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Guide for Structural Lightweight Aggregate Concrete

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

The guide is intended for all sections of ACI readership. It includes a definition of lightweight aggregate concrete for structural purposes and it discusses in condensed fashion the production methods for and inherent properties of structural lightweight aggregates. Other chapters follow on current practices for proportioning, miring, transporting, and placing; properties of hardened concretes; and the design of structural concrete with special reference to ACI 318.

Keywords: abrasion resistance; aggregates: air-entrained concretes; air entrainment; bond (concrete to reinforcement); cement content; coarse aggregates; compressive strength; concrete durability; concretes; creep properties; curing; deflection; fine aggregates; fire resistance; fire tests; flexural strength; fly ash; freeze-thaw durability; fresh concretes; hardened concretes; lightweight aggregate concretes; lightweight aggregates; mechanical properties; mix proportioning: modulus of elasticity; physical properties; production methods; quality control; ready-mixed concrete; shear strength; shrinkage; splitting tensile strength; structutal design; tensile strength; thermal conductivity; thermal expansion; thermal properties; thermal transmittance; water-cement ratio; workability.

FOREWORD

Structural lightweight aggregate concrete is an important and versatile material in modem construction. It has many and varied applications: multistory building frames and floors, curtain walls, shell roofs, folded plates, bridges, prestressed or precast elements of all types, and others. In many cases the architectural expression of form combined with functional design can be achieved more readily in structural lightweight concrete than in any other medium.

Many architects, engineers, and contractors recognize the inherent economies and concomitant advantages offered by this material, as evidenced by the many impressive lightweight concrete structures found today throughout the world. Structural lightweight aggregate concrete is structural concrete in the strictest sense.

Since the development of structural lightweight concrete has been essentially parallel to the earlier development of normal weight concrete, considerable use has been made of the large amount of information available on normal weight concrete. However, when the unique characteristics of lightweight aggregate and concrete have required departures from customary practice, these have been detailed in this guide.

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ACI 213R-87 supercedes ACI 213R-79 (Reaffirmed 1984).

CHAPTER 1 - INTRODUCTION

1.1 - Objective of the guide

The objective of the Guide for Structural Lightweight Aggregate Concrete is to provide the best practices of preparing and applying structural lightweight aggregate concrete. Using such practices, structures may be designed and their performance predicted with the same high degree of accuracy, and with the customary factors of safety, that is attained for normal weight structural concrete.

1.2 - Historical Development

1.2.1 *Early development through World War II* -Prior to 1917, S. J. Hayde developed a rotary kiln process for heat expansion of shales and clays to form hard, lightweight material which served as aggregates in making concrete of substantial strength and lower weight. At about the same time, F. J. Straub pioneered in the use of bituminous coal cinders as an aggregate for manufacture of concrete masonry units which attained high production volume following World War I, and which are still being manufactured today. Commercial production of expanded slag began in 1928; and in 1948, the first structural quality sintered shale lightweight aggregate was produced using a coal-bearing shale in eastern Pennsylvania. Pumice aggregate has been used in Europe for centuries. Also it has been used in the western part of the United States where deposits are readily available.

One of the earliest uses of reinforced lightweight concrete was in the construction of ships and barges by the Emergency Fleet Building Corp. of World War I.[1] Concrete of the required compressive strength of 5000 psi (34.47 MPa) was obtained with a unit weight of 110 lb/ft^3 (1760 kg/m^3) or less, using expanded shale aggregate. The Park Plaza Hotel in St. Louis and the Southwestern Bell Telephone Building in Kansas City, built during the 1920s are other examples of early applications of reinforced lightweight concrete in buildings. In the early 1930s, the use of lightweight concrete for the upper roadway of the San Francisco-Oakland Bay Bridge was a key to the economical design of the bridge. During World War II, history repeated itself with the construction of 105 lightweight concrete ships,[2] thereby conserving steel plate for other essential uses.

1.2.2 *Post World War II development*-Considerable impetus was given to the development of lightweight concrete shortly after World War II when a National Housing Agency survey was conducted on potential use of lightweight concrete for home construction. This led to an extensive study of concretes made with lightweight aggregates. Sponsored by the Housing and Home Finance Agency,[3] parallel studies were conducted simultaneously in the laboratories of the National Bureau of Standards[4] and the U.S. Bureau of Reclamation[5] to determine properties of concrete made with a broad range of lightweight aggregate types. These studies, and the earlier work by Richart and Jensen,[6] and Washa and Wendt,[7] and others, focused attention on the potential structural use of some lightweight aggregate concrete and initiated a renewed interest in lighter weight for building frames, bridge decks, and precast products in the early 1950s.

The design of a four story addition to an existing department store in Cleveland was made possible by the reduced dead load of lightweight concrete without necessity of foundation modification. Similarly, following the collapse of the original Tacoma Narrows Bridge, it was replaced by another suspension structure designed to incorporate additional roadway lanes without the necessity of replacing the original piers, due to the use of structural lightweight concrete in the deck.

During the 1950s many multistory structures were designed from the foundations up, taking advantage of reduced dead weight using lightweight concrete. Examples are the

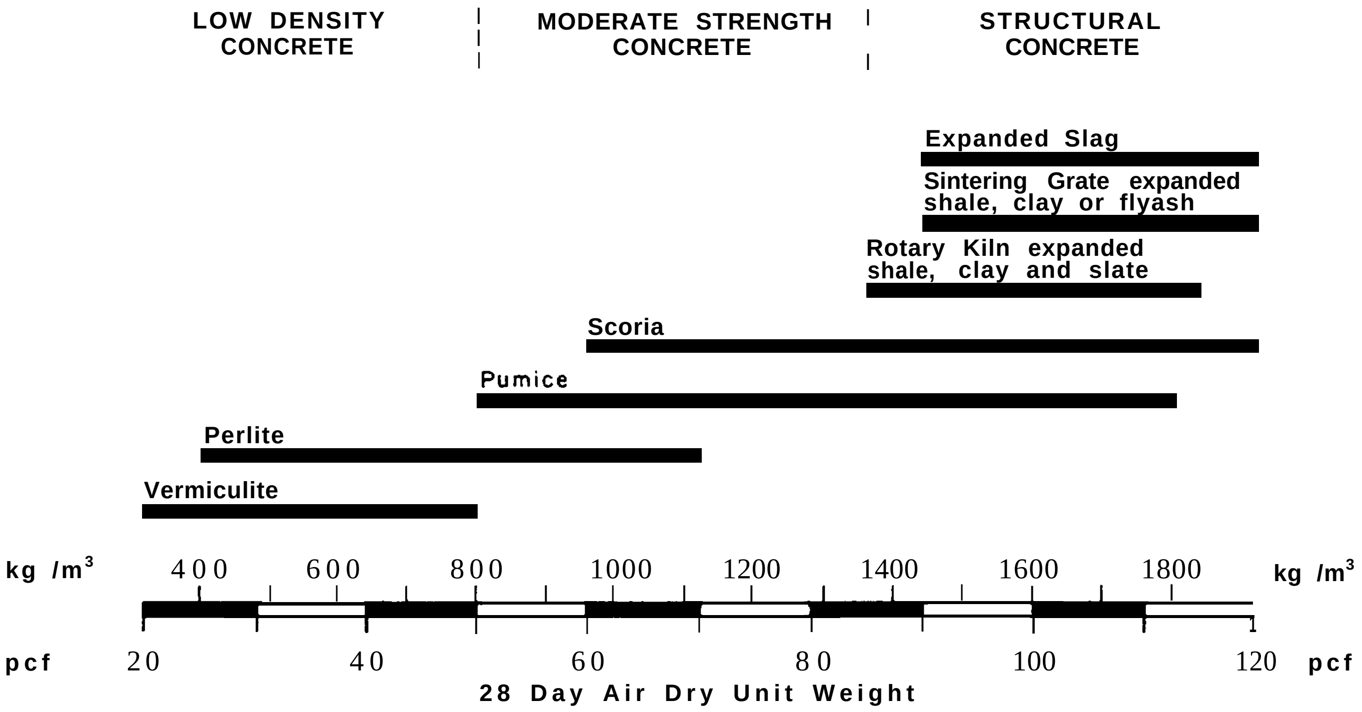


Fig. 1.4-Approximate unit weight and use classification of lightweight aggregate concretes

42-story Prudential Life Building in Chicago, which incorporated lightweight concrete floors, and the 18-story Statler Hilton Hotel in Dallas, which was designed with a lightweight concrete frame and flat plate floors.

