173); and Standard Practice for Making and Curing Concrete Test Specimens in the Field (ASTM C 31).

At the job start, the fresh properties, density, air content, and slump of the first batch or two should be determined to verify that the concrete conforms to the laboratory mixture. Small adjustments may then be made as necessary. In general, when variations in fresh density exceed 3 lb/ft^3 (50 kg/m^3), an adjustment in batch weights may be required to meet specifications. The air content of lightweight concrete should not vary more than ± 1-1/2 percentage points from the specified value to avoid adverse effects on concrete density, compressive strength, workability, and durability.

CHAPTER 4—PHYSICAL AND MECHANICAL PROPERTIES OF STRUCTURAL LIGHTWEIGHT-AGGREGATE CONCRETE

4.1—Scope

This chapter presents a summary of the properties of lightweight concrete. The information is based on many laboratory studies and records of a large number of existing structures that have provided satisfactory service for more than eight decades. The customary requirements for structural concrete are that mixture proportions proposed for the project should be based on laboratory tests or on mixtures with established records of performance.

4.2—Method of presenting data

In the past, properties of lightweight concrete have been compared with those of normalweight concrete, and usually the comparison standard has been a single normalweight material. With several million cubic yards of lightweight concrete being placed each year, such a comparison of properties may no longer be appropriate. The data on various structural properties are presented as reasonable conservative values to be expected in relationship to some fixed property such as compressive strength, density, or in the case of fire resistance, slab thickness.

4.3—Compressive strength

Compressive strength levels commonly required by the construction industry for design strengths of cast-in-place, precast, or prestressed concrete are economically obtained with lightweight concrete (Shideler 1957; Hanson 1964; Holm 1980a). Design strengths of 3000 to 5000 psi (21 to 35 MPa) are common. In precast and prestressing plants, design strengths above 5000 psi (35 MPa) are usual. In several civil structures, such as the Heidrun Platform and Norwegian bridges, concrete cube strengths of 60 MPa (8700 psi) have been specified (*fib* 2000). As discussed in Chapter 2, all aggregates have strength ceilings, and with lightweight aggregates, the strength ceiling generally can be increased by reducing the maximum size of the coarse aggregate. As with normalweight concrete, water-reducing plasticizing and mineral admixtures are frequently used with lightweight concrete mixtures to increase workability and facilitate placing and finishing.

4.4—Density of lightweight concrete

4.4.1—The fresh density of lightweight concrete is a function of mixture proportions, air contents, water demand, particle relative density, and absorbed moisture content of the lightweight aggregate. Decrease in the 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. The architect/engineer should specify a maximum fresh density as limits of acceptability should be controlled at time of placement.

Although there are numerous structural applications of lightweight concrete using both coarse and fine lightweight aggregates, usual commercial practice in North America is to design concrete with natural sand fine aggregates. Long-span bridges using concrete with three-way blends (coarse and fine lightweight aggregates and small amounts of natural sand) have provided long-term durability and structural efficiency (density/strength ratios) (Holm and Bremner 1994). Earlier research reports (Kluge, Sparks, and Tuma 1949; Price and Cordon 1949; Reichard 1964; and Shideler 1957) compared all concrete containing both fine and coarse lightweight aggregates with "reference" normalweight concrete. Later studies (Hanson 1964; Pfeifer 1967) supplemented the early findings with data based on lightweight concrete where the fine aggregate was a natural sand.

4.4.2—Self loads used for design should be based on equilibrium density that, for most conditions and members, may be assumed to be achieved after 90 days air-drying. Extensive North American studies demonstrated that despite wide initial variations of aggregate moisture content, equilibrium density was found to be 3 lb/ft^3 (50 kg/m^3) above oven-dry density (Fig. 4.1) for lightweight concrete. European recommendations for in-service density are similar (FIP 1983). Concrete containing high cementitous contents, and particularly those containing efficient pozzolans, will develop densities with a reduced differential between fresh and equilibrium density.

When weights and moisture contents of all the constituents of the concrete are known, a calculated equilibrium density can be determined according to ASTM C 567 from the following equations

$$O = (W_{df} + W_{dc} + 1.2W_{ct})/V \quad (4\text{-}1)$$

$$E = O + 3\ \text{lb/ft}^3\ (O + 50\ \text{kg/m}^3) \quad (4\text{-}2)$$

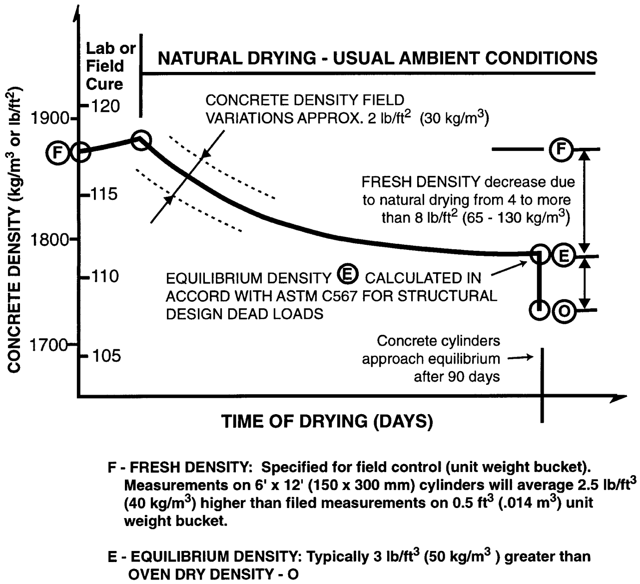


Fig. 4.1—Concrete density versus time of drying for structural lightweight concrete (Holm 1994).

where

O = calculated oven-dry density, lb/ft^3 (kg/m^3);
W_{df} = mass of dry fine aggregate in batch, lb (kg);
W_{dc} = mass of coarse aggregate in batch, lb (kg);
1.2 = factor to account for water of hydration;
W_{ct} = mass of cement in batch, lb (kg);
V = volume of concrete produced, ft^3 (m^3); and
E = calculated equilibrium density, lb/ft^3 (kg/m^3).

4.5—Specified-density concrete

Concrete containing limited amounts of lightweight aggregate that result in equilibrium concrete densities greater than 120 lb/ft^3 (1920 kg/m^3) but less than concrete composed entirely of normalweight aggregates is defined as specified-density concrete. The increasing usage of specified-density concrete is driven by engineers' decisions to optimize the concrete density to improve structural efficiency (strength-to-density ratio), to reduce concrete product transportation and construction costs, and to enhance the hydration of high cementitous content concrete with very low *w/cm*.

4.6—Modulus of elasticity

The modulus of elasticity of concrete depends on the relative amounts of paste and aggregate and the modulus of each constituent (LaRue 1946; Pauw 1960). Normalweight concrete has a higher E_c because the moduli of sand, stone, and gravel are greater than the moduli of lightweight aggregates. Figure 4.2 gives the range of modulus of elasticity values for lightweight concrete. Generally, the modulus of elasticity for lightweight concrete is considered to vary between 1/2 to 3/4 that of sand and gravel concrete of the same strength. Variations in lightweight aggregate grading usually have little effect on modulus of elasticity if the relative volumes of cement paste and aggregate remain fairly constant.

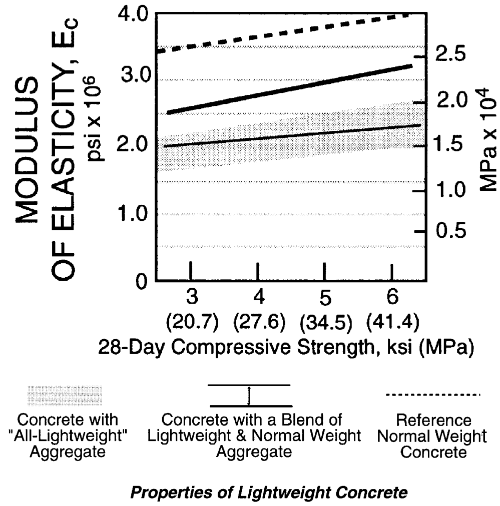


Fig. 4.2—Modulus of elasticity.

The formula for $E_c = w_c^{1.5} 33 \sqrt{f_c'} (w_c^{1.5} 0.043 \sqrt{f_c'})$ given in ACI 318, may be used for values of w between 90 and 155 lb/ft^3 (1440 and 2480 kg/m^3) and strength levels of 3000 to 5000 psi (21 to 35 MPa). Further discussion of this formula is given in Section 5.3. Concretes in service may deviate from this formula by up to 20%. When an accurate evaluation of E_c is required for a particular concrete, a laboratory test in accordance with the methods of ASTM C 469 should be carried out.

4.7—Poisson's ratio

Tests to determine Poisson's ratio of lightweight concrete by resonance methods showed that it varied only slightly with age, strength, or aggregate used, and that the values varied between 0.16 and 0.25 with the average being 0.21 (Reichard 1964). Tests to determine Poisson's ratio by the static method for lightweight and normalweight concrete gave values that varied between 0.15 and 0.25 and averaged 0.2.

While this property varies slightly with age, test conditions, and physical properties of the concrete, a value of 0.20 may be usually assumed for practical design purposes. An accurate evaluation can be obtained for a particular concrete by testing according to ASTM C 469.

4.8—Creep

Creep is the increase in strain of concrete under a sustained stress. Creep properties of concrete may be either beneficial or detrimental, depending on the structural conditions. Concentrations of stress, either compressive or tensile, may be reduced by stress transfer through creep, or creep may lead to excessive long-time deflection, prestress loss, or loss of camber. The effects of creep along with those of drying shrinkage should be considered and, if necessary, taken into account in structural designs.

4.8.1 *Factors influencing creep*—Creep and drying shrinkage are closely related phenomena that are affected by many factors, such as type of aggregate, type of cement, grading of aggregate, water content of the mixture, moisture content of aggregate at time of mixture, amount of entrained

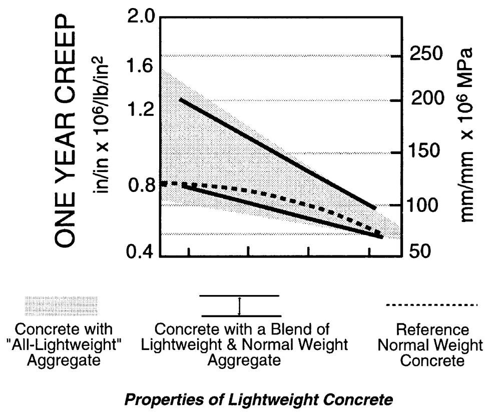


Fig. 4.3—Creep: normally cured concrete.

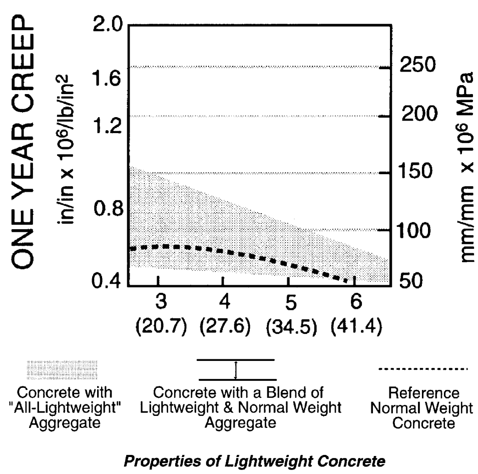


Fig. 4.4—Creep: steam-cured concrete.

air, age at initial loading, magnitude of applied stress, method of curing, size of specimen or structure, relative humidity of surrounding air, and period of sustained loading.

4.8.2 *Normally cured concrete*—Figure 4.3 shows the range in values of specific creep (creep per psi of sustained stress) for normally cured concrete, as measured in the laboratory (ASTM C 512), when under constant loads for 1 year. These diagrams were prepared with the aid of two common assumptions: superposition of creep effects are valid (that is, creep is proportional to stress within working stress ranges); and shrinkage strains, as measured on nonloaded specimens, may be directly separated from creep strains. The band for lightweight concrete containing normalweight sand is considerably narrower than that for the concrete containing both fine and coarse lightweight aggregate. Figure 4.3 suggests that a very effective method of reducing creep of lightweight concrete is to use a higher-strength concrete. A strength increase from 3000 to 5000 psi (21 to 35 MPa) significantly reduces creep.

4.8.3 *Steam-cured concrete*—Several investigations have shown that creep may be significantly reduced by low-pressure curing and very greatly reduced by high-pressure steam curing. Figure 4.4 shows that the reduction for low-pressure steamed concrete may be from 25 to 40% of the creep of similar concrete subjected only to moist curing.

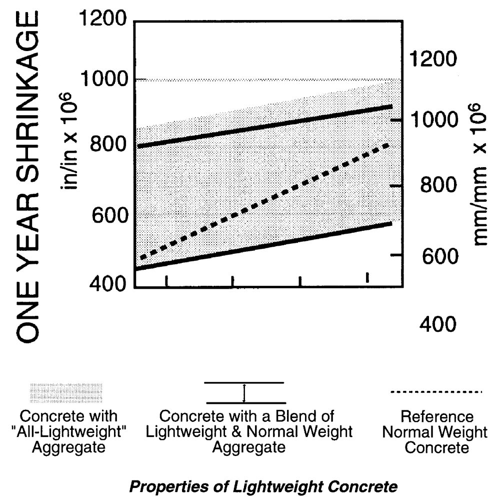


Fig. 4.5—Drying shrinkage: normally cured concrete.

4.9—Drying shrinkage

Drying shrinkage is an important property that can affect the extent of cracking, prestress loss, effective tensile strength, and warping. It should be recognized that large-size concrete members, or those in high ambient relative humidity, might undergo substantially less shrinkage than that exhibited by small laboratory specimens stored at 50% relative humidity.

4.9.1 *Normally cured concrete*—Figure 4.5 indicates wide ranges of shrinkage values after 1 year of drying for lightweight concrete with normalweight sand. Noting the position within these ranges of the reference concrete, it appears that low-strength lightweight concrete generally has greater drying shrinkage than that of the reference concrete. At higher strengths, however, some lightweight concrete exhibits lower shrinkage. Partial or full replacement of the lightweight fine aggregate by natural sand usually reduces shrinkage for concrete made with most lightweight aggregates.

4.9.2 *Atmospheric steam-cured concrete*—Figure 4.6 demonstrates the reduction of drying shrinkage obtained through steam curing. This reduction may vary from 10 to 40%. The lower portion of this range is not greatly different from that for the reference normalweight concrete.

4.10—Splitting tensile strength

The splitting tensile strength of concrete cylinders (ASTM C 496) is an effective method of measuring tensile strength.

4.10.1 *Moist-cured concrete*—Figure 4.7 indicates a narrow range of this property for continuously moist-cured lightweight concrete. The splitting tensile strength of the normalweight reference concrete is nearly intermediate within these ranges.

4.10.2 *Air-dried concrete*—The tensile strength of lightweight concrete that undergoes drying is more relevant in respect to the shear strength behavior of concrete in structures. During drying of the concrete, moisture loss progresses at a slow rate into the interior of concrete members, resulting in the development of tensile stresses at the exterior faces and balancing compressive stresses in the still-moist interior zones. Thus, the tensile resistance to external loading of

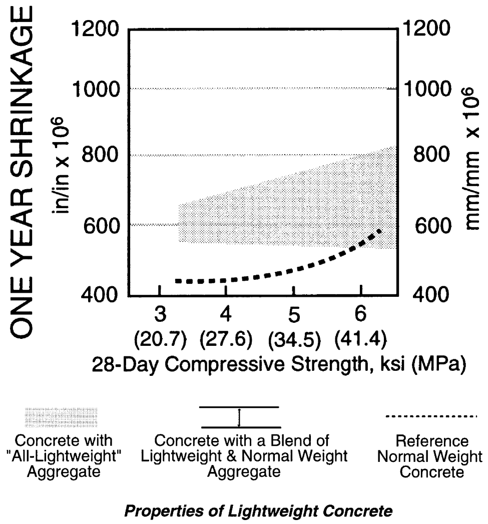


Fig. 4.6—Drying shrinkage: steam-cured concrete.

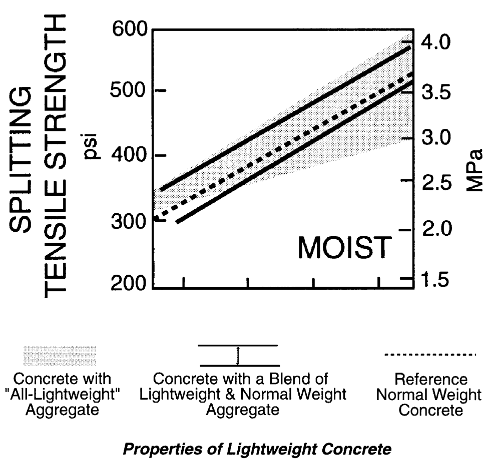


Fig. 4.7—Splitting tensile strength: moist-cured concrete.

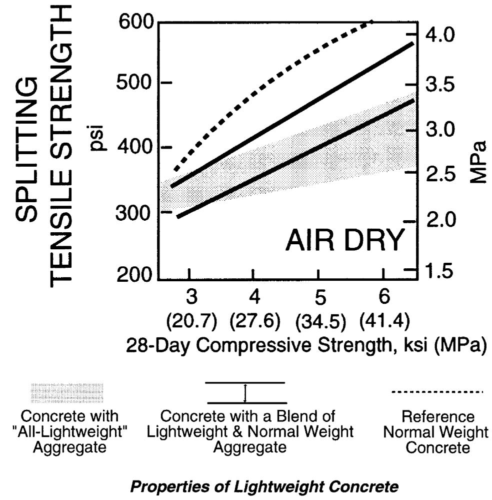


Fig. 4.8—Splitting tensile strength: air-dried concrete.