Such structural applications as these stimulated more concentrated research into the properties of lightweight concrete by several recognized national and international organizations. Construction of aggregate plants was accelerated and today lightweight aggregates of structural quality are available in most parts of the United States and Canada and many other countries. Construction of major structures in nearly all metropolitan areas of the United States and Canada continued in the 1960s at an increasing tempo.

New processes may be available in the future for producing lightweight aggregates. Aggregate produced by these new systems must be tested and proven to comply with the requirements for structural concrete.

1.3 - Economy of structural lightweight concrete

The use of lightweight aggregate concrete in a structure is usually predicated on lower overall costs. While lightweight concrete may cost more per cubic yard than normal weight concrete, the structure may cost less as a result of reduced dead weight and lower foundation costs. This is the basic reason, in most cases, for using structural lightweight concrete. Economy then depends on attaining a proper balance among cost of concrete per volume, unit weight, and structural properties. Normal weight concrete may be the least in cost per cubic yard, but will be heavier, resulting in greater dead loads, increased sizes in many sections, and therefore may require more concrete and reinforcing steel. Concrete in which the aggregate is entirely lightweight will usually be costlier per cubic yard, but will be the lightest, resulting in reduced dead loads, reduced section dimensions, less reinforcing steel, and lower handling and forming costs. Lightweight concrete in which natural sand is used for part or all of the fine aggregate will lie between the two extremes of cost of concrete per cubic yard and dead weight.

1.4 - Lightweight aggregates - classifications

There are many types of aggregates available which are classed as lightweight, and their properties cover wide ranges. To delineate those types which can be classed as structural, and which are therefore pertinent to this guide, reference is made to a concrete "spectrum," Fig. 1.4. This diagram indicates the approximate 28-day, air-dry unit weight range of three types of lightweight aggregate concretes along with the use to which each type is generally associated. The indicated dividing weights of these types (and the end points of each bar for each of the aggregates) are generally valid but should not be considered precise.

1.4.1 *Low density concretes*- These very light nonstructural concretes are employed chiefly for insulation purposes. With low unit weights, seldom exceeding 50 lb/ft^3 (800 kg/m^3), thermal conductivity is low. Compressive strengths, ranging from about 100 to 1000 psi (0.69 to 6.89 MPa), are characteristic.

1.4.2 *Structural concretes* - These concretes contain aggregates that fall on the other end of the scale and that are generally made with expanded shales, clays, slates, slags, pumice and scoria. Minimum compressive strength, by definition, is 2500 psi (17.24 MPa) (see Section 1.5). Most structural lightweight aggregates are capable of producing concretes with compressive strengths in excess of 5000 psi (34.47 MPa) and, with many of these, concretes can be made with strengths considerably greater than 6000 psi (41.36 MPa). Since the unit weights of structural lightweight aggregate concretes are considerably greater than those of low-density concretes, insulation efficiency is lower. However, thermal conductivity values for structural lightweight concrete are substantially better than for normal weight concrete.

1.4.3 *Moderate strength concretes*-The use of these concretes requires a fair degree of compressive strength, and thus they fall about midway between the structural and low-density concretes. These are sometimes designated as "fill" concretes. Compressive strengths are approximately 1000 to 2500 psi (6.89 to 17.24 MPa) and insulation characteristics are intermediate.

1.5-Definition of structural lightweight aggregate concrete

For clarification of the intent of this guide, the following definition of structural lightweight aggregate concrete has been established:

> *Structural lightweight concrete*-Structural concrete made with lightweight aggregate; the air-dried unit weight at 28 days is usually in the range of 90 to 115 lb/ft^3 (1440 to 1850 kg/m^3) and the compressive strength is more than 2500 psi (17.2 MPa).

It should be understood that this definition is not a specification. Job specifications may, at times, allow unit weights up to 120 lb/ft^3 (1900 kg/m^3). Although structural concrete with an air-dry unit weight of 90 to 100 lb/ft^3 (1450 to 1600 kg/m^3) is often used, most lightweight concrete structures weigh between 100 and 110 lb/ft^3 (1600 to 1760 kg/m^3). The aggregate producers in various localities should be contacted prior to design for advice on the range of unit weights available.

1.6 - Structural lightweight aggregates

1.6.1 *Processed aggregates*-This guide presents a summary of existing knowledge of elastic properties, compressive and tensile strength, time-dependent properties, durability, fire resistance, and other properties of structural lightweight aggregate concrete. It also recognizes that satisfactory field performance records are more important than results of laboratory studies. Laboratory data and field experience are available to satisfy these criteria mainly with respect to processed aggregates meeting the requirements of ASTM C 330 i.e., rotary kiln expanded shales, clays and slates; sintered shales, clays; and expanded slags.

1.6.2 *Naturally occurring and unprocessed aggregates*-It is recognized that structural concrete may be made with such types of lightweight aggregates, for example, as properly prepared naturally occurring scoria and pumice, and with suitable cinders. Throughout westernmost states there are a number of sources of pumice and scoria which are capable of meeting the requirements of ASTM C 330.

1.6.3 *Definition of terms*-For simplicity, the term "shale," as used in many portions of this guide, applies equally to aggregates processed from shales, clays, or slates. The terms pumice and scoria apply to aggregate of those groups meeting the requirements of ASTM C 330. Further, the terms "structural lightweight concrete" and "structural lightweight aggregate concrete", used interchangeably in this guide, should be interpreted as indicating structural concrete containing structural lightweight aggregate. The term "all-lightweight" indicates concrete in which both the coarse and fine fractions are lightweight aggregates; the term "sand-lightweight" indicates concrete with coarse lightweight aggregate and in which all of the fine fraction is normal weight sand. In many instances only partial replacement of the lightweight fines with normal weight sand is employed, and this will be so indicated in this guide.

CHAPTER 2 - STRUCTURAL LIGHTWEIGHT AGGREGATES

2.1 - Scope

A knowledge of the tested characteristics of the lightweight aggregate to be used is of prime importance to the designer and user of structural lightweight concrete. In this chapter general information is given on the types of lightweight aggregates commonly used in structural concrete, methods of production, and the basic properties of each type.

2.2 - Definitions

2.2.1 *Fine lightweight aggregates*-These size fractions of aggregates are composed primarily of processed or naturally occurring cellular materials of mineral origin which (a) are suited to the production of structural lightweight concrete as defined in Sections 1.5 and 2.2.3; (b) are properly graded with 85 to 100 percent passing the No. 4 sieve 3/16 in. (5 mm)]; (c) have a dry, loose weight not exceeding 70 lb/ft^3 (1120 kg/m^3); and (d) comply with all other requirements of ASTM C 330.

2.2.2 *Coarse lightweight aggregates*-The larger size fractions of lightweight aggregates are composed primarily of processed or naturally occurring cellular materials of mineral origin which (a) are suited to the production of structural lightweight concrete as defined in Sections 1.5 and 2.2.3; (b) are properly graded from 100 percent passing a designated maximum size sieve; (c) have a dry, loose weight not exceeding 55 lb/ft^3 (880 kg/m^3); and (d) comply with all other requirements of ASTM C 330. One or more of the following gradations are generally available:

- Structural coarse, ¾ in. to No. 4 (19 mm to 5 mm) or ½ in. to No. 4 (13 mm to 5 mm)
- Medium coarse, 3/8 in. to No. 8 (10 mm to 2.5 mm)

2.2.3 *Structural lightweight aggregate concrete*-As previously defined (Section 1.5), such concrete: (a) has a minimum compressive strength at 28 days of 2500 psi (17.24 MPa); (b) has a corresponding air-dry unit weight not exceeding 115 lb/ft^3 (1850 kg/m^3); and (c) consists of all lightweight aggregates or a combination of lightweight and normal weight aggregates.