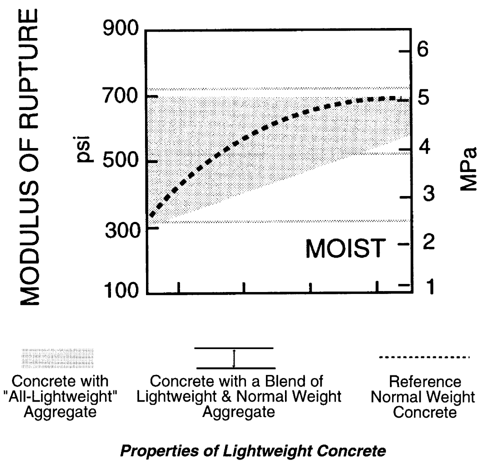


Fig. 4.9—Modulus of rupture: normally cured concrete.

drying lightweight concrete will be reduced from that indicated by continuously moist-cured concrete (Hanson 1961; Pfeifer 1967). Figure 4.8 indicates this reduced strength for concrete that has been moist-cured for 7 days followed by 21 days storage at 50% relative humidity (ASTM C 330). The splitting tensile strength of lightweight concrete varies from approximately 70 to 100% that of the normalweight reference concrete when comparisons are made at equal compressive strength.

The replacement of the lightweight fines by sand generally increases the splitting tensile strength of lightweight concrete subjected to drying (Pfeifer 1967; Ivey and Bluth 1966). In some cases, this increase is nonlinear with respect to the sand content so that, with some aggregates, partial sand replacement is as beneficial as complete replacement.

For lightweight concrete with a compressive strength up to 5000 psi (35 MPa), splitting tensile strength is used for estimating the diagonal tension resistance of lightweight concrete in structures. Tests have shown that the diagonal tension strengths of beams and slabs correlate closely with this property of the concrete (Hanson 1961).

4.11—Modulus of rupture

The modulus of rupture (ASTM C 78) is also a measure of the tensile strength of concrete. Figure 4.9 and 4.10 indicate ranges for normally cured and steam-cured concrete, respectively, when tested in the moist condition. For prism specimens, a nonuniform moisture distribution will reduce the modulus of rupture, but the moisture distribution within the structural member is not known and is unlikely to be completely saturated or completely dry. Studies have indicated that modulus of rupture tests of concrete undergoing drying are extremely sensitive to the transient moisture content and, under these conditions, may not furnish reliable results that are satisfactorily reproducible (Hanson 1961).

The values of the modulus of rupture determined from tests on high-strength lightweight concrete yield inconsistent correlation with code requirements. While Huffington (2000) reported that the tensile splitting and modulus of rupture test results generally met AASHTO requirements for high-strength lightweight concrete, Nassar (2002) found that in his investigation, the modulus of rupture levels were about 60 to 85% of code requirements of $\phi_m \times 7.5\sqrt{f_c'}$ where ϕ_m for sanded lightweight concrete is recommended to be 0.85.

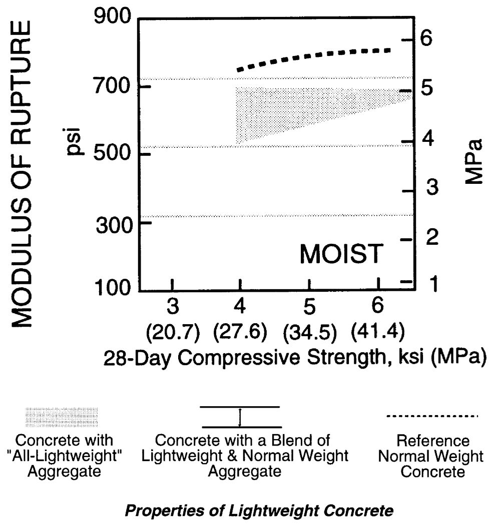


Fig. 4.10—Modulus of rupture: steam-cured concrete.

Nassar recommended that additional testing be conducted to verify the 0.85 factor for high-strength lightweight concrete.

4.12—Bond strength

ACI 318 includes a factor for development length of 1.3 to reflect the lower tensile strength of lightweight-aggregate concrete and allows that factor to be taken as $6.7\sqrt{f_c'}/f_{ct} \geq 1.0$ if the average splitting strength f_{ct} of the lightweight-aggregate concrete is specified. In general, design provisions require longer development lengths for lightweight-aggregate concrete.

Due to the lower strength of the aggregate, lightweight concrete should be expected to have lower tensile strength, fracture energy, and local bearing capacity than normal-weight concrete with the same compressive strength. As a result, the bond strength of bars cast in lightweight concrete, with or without transverse reinforcement, is lower than that in normalweight concrete, with that difference tending to increase at higher strength levels (Fig. 4.11) (Shideler 1957).

Previous reports by Committee 408 (1966, 1970) have emphasized the paucity of experimental data on the bond strength of reinforced concrete elements made with light-weight-aggregate concrete.

The majority of experimental results found in the literature are from different configurations of pullout tests. Early research by Lyse (1934), Petersen (1948), and Shideler (1957) concluded that the bond strength of steel in light-weight-aggregate concrete was comparable to that of normalweight concrete. Petersen tested beams made with expanded shale and expanded slag, and concluded that bond strength of reinforcement in lightweight-aggregate concrete was comparable to that of normalweight concrete. Shideler (1957) conducted pullout tests on 9 in. (230 mm) cube specimens with six different types of aggregates. No. 6 (19 mm) bars were embedded in specimens with compressive strengths of 3000 and 4500 psi (21 and 31 MPa), and No. 9 (29 mm) bars were used in 9000 psi (62 MPa) specimens. Although the bond strength of normalweight concrete specimens was slightly higher than that of lightweight

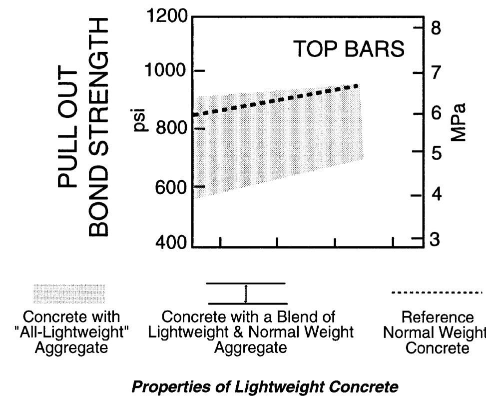


Fig. 4.11—Bond strength: pullout tests.

concrete specimens, Shideler stated that the difference was not significant.

Similar behavior has been observed in more recent studies. Based on a series of pullout test, Martin (1982) concluded that there was no significant difference between the bond strength of normalweight and lightweight-aggregate concrete. Berg (1981) obtained similar results from a pullout test; although, in a limited testing program involving beams, he observed lower bond strengths in specimens made with lightweight-aggregate concrete. The observed difference in strength was approximately 10%.

Clarke and Birjandi (1993) used a specimen developed by the British Cement Association (Chana 1990) and tested four lightweight aggregates with various densities available in the United Kingdom. In addition to the type of aggregate, the study investigated the effect of casting position. The fine aggregate in all mixtures was natural sand. Test results indicated that, with the exception of the lightest insulation grade aggregate, all specimens had higher bond strengths than those of specimens made with normalweight aggregate. This was partially attributed by the authors to the fact that natural sand, as opposed to lightweight aggregate, was used as fine aggregate.

In contrast to the studies just described, there are several studies that indicate significant differences between bond strengths in lightweight and normalweight aggregate concrete. In pullout tests, Baldwin (1965) obtained bond strengths for lightweight concrete that were only 65% of those obtained for normalweight concrete. These results contradicted the prevailing assumption at the time that bond strength in lightweight-aggregate concrete was similar to that of normal weight concrete (ACI Committee 408, 1966).

Robins and Standish (1982) conducted a series of pullout tests to investigate the effect of lateral stress on the bond strength of plain and deformed bars in specimens made with lightweight-aggregate concrete. As the lateral pressure applied to the specimens increased, the mode of failure changed from splitting to pullout. Bond strength increased with confining pressure for both normalweight and lightweight concrete. For specimens that failed by splitting, bond strength was 10 to 15% higher for normalweight concrete than for lightweight concrete; however, when the lateral pressure was large enough to prevent a splitting failure, the difference in bond strength was much higher—on the order of 45%.

Mor (1992) tested No. 6 (19 mm) bars embedded in 3 x 3 x 20 in. (76 x 76 x 508 mm) pullout specimens to investigate the effect of condensed silica fume on the bond strength of normalweight and lightweight-aggregate concrete. For his specimens without silica fume, the maximum bond stress for specimens made with lightweight concrete was 88% of that of specimens made with normalweight concrete. For concrete with 13 to 15% condensed silica fume, the ratio was 82%. The specimens made with lightweight concrete developed splitting failures at 75 to 80% of the slip of specimens made with normalweight concrete. The use of silica fume had little effect on bond strength, with an increase of 2% for normalweight concrete and a decrease of 5% for lightweight concrete.

Overall, the data indicate that the use of lightweight concrete can result in bond strengths that range from nearly equal to 65% of the values obtained with normalweight concrete. For special structures such as long-span bridges with very high strengths and major offshore platforms, a testing program based on the materials selected to the project is recommended.

4.13—Ultimate strength factors

4.13.1 *Ultimate strain*—Figure 4.12 gives a range of values for ultimate compressive strain for concrete containing both coarse and fine lightweight aggregate and for normalweight concrete. These data were obtained from unreinforced specimens eccentrically loaded to simulate the behavior of the compression side of a reinforced beam in flexure (Hognestad, Hanson, and McHenry 1955). The diagram indicates that the ultimate compressive strain of most lightweight concrete (and of the reference normalweight concrete) may be somewhat greater than the value of 0.003, assumed for design purposes.

4.14—Durability

Numerous accelerated freezing-and-thawing testing programs conducted on lightweight concrete in North America and in Europe 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 concrete proportioned with a high-quality binder provides satisfactory durability results when tested under usual laboratory freezing-and-thawing programs. Observations of the resistance to deterioration in the presence of deicing salts on mature bridges indicate similar performance between lightweight and normalweight concrete. Comprehensive investigations into the long-term weathering performance of bridge decks and marine structures exposed for many years to severe environments support the findings of laboratory investigations and suggest that properly proportioned and placed lightweight concrete performs equal to or better than normalweight concrete (Holm 1994).

Core samples taken from hulls of 80-year-old lightweight concrete ships as well as 40- to 50-year-old lightweight concrete bridges have shown that concrete having a dense

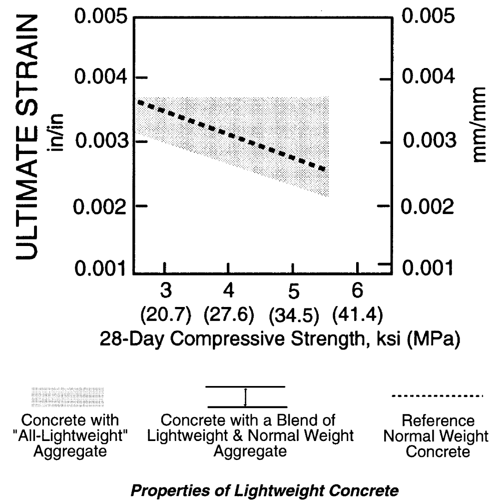


Fig. 4.12—Ultimate strain.

contact zone at the aggregate/matrix interface has low levels of microcracking throughout the mortar matrix. The explanation for this demonstrated record of high resistance to weathering and corrosion is due to several physical and chemical mechanisms, including superior resistance to microcracking developed by significantly higher aggregate/matrix adhesion and the reduction of internal stresses due to elastic matching of coarse aggregate and matrix phases (Holm, Bremner, and Newman 1984). High ultimate strain capacity is also provided by lightweight concrete as it has a high strength/modulus ratio. The strain at which the disruptive dilation of concrete starts is higher for lightweight concrete than for equal-strength normalweight concrete. A well-dispersed pore system provided by the surface of the lightweight fine aggregates may also assist the air-entrainment system and serve an absorption function by reducing concentration levels of deleterious materials in the matrix phase (Holm 1980b).

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

It is widely recognized that while the 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 concrete exposed to natural freezing and thawing. When freezing-and-thawing tests are conducted, ASTM C 330 requires the following modification to the procedures of ASTM C 666, "Unless otherwise specified, remove the lightweight concrete specimens from moist curing at an age of 14 days and allow to air-dry for another 14 days exposed to a relative humidity of 50 ± 5% and a temperature of 73.5 + 3.5 °F (23 ± 2 °C). Then submerge the specimens in water for 24 h before the freezing and thawing test." Durability characteristics of any concrete, both normalweight 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 to protect steel reinforcing from corrosion, which is clearly the dominant form of structural deterioration observed in current construction. The matrix protective quality of nonstructural, insulating concrete proportioned for thermal resistance by using high-air and low-cement contents will be significantly reduced. Very low density, nonstructural concrete will not provide resistance to the intrusion of chlorides and carbonation, comparable to the long-term satisfactory performance demonstrated with high-quality, lightweight concrete.

4.14.1—*Carbonation in mature marine structures*

4.14.1.1 *General*—Carbonation in concrete is the reaction of carbon dioxide from the air with calcium hydroxide liberated from the hydration process. This reaction produces calcium carbonate that can neutralize the natural protection of steel reinforcement afforded by the concrete.

The concern for carbonation is predicated on the pH in concrete lowering from approximately 13 to the vicinity of 9, which in turn neutralizes the protective layer over the reinforcing steel, making it vulnerable to corrosion. Two primary mechanisms protect steel from corrosion: the combination of an adequate depth of cover with a sufficiently high-quality cover concrete. This quality is usually related to *w/cm* or strength (relatively easy properties to quantify), but is more closely related to permeability and strain capacity of the cover concrete.

4.14.1.2 *Concrete ships, Cape Charles, Va.*—Holm, Bremner, and Vaysburd (1988) reported the results of carbonation measurements conducted on cores drilled from the hull of several concrete ships built during World War II. The ships were used as breakwaters for a ferryboat dock in the Chesapeake Bay at Cape Charles, Virginia. They were constructed with carefully inspected high-quality concrete made with rotary kiln-produced fine and coarse expanded aggregates and a small volume of natural sand. High-cement contents were used to achieve compressive strengths in excess of 5000 psi (35 MPa) at 28 days with a density of 108 lb/ft^3 (1730 kg/m^3) (McLaughlin 1944). Despite freezing and thawing in a marine environment, the hulls and superstructure of this nonair-entrained concrete are in good condition after more than five decades of exposure. The only less-than-satisfactory performance was observed in some areas of the main decks. These areas experienced a delamination of the 3/4 in. (20 mm) concrete cover protecting four layers of large-sized undeformed (typically 1 in. [25 mm] square) reinforcing bars spaced 4 in. (100 mm) on centers. In retrospect, this failure plane is understandable and would have been avoided by the use of modern prestressing procedures. Cover for hull reinforcing was specified at 7/8 in. (22 mm), with all other reinforcement protected by only 1/2 in. (13 mm).

Without exception, the reinforcing steel bars cut by the 18 cores taken were rust-free. Cores that included reinforcing steel were split along an axis parallel to the plane of the reinforcing in accordance with the procedures of ASTM C 496. Visual inspection revealed negligible corrosion when the bar was removed. After the interface was sprayed with phenolphthalein, the surfaces stained a vivid red, indicating no carbonation at the steel-concrete interface.

Carbonation depth, as revealed by spraying the freshly fractured surface with a standard solution of phenolphthalein, averaged 0.04 in. (1 mm) for specimens taken from the main deck, was between 0.04 and 0.08 in. (1 and 2 mm) for concrete in exposed wing walls, and was virtually nonexistent in the hull and bulkheads. Coring was conducted from the waterline to as much as 16 ft (5 m) above high water. In no instances could carbonation depths greater than 0.08 in. (2 mm) be found. In isolated instances, flexural cracks up to 0.31 in. (8 mm) in depth were encountered, and these had carbonated in the plane of the crack. The carbonation did not appear to progress more than 0.004 in. (0.1 mm) perpendicular to the plane of the crack.

High-quality, low-permeability concrete will inhibit the diffusion of carbon dioxide, and concrete with a high moisture content will reduce the diffusion rate to that of a gas through water rather than that of a gas through air.

4.14.1.3 *Chesapeake Bay Bridge, Annapolis, Md.*—Concrete cores taken from the 35-year-old Chesapeake Bay Bridge revealed carbonation depths of 0.08 to 0.31 in. (2 to 8 mm) from the top of the bridge deck and 0.08 to 0.51 in. (2 to 13 mm) from the underside of the bridge deck. The higher carbonation depth on the underside reflects increased gas diffusion associated with the drier surface of the bridge. The 1.14 in. (36 mm) asphalt-wearing course appears to have inhibited drying and thus reduced carbonation depth on top (Holm 1983; Holm, Bremner, and Newman 1984).

4.14.1.4 *Coxsackie Bridge, New York*—Cores drilled with the cooperation of the New York State Thruway Authority from the 15-year-old exposed deck surface of the Interchange Bridge at Coxsackie revealed 0.20 in. (5 mm) carbonation depths for the top surface and 0.39 in. (10 mm) from the bottom. Despite almost 1000 saltings of the exposed deck, there was no evidence of corrosion in any of the reinforcing bars cut by the six cores taken (Holm, Bremner, and Newman 1984).

4.14.1.5 *Bridges and viaducts in Japan*—The results of measurements of carbonation depths on mature marine structures in North America are paralleled by data reported by Ohuchi et al. (1984). These investigators studied the chloride penetration, depth of carbonation, and incidence of microcracking in both lightweight and normalweight concrete on the same bridges, aqueducts, and caissons after 19 years of exposure. The high-durability performance of those structures (as measured by the carbonation depths, microcracking, and chloride penetration profiles reported by Ohuchi et al. [1984]) is similar to studies conducted on mature lightweight concrete bridges in North America (Holm, Bremner, and Newman 1984).

4.14.2 *Permeability and corrosion protection*—While current technical literature contains numerous reports on the permeability of concrete, only a limited number of papers report experiments in which lightweight and normalweight concrete were tested under the same conditions. Furthermore, almost all studies measuring permeability used test conditions that were static. While this approach is appropriate for dams and water-containing structures, it is not relevant to bridges and parking structures, which are constantly subjected to dynamic stress and strain. Cover concrete is expected to maintain its protective impermeable integrity despite the accumulation of shrinkage, thermal, and structural load-related strains.

Permeability investigations conducted on lightweight and normalweight concrete exposed to the same testing criteria have been reported by Khokrin (1973), Nishi et al. (1980), Keeton (1970), Bamforth (1987) and Bremner, Holm and McInerny (1992). It is of interest that, in every case, despite wide variations in concrete strengths, testing media (water, gas, and oil), and testing techniques (specimen size, media pressure, and equipment), lightweight concrete had equal or lower permeability than its normalweight counterpart. Khokrin (1973) further reported that the lower permeability of lightweight concrete was attributed to the elastic compatibility of the constituents and the enhanced bond between the coarse aggregate and the matrix. In the Onoda Cement Company tests (Nishi et al. 1980), concrete with a *w/cm* of 0.55, moist-cured for 28 days when tested at 128 psi (0.88 MPa) water pressure had a depth of penetration of 1.38 in. (35 mm) for normalweight concrete and 0.95 in. (24 mm) for lightweight concrete. When tested with seawater, penetration was 0.59 and 0.47 in. (15 and 12 mm) for normalweight concrete and lightweight concrete, respectively. The author suggested that the reason for this behavior was "a layer of dense hardened cement paste surrounding the particles of artificial lightweight coarse aggregate." The U.S. Navy-sponsored work by Keeton (1970) reported the lowest permeability with high-strength lightweight concrete. Bamforth (1987) incorporated lightweight concrete as one of the four concretes tested for permeability to nitrogen gas at 145 psi (1 MPa) pressure level. The normalweight concrete specimens included high-strength 13,000 psi (90 MPa) concrete and concrete with a 25% fly ash replacement, by mass or volume. The sanded lightweight concrete (7250 psi [50 MPa]), 6.4% air with a density of 124 lb/ft^3 (1985 kg/m^3) demonstrated the lowest water and air permeability of all mixtures tested.

Fully hydrated portland cement paste of low *w/cm* has the potential to form an essentially impermeable matrix that should render concrete impermeable to the flow of liquids and gases. In practice, however, this is not the case, as microcracks form in concrete during the hardening process, as well as later, due to shrinkage, thermal, and applied stresses. In addition, excess water added to concrete for easier placing will evaporate, leaving pores and conduits in the concrete. This is particularly true in exposed concrete decks where concrete has frequently provided inadequate protection for steel reinforcement.

Mehta (1986) observed that the permeability of a concrete composite is significantly greater than the permeability of either the continuous matrix system or the suspended coarse-aggregate fraction. This difference is primarily related to extensive microcracking caused by mismatched concrete components responding differentially to temperature gradients, service load strains, and volume changes associated with chemical reactions taking place within the concrete. In addition, channels develop in the transition zone surrounding normalweight coarse aggregates, giving rise to unimpeded moisture movements. While separations caused by the evaporation of bleed water adjacent to ordinary aggregates are frequently visible to the naked eye, such defects are essentially unknown in lightweight concrete. The continuous, high-quality matrix fraction surrounding lightweight aggregate is the result of several beneficial processes. Khokrin (1973) reported on several investigations that documented the increased transition zone microhardness due to pozzolanic reaction developed at the surface of the lightweight aggregate. Bremner, Holm, and deSouza (1984) conducted measurements of the diffusion of the silica out of the coarse lightweight-aggregate particles into the cement paste matrix using energy-dispersive x-ray analytical techniques. The results correlated with Khokrin's observations that the superior contact zone in lightweight concrete extended approximately 60 μm from the lightweight aggregate particles into the continuous matrix phase.

The contact zone in lightweight concrete is the interface between two porous media: the lightweight-aggregate particle and the hydrating cement binder. This porous media interface allows for hygrol equilibrium to be reached between the two phases, thus eliminating weak zones caused by water concentration. In contrast, the contact zone of normalweight concrete is an interface between the nonabsorbent surface (wall effect) of the dense aggregate and a water-rich binder. The accumulation of water at that interface is subsequently lost during drying, leaving a porous, low-quality matrix at the interface.

One laboratory report comparing normalweight concrete and lightweight concrete indicated that, in the unstressed state, the permeabilities were similar. At higher levels of stress, however, the lightweight concrete could be loaded to a higher percentage of its ultimate compressive strength before microcracking causes a sharp increase in permeability (Sugiyama, Bremner, and Holm 1996). In laboratory testing programs, the concrete is maintained at constant temperature, there are no significant shrinkage restraints, and field-imposed stresses are absent. Because of the as-batched moisture content of the lightweight aggregate before mixing, this absorbed water provides for extended moist curing. The water tends to wick out from the coarse aggregate pores into the finer capillary pores in the cement paste, thereby extending moist curing. Because the potential pozzolanic surface reaction is developed over a long time, usual laboratory testing that is completed in less than a few months may not adequately take this into account.

4.14.3 *Influence of contact zone on durability*—The contact zone is the transition layer of material connecting the coarse-aggregate particle with the enveloping continuous mortar matrix. Analysis of this linkage layer requires consideration of more than the adhesion developed at the interface (contact zone) and should include the transitional layer that forms between the two phases. Collapse of the structural integrity of a conglomerate may come from the failure of one of the two phases or from a breakdown in the contact zone causing a separation of the still-intact phases. The various mechanisms that act to maintain continuity, or

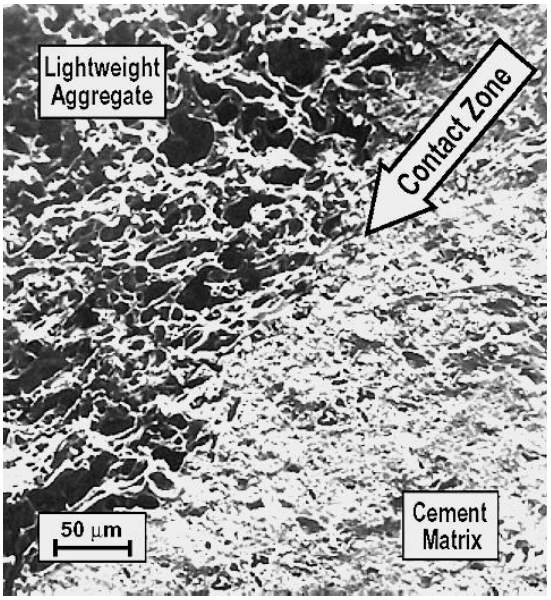


Fig. 4.13—Micrograph of contact zone.

Table 4.1—Microhardness in and beyond the contact zone *c/z* of concrete with differing *w/cm* and various coarse aggregates (Khokrin 1973)

	w/cm					
	0.3		0.4		0.5	
Coarse aggregate type	In *c/z*	Beyond *c/z*	In *c/z*	Beyond *c/z*	In *c/z*	Beyond *c/z*
Lightweight aggregate B	160	92	143	78	136	76
Lightweight aggregate O	167	94	138	73	125	68
Crushed diabase	81	79	—	—	—	—
Crushed limestone	81	81	—	—	—	—

that cause separation, have not received the same attention as has the air-void system necessary to protect the paste. Aggregates are often inappropriately dismissed as being inert fillers and, as a result, they and the associated transition zone have until recently received very modest attention.

For concrete to perform satisfactorily in severe exposure conditions, it is essential that a good bond develops and is maintained between the aggregate and the enveloping continuous mortar matrix. A high incidence of interfacial cracking or aggregate debonding will have a serious effect on durability if these cracks fill with water and subsequently freeze. An equally serious consequence of microcracking is the easy path provided for the ingress of salt water into the mass of the concrete. To provide an insight into the performance of different types of concrete, a number of mature structures that have withstood severe exposure were examined. The morphology and distribution of chemical elements at the interface were studied and reported by Bremner, Holm, and deSouza (1984).

The contact zone in lightweight concrete has been demonstrated to be significantly superior to that of normal-weight concrete that does not contain silica fume (Holm, Bremner, and Newman 1984; Khokrin 1973). This profound improvement in the quality, integrity, and microstructure stems from a number of characteristics unique to lightweight concrete, including, but not limited to, the following:

- The alumina- and silicate-rich surface of the fired ceramic aggregate, which is pozzolanic and combines with $Ca(OH_2)$ liberated by hydration of the portland cement;
- Reduced microcracking at the matrix lightweight aggregate interface because of the elastic similarity of the aggregate and the surrounding cementitious matrix; and
- Hygrol equilibrium between two porous materials (lightweight aggregate and a porous cementitious matrix) as opposed to the usual condition with normal-weight aggregate where bleed-water lenses around coarse natural aggregates have *w/cm* significantly higher than in the bulk of the matrix. When silica fume is added, the high-quality microstructure of the contact zone of concrete containing lightweight aggregate is moderately enhanced. When used in concrete containing normalweight aggregates, however, this zone of weakness is profoundly improved.

4.14.3.1 *Contact zone of mature concrete subjected to severe exposure*—Micrographs of the contact zone of specimens were prepared for examination in a scanning electron microscope equipped with an energy-dispersive x-ray analyzer. An example is Fig. 4.13, which shows a micrograph from the waterline of a more than 60-year-old concrete ship that was reported by Holm, Bremner, and Newman (1984). This micrograph confirms that a very tight bond develops between the lightweight aggregate and the mortar matrix. Normalweight cores taken from bridges that also contained lightweight decks were also examined and revealed separation between the normalweight aggregate and the matrix, but not at the lightweight-aggregate interface.

Russian studies on the durability of lightweight concrete (Khokrin 1973) included results of scanning electron microscopy that revealed new chemical formations at the contact zone between the matrix and keramzite (rotary kiln-produced expanded clay or shale). These micrographs confirmed earlier tests in which x-ray diffraction of ground keramzite taken before and after immersion in a saturated lime solution attested to the presence of a chemical reaction.

Khokrin (1973) also reported on microhardness tests of the contact zone of lightweight concrete and normalweight concrete, which established the width of the contact zone as approximately 60 µm. These results are shown in Table 4.1.

Virtually all commercial concrete exhibits some degree of bleeding and segregation. This is primarily due to the difference in density of the various ingredients and can be minimized with the use of proper mixture proportioning. The influence of bleeding upon the tensile strength of normalweight concrete was studied by Fenwick and Sue (1982). This report described the effects of the rise of bleed water through the mixture, the entrapment of air pockets below the larger coarse aggregate particles, and the poor paste quality at the interface due to the excessive concentrations of water. Reductions in mechanical properties are inevitable as a result of the interface flaws, as they limit interaction between the two distinctly different phases.

However significant any reduction in compressive and tensile strength due to a poorly developed contact zone, the effect on permeability is even greater. Permeability leads to increased penetration of aggressive agents that accelerate corrosion of embedded reinforcement. The permeability of concrete is then the permeability of each of its two fractions. A plausible explanation could be the effect of the interface flaws linking up with microcracking in the mortar phase of the matrix.

The phenomenon of bleed water collecting and being trapped under coarse particles of lightweight aggregate is considerably diminished, if not essentially eliminated, by the absorption of a small but significant amount of water from the fresh concrete into the interior of the lightweight aggregate. This has been verified in practice by the examination of the contact zone of lightweight concrete split cylinders and by visual examination of sand-blasted vertical surfaces of North American building structures. This observation should not be surprising because with lightweight concrete, the aggregate/ matrix interface is a boundary between two porous media, while with normalweight concrete, there is an abrupt transition at the porous/solid phase interface.

Fagerlund (1972, 1978) has presented reports that analyze the contact zone in mortar and concrete. These reports provide equations that describe the influence of the contact zone on strength parameters. Fagerlund supported the analyses with micrographs that clearly identified various degrees of interaction, from almost complete phase separation for normalweight aggregates to cases involving expanded aggregates in which the boundary between the two phases is not possible to discern. The fact that the high-quality contact zones in lightweight concrete have maintained their integrity throughout their service life of the structures provides reassurance of effective long-term interaction of the components of the concrete composite (Holm 1983).

4.14.3.2 *Implications of contact zone on failure mechanisms*—Exposed concrete must endure the superposition of a dynamic system of forces, including variable live loads, variable temperatures, moisture gradients, and dilation due to chemical changes. These factors cause a predominantly tensile-related failure. Yet, the uniaxial compressive strength is traditionally considered the preeminent single index of quality despite the fact that concrete almost never fails in compression. The simplicity and ease of compression testing has perhaps diverted the focus from a perceptive understanding and development of appropriate measurement techniques that quantify durability characteristics.

In general, weakest-link mechanisms are undetected in uniaxial compression tests due to concrete's forgiving load-sharing characteristics in compression, that is, localized yielding and closing of stress related, temperature, and volume change cracks. Weakest- link mechanisms, however, are important in tensile zones that arise from applied loads and exposure conditions. In many types of concrete, the contact zone may be the weakest link that is decisive in determining the long-term behavior of the contact zone.

4.14.3.3 *Accommodation at the aggregate-matrix interface*—Additionally, a full understanding has yet to be developed regarding the accommodation mechanism, by which the pores closest to the aggregate-matrix interface provide an accessible space for products of various reactions to form in spaces without causing deleterious expansion. Research has identified ettringite, alkali-silica gel, marine salts, and corrosion products in these near-surface pores. There remains the unfinished work of integrating these findings to explain how these products impact long-term performance (Holm and Bremner 2000).

4.15—Absorption

Lightweight concrete planned for exposed applications will, of necessity, be of high quality. Testing programs have revealed that high-quality lightweight concrete specimens absorbed very little water and thus maintained their low density. As mentioned previously, this was not unexpected. In a series of publications, it was reported that the permeability of lightweight concrete was extremely low and generally equal to or significantly lower than that reported for the normalweight concrete specimens. Similar results and conclusions by Russian, Japanese, and English investigators confirmed these findings. All attributed the low permeability to the profound influence of the high-integrity contact zone possessed by lightweight concrete

In investigations of high-strength lightweight concrete for the Arctic, Hoff (1992) reported that specimens that had a period of drying followed by water immersion at atmospheric pressure did not refill all the void space caused by drying. Pressurization caused an additional density increase of approximately 2.5 lb/ft^3 (40 kg/m^3). Before the introduction of the test specimens into the seawater, all concrete lost mass during the drying phase of curing, although concrete with a compressive strength of 9000 psi (62 MPa) lost little due to its very dense matrix.

4.16—Alkali-aggregate reaction

ACI 201.1R reports no documented instance of in-service distress caused by alkali reactions with lightweight aggregate. Mielenz (1994) indicates that although the potential exists for alkali-aggregate reaction with some natural lightweight aggregates, the volume change may be accommodated without necessarily causing structural distress. The surface of fine aggregate fractions of expanded shales, clays, and slates are known to be pozzolanic and may also serve to inhibit disruptive expansion (Boyd, Bremner and Holm 2000; Holm and Bremner 2000). No evidence of alkali-lightweight-aggregate reactions were observed in tests conducted on 70-year-old marine structures and several more than 30-year-old lightweight concrete bridge decks (Holm 1994).

Though laboratory studies and field experience have indicated no deleterious expansion resulting from the reaction between cement and silica in the lightweight component of the aggregates, the natural aggregate portion of a sand-lightweight concrete mixture should be evaluated in accordance with applicable ASTM standards.

Many lightweight concrete mixtures designed for an equilibrium density in the range of 110 lb/ft^3 (1760 kg/m^3) and above are produced using either natural sand or a naturally

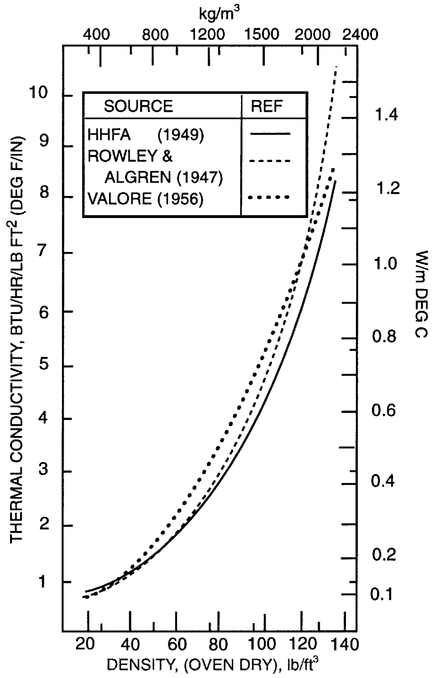


Fig. 4.14—Relation of average thermal conductivity k *values of concrete in oven-dry condition to density (Valore 1980).*

occurring coarse aggregate. In either case, these natural aggregates should be considered a potential source to develop alkali-aggregate reactions until they have been demonstrated by an appropriate ASTM test procedure or by having an established service history to be of negligible effect.

4.17—Thermal expansion

Determinations (Price and Cordon 1949) of linear thermal expansion coefficients made on lightweight concrete indicate values are 4 to 5×10^{-6} in./in./°F (7 to 11×10^{-6} mm/mm/°C), depending on the amount of natural sand used.