2.3 - Internal structure of aggregates

In all cases the lightweight aggregates used in structural concrete are light in weight due to the cellular structure of the individual aggregate particles. This cellular structure within the particles is formed at high temperatures, generally 2000 F (1100 C) or higher, by one of more of the following processes:

(a) Formation of gases, due to reaction of heat on certain constituents in the raw materials, coincidental with incipient fusion of the mineral, so that the gases are entrapped in a viscous, pyroplastic mass causing bloating or expansion.

(b) After heating, subjecting a softened or molten mass to intermixing with controlled amounts of water or steam so that a cellular structure is produced by entrapped steam and other gas and is retained on cooling of the mass.

(c) Burning off of combustible materials within a matrix. The cells in the aggregate particle may vary from microscopic to macroscopic in size, and be either predominantly interconnected or discrete.

2.4 - Production of aggregates

Raw materials used in commercial production of structural lightweight aggregates are generally (a) suitable natural deposits of shales, clays, or slates; or (b) by-products of other industries, such as iron blast furnace slags. Reparation of raw materials can range from negligible to extensive prior to treatment to produce expansion. In many cases crushing to suitable sizes is the only prerequisite. In the cases of finely divided materials such as silty and laminar clays, and fly ash, the raw material may need to be agglomerated with water, or possibly require addition of supplementary binder, fuel, gas-forming or fluxing agents, prior to heating.

Several different methods are used to produce structural lightweight aggregates, and the aggregates produced may vary widely in their characteristics. Any single description will seldom apply fully to any raw material or process. A generalized description follows for the several principal processes used.

2.4.1 *Rotary kiln process*-Basically the rotary kiln is a long, nearly horizontal cylinder lined with refractory materials. Raw material is introduced in a continuous stream at the upper end, and due to slow rotation and slope of the kiln, it progresses to the lower or burner end. The heat causes simultaneous formation of gases and onset of a pyroplastic condition in the material. The viscosity of the softened mass is sufficient to entrap the gases and to form an internal cellular structure. This structure is retained on cooling as a vitrified hard material.

2.4.1.1 *Crushed material*-In one variation of the rotary kiln process, the bloated material is discharged, cooled, and then crushed and screened to required aggregate gradations . The resultant particles tend to be cubical or angular in shape and to have a varying percentage of particles with a smooth shell.

2.4.1.2 *Presized or "coated" material*-In another variation, raw material is presized, by crushing and screening or by pelletizing, before introduction into the kiln and the individual particles are bloated with little or no agglomeration. The resultant particles tend to have a smooth shell or coating outside of the cellular interior.

2.4.1.3 *Combination material*-Frequently there is a combination of the two procedures in which most of the coarse aggregate will consist of uncrushed particles, obtained by screening, and most of the fine particles are obtained by crushing the fired product.

2.4.2 *Sintering process*-In the sintering process, raw materials are used which either contain carbonaceous matter that serves as fuel or are mixed with fuel, such as finely ground coal or coke.

2.4.2.1 *Crushed material*-In one variation of this process an even layer of such a mixture, suitably premoistened, is carried by a traveling grate under drying and ignition hoods and subsequent burners in such a manner that burning, initiated at the surface, continues through the full depth of the bed. Gases are formed causing expansive action, coincident with the onset of pyroplasticity, so that the material is sufficiently viscous to entrap the gas and thereby create the cellular structure. The clinker formed is then cooled, crushed, and screened to required aggregate gradations. In some cases the cellular structure results from the burnout of carbonaceous matter and loss of moisture, and fusion of fine particles of the original raw material. The finished product tends to be generally sharp and angular with a vesicular surface texture.

2.4.2.2 *Pelletized material*-In a second variation of the sintering process, clay or pulverized shale is mixed with moisture and fuel, and then pelletized or extruded before burning. The resultant product tends to be generally rounded or cylindrical in shape.

2.4.3 *Expansion of slag*-Three main processes are used in expanding molten blast furnace slag.

2.4.3.1 *Machine process*-The molten slag at a temperature in excess of 2200 F (1200 C) is rapidly agitated in a machine with a controlled amount of water and subsequently cooled and crushed. The cellular structure is formed primarily by entrapment of steam, and secondarily from gases evolved by reaction of minor constituents in the slag with the water vapor.

2.4.3.2 *Pit process*-The molten slag, at temperatures in the range of 2200 to 2500 F (1200 to 1400 C), is treated with a controlled amount of injected water and is subsequently cooled and crushed. Expansive action occurs as entrapped water turns to steam and causes formation of the cellular structure..

2.4.3.3 *Pelletizing process*-The molten slag at a temperature in excess of 2200 F (1200 C) is treated with limited amounts of water and distributed by a vibrating, water cooled, carbon feeder to a rotating drum. Fins on the drum break the slag into small particles that solidify into rounded pellets as they are thrown through the air.

2.5 - Aggregate properties

Each of the properties of lightweight aggregates may have some bearing on the properties of the plastic and hardened concrete. It should be recognized, however, that properties of lightweight concrete, in common with those of normal weight concrete, are greatly influenced by the quality of the cement paste. Specific properties of aggregates which may affect the properties of the concrete are as follows.

2.5.1 *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 aggregate influence proportioning of mixes in such factors as workability, fine-to-coarse aggregate ratio, cement content, and water requirement. These effects are. analogous to those obtained with normal weight aggregates of such diverse particle shapes as exhibited by rounded gravel, crushed limestone, traprock, or manufactured sand.

2.5.2 *Bulk specific gravity*-Due to their cellular structure, the specific gravity of lightweight aggregates is lower than that of normal weight aggregates. The bulk specific gravity 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 bulk specific gravities of coarse lightweight aggregates, corrected to the dry condition, is about ⅓ to ⅔ of that for normal weight aggregates. For specific gravities below this range the cement requirement may be uneconomically high to produce the required strength, and above this range the weight may be too high to meet ASTM requirements for lightweight concrete.

With present ASTM test methods, it may be difficult to accurately determine bulk specific gravity and water absorption for some coarse lightweight aggregates and for many fine lightweight aggregates.

2.5.3 *Unit weight*-Unit weight of lightweight aggregate is significantly lower, due to the cellular structure, than that of normal weight aggregates. For the same gradation and particle shape, unit weight of aggregate is essentially proportional to specific gravity. However, aggregates of the same specific gravity may have markedly different unit weights, 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 which, for the same specific gravity and grading, may differ by 10 lb/ft^3 (160 kg/m^3) in the dry, rodded condition. Rounded and angular lightweight aggregates of the same specific gravity may differ by 5 lb/ft^3 (80 kg/m^3) or more in the dry, loose condition, but the same weight of either will occupy the same volume in concrete. This should be considered in assessing the workability using different aggregates.

2.5.4 *Maximum size*-The maximum size grading designations of lightweight aggregates generally available are ¾ in. (19 mm), ½ in. (13 mm), or ⅜ in. (10 mm). Maximum size of aggregate influences such factors as workability, ratio of fine to coarse aggregate, cement content, optimum air content, potential strength ceiling, and drying shrinkage.

2.5.5 *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. There is no reliable correlation between aggregate strength and concrete strength and lower particle strength would not preclude use of an aggregate in structural concrete.

2.5.5.1 *Strength ceiling*-The concept of "strength ceiling" may be useful in indicating the maximum compressive strength attainable in concrete made with a given aggregate using a reasonable quantity of cement. A mix is near its strength ceiling when similar mixes 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 high-quality normal weight aggregates.