4.18—Heat flow properties

4.18.1 *Thermal conductivity*—The value of thermal conductivity k is a specific property of a material rather than of a construction and is a measure of the rate at which heat (energy) passes perpendicularly through a unit area of homogeneous material of unit thickness for a temperature gradient of 1 degree:

U.S. units, k = Btu/h·ft^2 (°F/in.)

(SI units, k = W/m · °C)

Thermal resistivity is the resistance per unit of thickness and is equal to $1/k$.

Thermal conductivity has been determined for concrete ranging in oven-dry density from less than 20 lb/ft^3 to over 200 lb/ft^3 (320 to 3200 kg/m^3). Conductivity values are generally obtained from guarded hot-plate specimens (ASTM C 177) tested in an oven-dry condition.

When conductivity values for concrete having a wide range of densities are plotted against oven-dry density, best-fit curves show a general dependence of k on density, as shown in Fig. 4.14. Also shown is the fact that different investigators have found different relationships. These differences are accounted for by differences in aggregate mineralogical type and microstructure, as well as in grading. Differences due to cement content, as well as matrix density and pore structure also result. Some differences in test methods and specimen sizes also existed.

Valore (1980) plotted over 400 published test results of density w against the logarithm of conductivity k and suggested the following equation

$$k = 0.5e^{0.02w}(k = 0.072e^{0.00125w}) \qquad (4\text{-}3)$$

An accurate k value for a given concrete, based on testing by the method of ASTM C 177, is preferable to a calculated value. For usual construction, however, the formula provides a good base for estimating k for concrete in the oven-dry condition and, in addition, may easily be revised for air-dry conditions.

4.18.2 *Effect of moisture on thermal conductivity of concrete*—Increasing the free moisture content of hardened concrete causes an increase in thermal conductivity. Valore (1980) stated that k increases by 6% for each 1% increment in free or evaporable moisture by weight in relation to oven-dry density. The corrected conductivity may be calculated as follows

$$k(\text{corrected}) = k(\text{oven-dry}) \times \left(1 + 6\frac{(w_m - w_o)}{w_o}\right) \qquad (4\text{-}4)$$

where w_m and w_o are densities in moist and oven-dry conditions, respectively.

4.18.3 *Equilibrium moisture content of concrete*—Concrete in a wall is not in an oven-dry condition; it is in equilibrium with the relative humidity of the environment. Because k values shown are for oven-dry concrete, it is necessary to know the moisture content for concrete in equilibrium with its normal environment in service and then apply a moisture correction factor for estimating k under anticipated service conditions. The relative humidity within masonry units in a wall will vary with type of occupancy, geographical location, exposure, and with the seasons, and it is normally assumed to be 50%. Also, it is normally assumed that exterior surfaces of single-wythe walls are protected by a breathing-type paint, stucco, or surface-bonding fibered-cement plaster. For single-wythe walls, such protection is necessary to minimize rain penetration. For cavity walls, the average moisture content of both wythes, even with the exterior wythe unpainted, will be approximately equal to that of the protected single-wythe wall.

Data from various sources for normalweight and lightweight concrete and for low-density insulation concrete have been summarized by Valore (1956, 1980). Average long-term moisture contents for concrete are in good agreement with data given herein for concrete masonry units.

Under certain conditions, condensation within a wall can cause high moisture content, and this should be considered in selecting an appropriate conductivity value.

4.18.4 *Recommended moisture factor correction for thermal conductivity*—A 6 to 9% increase in k per 1% increase of moisture content, by weight, are recommended for lightweight-aggregate concrete (of all types) and normalweight concrete, respectively. These factors are for use where exposure conditions or other factors produce moisture contents known to depart appreciably from recommended standard moisture contents of 2% for ordinary concrete and 4% (by volume) for lightweight concrete.

A simple constant factor can be used for masonry unit and concrete under conditions of normal protected exposure. The k values, when corrected for equilibrium moisture in normal protected exposure, are to be increased by 20% over standard values for oven-dry concrete. This results in the Valore equation of Fig. 4.15, which now becomes in that figure

$$k = 0.6e^{0.02w}, \text{ Btu/h} \cdot \text{ft}^2\ °\text{F} (k = 0.00125w, \text{ W/m} \cdot °\text{C}) \quad (4\text{-}5)$$

where $e = 2.71828$ and w is the oven-dry density of concrete, in kg/m^3 and lb/ft^3, respectively.

4.18.5 *Cement paste as insulating material*—The oven-dry density of mature portland cement paste ranges from 100 lb/ft^3 (1600 kg/m^3) for a *w/cm* of 0.4, to 67 lb/ft^3 (1075 kg/m^3) for a *w/cm* of 0.8. This range for *w/cm* encompasses structural concrete. Other data on moist-cured neat cement cellular concrete (aerated cement paste) permit the development of k-density relationships for oven-dried, air-dried, and moist pastes (Valore 1980). The latter work shows that neat cement cellular concrete and autoclaved cellular concrete follow a common k-density curve.

4.18.6 *Thermal transmittance—U*-value is thermal transmittance; it is a measure of the rate of heat flow through a building construction, under certain specified conditions. It is expressed in the following units: U = Btu/h · ft^2 · °F (U = W/m^2 · °C).

The U-value of a wall or roof consisting of homogeneous slabs of material of uniform thickness is calculated as the reciprocal of the sum of the thermal resistance of individual components of the construction

$$U = \frac{1}{R_1 + R_2 + R_3 + \ldots R_n} \quad (4\text{-}6)$$

where R_1, R_2, etc., are resistances of the individual components and also include standard constant R values for air spaces and interior and exterior surface resistances. R is expressed in the following units: R = h · ft^2 · °F/Btu (R = m^2 · K/W)

Thermal resistances of individual solid layers of a wall are obtained by dividing the thickness of each layer by the thermal conductivity k for the particular material of which the layer consists.

4.19—Fire endurance

Lightweight concrete is more fire resistant than ordinary normalweight concrete because of its lower thermal conductivity, lower coefficient of thermal expansion, and the inherent fire stability of an aggregate already heated to over 2000 °F (1100 °C) (Abrams and Gustaferro 1968; Abrams 1971; Carlson 1962; Selvaggio and Carlson 1964; ESCSI 1980; Prestressed Concrete Institute 1992).

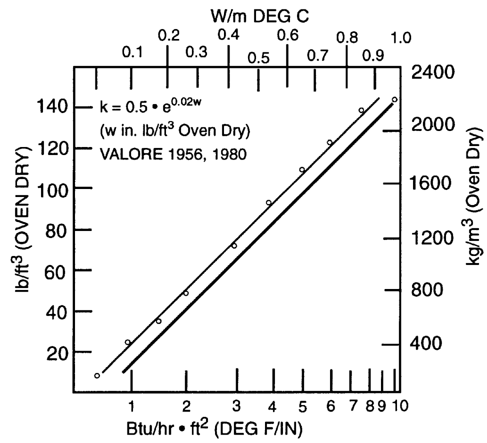


Fig. 4.15—Relation of average k *values of concrete to dry density (Valore 1980).*

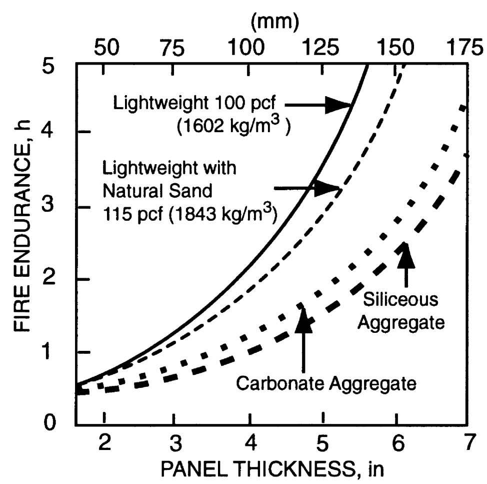


Fig. 4.16—File endurance (heat transmission) of concrete slabs as a function of thickness for naturally dried specimens (Abrams and Gustaferro 1968).

4.19.1 *Heat transmission*—Research on fire endurance comparing lightweight-aggregate concrete with normalweight concrete is shown in Fig. 4.16.

4.19.2 *Cover requirements*—The thickness of concrete between reinforcing steel (or structural steel) and the nearest fire-exposed surface is called cover. For fire ratings, the reinforcing steel cover requirements for lightweight concrete may be slightly lower than those for normalweight concrete.

4.19.3 *Fire resistance of high-strength lightweight concrete*—While there is more than 50 years of experience and a multitude of fire tests conducted on lightweight concrete of strength levels appropriate for commercial construction—3000 to 5000 psi (21 to 35 MPa)—the availability of data on high-strength lightweight concrete has, until recently, been very limited.

Tests by Bilodeau et al. (1995) and Bilodeau, Malhotra, and Hoff (1998) have reported that, because of the extremely low permeability generally associated with high-strength concrete, there is significantly reduced resistance to damage due to spalling. Because of the higher moisture contents of concrete containing lightweight aggregate with high, as-batched absorbed water contents, there is increased risk of spalling. Because of the use of high-strength lightweight concrete on several offshore platforms where intense hydrocarbon fires could develop, there was an obvious need for finding a remedy for this serious potential problem.

Several reports have documented the beneficial influence of adding small quantities of polypropylene fibers to high-strength concrete as demonstrated by exposure to fire testing that was more intense than the exposure conditions (time-temperature criteria) specified by ASTM E 119. Apparently, the fibers melt and provide conduits for release of the pressure developed by the conversion of moisture to steam. Jensen et al. (1995) reported the results of tests conducted at the Norwegian Fire Research Laboratories. These studies included the determination of mechanical properties at high temperature, the improvement of spalling resistance through material design, and the verification of fire resistance and residual strength of structural elements exposed to fire. The addition of 0.1 to 0.2% polypropylene fibers in the lightweight concrete mixture provided a significant reduction of spalling. Fire tests on beams confirmed previous findings that greater spalling (exposed reinforcement) occurred on reinforced and prestressed lightweight concrete beams than occurred on normalweight concrete beams. Reduced or no spalling, however, occurred on lightweight concrete beams with polypropylene fibers. Also, no spalling was observed on lightweight concrete beams with passive fire protection (a special cement-based mortar with expanded polystyrene balls that did not contain fibers).

4.20—Abrasion resistance

Abrasion resistance of concrete depends on strength, hardness, and toughness characteristics of the cement paste and the aggregates, and the bond between these two phases. Most lightweight aggregates suitable for structural concrete are composed of solidified vitreous material comparable to quartz on the Mohs scale of hardness. Due to its pore system, however, the net resistance to wearing forces may be less than that of a solid particle of most natural aggregates. 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 normalweight concrete. Limitations are necessary in certain commercial applications where steel-wheeled industrial vehicles are used, but such surfaces generally receive specially prepared surface treatments. Hoff (1992) reported that specially developed testing procedures that measured ice abrasion of concrete exposed to arctic conditions demonstrated essentially similar performance for lightweight and normalweight concrete.

CHAPTER 5—DESIGN OF STRUCTURAL LIGHTWEIGHT-AGGREGATE CONCRETE

5.1—Scope

The availability and proven performance of lightweight aggregates has led to the improved functionality and economical design of buildings, bridges, and marine structures for more than 80 years. During much of this period, designs were based on the usual properties of concrete, properly adjusted by the engineers but without adequate guidance of recommended practices specifically pertaining to lightweight concrete. With the adoption of the 1963 ACI Building Code, lightweight- aggregate concrete received full recognition as an acceptable structural medium. General guidelines for the engineer and for the construction industry were included.

This chapter assists in the interpretation of the ACI 318 requirements for lightweight concrete. It also condenses many practical design aspects pertaining to lightweight concrete and provides the engineer with additional information for design.

A engineer should obtain information on the properties of concrete made with specific lightweight aggregate (or aggregates) available for a given project. These aggregates should fall within the frame of reference presented in this guide, and the specifications should be prepared so that only suitable lightweight aggregates will be used.

5.2—General considerations

Lightweight concrete has been shown by test and performance (refer to Chapter 4) to behave structurally in much the same manner as normalweight concrete, but at the same time, to provide some improved concrete properties—notably reduced weight, better insulation, and improved microstructure. For certain properties of concrete, the differences in performance are those of degree. Generally those properties that are a function of tensile strength (shear, development length, and modulus of elasticity) are sufficiently different from those of normalweight concrete to require design modification.

5.3—Modulus of elasticity

It has been shown that the modulus of elasticity of concrete is a function of density and compressive strength. The formula $E_c = w_c^{1.5} 33\sqrt{f_c'}$ $(E_c = w_c^{1.5} 0.043\sqrt{f_c'})$ presented in ACI 318, defines this relationship. Variations of the ACI formula for E_c at the high strength used in prestressed concrete are covered later in this section. Depending on how critically the values E_c will affect the nature of the design, the engineer should decide whether the values determined by the formula are sufficiently accurate or whether to determine E_c values from tests on the specified concrete.

Essentially, a lower E_c value for lightweight concrete means that it is more flexible because stiffness is defined as the product of modulus of elasticity and moment of inertia, *EI*. Reduced stiffness can be beneficial at times, and the use of lightweight concrete should be considered in these cases instead of normalweight concrete. In cases requiring improved impact or dynamic response, where differential foundation settlement may occur, and in certain types or configurations of shell roofs, the property of reduced stiffness may be desirable.

5.4—Tensile strength

Shear, torsion, anchorage, bond strength, development length, and crack resistance are related to tensile strength that is, in turn, dependent on the 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, or the concrete's moisture content and distribution. The tensile-splitting 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. A minimum tensile-splitting strength of 290 psi (2.0 MPa) 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 (Hanson 1958, 1961). 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 before the start of projects where development of early-age tensile-related handling forces occur such as precast or tilt-up members.

Tensile strength tests on lightweight concrete specimens that undergo some drying correlate well 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 7-day moist and 21-day laboratory air drying at 73.4 °F (23 °C) at 50% relative humidity before conducting splitting tests. Lightweight concrete splitting tensile strengths vary from approximately 75 to 100% of normal-weight concrete of equal compressive strength. Replacing lightweight fine aggregate with normalweight fine aggregate will normally increase tensile strength. Further, natural drying will increase tensile-splitting strengths.

5.5—Shear and diagonal tension

From a shear and diagonal tension perspective, light-weight concrete members behave in fundamentally the same manner as normalweight concrete members. In both cases, the shear and diagonal tension *contribution* of the concrete member is determined primarily on the tensile capacity of an unreinforced web. Because most concrete in construction is subjected to air-drying, lightweight concrete will generally have lower tensile strength than normalweight concrete of equal compressive strength. ACI 318 provides two alternate approaches by which the permissible shear capacity in a lightweight concrete member may be determined. The permissible shear capacity may be determined by using the splitting-tensile strength f_{ct} for the specific aggregate to be used or by using a fixed percentage of a similar-strength normalweight concrete.

Using the first approach to calculate the permissible shear, the value of $f_{ct}/6.7$ is substituted for $\sqrt{f_c'}$ in the provisions of ACI 318.

Most lightweight aggregate producers have sufficient data available to estimate *realistically* the range of values that *can* be achieved. A realistic value of f_{ct} for design purposes should be established for each desired compressive strength and composition of concrete. The f_{ct} values on which the structural design is based should be incorporated in the concrete specifications for the job. Splitting cylinder strength tests, if required, should be performed on laboratory mixtures similar to those proposed for the project. These tests should be performed in accordance with ASTM C 496. Splitting cylinder strength is a laboratory aggregate evaluation and is not to be conducted on field concrete.

A second, generally conservative approach in calculating the permissible shear may be used when the engineer is unable or is hesitant to specify f_{ct} values. Reduction factors are available that may be used to determine the shear capacity of lightweight concrete as a fixed percentage of normalweight concrete shear. Research on the splitting-tensile strength of lightweight concrete shows an improvement in tensile strength when natural sand is used in place of the lightweight fine aggregate (Pfeifer 1967). Two reduction factors have therefore been established: 75% of normal-weight values for concrete containing both fine and coarse lightweight aggregates; and 85% of normalweight values for combinations of natural sand fine aggregates and lightweight coarse aggregates.

Most of the research addressing tensile strength, shear strength, and development lengths of structural lightweight concrete that formed the basis for existing ACI 318 Building Code requirements were limited to concrete with a compressive strength of less than 6000 psi (41 MPa). When concrete strengths of greater than 6000 psi (41 MPa) are *specified*, the determination of the appropriate tension, shear, and development length parameters should be based on a comprehensive testing program that is conducted on the materials selected for the project. For some lightweight aggregates, the tensile strength ceiling may be reached earlier than the compressive strength ceiling.

A comprehensive investigation into the shear strength of higher-strength (41 to 69 MPa [6 to 10 ksi]) reinforced and prestressed lightweight concrete beams has been reported by Ramirez et al. (1999). Measurements during the beam tests and observations of the structural behavior enabled the evaluation of the ACI 318-95, AASHTO Standard (1995) and AASHTO LRFD (1994) shear design methods for the types of beams tested.

Ramirez et al. (1999) reported that for the reinforced concrete specimens:

- Despite the fact that the sand-lightweight concrete beams had higher measured shear capacities than those calculated using code/specification methods considered in their report, the lightweight concrete beams were, on average, 82% of the measured shear capacity of the companion normalweight beams. The 0.85 reduction factor used by the current specifications does not adequately account for the reduction of shear strength in sand-lightweight concrete beams. The trend observed is important especially for the case of beams with low to minimum amounts of shear reinforcement where the concrete contribution is a larger fraction of the total shear strength;

- While all reinforced (nonprestressed) concrete beams had measured shear capacities that exceeded both the ACI 318-95/AASHTO (simple method) and the AASHTO LRFD (general method), the degree of conservatism was greater for the normalweight concrete then the lightweight concrete beams;
- The degree of conservatism in the calculated capacities decreases for the lightweight concrete beams tested; and
- For the beams tested, the ACI 318-95/AASHTO (simple) method produced estimates of shear strength 6% more conservative than did the AASHTO LRFD (general method).

For the high-strength prestressed and lightweight concrete concrete beams tested, Ramierez et al. found the following:

- The measured shear capacities of the beams using a normal 41 and 69 MPa (6 and 10 ksi) concrete were nearly equal. Therefore, the minimum amount of transverse reinforcement presented by the AASHTO LRFD did not provide the same level of conservatism for the higher strength beams;
- For the high strength prestressed lightweight concrete beams tested both the AASHTO LRFD (general method) and the ACI 318-95 / AASHTO (simple method) provide conservative estimates of the shear strength; and
- For the high-strength prestressed lightweight concrete beams tested, the degree of conservatism afforded by the AASHTO (simple) method were nearly equal.

Based on the results of this comprehensive testing program, Ramirez et al. (1999) recommended more research in the area of high-strength prestressed lightweight concrete beams, especially with regard to the minimum requirements of transverse reinforcement needed.

Because a reduction in self-weight leads to a substantial reduction in total load on lightweight concrete members, shear capacity reduced to as much as 75% of normalweight concrete may not necessarily lead to a decrease in relative structural efficiency.

5.6—Development length

5.6.1 *Deformed reinforcement*—Because of the lower particle strength, lightweight concrete has lower bond-splitting capacities and a lower postelastic strain capacity than normalweight concrete. North American design practice (ACI 318) requires longer embedment lengths for reinforcement bars in lightweight concrete than for normalweight concrete. Unless tensile-splitting strengths are specified, ACI 318 requires the development lengths for lightweight concrete to be increased by a factor of 1.3 over the lengths required for normalweight concrete.

5.6.2 *Prestressed concrete*—Meyer and Kahn (2000) in their paper on development length in high-strength lightweight concrete reported the following:

- An evaluation of code provisions using the results of 12 tests on high-strength prestressed lightweight concrete girders showed the transfer and development length requirements of the current AASHTO and ACI equations to be conservative; and
- Test results showed that shear cracking in the transfer length region across the bottom strands did not induce strand slip if stirrup density was doubled over the current AASHTO specified density in that region.

Thatcher et al. (2002) reported that while the ACI and AASHTO codes provide a conservative estimate of the transfer length of normalweight concrete, their test results showed that transfer length of lightweight concrete was underestimated. Kolozs suggested that the modulus of elasticity was a consistent factor in determining the transfer length for both normal and lightweight concretes and that most models do not accurately predict the behavior of lightweight concrete. On the other hand, Thatcher et al.'s tests indicate that the ACI and AASHTO codes provide a conservative estimate of the development length for both normalweight and lightweight concretes tested in his study.

Nassar's (2002) conclusions differ. Based on the results of tests on large-span high-performance prestressed lightweight concrete beams, he reported:

- That until additional data emerges for transfer length in high-strength lightweight concrete beams, code guidance be raised to $60d_b$ per AASHTO LRFD stipulation and/or $f_{si}d_b/3$ to maintain a more conservative representation; and
- The development length results from his tests were inconclusive, and the ACI and AASHTO code requirements may be marginally acceptable for high-strength prestressed lightweight concrete. Until additional testing is conducted, it is recommended that the equation for the development length be modified by a factor of 1/0.85, resulting in an 18% increase in code requirements.

With closely spaced and larger-diameter prestressing strands that can cause high splitting forces, this increase may no longer be conservative. A conservative design approach or a preproject testing program may be advisable for special structures, larger-diameter strands, short-span decks, or combinations of highly reinforced thin members using high-strength, lightweight concrete. Additional research on development-length requirements and the need for greater amounts of confining reinforcement for prestressing strands in high-strength lightweight concrete and specified-density concrete is clearly warranted.

5.7—Deflection

5.7.1 *Initial deflection*—ACI 318 specifically includes modifications of formulas and minimum thickness requirements that reflect the lower modulus of elasticity, lower tensile strength, and lower modulus of rupture of lightweight concrete.

ACI 318 also lists the minimum thickness of beams for one-way slabs unless deflections are computed and requires a minimum increase of 9% in thickness for lightweight members over normalweight. Thus, using the values in this table, lightweight structural members with increased thickness are not expected to deflect more than normalweight members under the same superimposed load.

5.7.2 *Long-term deflection*—Analytical studies of long-term deflections can be made, taking into account the effects that occur from creep and shrinkage. Final deflection can then be compared with the initial deflection due to elastic strains only. Comparative shrinkage values for concrete vary appreciably with variations in component materials. In typical cases, the shrinkage of lightweight concrete may be somewhat greater than normalweight concrete of the same strength. An analysis of deflection due to elastic strain, creep, and shrinkage leads to the same factor given in ACI 318, and this factor for obtaining long-term deflections should be used for both types of concrete. More refined approaches to estimating deflections are usually not warranted.

5.8—Columns

The design of columns using lightweight concrete is essentially the same as for normalweight concrete. The reduced modulus should be used in the code sections in which slenderness effects are considered.

Extensive tests (Pfeifer 1968; Washa and Fluck 1952) comparing the time-dependent behavior of lightweight and normalweight columns developed the following facts:

- Instantaneous shortening caused by initial loading can be accurately predicted by elastic theory. Such shortening of a lightweight concrete column will be greater than that of a comparable normalweight column due to the lower modulus of elasticity of lightweight concrete;
- Time-dependent shortening of lightweight and normalweight concrete may differ when small unreinforced specimens are compared. These differences, however, are minimized when large reinforced concrete columns are tested as both increasing size and amount of longitudinal reinforcements reduces time-dependent shortening. Measured time-dependent shortening was compared with those predicted by theory, and satisfactory correlations were found; and
- Measured ultimate strengths were compared with theory and good correlations were found. Both concrete type and previous loading had no effect on this correlation.

5.9—Prestressed lightweight concrete

5.9.1 *Applications*—Prestressed lightweight concrete has been widely used for more than 40 years in North America, in nearly every application for which prestressed normalweight concrete has been used. The most beneficial applications are those in which the unique properties of prestressed lightweight concrete are fully utilized.

Prestressed lightweight concrete has been used extensively in roofs, walls, and floors of buildings. Prestressed lightweight concrete has found extensive use in flat plate and beam types of construction. For these uses, the reduced dead weight with its lower structural, seismic, and foundation loads, the better thermal insulation, significantly better fire resistance, and lower transportation cost have usually been the determining factors in the selection of prestressed lightweight concrete.

5.9.2 *Properties*—When lightweight concrete is used with prestressing, it should possess two important properties: the aggregates should be of high quality, and the concrete mixture must have high strength.

The following is a summary of the properties of prestressed lightweight concrete:

Equilibrium density—The range is typically between 100 to 120 lb/ft^3 (1600 to 1920 kg/m^3). Several bridges have incorporated a specified equilibrium density of approximately 130 lb/ft^3 (2080 kg/m^3) (Holm and Ries 2000).

Compressive strength—Typically, higher-strength concrete is used with prestressing. In general, the commercial range of strength is between 5000 to 6000 psi (35 to 41 MPa) or higher.

Modulus of elasticity—An approximate formula for evaluating the modulus of elasticity of lightweight concrete in high-strength prestressed applications can be achieved by a modification of the formula listed in ACI 318. In general, the ACI formula for evaluating E_c tends to overestimate E_c values for high-strength normalweight concrete, and the disparity is even greater with high-strength lightweight concrete.

When accurate values of E_c are required, it is suggested that either a laboratory test or the following formula modified for lightweight concrete be used for a first estimate

$$E_c = w_c^{1.5} C \sqrt{f_c'}$$

where C is a coefficient depending upon the strength of the concrete and the other symbols are the same as those used in ACI 318 (Pauw 1960).

$$C = 31 \text{ when } f_c' = 5000 \text{ psi} \tag{5-1}$$

$$(C = 0.040 \text{ when } f_c' = 35 \text{ MPa})$$

$$C = 29 \text{ when } f_c' = 6000 \text{ psi} \tag{5-2}$$

$$(C = 0.038 \text{ when } f_c' = 41 \text{ MPa})$$

Combined loss of prestress—The Prestressed Concrete Institute's Design Handbook (1992) provides guidance for estimating the prestress loss due to elastic shortening, creep, shrinkage, and other factors. Estimates for creep strains for lightweight concrete are shown to be greater than for normalweight concrete. No distinction is made between lightweight and normalweight concrete for estimated shrinkage after both moist and accelerated curing. The handbook recommends that total loss of prestress in typical members will range from about 25,000 to 50,000 psi (170 to 340 MPa) for normalweight concrete and from about 30,000 to 55,000 psi (210 to 380 MPa) for members using lightweight coarse aggregate and natural sand.

Thermal insulation—The thermal insulation of lightweight concrete has a significant effect on prestressing applications because of the following factors:

- Greater temperature differential in service between the

side exposed to sun and the inside may cause greater camber. The top member of a stack of precast products should be covered during the initial drying stage;
- Better response to steam curing;
- Greater suitability for winter concreting; and
- Better fire resistance.

Dynamic, shock, vibration, and seismic resistance—Prestressed lightweight concrete appears at least as good as normalweight concrete and may be even better due to its lower modulus of elasticity.

Cover requirements—Where fire requirements dictate the cover requirements, the insulating effects developed by the lower density and the fire stability offered by a preheated-to-1200 °C aggregate may be used advantageously.

5.10—Thermal design considerations

In concrete elements exposed to the environment, the choice of lightweight concrete will provide several distinct advantages over normalweight concrete (Fintel and Khan 1965, 1966, 1968). These physical properties are covered in detail in Chapter 4:

- The lower thermal diffusivity provides a thermal inertia that lengthens the time for exposed members to reach any steady-state temperature;
- Due to this resistance, the effective interior temperature change will be smaller under transient temperature conditions. This time lag will moderate the solar build-up and nightly cooling effects;
- The lower coefficient of linear thermal expansion that is developed in the concrete due to the lower coefficient of thermal expansion of the lightweight aggregate itself is a fundamental design consideration in exposed members; and
- The lower modulus of expansion will develop lower stress changes in members exposed to thermal strains.

A comparative thermal investigation studying the shortening developed by the average temperature of an exposed column restrained by the interior frame demonstrated the fact that the axial shortening effects were about 30% smaller for lightweight concrete, and the stresses due to restrained bowing were about 35% less with lightweight concrete than with normalweight concrete (Fintel and Kahn 1965, 1966, 1968).

For an exact structural analysis, use data on local aggregates obtained from lightweight and normalweight aggregate suppliers.

5.11—Seismic design

Lightweight concrete is particularly adaptable to seismic design and construction because of the significant reduction in inertial forces. A large number of multistory buildings and bridge structures have effectively used lightweight concrete in areas subject to earthquakes.

The lateral or horizontal forces acting on a structure during earthquake motions are directly proportional to the inertia or mass of that structure. These lateral forces may be calculated by recognized formulas and are applied with the other load factors.

5.11.1 *Ductility*—The ductility of concrete structural frames should be analyzed as a composite system—that is, as reinforced concrete. Studies by Ahmad and Batts (1991) and Ahmad and Barker (1991) indicate, for the materials tested, that the ACI rectangular stress block is adequate for strength predictions of high-strength lightweight concrete beams, and the recommendation of 0.003 as the maximum usable concrete strain is an acceptable lower bound for reinforced lightweight concrete members with strength greater than 6000 psi. Moreno (1986) found that while lightweight concrete exhibited a rapidly descending portion of the stress-strain curve, it was possible to obtain a flat descending curve with reinforced members that were provided with a sufficient amount of confining reinforcement slightly greater than that with normalweight concrete. Additional confining steel is recommended to compensate for the lower postelastic strain behavior of lightweight concrete. This report also included results that showed that it was economically feasible to obtain the desired ductility by increasing the amount of steel confinement.

Rabbat et al. (1986) came to similar conclusions when analyzing the seismic behavior of lightweight and normalweight concrete columns. This report focused on how properly detailed reinforced concrete column-beam assemblages could provide ductility and maintain strength when subjected to inelastic deformations from moment reversals. These investigations concluded that properly detailed columns made with lightweight concrete performed as well under moment reversals as normalweight concrete columns. ACI 318 places a compressive strength limit of 5000 psi (35 MPa) for concrete members unless supported by test results for higher strengths.

5.12—Fatigue

The first recorded North American comparison of the fatigue behavior between lightweight and normalweight was reported by Gray, McLaughlin, and Antrim (1961). These investigators concluded that the fatigue properties of lightweight concrete are not significantly different from the fatigue properties of normalweight concrete.

This work was followed by Ramakrishnan, Bremner, and Malhotra (1992), who found that, under wet conditions, the fatigue endurance limit was the same for lightweight and normalweight concrete.

Because of the significance of oscillating stresses that would be developed by wave action on offshore structures, and due to the necessity for these marine structures to use lightweight concrete for buoyancy considerations, a considerable amount of research has been completed determining the fatigue resistance of high-strength lightweight concrete and comparing these results with the characteristics of normalweight concrete. Hoff (1994) reviewed much of the North American and European data and concluded that, despite the lack of a full understanding of failure mechanisms, "under fatigue loading, high-strength lightweight concrete performs as well as high-strength normalweight concrete and, in many instances, provides longer fatigue life." It is, however, the long-term service performance of real structures that provides improved confidence in material behavior

*Fig. 5.1—Barge-mounted frame-placed beams. To the right is the old truss bridge. Both will carry U.S. 19 traffic. (*Engineering News Record*, June 4, 1964.)*

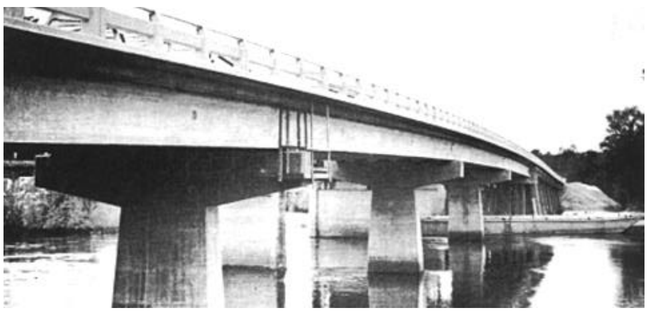


Fig. 5.2—Concrete weighing less than 120 lb/ft^3 *permitted 120 ft spans for Florida bridge. (*Engineering News Record*, June 4, 1964).*

rather than the extrapolation of conclusions obtained from laboratory investigations.

The long-term field performance of lightweight-concrete bridge members constructed in Florida in 1964 (Fig. 5.1 and Fig. 5.2) was evaluated in an in-depth investigation conducted in 1992. Comprehensive field measurements of service load strains and deflections taken in 1968 and 1992 were compared with the theoretical bridge responses predicted by a finite element model that is part of the Florida Department of Transportation bridge rating system (Brown and Davis 1993). The original 1968 loadings and measurements of the bridge were duplicated in 1992 and compared with calculated deflections, as shown in Fig. 5.3 (Brown, Larsen, and Holm 1995). Maximum deflection for one particular beam due to a midpoint load was 0.28 in. (7.1 mm) measured at 60.5 ft (18.4 m) from the unrestrained end of the span. This compares very well with the original deflection, which was recorded to be 0.26 in. (6.6 mm) measured at 50.5 ft (15.4 m). Rolling load deflections measured in 1968 and 1992 were also comparable, but slightly less in magnitude than the static loads.

Strain measurements across the bridge profile were also duplicated, and these compared very closely for most locations in areas of significant strain. Comparison of the 1992 and 1968 data shows bridge behavior to be essentially similar, with the profiles closely matched.

It appears that dynamic testing of the flexural characteristics of the 31-year-old long-span lightweight-concrete bridge corroborates the conclusions of fatigue investigations

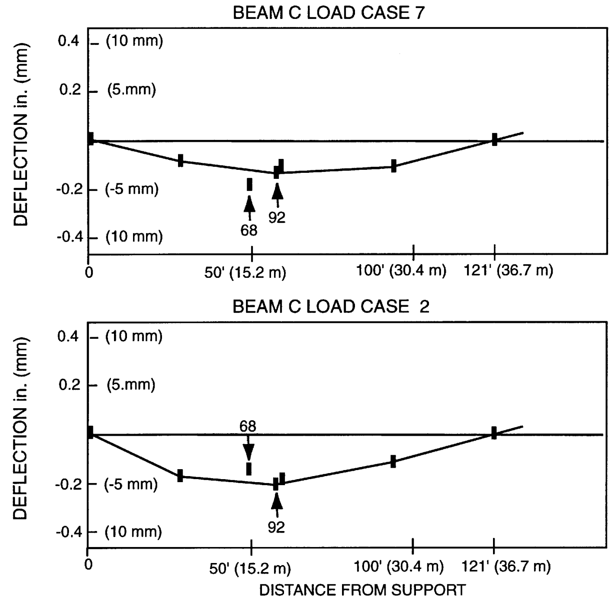


Fig. 5.3—Florida DOT predicted deflections compared with 1968 and 1992 measurements (Brown, Larsen, and Holm 1995).

conducted on small specimens tested under controlled conditions in several laboratories (Hoff 1994; Gjerde 1982; Gray, McLaughlin, and Antrim 1961). In these investigations, it was generally observed that the lightweight concrete performed as well as and, in most cases, somewhat better than the normalweight control specimens. Several investigators have suggested that the improved performance was due to the elastic compatibility of the lightweight aggregate particles to that of the surrounding cementitious matrix. In lightweight concrete, the elastic modulus of the constituent phases (coarse aggregate and the enveloping mortar phase) are relatively similar, while with normalweight concrete, the elastic modulus of most normalweight concrete may be as much as three to five times greater than its enveloping matrix (Bremner and Holm 1986). With lightweight concrete, the elastic similarity of the two phases of a composite system results in a profound reduction of stress concentrations and a leveling out of the average stress over the cross section of the loaded member. Normalweight concrete having a significant elastic mismatch will inevitably develop stress concentrations that may result in extensive microcracking in the concrete composite.