Strength ceiling is influenced predominantly by the coarse aggregate. It has been found that 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 ¾ in. (19 mm) maximum size of a specific lightweight aggregate was 5000 psi (34.47 MPa); for the same cement content [750 lb/yd^3 (450 kg/m^3)] the strength was increased to 6100 and 7600 psi (42.06 MPa and 52.4 MPa) when the maximum size of the aggregate was reduced to ½ in. (13 mm) and ⅜ in. (10 mm), respectively, whereas concrete unit weights were concurrently increased by 3 and 5 lb/ft^3 (48 and 80 kg/m^3).

2.5.6 *Moisture content and absorption*-Lightweight aggregates, due to their cellular structure, are capable of absorbing more water than normal weight aggregates. Based on a 24 hr absorption test, lightweight aggregates generally absorb from 5 to 20 percent by weight of dry aggregate, depending on the pore structure of the aggregate. Normally, however, under conditions of outdoor storage in stockpiles, moisture content will usually not exceed two-thirds of the 24 hr absorption.

In contrast, normal weight aggregates usually will absorb less than 2 percent of moisture. However, the moisture content in a normal weight aggregate stockpile may be as high as 5 to 10 percent or more. The important difference is that the moisture content in lightweight aggregates is largely absorbed into the interior of the particles whereas in normal weight aggregates it is largely surface moisture. These differences become important in mix proportioning, batching and control as discussed in Sections 3.4, 3.5, and 3.7.

Rate of absorption in lightweight aggregates is a factor which also has a bearing on mix proportioning, handling, and control of concrete, and depends on the aggregate particle surface pore characteristics plus other factors. It should be noted that the water which is internally absorbed in the lightweight aggregate is not immediately available to the cement as mixing water, as will be discussed in Section 3.2.3. Nearly all moisture in the natural sand, on the other hand, may be surface moisture which is available to the cement.

CHAPTER 3 - PROPORTIONING, MIXING AND HANDLING

3.1 - Scope

Proportioning of structural lightweight concrete mixtures is the determination of economical combinations of the several constituents-portland cement, aggregate, water, and usually admixtures-in a way that the optimum combination of properties is developed in both the plastic and hardened state.

A prerequisite to the selection of mixture proportions is a knowledge of the properties of the constituent materials.

Generally these constituents are required to comply with the pertinent ASTM specification.

Based on a knowledge of the properties of the constituents, and their interrelated effects on the concrete, structural lightweight concrete can be proportioned and produced to have, within reasonable limits, the specific properties most suited to the finished structure.

It is within the scope of this chapter to discuss:

(a) Criteria on which concrete mixture proportions are based

(b) The materials which make up the concrete mixture

(c) The methods by which these are proportioned

The subjects of mixing, delivery, placing, finishing, and curing also will be discussed, particularly where these procedures differ from those associated with normal weight concrete. The chapter will conclude with a brief discussion on laboratory and field control.

3.2 - Mix 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 mix, the engineer is concerned with obtaining predictable specific values of properties for a particular situation.

The specifications of the structural engineer, for lightweight concrete, usually require minimum permissible values for compressive 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 unit weight.

Insofar as physical properties of the concrete are concerned, the usual specification is limited to these items. From a construction standpoint, such properties of freshly mixed concrete as bleeding, workability, and finishability must also be considered. It is possible in mix proportioning, especially with lightweight concrete, to optimize these properties. Some properties are to a large extent interdependent and improvement in one property, such as workability, may affect other properties such as unit weight or strength. The final criterion to be met is overall performance in the structure as intended by the architect/engineer.

3.2.1 *Specified physical properties*

3.2.1.1 *Compressive strength*-This property is also discussed in Section 4.3. The various types of lightweight aggregates available will not always produce similar compressive strengths for concretes of a given cement content and slump.

Compressive strength of structural concrete is specified according to engineering requirements of a structure. Normally, strengths specified will range from 3000 to 4000 psi (20.68 to 27.58 MPa) and less frequently up to 6000 psi (41.36 MPa) or higher. It should not be expected that the higher strength values can be attained consistently by concretes made with every lightweight aggregate classified as “structural,” although some are capable of producing very high strengths consistently.

3.2.1.2 *Unit weight*-From the load-resisting considerations of structural members, reduced unit weight of lightweight concrete can lead to improved economy of structures despite an increased unit cost of concrete.

Unit weight is therefore a most important consideration in the proportioning of lightweight concrete mixtures. While this property depends primarily on the unit weight or density of the lightweight or normal weight aggregates, it is also influenced by the cement, water and air contents, and to a small extent, by the proportions of coarse to fine aggregate. Within somewhat greater limits the unit weight can be tied by adjusting proportions of lightweight and normal weight aggregates. For instance, 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 fines with normal weight sand could increase the unit weight by approx. 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 structural lightweight concrete.

If the concrete producer has available several different sources of lightweight aggregate, optimum balance of cost and concrete performance may require detailed investigation. Only by comparing concretes of the same compressive strength and of the same air-dry unit weight can the fundamental differences of concretes made with different aggregates be properly evaluated.

In some areas, only a single source of lightweight aggregate is available. In this case, the concrete producer needs only to determine that weight level of concrete which satisfies the economy and specified physical properties of the structure.

3.2.1.3 *Modulus of elasticity*-This property is discussed in detail in Sections 4.6 and 5.3. Although values for E_c are not always specified, this information is usually available for concretes made with specific lightweight aggregates.

3.2.1.4 *Slump*-Slump should be the lowest value consistent with the ability to satisfactorily place, consolidate, and finish the concrete (see Section 3.6.1 on finishing).

3.2.1.5 *Entrained-air content*-Air entrainment in lightweight concrete, as in normal weight concrete, improves durability. Moreover in concretes made with some lightweight aggregates, it is a particularly effective means of improving workability of otherwise harsh mixtures. The mixing water requirement is then lowered while maintaining the same slump, thereby reducing bleeding and segregation.

Recommended ranges of total air contents for lightweight concrete are:

Maximum size of aggregate	Air content percent by volume
$^3/_4$ in. (19mm)	4 to 8
$^3/_8$ in. (10mm)	5 to 9

At times there is a temptation to use a large proportion of normal weight sand in lightweight concrete to reduce costs, and then to use a high air content to meet weight requirements. Such a practice usually becomes self-defeating because compressive strength is thereby lowered 150 psi (1.03 MPa) or more for each increment of one percent of air beyond the recommended ranges. The cement content must then be increased to meet strength requirements. Although the percentages of entrained air required for workability and frost resistance reduce the unit weight of the concrete, it is not recommended that air contents be increased beyond the upper limits given above, simply to meet unit weight requirements. Adjustment of proportions of aggregates, principally by limiting the normal weight aggregate constituent, is the safest, and usually the more economical way to meet specified unit weight requirements.

3.2.2 *Workability and finishability*

3.2.2.1 *Workability*-Workability is probably the most important property of freshly mixed lightweight concrete. Without adequate workability it is difficult, if not impossible, to attain all the other desired properties of hardened concrete. The most satisfactory method developed to evaluate this property is the slump test when used in conjunction with the judgment of the technician.

The engineer should also keep in mind that lightweight concrete with entrained air has an established record of durability, and that the percentages of entrained air required for workability will usually also be sufficient to impart durability and other desirable properties.

3.2.2.2 *Finishability*-With most lightweight aggregates a properly proportioned, cohesive, lightweight concrete mixture with good workability will normally be finishable. Some lightweight aggregates may be deficient in minus No. 30 (0.6 mm) sieve material. When this occurs, the finishability can usually be improved by using a portion of normal weight sand, by increasing the cement content, or by using satisfactory mineral fines. If practical, sands with a low fineness modulus, such as those used in masonry mortars or finer, should be selected to supplement lightweight fine aggregate with such a deficiency. With increased fineness, less normal weight sand will be required to provide satisfactory finishability; thus the increase in weight of concrete will be minimized.