Additionally, because of the pozzolanic reactivity of the surface of the vesicular aggregate that has been fired at temperatures above 2012 °F (1100 °C) (Khokrin 1973), the quality and integrity of the contact zone of lightweight concrete is considerably improved. As the onset of microcracking is most often initiated at the weak link interface between the dense aggregate and the enveloping matrix, it follows that lightweight concrete will develop a lower incidence of microcracking (Holm, Bremner, and Newman 1984).

5.13—Specifications

Lightweight concrete may be specified and proportioned on the basis of laboratory trial batches or on field experience with the materials to be used. Most lightweight aggregate suppliers have mixture composition information available for their material, and many producers provide field control and technical service to ensure that the specified concrete quality will be used.

The average strength requirements for lightweight concrete do not differ from those for normalweight concrete for the same degree of field control.

Splitting-tensile strength tests should not be used as a basis for field acceptance of lightweight concrete.

The analysis of the load-carrying capacity of a lightweight concrete structure, either by cores or load tests, should be the same as for normalweight concrete.

Equilibrium density should be calculated in accordance with ASTM C 567.

Maximum fresh density should be determined by the designer, ready-mix supplier, and the lightweight aggregate supplier before starting the project.

CHAPTER 6—HIGH-PERFORMANCE LIGHTWEIGHT CONCRETE

6.1—Scope and historical development

While it is clearly understood that high strength and high performance are not synonymous, one may consider the first modern use of high-performance concrete to be when the American Emergency Fleet Corporation built lightweight concrete ships with specified compressive strengths of 5000 psi (35 MPa) during 1917 to 1920. Commercial normalweight concrete strengths of that time were approximately 2500 psi (17 MPa).

Lightweight concrete has achieved high strength levels by incorporating various pozzolans (fly ash, silica fume, metakaolin, calcined clays, and shales) combined with mid-range or high-range water-reducing admixtures, or both. Because of durability concerns, the *w/cm* has, in many cases, (that is, bridges, marine structures) been specified to be less than 0.45, and for severe environments, a significantly lower *w/cm* has been specified. Limiting water content and designing to an air content of 4 to 5% may result in an equilibrium density higher than 120 lb/ft^3 (1920 kg/m^3).

While structural-grade lightweight aggregates are capable of producing concrete with compressive strengths in excess of 5000 psi (35 MPa), several lightweight aggregates have been used in concrete that developed compressive strengths from 7000 to 10,000 psi (48 to more than 69 MPa). In general, an increase in density will be necessary when developing higher compressive strengths. High-strength lightweight concrete with compressive strengths of 6000 psi (41 MPa) are widely available commercially and testing programs on lightweight concrete with a compressive strength approaching 10,000 psi (69 MPa) are ongoing.

6.2—Structural efficiency of lightweight concrete

The entire hull structure of the USS Selma and 18 other concrete ships were constructed with 5000 psi, high-performance lightweight concrete in the ship building program in Mobile, Alabama starting in 1917. The structural efficiency as defined by the strength/density (*S*/*D*) ratio of the concrete used in the USS Selma was extraordinary for that time. Improvements in structural efficiency of concrete since that time are shown schematically in Fig. 6.1—an upward trend in the 1950s with the introduction of prestressed concrete, followed by production of high-strength normalweight concrete for columns of very tall cast-in-place concrete-frame commercial buildings. Most increases came as a result of improvements in the cementitious matrix brought about by new generations of admixtures such as high-range water-reducers, and the incorporation of high-quality pozzolans such as silica fume, metakaolin, and fly ash. History suggests, however, that the first major breakthrough came as a result of the lightweight concrete ship-building program in 1917.

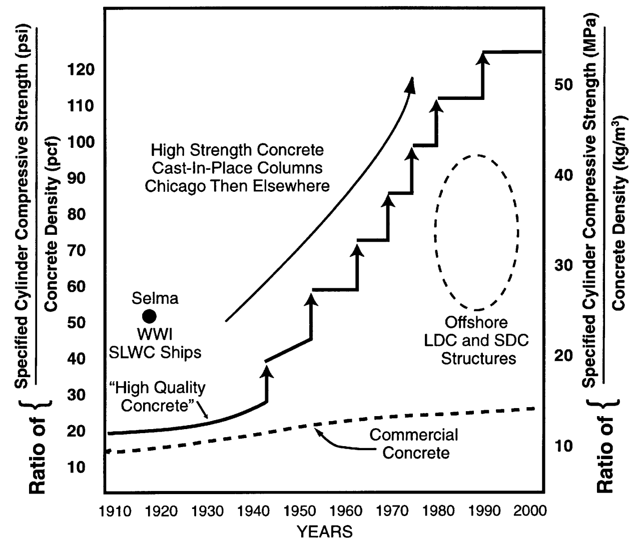


Fig. 6.1—The structural efficiency of concrete. The ratio of specified compressive strength to density (psi/[lb/ft^3]) (Holm and Bremner 1994).

6.3—Applications of high-performance lightweight concrete

6.3.1 *Precast structures*—High-strength lightweight concrete with a compressive strength in excess of 5000 psi (35 MPa) has been successfully used for almost four decades by North American precast and prestressed concrete producers. Presently, there are ongoing investigations into longer-span lightweight precast concrete members that may be feasible from a trucking/lifting/logistical point of view.

The 1994 Wabash River Bridge is a good example where a 17% density reduction was realized. The 96 lightweight prestressed post-tensioned bulb-tee girders were 175 ft (53.4 m) long, 7.5 ft (2.3 m) deep, and weighed 96 tons (87.3 metric tons) each. The 5-day strengths exceeded 7000 psi (48 MPa). High-performance concrete was used because it saved the owner $1.7 million, or 18% of the total project cost. (ESCSI 2001).

Parking structure members with 50 to 60 ft (15 to18 m) spans are often constructed with double tees with an equilibrium density of approximately 115 lb/ft^3 (1850 kg/m^3). This mass

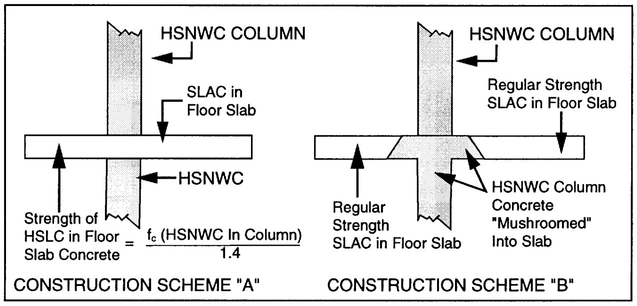


Fig. 6.2—Alternative construction schemes for transfer of high-strength normalweight concrete column loads through floor slabs (Holm and Bremner 1994).

reduction is primarily for lifting efficiencies and lowering transportation costs.

Precast lightweight concrete has frequently been used in long-span roof framing as was the case in the 120 ft (37 m) long single tees used in 1974 in the University of Nebraska sports center.

6.3.2 *Buildings*—Among the thousands of buildings built in North America incorporating high-strength lightweight concrete, the following examples have been selected for their pioneering and unique characteristics.

6.3.2.1 *Federal Post Office and Office Building*—The 450 ft (140 m) multipurpose building constructed in 1967 with five post office floors and 27 office tower floors was the first major New York City building application of post-tensioned floor slabs. Concrete tensioning strengths of 3500 psi (24 MPa) were routinely achieved for 3 days for the 30 x 30 ft (9 x 9 m) floor slabs with a design target strength of 6000 psi (41 MPa) at 28 days. Approximately 30,000 yd^3 (23,000 m^3) of lightweight concrete were incorporated into the floors and the cast-in-place architectural envelope, which serves a structural as well as an aesthetic function. (Holm and Bremner 1994).

6.3.2.2 *The North Pier Apartment Tower, Chicago, 1991*—This project used high-performance lightweight concrete in the floor slabs as an innovative structural solution to avoid construction problems associated with the load transfer from high-strength normalweight concrete columns through the floor slab system. ACI 318 requires a maximum ratio of column compressive strength, which in this project was 9000 psi (62 MPa) and the intervening floor slab concrete to be less than 1.4. By using high-strength lightweight concrete in the slabs with a strength greater than 6430 psi (44 MPa), the floor slabs could be placed using routine placement techniques, thus avoiding scheduling problems associated with the mushroom technique (Fig. 6.2). In the mushroom technique, the high-strength column concrete is overflowed from the column and intermingled with the floor slab concrete. The simple technique of using high-strength floor slab concrete in the North Pier project avoided delicate timing considerations that were necessary to avoid cold joints (Holm and Bremner 1994).

6.3.2.3 *The Bank of America, Charlotte, N.C.*—This concrete structure is the tallest in the southeastern United States with a high-strength concrete floor system consisting

Fig. 6.3—Bank of America, Charlotte, N.C. (from Holm and Bremner 1994, with permission of Edward Arnold Publishers, London).

of 4-5/8 in. (117 mm) thick slabs supported on 18 in. (460 mm) deep post-tensioned, concrete beams centered on 10 ft (3.0 m). The lightweight concrete floor system was selected to minimize the dead weight and to achieve the required 3 h fire rating (Fig. 6.3 and Table 6.1).

6.3.3 *Bridges*—More than 500 bridges have incorporated lightweight concrete into decks, beams, girders, or piers. Transportation engineers generally specify higher concrete strengths primarily to ensure high-quality mortar fractions (high compressive strength combined with high air content) that will minimize maintenance. Several mid-Atlantic state transportation authorities have completed more than 20 bridges using a laboratory target strength of 5200 psi (36 MPa), 6 to 9% air content, and a density of 115 lb/ft^3 (1840 kg/m^3). The following are the principal advantages of using lightweight concrete in bridges and the rehabilitation of existing bridges:

- Increased width or number of traffic lanes;
- Increased load capacity;
- Balanced cantilever construction;
- Reduction in seismic inertial forces;
- Increase cover with equal weight, thicker slabs;
- Improve deck geometry with thicker slabs; and
- Longer spans save pier costs.

6.3.3.1 *Increased number of lanes during bridge rehabilitation*—Thousands of bridges in the United States are functionally obsolete with unacceptably low load capacity or an insufficient number of traffic lanes. To remedy limited

Table 6.1—Mixture proportions and physical properties for concrete pumped on Bank of America project, Charlotte, N.C., 1991

Mixture no.	1	2*	3
Mixture proportions			
Cement, Type III, lb/yd³ (kg/m³)	550 (326)	650 (385)	750 (445)
Fly ash, lb/yd³ (kg/m³)	140 (83)	140 (83)	140 (83)
LWA 20 mm to No. 5, lb/yd³ (kg/m³)	900 (534)	900 (534)	900 (534)
Sand, lb/yd³ (kg/m³)	1370 (813)	1287 (763)	1203 (714)
Water, gal./yd³ (L/m³)	296 (175)	304 (180)	310 (184)
WRA, fl oz./yd³ (L/m³)	27.6 (0.78)	31.6 (0.90)	35.6 (1.01)
HRWRA, fl oz./yd³ (L/m³)	53.2 (1.56)	81.4 (2.31)	80.1 (2.27)
Fresh concrete properties			
Initial slump, in. (mm)	2-1/2 (63)	2 (51)	2-1/4 (57)
Slump after HRWRA, in. (mm)	5-1/8 (130)	7-1/2 (191)	6-3/4 (171)
Air content	2.5	2.5	2.3
Unit weight, lb/ft³ (kg/m³)	117.8 (1887)	118.0 (1890)	118.0 (1890)
Compressive strength, psi (MPa)			
4 days	4290 (29.6)	5110 (35.2)	5710 (39.4)
7 days	4870 (33.6)	5790 (39.9)	6440 (44.4)
28 days (average)	6270 (43.2)	6810 (47.0)	7450 (51.4)
Splitting-tensile strength, psi (MPa)	520 (3.59)	540 (3.72)	565 (3.90)

*Mixture selected and used on project.

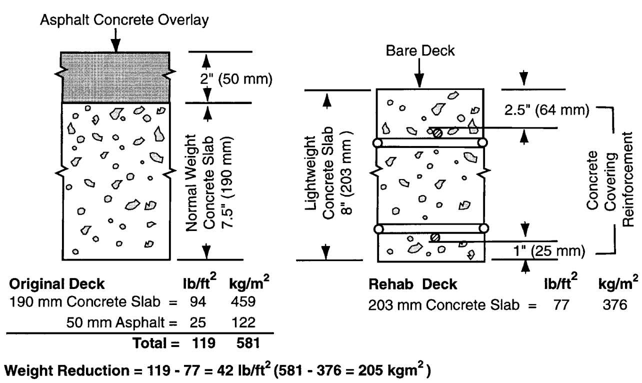


Fig. 6.4—Original and rehabilitated decks for Whitehurst Freeway (Stolldorf and Holm 1996).

lane capacity, Washington, D.C. engineers replaced a four-lane bridge originally constructed with normalweight concrete with five new lanes made with lightweight concrete providing a 50% increase in one-way, rush-hour traffic without replacing the existing structure, piers, or foundations. Similarly, on Interstate 84, crossing the Hudson River at Newburgh, N.Y., two lanes of normalweight concrete were replaced with three lanes of lightweight concrete on a parallel span, allowing three-lane traffic in both east- and west-bound lanes.

6.3.3.2 *Increased load capacity*—The elevated section of the Whitehurst Freeway was upgraded to an HS20 loading criteria during the rehabilitation of the Washington, D.C., corridor system structure with only limited modifications to the steel framing superstructure. An improved load-carrying

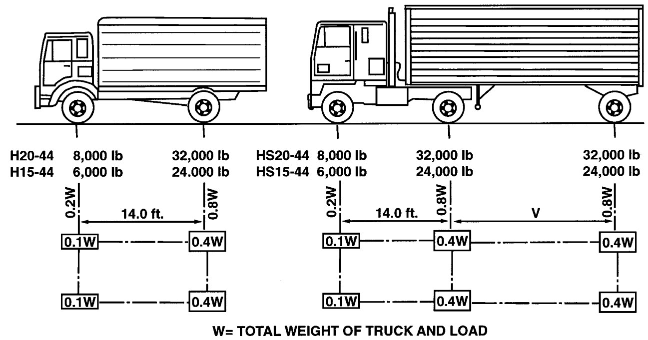


Fig. 6.5—AASHTO H20-44 and HS20-44 loadings (Stolldorf and Holm 1996).

capacity was obtained because of the significant dead load reduction brought about by using lightweight concrete to replace the normalweight concrete and asphalt overlay used in the original deck slab (Fig. 6.4).

The original elevated freeway structure was designed for HS20 live load according to the AASHTO 1941 specifications. With the significantly lighter replacement concrete deck, a minimum of the structural steel framing required strengthening, and little interruption at the street level below was required to upgrade the substructure to an HS20 live load criteria (Fig. 6.5) (Stolldorf and Holm 1996).

6.3.3.3 *Bridges incorporating both lightweight-concrete spans and normalweight concrete spans*—A number of bridges have been constructed where high-performance lightweight concrete has been used to achieve balanced load-free cantilever construction. On the Sandhornoya Bridge, completed in 1989 near the Arctic Circle city of Bodo, Norway, the 350 ft (110 m) sidespans of a three-span bridge were constructed with high-strength lightweight concrete with a cube strength of 8100 psi (55 MPa) that balanced the construction of the center span of 505 ft (154 m) that used normalweight concrete with a cube strength of 6500 psi (45 MPa) (Fergestad 1996).

The Raftsundet Bridge in Norway, also north of the Arctic Circle, with a main span of 978 ft (298 m), was the longest concrete cantilevered span in the world when the cantilevers were joined in June 1998; 722 ft (220 m) of the main span was constructed with high-strength, lightweight-aggregate concrete with a cube strength of 8700 psi (60 MPa). The side spans and piers in normalweight concrete had a cube strength of 9400 psi (65 MPa) (Fig. 6.6) (ESCSI 2001).

6.3.4 *Marine structures*—Because offshore concrete structures may be constructed in shipyards or graving docks located considerable distances from the site where the structure may be, then floated and towed to the project site, there is a special need to reduce mass and improve structural efficiency, especially where shallow-water conditions mandate lower draft structures. The structural efficiency is even more pronounced when lightweight concrete is submerged as shown as follows.

The density ratio

$$\frac{\text{(heavily reinforced normalweight concrete)}}{\text{(heavily reinforced lightweight concrete)}}$$

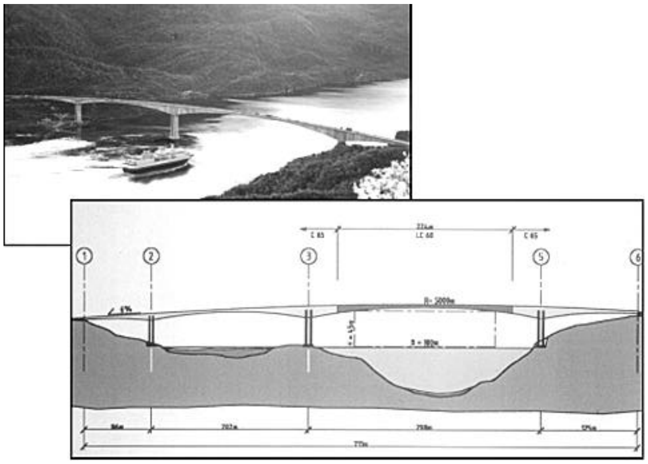


Fig. 6.6—Raftsundet Bridge (ESCSI 2000).

in air is (2.50[156 lb/ft^3])/[2.00(125 lb/ft^3)] = 1.25; when submerged is (2.50 – 1.00)/(2.00 – 1.00) = 1.50.

6.3.4.1 *Tarsiut Caisson Retained Island, 1981*—The first arctic structure using high-performance lightweight concrete was the Tarsiut Caisson retained island built in Vancouver, British Columbia, and barged to the Canadian Beaufort Sea (Fig. 6.7). Four large, prestressed concrete caissons 226 x 50 x 35 ft (69 x 15 x 11 m) high were constructed in a graving dock in Vancouver, towed around Alaska on a submersible barge, and founded on a berm of dredged sand 25 mi (40 km) from shore. The extremely high concentration of reinforcement resulted in a steel-reinforced concrete density of 140 lb/ft^3 (2240 kg/m^3). The use of high-strength lightweight concrete was essential to achieving the desired floating and draft requirements. (ESCSI 2001).

6.3.4.2 *Heidron floating platform, 1996*—Because of the deep water, 1130 ft (345 m), over the Heidron oil fields, an early decision was made to improve buoyancy and construct the first floating platform with high-performance lightweight concrete. The hull of the floating platform, approximately 91,000 yd^3 (70,000 m^3), was constructed entirely of high-strength lightweight concrete with a maximum density of 125 lb/ft^3 (2000 kg/m^3). Heidron was built in Norway and towed to the North Sea. A mean density of 121 lb/ft^3 (1940 kg/m^3), a mean 28-day cube compressive strength of 11460 psi (79 MPa), and a documented cylinder/cube strength ratio of 0.90 to 0.93 are reported in reference (FIB 2000) (ESCSI 2001).

6.3.4.3 *Hibernia oil platform, 1998*—The ExxonMobil Oil Hibernia offshore gravity-based structure is a significant application of specified-density concrete. To improve buoyancy of the largest floating structure built in North America, lightweight aggregate replaced approximately 50% of the normalweight coarse fraction in the high-strength concrete used (Fig. 6.8). The resulting density was 135 lb/ft^3 (2160 kg/m^3). Hibernia was built in a dry dock in Newfoundland, Canada, and then floated out to a deep water harbor area where construction continued. When finished, the more than 1-million ton structure was towed to the Hibernia North Sea oil field site and set in place on the ocean floor. A comprehensive testing program was reported by Hoff et al. (1995).

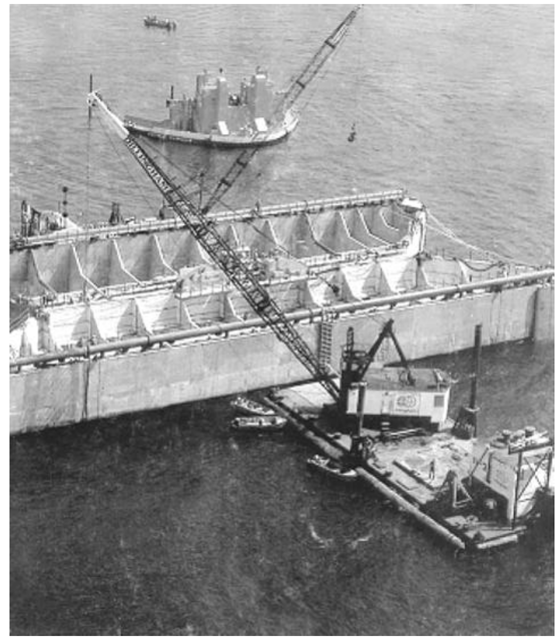


Fig. 6.7—Tarsuit Caisson Retained Island (from Concrete International *1982).*

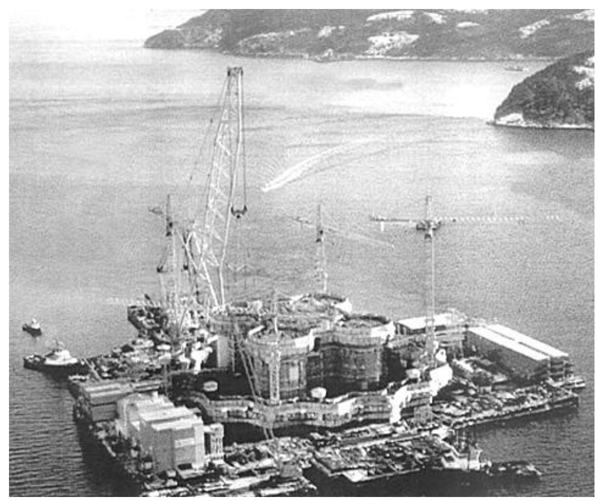


Fig. 6.8—Hibernia Offshore Platform (ESCSI 2001).

6.3.5 *Floating bridge pontoons*—High-performance lightweight concrete was used very effectively in both the cable-stayed bridge deck and the separate but adjacent floating concrete pontoons supporting a low-level steel box-girder bridge near the city of Bergen, Norway (Fig 6.9). The pontoons are 138 ft (42 m) long and 67 ft (20.5 m) wide and were cast in compartments separated by watertight bulkheads. The design of the compartments was determined by the concept that the floating bridge would be serviceable despite the loss of two adjacent compartments due to an accident.

6.4—Reduced transportation cost

For more than 20 years, precast manufacturers have evaluated trade-offs between physical properties and transportation costs. In one study, a typically used limestone control concrete was paralleled by other mixtures in which 25, 50, 75, and 100% of the limestone coarse aggregate was

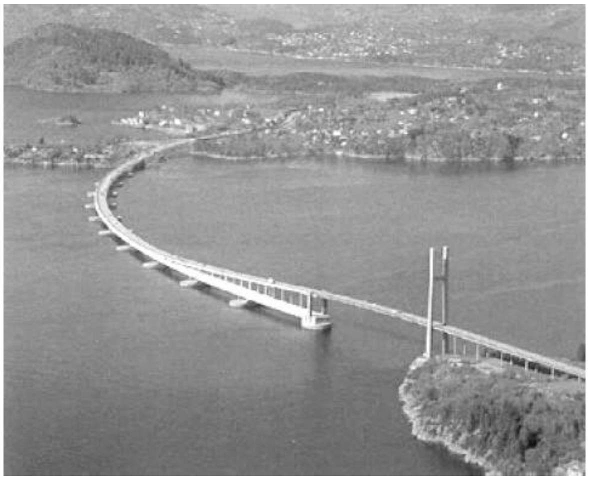


Fig. 6.9—Nordhordland Bridge, Bergen, Norway (Elkem Micro Silica 2000).

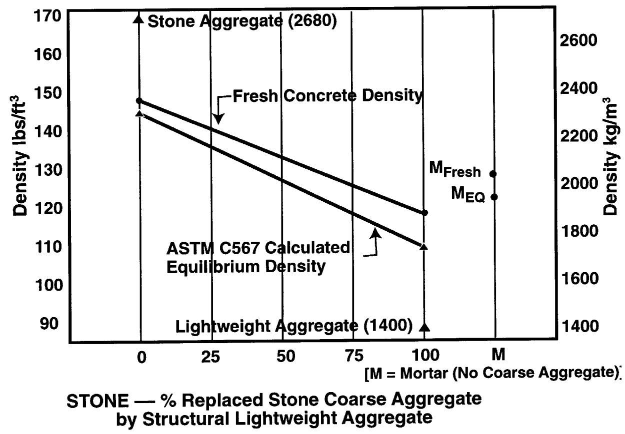


Fig. 6.10—Fresh and ASTM C 567-calculated equilibrium concrete density with varying replacements of limestone coarse aggregate with structural lightweight aggregate (Holm and Ries 2000).

replaced by an equal absolute volume of lightweight aggregate. Results of the testing program that measured compressive, tension, and modulus with density data shown in Fig. 6.10 are reported (Holm and Ries 2000).

Because of weight limits on roads, this precast producer developed lightweight mixtures that reduced the weight of members allowing an increased number of precast elements per truck. By adjusting the density of the concrete, precasters are able to minimize the number of truck deliveries without exceeding highway load limits, while lowering project cost. Opportunities for increased trucking efficiency are greater when transporting smaller concrete products, such as hollow core plank, wallboard, precast steps, and imitation stone.

6.5—Enhanced hydration due to internal curing

Expanded lightweight aggregates with high internal moisture contents may be substituted for normalweight aggregates to provide internal curing in concrete containing a high volume of cementitious materials. High cementitious concrete is vulnerable to self-desiccation and benefits significantly from the added internal moisture. This application is especially helpful for concrete containing high volumes of silica fume that are sensitive to curing procedures. In this application, density reduction is a by-product.

Time-dependent improvement in the quality of concrete containing lightweight aggregate is greater than that with normalweight aggregate. This is due to better hydration of the cementitious fraction provided by moisture available from the slowly released reservoir of water absorbed within the pores of the expanded aggregate. This process of internal curing is made possible when the moisture content of expanded aggregate, at the time of mixing, is in excess of that achieved in 1-day submersion. The fact that absorbed moisture within an expanded aggregate batched with a high degree of saturation (percent of internal pore volume occupied by water) was available for internal curing has been known for several decades and first documented in 1967 (Campbell and Tobin 1967). This comprehensive program compared strengths of cores taken from field-cured exposed slabs with test results obtained from laboratory specimens cured strictly in accordance with ASTM procedures. Their tests confirmed that availability of absorbed moisture within the expanded aggregate produced a more forgiving concrete that was less sensitive to poor field-curing conditions.

It appears that Philleo (1991) was the first to recognize the potential benefits to high-performance normalweight concrete with the addition of expanded lightweight aggregate containing high volumes of absorbed moisture. Weber and Reinhardt (1995) have also conclusively demonstrated reduced sensitivity to poor curing conditions in high-strength normalweight concrete containing an adequate volume of high moisture content expanded aggregates.

The benefits of internal curing are increasingly important when pozzolans (silica fume, fly ash, metokaolin, calcined shales, clays, and lightweight aggregate fines) are included in the mixture. It is well known that the pozzolanic reaction of finely divided alumina-silicates with calcium hydroxide liberated as cement hydrates is contingent upon the availability of moisture. Additionally, internal curing provided by absorbed water minimizes the plastic (early) shrinkage due to rapid drying of concrete exposed to unfavorable drying conditions.

While the improvements in long-term strength gain have been observed, the principal contribution of internal curing rests in the reduction of permeability that develops from a significant extension in the time of curing. Powers, Copeland, and Mann (1959) showed that extending the time of curing increased the volume of cementitious products formed, which caused the capillaries to become segmented and discontinuous. While internal curing is typically provided by an expanded coarse aggregate in high- performance concrete applications, expanded fine aggregate is more effective in distributing available moisture for internal curing. As Hoff (2003) and Bentz and Snyder (1999) have pointed out, a much more efficient spatial distribution could be accomplished by a partial replacement of the sand fraction with expanded fine aggregate.

CHAPTER 7—REFERENCES

7.1—Referenced standards and reports

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

American Concrete Institute

ACI 201.1R Guide for Making a Condition Survey of Concrete in Service
ACI 201.2R Guide to Durable Concrete
ACI 211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete
ACI 211.2 Standard Practice for Selecting Proportions for Structural Lightweight Concrete
ACI 212.3R Chemical Admixtures for Concrete
ACI 216.1 Standard Method for Determining Fire Resistance of Concrete and Masonry Construction Assemblies
ACI 232.2R Use of Fly Ash in Concrete
ACI 233R Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete
ACI 234R Guide for the Use of Silica Fume in Concrete
ACI 302.1R Guide for Concrete Floor and Slab Construction
ACI 304.5R Batching, Mixing, and Job Control of Lightweight Concrete
ACI 308.1 Standard Specification for Curing Concrete
ACI 318 Building Code Requirements for Structural Concrete and Commentary

ASTM International

ASTM C 31 Practice for Making and Curing Concrete Test Specimens in the Field
ASTM C 33 Standard Specification for Concrete Aggregates
ASTM C 78 Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
ASTM C 94 Specification for Ready-Mixed Concrete
ASTM C 127 Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate
ASTM C 138 Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
ASTM C 143 Test Method for Slump of Hydraulic-Cement Concrete
ASTM C 150 Standard Specification for Portland Cement
ASTM C 172 Standard Practice for Sampling Freshly Mixed Concrete
ASTM C 173 Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
ASTM C 177 Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus
ASTM C 330 Standard Specification for Lightweight Aggregates for Structural Concrete
ASTM C 331 Standard Specification for Lightweight Aggregates for Concrete Masonry Units
ASTM C 332 Standard Specification for Lightweight Aggregates for Insulating Concrete
ASTM C 469 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
ASTM C 496 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
ASTM C 512 Standard Test Method for Creep of Concrete in Compression
ASTM C 567 Standard Test Method for Density of Structural Lightweight Concrete
ASTM C 595 Specification for Blended Hydraulic Cements
ASTM, C 618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for use as a Mineral Admixture in Concrete
ASTM C 666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A)
ASTM C 1157 Standard Performance Specification for Hydraulic Cement
ASTM E 119 Standard Test Method for Fire Tests for Building Construction and Materials

These publications may be obtained from these organizations:
American Concrete Institute
PO Box 9094
Farmington Hills, Mich. 48333-9094

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

7.2—Cited references

AASHTO, 1994, *AASHTO LRFD*, American Association of State and Highway Transportation Officials, Washington, D.C.

AASHTO, 1995, *AASHTO Standard*, American Association of State and Highway Transportation Officials, Washington, D.C.

Abrams, M. S., 1971, "Compressive Strength of Concrete at Temperatures to 1600 °F," *Temperature and Concrete*, SP-25, American Concrete Institute, Farmington Hills, Mich., pp. 33-58.

Abrams, M. S., and Gustaferro, A. H., 1968, "Fire Endurance of Concrete Slabs as Influenced by Thickness, Aggregate Type, and Moisture," *Journal PCA Research and Development Laboratories,* V. 10, No. 2, pp. 9-24.

ACI Committee 318, 1995, "Building Code Requirements for Structural Concrete (ACI 318-95) and Commentary (318R-95)," American Concrete Institute, Farmington Hills, Mich., 369 pp.

ACI Committee 408, 1966, "Bond Stress—The State of the Art," ACI JOURNAL, *Proceedings* V. 63, No. 11, Nov., pp. 1161-1190.

ACI Committee 408, 1970, "Bond Stress—The State of the Art (ACI 408-1)," American Concrete Institute, Farmington Hills, Mich., 22 pp.

ACI Committee 408, 2001, "Splice and Development Length of High Relative Rib Area Reinforcing Bars in Tension (ACI 408.3-01) and Commentary (408.3R-01)," American Concrete Institute, Farmington Hills, Mich., 6 pp.

Ahmad, S. H., and Barker, R., 1991, "Flexural Behavior of Reinforced High-Strength Lightweight Concrete Beams," *ACI Structural Journal*, V. 88, No. 1, Jan.-Feb., pp. 69-77.

Ahmad, S. H., and Batts, J., 1991, "Flexural Behavior of Doubly Reinforced High-Strength Lightweight Concrete Beam with Web Reinforcement," *ACI Structural Journal*, V. 88, No. 3, May-June, pp. 351-358.

Baldwin, J. W., Jr., 1965, "Bond of Reinforcement in Lightweight Aggregate Concrete," presented at ACI Convention, University of Missouri, Columbia, Mo., Mar.

Bamforth, P. B., 1987, "The Relationship Between Permeability Coefficients for Concrete Obtained Using Liquid and Gas," *Magazine of Concrete Research,* V. 39, No. 13, pp. 3-11.

Bentz, D. P., and Snyder, K. A., 1999, "Protected Paste Volume in Concrete: Extension to Internal Curing Using Saturated Lightweight Fine Aggregate," *Cement and Concrete Research*, V. 29, pp. 1863-1867.

Berg, O., 1981, "Reinforced Structures In Lightweight-Aggregate Concrete," *Publication* 81.3, Chalmers University of Technology, Goteborg.

Bilodeau, A.; Chevrier, R.; Malhotra, V. M.; and Hoff, G. C., 1995, "Mechanical Properties, Durability and Fire Resistance of High-Strength Lightweight Concrete," *International Symposium on Structural Lightweight-Aggregate Concrete,* Sandefjord, Norway, pp. 432-443.

Bilodeau, A.; Malhotra, V. M; and Hoff, G. C., 1998, "Hydrocarbon Fire Resistance of High Strength Normal Weight and Lightweight Concrete Incorporating Polypropylene Fibers," *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, Sixth CANMET/ACI Conference*,* Supplementary Volume, V. M. Malhotra, ed., Bangkok, Thailand.

Boyd, S.; Bremner, T. W.; and Holm, T. A., 2000, "Addition of Lightweight Aggregate Reduces Expansion in Concrete Containing Highly Reactive Normalweight Aggregate," *11th ICAAR International Conference,* M. A. Berube, B. Fournier, and B. Durand, eds., Quebec, Canada, pp. 593-602.

Bremner, T. W., and Holm T. A., 1986, "Elastic Compatibility and the Behavior of Concrete," ACI JOURNAL, *Proceedings* V. 83, No. 2, Mar.-Apr., pp. 244-250.

Bremner, T. W.; Holm, T. A.; and deSouza, J., 1984, "Aggregate-Matrix Interaction in Concrete Subject to Severe Exposure," *FIP-CPCI International Symposium on Concrete Sea Structures in Arctic Regions,* Calgary, Canada, 7 pp.