3.2.3 *Water-cement ratio*-With lightweight concrete, the water-cement ratio is not generally used, primarily due to uncertainty of calculating that portion of the total water in the mix which is applicable. The water absorbed in the aggregate prior to mixing is not part of the cement paste, and complication is introduced by absorption of some indeterminate part of the water added at the mixer. However, it is quite probable that this absorbed water is available for continued hydration of the cement after normal curing has ceased. The general practice with lightweight aggregates is to proportion the mix, and to assess probable physical characteristics of the concrete, on the basis of a given cement content at a given slump for particular aggregates.

3.3 - Materials

Concrete is composed essentially of cement, aggregates and water. In some cases an admixture is added, generally for the purpose of entraining air, but occasionally for special reasons such as modifying setting time or reducing water content. When ingredients vary, as in the case of aggregates from different sources, or cements of different types, or by the use of admixtures, concrete properties may differ appreciably even though the cement content and slump are held constant. It is preferable, therefore, to make laboratory tests of all the ingredients, and to proportion concrete mixtures to meet specifications and specific job requirements with the actual combinations of materials that are economically available.

3.3.1 *Hydraulic cement*-The cement should meet the requirements of ASTM C 150 or ASTM C 595 (see ACI 225R). Where close control of air content is required, the use of dispensed air-entraining agents are customarily used since the amount of entrained air depends on characteristics of the fine aggregates and on the mixing conditions.

3.3.2 *Lightweight aggregates*-Lightweight aggregate should meet requirements of ASTM C 330 for lightweight aggregates for structural concrete. Surfaces of aggregate particles have pores varying in size from microscopic to those visible to the eye. Water absorption and rate of absorption may vary widely. These differing characteristics account for the wide range in amounts of mixing water needed to produce a concrete of a given consistency with different aggregates. This wide range in water requirements is reflected in a corresponding range of cement contents necessary to produce a given strength with aggregates from different sources. The inherent strength of coarse aggregate particles also has an important effect on the cement requirement, particularly for higher strength concretes. The mix proportions provided by lightweight aggregate producers generally provide recommended cement content and other mix proportions that should be used as a starting point in trial batches for selecting mix proportions.

3.3.3 *Normal weight aggregates*-Any normal weight aggregates (see ACI 221R) used in structural lightweight concrete should conform to the provisions of ASTM C 33. If finer sand is desired as a supplement, it should conform to ASTM C 144.

3.3.4 *Admixtures*-Admixtures should conform to appropriate ASTM specifications, and guidance for use of admixtures may be obtained from ACI 212.1R and ACI 212.2R.

3.4 - Proportioning and adjusting mixes

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 which provide guides in approaching optimum combinations of materials, but final proportions should be established by laboratory trial mixes, which are then adjusted to provide practical field batches, in accordance with ACI 211.2.

The principles and procedures for proportioning normal weight concrete, such as the absolute volume method in Section 3.4.1 may be applied in many cases to lightweight concrete. With some aggregates, these procedures are difficult to use, and other methods have been developed. The local aggregate producers should be consulted for the particular recommended procedures.

3.4.1 *Absolute volume method* - In utilizing the absolute volume method, the volume of plastic concrete produced by any combination of materials is considered equal to the sum of the absolute volumes of cement, aggregate, net water, and entrained air. proportioning by this method requires the determination of water absorption and the bulk specific gravity of the separate sizes of aggregates in a saturated surface-dry condition. The principle involved is that the "mortar" volume consists of the total of the volumes of cement, fine aggregate, net water, and entrained (or entrapped) air. This mortar volume must be sufficient to fill the voids in a volume of dry, rodded coarse aggregate, plus sufficient additional volume to provide satisfactory workability. This recommended practice is set forth in ACI 211.1, and it represents the most widely used method of proportioning for normal weight concrete mixtures. While the saturated surface-dry condition in most fine and many coarse lightweight aggregates[9,10] may be difficult to assess accurately, the absolute volume method can be useful in selecting proportions for structural lightweight concretes with some lightweight aggregates.

3.4.2 *Volumetric method* - The volumetric method is described with examples in ACI 211.1. It consists essentially of making a trial mix using estimated volumes of cement, coarse and fine aggregate, and sufficient added water to produce the required slump. The resultant mix is observed for workability and finishability characteristics. Tests are made for slump, air content, and fresh unit weight. Calculations are made for yield (the total batch weight divided by the plastic unit weight) and for actual quantities or weights of materials per unit volume (yd^3 or m^3) of concrete. Necessary adjustments are calculated and further trial mixes made until satisfactory proportions are attained. Prerequisite to the trial mixes is a knowledge of the dry-loose unit weights of aggregates, the moisture contents of the aggregates, an approximation of the optimum ratio of coarse and fine aggregates, and an estimate of required cement content to give the strength desired.

3.4.3 *Specific gravity factor method-Trial mix basis*-The specific gravity factor method, trial mix basis, is described with examples in ACI 211.2. A trial batch is prepared as in Section 3.4.2 and observations and tests made as mentioned. Displaced volumes are calculated for the cement, air, and total water (added water less net amount of absorbed water). The remaining volume is then assigned to the coarse and fine aggregates, assuming that the volume occupied by each is proportional to its dry-loose unit weight. The specific gravity factor is calculated as the relationship between the dry weight of the aggregate in the mix and the displaced volume it is assumed to occupy. The value so determined is not an actual specific gravity but is only a factor. This factor may, however, be used in subsequent calculations as though it were the apparent specific gravity, using the principles of absolute volumes, so long as the moisture content and density of the aggregates remains unchanged.

3.5 - Mixing and delivery

The fundamental principles of ASTM C 94 apply to structural lightweight concrete as they do to normal weight concrete. Also, it is recommended that immediately prior to discharge, the mixer should be rotated approximately ten revolutions at mixing speed to minimize segregation.

In those cases involving aggregates with relatively low water absorption, no special prewetting is required prior to batching and mixing of the concrete. Such aggregates are sometimes stocked in the kiln-dry condition, and at other times they contain some amount of moisture. These aggregates may be handled according to the procedures which have been established in the ready-mixed concrete industry (see ACI 301). In so treating these aggregates, it should be realized that the water to be added at the batching plant should provide the required slump at the job; i.e., the added water may give high slump at the plant but water absorption into the aggregate will provide the specified slump at the building site.

In other cases, the absorptive nature of the lightweight aggregate may require prewetting to as uniform a moisture content as possible, or premixing with water, prior to addition of 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 utilized in prop erly placing normal weight concrete. ACI 304 discusses in detail proper and improper methods of placing concrete. The most important consideration in handling and placing concrete is to avoid separation of the coarse aggregate from the mortar portion of the mixture. The basic principles required to secure a good lightweight concrete job are:

- A workable mix utilizing a minimum water content
- Equipment capable of expeditiously handling and placing the concrete
- Proper consolidation
- Good quality workmanship

A well proportioned lightweight concrete mix can generally be placed, screeded, and floated with substantially less effort than that required for normal weight concrete. Overvibration or overworking is often a principal cause of finishing problems in lightweight concrete. Overmanipulation only serves to drive the heavier mortar away from the surface where it is required for finishing, and to bring an excess of the lighter coarse aggregate to the surface. Upward movement of coarse lightweight aggregate can also occur in mixes in which the slump exceeds the recommendations of Section 3.6.1.1.

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

3.6.1.1 *Slump*-Slump is a most important factor in achieving a good floor surface with lightweight concrete and generally should be limited to a maximum of 4 in. (100 mm). A lower slump, of about 3 in. (75 mm), imparts sufficient workability and also maintains cohesiveness and "body," thereby preventing the lighter coarse particles from working up through the mortar to the surface. (This is the reverse of normal weight concretes where segregation results in an excess of mortar at the surface.) In addition to "surface" segregation, a slump in excess of 4 in. (100 mm) will cause unnecessary finishing delays.

3.6.1.2 *Surface preparation*-Surface preparation prior to troweling is best accomplished with magnesium or aluminum screeds and floats which minimize surface tearing and pullouts. Vibrating screeds and "jitterbugs" (grate tamper or roller type) may be used to advantage in depressing coarse particles and developing a good mortar surface for troweling.

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

(a) Prevent segregation by:
  1. Use of a well-proportioned and cohesive mix
  2. Requiring a slump as low as possible
  3. Avoiding overvibration

(b) Time the finishing operations properly

(c) Use magnesium, aluminum, or other satisfactory finishing tools

(d) Perform all finishing operations after free surface bleeding water has disappeared

(e) Cure the concrete properly

3.6.2 *Curing*-On completion of the final 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 contains information on proper curing of concrete floor slabs. The two methods of curing commonly used in the field are (a) water curing (wet coverings, ponding and sprinkling or soaking), and (b) moisture retention cure (polyethylene film, waterproof paper, and spray-applied curing compound membranes). In construction practice, 7 days of curing is generally considered adequate with a temperature in excess of 50 F (10 C). Refer to ACI 308.

3.7 - Pumping structural lightweight concrete

3.7.1 *General Considerations*-The types of aggregates discussed generally have a surface texture that can vary from angular crushed to rounded coated. In general, they have the following in common:

- Made up of nonconnected voids
- Bulk saturated specific gravities of 1.10 to 1.60
- Top size of $^3/_4$ in. (19 mm)

The ability of the lightweight aggregate to absorb relatively large amounts of water in 24 hr is a possible cause for the difficulty in pumping structural lightweight. For this reason it is of primary importance to presoak or presaturate the lightweight aggregate before mixing concrete. The presaturating can be accomplished by any of the following:

A. ATMOSPHERIC-Using a soaker hose or sprinkler system. A minimum of 24 hr should be allowed with 72 hr or more preferred. This is dependent on the rate of absorption of the aggregate so the supplier should be consulted. This can be done at the aggregate plant or batch plant.

B. THERMAL-By immersion of partially cooled aggregate in water. It must be carefully controlled and is feasible only at the aggregate plant.

C. 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 also is recommended for the aggregate plant only. (This method is covered by a patent.)

Presaturation minimizes the ability of the aggregate to absorb water, therefore minimizing the slump loss during pumping. This additional moisture also increases the loose density of the lightweight aggregate which in turn increases the density of the plastic concrete. This increased weight due to presaturation will eventually be lost to the atmosphere in drying and provides for additional internal curing.

3.7.2 *Proportioning pump mixes*-When considering pumping of lightweight aggregate, some adjustments may be necessary to achieve the desired characteristics. The architect, engineer, and contractor should be familiar with any mix 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.

Assuming the project specifications will allow pumping, the following general rules apply. These are based on the use of lightweight coarse aggregate and normal weight fine aggregate.

A. Presaturate lightweight aggregate by one of the methods given above.

B. Maintain a 564 lb/yd^3 (335 kg/m^3) minimum cement content.

C. Use selected admixtures that will aid in pumping.
  1. Air entrainment sufficient for 5 to 8 percent air
  2. Water reducer
  3. Fly ash or natural pozzolan
  4. Pumping aid

D. To facilitate pumping, adjustments in the ***standard*** mix proportion usually consist of some slight reduction in the volume of coarse aggregate, with a corresponding increase in the volume of fine aggregate.

E. Cementitious content should be sufficient to accommodate a 4 to 6 in. (100 to 150 mm) slump.

F. Use a natural sand that is well graded with the fineness modulus preferably between 2.2 and 2.7. Consider the possible addition of a fine sand if this fineness modulus is not available.

G. Use a properly combined coarse and fine aggregate gradation proportioned by volume that will prevent the paste from being squeezed through the voids between aggregate particles. The gradation comparison should be made by volume rather than by weight to account for differences in specific gravity of various particle sizes.

It should be noted that it may sometimes be 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 should be made at discharge end of the pumping system, as suggested in ACI 304.5R.

3.7.3 *Pump and pump system*-After the above items are discussed and implemented the most important function has yet to be completed-pumping of the concrete. Listed below are some of the key items pertinent to the pump and pumping system.

A. Use the largest size line available, preferably a minimum of 5 in. (125 mm).

B. All lines should be clean, the same size, and "buttered" with grout at the start.

C. Avoid rapid size reduction from the pump to line. For example, 10- to 4-in. (250- to 100-mm) diameter in 4 ft (1.2 m) will not work as well as 10 to 6 in (250 to 150 mm) in 8 ft (2.4 m), then 6 to 4 in. (150 to 100 mm) in 4 ft (1.2 m).

D. Reduce the operating pressure by:
  - Slowing down rate of placement
  - Using as much steel line and as little rubber line as possible
  - Limiting the number of bends
  - Making sure the lines are tightly joined and gasketed

A field trial should be run using the pump and mix design intended for the project. Observers present should include representatives of the contractor, ready-mixed concrete producer, architect and engineer, pumping service, testing agency and aggregate supplier. In the pump trial, the height and length the concrete is to be moved should be taken into account. Since 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 run with steel line.

1.0 ft (0.31 m) vertical = 4.0 ft (1.22 m) horizontal
1.0 ft (0.31 m) rubber hose = 2.0 ft (0.61 m) of steel
1.0 ft (0.31 m) 90 degree bend = 3.0 ft (0.91 m) of steel

3.8 - Laboratory and field control

Changes in absorbed moisture or density of lightweight aggregates (which result from variations in initial moisture content, gradation, or specific gravity) and variations in entrained-air content suggest frequent checks (see ACI 211.1) of the fresh concrete at the job site to assure consistent quality. Sampling should be in accordance with ASTM C 172. Four simple tests are normally required: (a) standard slump test, ASTM C 143, (b) unit weight of the fresh concrete, ASTM C 567, (c) entrained-air content, ASTM C 173, and (d) compressive strength, ASTM C 31.

At the job start, the plastic properties, unit weight, air content, and slump, of the first batch or two should be determined to verify that the concrete conforms to the laboratory mix. Small adjustments may then be made as necessary. In general when variations in fresh unit weight exceed ± 2 percent, an adjustment in batch weights will be required to meet specifications. The air content of lightweight concrete, should not vary more than ± 1.5 percentage points from specified value to avoid adverse effects on compressive strength, workability, or durability, (see Section 3.2.1.5).

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

4.1 - Scope

This chapter presents a summary of the properties of structural lightweight aggregate concrete. The information is based on many laboratory studies as well as records of a large number of existing structures that have provided satisfactory service over the years.[11-41,44-61]

The customary requirements for structural concrete are that the mix proportions should be based on laboratory tests or on mixes with established records of performance indicating that the proposed combinations of ingredients will perform as required. The data that are presented may be considered the properties anticipated.

4.2 - Method of presenting data

In the past, properties of lightweight concrete have been compared with those of normal weight concrete, and usually the comparison standard has been a single normal weight material. With several million cubic yards of structural lightweight concrete being placed each year, a comparison of properties is usually no longer considered necessary. With numerous recognized structural lightweight aggregates available, it is as difficult to furnish absolute property values as it is for normal weight concretes made from various aggregate sources. For this reason, the data on various structural properties are presented as the reasonable conservative values to be expected in relationship to some fixed property such as compressive strength, unit weight, or in the case of fire resistance, slab thickness.

References given at the end of this chapter consist of laboratory reports as well as papers, suggested guides, specifications and standards. In addition, references that discuss structural lightweight concrete structures are included to present studies of the extensive use of structural lightweight aggregate concrete.

4.3 - Compressive strength

Compressive strength levels required by the construction industry for the usual design strengths of cast-in-place, precast or prestressed concrete can be obtained economically with the structural lightweight aggregates in use today.[8,13,18,19,23] Design strengths of 3,000 to 5,009 psi (20.68 to 34.47 MPa) are common. In precast and prestressing plants design strengths of 5,000 psi (34.47 MPa) are usual.