Bremner, T. W.; Holm, T. A.; and McInerney, J. M., 1992, "Influence of Compressive Stress on the Permeability of Concrete," *Structural Lightweight Concrete Performance*, SP-136, T. A. Holm and A. M. Vaysburd, eds., American Concrete Institute, Farmington Hills, Mich., pp. 345-356.

Bremner, T. W.; Holm, T. A.; and Stepanova, V. F., 1994, "Lightweight Concrete—A Proven Material for Two Millennia," *Proceedings of Advances in Cement and Concrete,* S. Sarkar and M. W. Grutzeck, eds., University of New Hampshire, Durham, S.C., pp. 37-41.

Brown, W. R., III; and Davis, C. R., 1993, "A Load Response Investigation of Long Term Performance of a Prestressed Lightweight Concrete Bridge at Fanning Springs, Florida," Florida Department of Transportation, State Materials Office, Gainesville, Fla.

Brown, W. R., III; Larsen, T. J.; and Holm, T. A., 1995, "Long Term Service Performance of Lightweight Concrete Bridge Structures," *International Symposium on Structural Lightweight-Aggregate Concrete,* Sandefjord, Norway.

Campbell, R. H., and Tobin, R. E., 1967, "Core and Cylinder Strengths of Natural and Lightweight Concrete," ACI JOURNAL, *Proceedings* V. 64, No. 4, Apr., pp. 190-195.

Carlson, C. C., 1962, "Fire Resistance of Prestressed Concrete Beam—Study and Influence of Thickness of Concrete Covering Over Prestressing Steel Strands," *Research Dept. Bulletin,* No. 147, Portland Cement Association, Skokie, Ill.

Chana, P. S., 1990, "A Test Method To Establish Realistic Bond Stresses," *Magazine of Concrete Research*, V. 42, No. 151, pp. 83-90.

Clarke, J. L., and Birjandi, F. K., 1993, "Bond Strength Tests For Ribbed Bars in Lightweight-Aggregate Concrete," *Magazine of Concrete Research*, V. 45, No. 163, pp. 79-87.

Expanded Shale, Clay and Slate Institute (ESCSI), 1971, "Lightweight Concrete—History, Application, Economics," Salt Lake City, Utah, 44 pp.

Expanded Shale, Clay and Slate Institute (ESCSI), 1980, "Fire Resistance of Expanded Shale, Clay and Slate Structural Lightweight Concrete," Salt Lake City, Utah., pp. 1-4.

Expanded Shale, Clay and Slate Institute (ESCSI), 1996, "Pumping Structural Lightweight Concrete," Salt Lake City, Utah., 4 pp.

Expanded Shale, Clay and Slate Institute (ESCSI), 2001, "Building Bridges and Marine Structures," Salt Lake City, Utah., 16 pp.

Fagerlund, G., 1972, "Studier av Fasgranser Ballastkorn-Cementpasta I Cementbruk Ogh Betong," *Report* 29, Institutionen for Byognadsteknik Tekntska Hogskolen, Lund. (in Swedish)

Fagerlund, G., 1978, "Frost Resistance of Concrete with Porous Aggregate," Cement Ogh Betong Institue, Stockholm, Sweden.

Fenwick, R. C., and Sue, C. F., 1982, "The Influence of Water Gain Upon the Tensile Strength of Concrete," *Magazine of Concrete Research,* V. 34, No. 120, 10 pp.

Fergestad, S., 1996, "Bridges Built with Lightweight Concrete," *Proceedings of the International Symposium on Lightweight Concrete Bridges,* Sponsored by CALTRANS, Sacramento, Calif.

fib, 2000, "Lightweight-Aggregate Concrete," *Bulleting* 8, Federation Internationale du Beton, Lausanne, Switzerland.

Fintel, M., and Khan, F. R., 1965, "Effects of Column Exposure in Tall Structures—Temperature Variations and their Effects," ACI JOURNAL*, Proceedings* V. 62, No. 12, Dec., pp. 1533-1536.

Fintel, M., and Khan, K. F., 1966, "Analysis of Length Changes of Exposed Columns," ACI JOURNAL, *Proceedings* V. 63, No. 8, Aug., pp. 843-864.

Fintel, M., and Kahn, K. F., 1968, "Design Considerations and Field Observations of Buildings," ACI JOURNAL, *Proceedings* V. 65, No. 2, Feb., pp. 99-110.

FIP (Ferdeation Internationale de la Precontrainte), 1983, *FIP Manual of Lightweight Concrete*, 2nd Edition, John Wiley and Sons, New York.

Gjerde, 1982, "Structural Lightweight-Aggregate Concrete for Marine and Offshore Applications," Norwegian Contractors, Oslo, Norway.

Gray, W. H.; McLaughlin, J. F.; and Antrim, J. O., 1961, "Fatigue Properties of Lightweight-Aggregate Concrete," ACI JOURNAL, *Proceedings* V. 58, No. 6, Aug., pp. 142-62.

Hanson, J. A., 1958, "Shear Strength of Lightweight Reinforced Concrete Beams," ACI JOURNAL, *Proceedings* V. 55, No. 3, pp. 387-404.

Hanson, J. A., 1961, "Tensile Strength and Diagonal Tension Resistance of Structural Lightweight Concrete," ACI JOURNAL, *Proceedings* V. 58, No. 1, pp. 1-40.

Hanson, J. A., 1964, "Replacement of Lightweight Aggregate Fines with Natural Sand in Structural Concrete," ACI JOURNAL, *Proceedings* V. 61, No. 7, pp. 779-793.

HHFA, 1949, "Lightweight Aggregate Concrete," Housing and Home Finance Agency, Washington, D.C., Aug.

Hoff, G. C., 1992, "High Strength Lightweight-Aggregate Concrete for Arctic Applications," *Structural Lightweight Aggregate Concrete Performance*, SP-136, T. A. Holm and A. M. Vaysburd, eds., American Concrete Institute, Farmington Hills, Mich., pp. 1-245.

Hoff, G. C., 1994, "Observations on the Fatigue Behavior of High Strength Lightweight Concrete," *High-Performance Concrete*, Proceedings of the ACI International Conference, SP-149, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, Mich., pp. 785-822.

Hoff, G. C., 2003, "Internal Curing of Concrete Using Lightweight Aggregate," *Theodore Bremner Symposium on High-Performance Lightweight Concrete*, J. P. Ries and T. A. Holm, eds., Presented at Sixth CANMET/ACI International Conference on Durability of Concrete, pp. 185-204.

Hoff, G. C., et al., 1995, "The Use of Structural Lightweight Aggregates in Offshore Concrete Platforms," *International Symposium on Structural Lightweight-Aggregate Concrete,* Sandefjord, Norway, pp. 349-362.

Hognestad, E.; Hanson, N. W.; and McHenry, D., 1955, "Concrete Stress Distribution in Ultimate Strength Design," ACI JOURNAL, *Proceedings* V. 52, No. 4, Dec., pp. 455-480.

Holm, T. A., 1980a, "Physical Properties of High Strength Lightweight-Aggregate Concrete," *Second International Congress of Lightweight Concrete,* London., 10 pp.

Holm, T. A., 1980b, "Performance of Structural Lightweight Concrete in a Marine Environment," *Performance of Concrete in Marine Environment*, SP-65, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, Mich., pp. 589-608.

Holm, T. A., 1983, "Three Decades of Durability," *The Military Engineer,* Sept.-Oct., 4 pp.

Holm, T. A., 1994, "Lightweight Concrete and Aggregates," *Tests and Properties of Concrete and Concrete-Making Materials,* STP 169C, 522-32, P. Klieger and J. F. Lamond, eds., ASTM International, West Conshohocken, Pa.

Holm, T. A., and Bremner, T. W., 1994, "High-Strength Lightweight-Aggregate Concrete," *High-Performance Concrete and Applications*, S. P. Shah and S. H. Ahmad, eds., Edward Arnold, London, pp. 341-374.

Holm, T. A., and Bremner, T. W., 2000, "State-of-the-Art Report on High-Strength, High-Durability Structural Low-Density Concrete for Applications in Severe Marine Environments," U.S. Army Corps of Engineers, Engineering Research and Development Center.

Holm, T. A.; Bremner, T. W.; and Newman, J. B., 1984, "Lightweight Aggregate Concrete Subject to Severe Weathering," *Concrete International*, V. 6, No. 6, June, pp. 49-54.

Holm, T. A.; Bremner, T. W.; and Vaysburd, A., 1988, "Carbonation of Marine Structural Lightweight Concretes," *Performance of Concrete in Marine Environment,* Second International Conference, SP-109, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, Mich., pp. 667-676.

Holm, T. A., and Ries, J. P., 2000, "Specified-Density Concrete—A Transition" *Second International Symposium on Structural Lightweight-Aggregate Concrete*, Kristiansand, Norway.

Huffington, J. A., 2000, "Development of High-Performance Lightweight Concrete Mixes for Prestressed Bridge Girders," University of Texas at Austin, Tex., May.

Ivey, D. L., and Bluth, E., 1966, "Splitting Tension Test of Structural Lightweight Concrete," *Journal of Materials*, ASTM International, V. 1, No. 4, pp. 859-871.

Jensen, J. J.; Hammer, T. A.; Ophelm, E.; and Hansen, P. A, 1995, "Fire Resistance of Lightweight-Aggregate Concrete," *International Symposium on Structural Lightweight-Aggregate Concrete,* Ivar Holand, ed., Sandefjord, Norway, Tor Arne Hammer, Finn Fluge, pp. 192-204.

Keeton, P., 1970, "Permeability Studies of Reinforced Thin-Shell Concrete," *Technical Report R692 YF51.001, 01.001,* Naval Engineering Laboratory, Port Hueneme, Calif., 52 pp.

Khokrin, 1973, "The Durability of Lightweight Concrete Structural Members," Kuibyshev, USSR, 114 pp. (in Russian)

Kluge, R. M.; Sparks, M. M.; and Tuma, E. C., 1949, "Lightweight Aggregate Concrete, ACI JOURNAL, *Proceedings* V. 45, No. 5, May, pp. 625-642.

LaRue, H. A., 1946, "Modulus of Elasticity of Aggregates and its Effect on Concrete," *Proceedings* 46, ASTM International, West Conshohocken, pp. 1298-3098.

Lyse, I., 1934, "Lightweight Slag Concrete," ACI JOURNAL, *Proceedings* V. 31, No. 1, pp. 1-20.

Martin, H., 1982, "Bond Performance of Ribbed Bars," *Bond in Concrete—Proceedings of the International Conference on Bond in Concrete*, Paisley, Applied Science Publishers, London, pp. 289-299.

McLaughlin, T., 1944, "Powered Concrete Ships," *Engineering News-Record,* V. 19, Oct., pp. 94-98.

Mehta, P. K., 1986, *Concrete: Structure Properties and Materials,* Prentice Hall, Englewood Cliffs, N.J., 548 pp.

Meyer, K. F., and Kahn, L. F., 2002, "Transfer and Development Length of High Strength Lightweight Concrete," Presented at ACI Symposium on High Performance Structural Lightweight Concrete, Phoenix, Ariz., Oct.

Mielenz, R. C., 1994, "Petrographic Evaluation of Concrete Aggregates," Chapter 31, also ASTM C 169, *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, pp. 341-365.

Mor, A., 1992, "Steel-Concrete Bond in High-Strength Lightweight Concrete," *ACI Materials Journals*, V. 89, No. 1, Jan.-Feb., pp. 76-82.

Moreno, J., 1986, "Lightweight Concrete Ductility," *Concrete International,* V. 8, No. 11, Nov., pp. 15-18.

Morgan, M. H., 1960, *Vitruvius, the Ten Books on Architecture Translation*, Dover Publications, New York.

Muller-Rochholz, J., 1979, "Determination of the Elastic Properties of Lightweight Aggregate by Ultrasonic Pulse Velocity Measurements," *International Journal of Lightweight Concrete,* V. 1, No. 2, Lancaster, U.K.

Nassar, A. J., 2002, "Investigation of Transfer Length, Development Length, Flexural Strength and Prestress Loss Trend in Fully Bonded High-Strength Lightweight Prestressed Girders," Virginia Polytechnic Institute and State University, May 15, 136 pp.

Nishi, S.; Oshio, A.; Sone, T.; and Shirokuni, S., 1980, "Watertightness of Concrete Against Sea-Water," Onoda Cement Co., Ltd., Japan.

Ohuchi, T.; Hara, M.; Kubota, N.; Kobayoshi, A.; Nishioka, S.; and Yokoyama, M., 1984, "Some Long-Term Observation Results of Artificial Lightweight Aggregate Concrete for Structural Use in Japan," *International Symposium on Long-Term Observation of Concrete Structures,* Budapest, Hungary, V. II, pp. 274-282.

Pauw, A., 1960, "Static Modulus of Elasticity of Concrete as Affected by Density," ACI JOURNAL, *Proceedings* V. 57, No. 6, pp. 679-688.

Petersen, P. H., 1948, "Properties of Some Lightweight-Aggregate Concretes with and without an Air-Entraining Admixture," *Building Materials and Structures Report* BMS 112, U.S. Department of Commerce, National Bureau of Standards, Aug., 7 pp.

Pfeifer, D. W., 1967, "Sand Replacement in Structural Lightweight Concrete," ACI JOURNAL, *Proceedings* V. 64, No. 7, July, pp. 384-392.

Pfeifer, D. W., 1968, "Sand Replacement in Structural Lightweight Concrete-Creep and Shrinkage Studies," ACI JOURNAL, *Proceedings* V. 65, No. 2, Feb., pp. 131-140.

Philleo, R., 1991, "Concrete Science and Reality," *Materials Science of Concrete II*, J. P. Skalny and S. Mindess, eds., American Ceramic Society, Westerville, Ohio, 8 pp.

Powers, T. E.; Copeland, L. E.; and Mann H. M., 1959, "Capillary Continuity of Discontinuity in Cement Pastes," *Journal Portland Cement Research and Development Labs,* No. 2, May, pp. 38-48.

Prestressed Concrete Institute, 1995, *PCI Design Handbook,* 5th Edition, Chicago, Ill., 614 pp.

Price, W. H., and Cordon, W. A., 1949, "Tests of Lightweight-Aggregate Concrete Designed for Monolithic Construction," ACI JOURNAL, *Proceedings* V. 45, pp. 581-600.

Rabbat, B. G.; Daniel, J. I.; Weinman, T. L.; and Hanson, N. W., 1986, "Seismic Behavior of Lightweight and Normal Weight Concrete Columns," ACI JOURNAL, *Proceedings* V. 83, No. 1, Jan.-Feb., pp. 69-79.

Ramakrishnan, V.; Bremner, T. W.; and Malhotra, V. M., 1992, "Fatigue Strength and Endurance Limit of Lightweight Concrete," *Structural Lightweight Aggregate Concrete Performance*, SP-136, V. M. Malhotra, ed., American Concrete Institute, Farmington Hills, Mich., pp. 397-420.

Ramirez, J.; Olek, J.; Rolle, E.; and Malone, B., 1999, "Performance of Bridge Decks and Girders with Lightweight-Aggregate Concrete," FHWA/IN/JTRP – 98/17, Purdue University, West Lafayette, Ind., May, 161 pp.

Reichard, T. W., 1964, "Creep and Drying Shrinkage of Lightweight and Normalweight Concretes," *Monogram* No. 74, National Bureau of Standards, Washington, D.C., 30 pp.

Robins, P. J., and Standish, I. G., 1982, "Effect of Lateral Pressure on Bond of Reinforcing Bars in Concrete," *Bond in Concrete—Proceedings of the International Conference on Bond in Concrete,* Paisley, Applied Science Publishers, London, pp. 262-272.

Selvaggio, S. L., and Carlson, C. C., 1964, "Fire Resistance of Prestressed Concrete Beams: Study and Influence of Aggregate and Load Intensity," *PCA Research and Development Laboratories Journal,* V. 6, No. 1, Portland Cement Association, Skokie, Ill., pp. 41-64.

Shideler, J. J., 1957, "Lightweight Aggregate Concrete for Structural Use," ACI JOURNAL, *Proceedings* V. 54, pp. 298-328.

Stolldorf, D. W., and Holm, T. A., 1996, "Bridge Rehabilitation Permits Higher Live Loads," *Materials for the New Millennium*, ASCE Materials Conference, Washington, D.C., Nov.

Sugiyama, T.; Bremner, T. W.; and Holm, T. A., 1996, "Effect of Stress on Gas Permeability in Concrete," *ACI Materials Journal*, V. 93, No. 5, Sept.-Oct., pp. 443-450.

Thatcher, D. B.; Heffington, J. A.; Kolozs, G. S.; Sylva, G. S.; Breen, J. E.; and Burns, N. H., 2002, "Structural Lightweight Concrete Prestressed Girders and Panels," Center for Transportation Research, University of Texas at Austin, Jan.

Valore, R. C., Jr., 1956, "Insulating Concretes," ACI JOURNAL, *Proceedings* V. 53, No. 5, pp. 509-532.

Valore, R. C., 1980, "Calculation of U-Values of Hollow Concrete Masonry," *Concrete International*, V. 2, No. 2, Feb., pp. 40-63.

Washa, G. W., and Fluck, P. G., 1952, "Effect of Compressive Reinforcement on the Plastic Flow of Reinforced Concrete Beams," ACI JOURNAL, *Proceedings* V. 49, No. 10, Oct., pp. 89-108.

Weber S., and Reinhardt, 1995, "A Blend of Aggregates to Support Curing of Concrete," *Proceedings of the International Structural Lightweight Concrete,* Sandefjord, Norway.

7.3—Other references

Rowley, F. R., and Algren, A. R., 1947, "Thermal Conductivity of Building Materials," *Bulletin* No. 12, Engineering Experiment Station, University of Minneapolis, Minn., 134 pp.