As discussed in Section 2.5.5.1, all aggregates have strength ceilings and with lightweight aggregates the strength ceiling generally can be increased at the same cement content and slump by reducing the maximum size of the coarse aggregate. For example, with a particular lightweight aggregate the ceiling might be 5,500 psi (37.92 MPa) with a $^{3}/_{4}$ in. (19 mm) top size of coarse material. By reducing the top size to $^{1}/_{2}$ in. (12.5 mm) or $^{3}/_{8}$ in. (9.5 mm) the ceiling might be increased to 6,500 (44.81 MPa) or in excess of 7,000 psi (48.25 MPa).

The compressive strength of lightweight aggregate is usually related to cement content at a given slump rather than water-cement ratio. Water-reducing or plasticizing admixtures are frequently used with lightweight concrete mixtures to increase workability and facilitate placing and finishing.

In most cases, compressive strength can be increased with the replacement of lightweight fine aggregate with a good quality of normal weight sand.[26,28] The aggregate producer should be consulted.

4.4 - Cement content

The cement and water contents required for a particular strength and slump have significant effects on the hardened concrete properties.

With lightweight concrete, mix proportions are generally expressed in terms of cement content at a particular slump rather than by the water-cement ratio. Increasing the mixing water without increasing the cement content will increase slump and also increase the effective water-cement ratio.

The usual range of compressive strengths may be obtained with reasonable cement contents with the lightweight aggregates being used for structural applications today. Generally air-entraining admixtures are found advantageous. The following table, which is based on a number of tests of job concretes, suggests the range of cement contents for 28 day compressive strengths for concretes with 3 to 4 in. (75 to 100 mm) of slump and 5 to 7 percent air contents.

Table 4.4 - Approximate relationship between average compressive strength and cement content

Compressive strength psi	(MPa)	Cement content lb/yd^3 (kg/m^3) All-lightweight	Sand-lightweight
2500	(17.24)	400-510 (237-303)	400-510 (237-303)
3000	(20.68)	440-560 (261-332)	420-560 (249-332)
4000	(27.58)	530-660 (314-392)	490-660 (291-392)
5000	(34.47)	630-750 (374-445)	600-750 (356-445)
6000	(41.37)	740-840 (439-498)	700-840 (415-498)

Specified Notes: (1)For compressive strengths of 3000 psi (20.68 MPa) or less, in order to obtain proper qualities for finishing, cement contents may be higher than necessary for the compressive strength. (2)For compressive strengths in excess of 5000 psi (34.47 MPa), the aggregate producer should be consulted for specific recommendations. Type of cement, method of curing, types of admixtures, extent of mix controls, etc., all have a bearing on the cement content compressive strength relationship. This table is offered merely as a guide, and the aggregate producer should be consulted for more specific recommendations.

4.5 - Unit weight

Weight reduction for concrete of structural quality is the primary advantage of lightweight concrete. Depending upon the source of material, structural grade lightweight concrete can be obtained in a dry weight range of 90 to 115 lb/ft^3 (1440 to 1840 kg/m^3).

Producers of structural lightweight aggregate stock the material in various size fractions. Each producer usually is able to furnish at least the standard sixes of coarse, intermediate and fine aggregate. ASTM limits the weight of the coarse fractions-the first two-to 55 lb/ft^3 (880 kg/m^3) and the sand or fine fraction to 70 lb/ft^3 (1120 kg/m^3) dry loose basis. Generally the coarse fractions weigh from 38 to 53 lb/ft^3 (608 to 848 kg/m^3) with the larger top size being the lighter for a particular source of material. The sand size will generally range from 50 to 68 lb/ft^3 (800 to 1088 kg/m^3).

By combining two or more of these size fractions or by replacing some or all of the fine fraction with a good local normal weight sand weighing from 95 to 110 lb/ft^3, (1520 to 1760 kg/m^3) a weight range of concrete of 100 to 115 lb/ft^3 (1600 to 1840 kg/m^3) can be obtained. The aggregate producer is the best source of information for the proper combinations to achieve a specific unit weight for a satisfactory structural lightweight concrete.

With a particular lightweight aggregate, normal weight sand replacement will increase the unit weight at the same compressive strength by about 5 to 10 lb/ft^3 (80 to 160 kg/m^3). With the same source of material the additional cement required will increase the weight of 5000 psi (34.47 MPa) concrete over 3000 psi (20.68 MPa) concrete approximately 3 to 6 lb/ft^3 (48 to 96 kg/m^3).

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.[50,51] Sand and gravel concrete has a higher E_c because the moduli of sand and gravel are greater than the moduli of structural lightweight aggregates. Fig. 4.6 gives the range of modulus of elasticity values for structural all-lightweight concrete and for sand-lightweight concrete. Generally the modulus of elasticity for structural lightweight concrete is considered to vary between ½ to ¾ that of sand and gravel concrete of the same strength. Variations in lightweight aggregate gradation usually have little effect on modulus of elasticity if the relative volumes of cement paste and aggregate remain fairly constant.

The formula for $E_C = w_c^{1.5}\, 33 \sqrt{f_c'} (w_c^{1.5}\, 0.043 \sqrt{f_c'})$ given in the ACI 318 Building Code, may be used for values of w between 90 and 155 lb/ft^3 (1440 and 2480 kg/m^3). Further discussion of this formula is given in Section 5.3. Concretes in service may comply with this formula only within ±15 to 20 percent. An accurate evaluation of E_C may be obtained for a particular concrete by laboratory test in accord with the methods of ASTM C 469.

4.7 - Poisson's ratio

Tests[41] 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. Tests to determine Poisson's ratio by the static method for lightweight and sand-and-gravel concrete gave values that varied between 0.15 and 0.25 and averaged 0.20. Dynamic tests yielded only slightly higher values.

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

4.8 - Creep

Creep[75-79] is the increase in strain of concrete due to 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, gradation of aggregate, water content of the mix, moisture content of aggregate at time of mix, amount of entrained 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*-Fig. 4.8.2 shows the range in values of specific creep (creep per psi of sustained stress) for normally cured concrete, as measured in the laboratory (see ASTM C 512), when under constant loads sustained for a period of one year. These diagrams were prepared with the aid of two common assumptions: (a) superposition of creep effects are valid (i.e., creep is proportional to stress within working stress ranges); and (b) shrinkage strains, as measured on nonloaded specimens, may be directly separated from creep strains. The band of creep properties for all-lightweight aggregate concrete is wide for concrete having a low 28 day compressive strength but it sharply decreases as compressive strength increases. The band for sand-lightweight concrete is narrower than that for the all-lightweight concrete for all 28 day compressive strengths.[29] Fig. 4.8.2 suggests that a very effective method of reducing creep of lightweight concrete is to use higher strength concrete. A strength increase from 3000 to 5000 psi (20.68 to 34.47 MPa) reduces the creep of all-lightweight concrete from 20 to 40 percent.

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. Fig. 4.8.3 shows that the reduction for low-pressure steamed concrete may be from 25 to 40 percent of the creep of similar concretes subjected only to moist curing. The reduction for high-pressure steamed concrete may be from 60 to 80 percent of the creep of similar concretes subjected only to moist curing. High-pressure steam-cured concrete has the lowest creep values and the lowest prestress loss due to creep and shrinkage, while moist-cured concrete has the highest values.

4.9 - Drying shrinkage

Drying shrinkage is an important property that affects 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 humidities, may undergo substantially less shrinkage than that exhibited by small laboratory specimens stored at 50 percent relative humidity (see ACI 318R).

4.9.1 *Normally cured concrete*-Fig. 4.9.1 indicates wide ranges of shrinkage values after one year of drying for

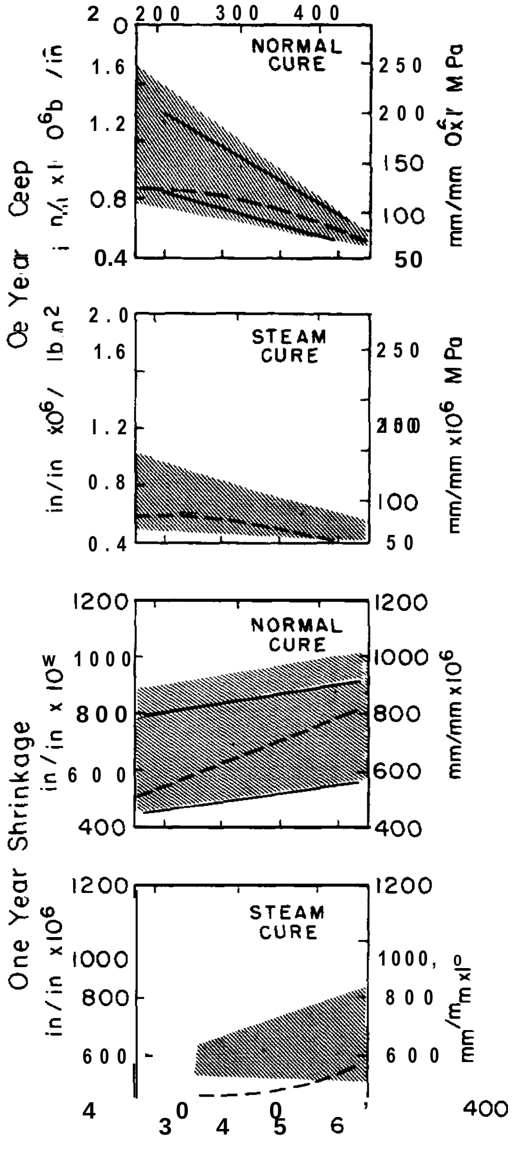


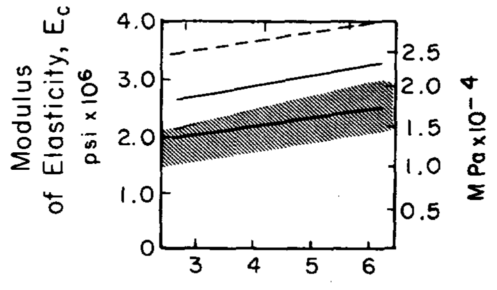
Fig. 4.8.2

Fig. 4.8.3

Fig. 4.9.1

Fig. 4.9.2

Fig. 4.6



Properties of lightweight concrete

Fig. 4.6 - Modulus of elasticity

Fig. 4.8.2 - Creep - normally cured concrete

Fig. 4.8.3 - Creep - steam-cured concrete

Fig. 4.9.1 - Drying shrinkage - normally cured concrete

Fig. 4.9.2 - Drying shrinkage - steam-cured concrete

Fig.4.10.1

Fig. 4.10.2

Fig. 4.11(a)

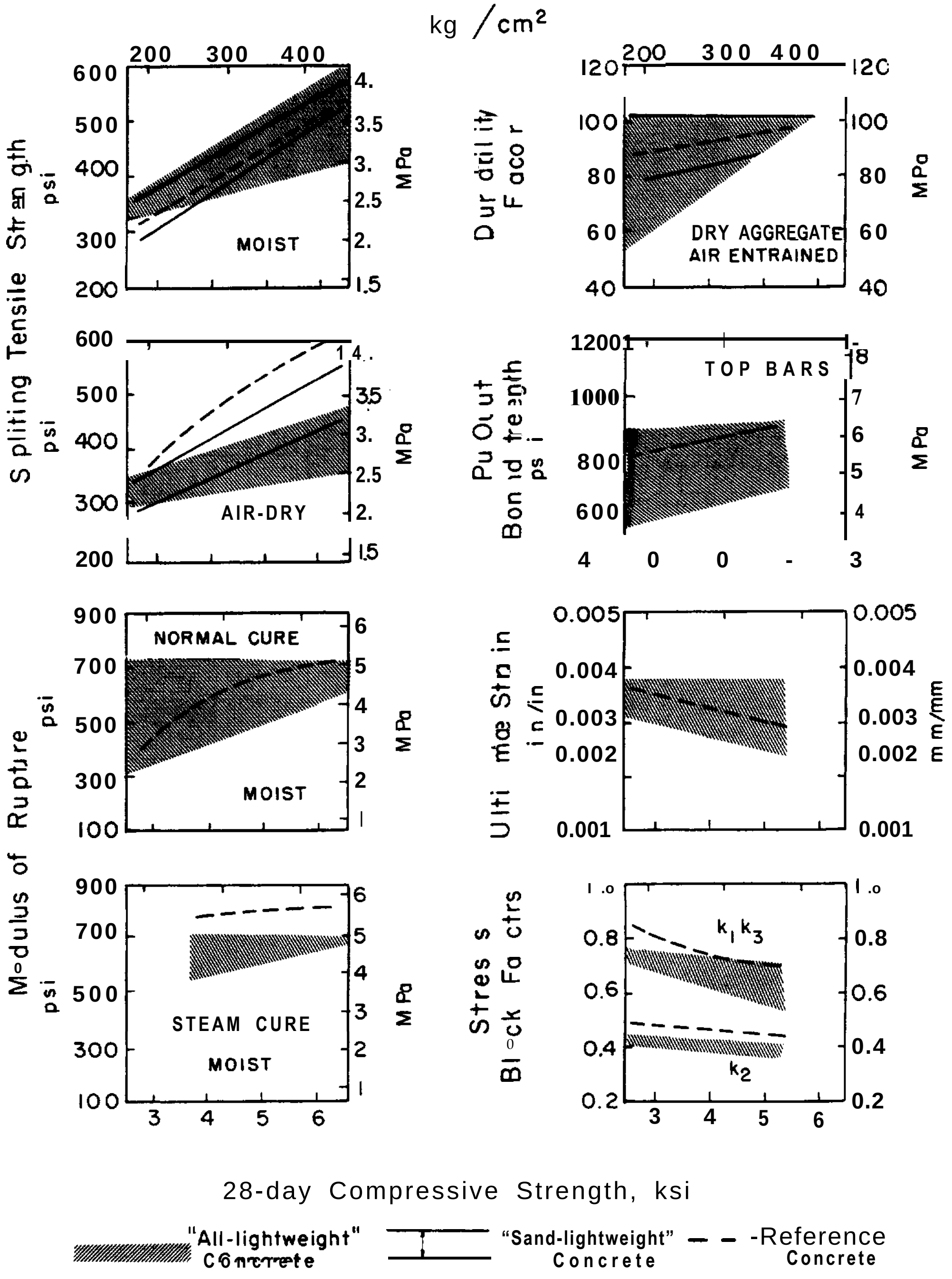
Fig. 4.11(b)

Fig. 4.12

Fig. 4.13

Fig. 4.14.1

Fig. 4.14.2



Properties of lightweight concrete

Fig. 4.10.1 - Splitting tensile strength - moist-cured concrete

Fig. 4.10.2 - Splitting tensile strength - air-dried concrete

Fig. 4.11(a) - Modulus of rupture - normally cured concrete

Fig. 4.11(b) - Modulus of rupture - steam-cured concrete

Fig. 4.12 - Durability factors - freezing and thawing

Fig. 4.13 - Bond strength - pullout tests

Fig. 4.14.1 - Ultimate strain

Fig. 4.14.2 - Stress block factors

all-lightweight and sand-lightweight concretes. 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 concretes exhibit lower shrinkage. Partial or full replacement of the lightweight fines by natural sand usually reduces shrinkage for concretes made with most lightweight aggregates.[22,26,29]

4.9.2 *Atmospheric steam-cured concrete*-Fig. 4.9.2 demonstrates the reduction of drying shrinkage obtained through steam curing.[15,20,41] This reduction may vary from 10 to 40 percent. The lower portion of this range is not greatly different from that for the reference normal weight concrete.

4.10 - Splitting tensile strength

The splitting tensile strength[14] of concrete cylinders (ASTM C 496) is a convenient relative measure of tensile strength. The test is performed by application of diametrically opposite compressive loads to a concrete cylinder laid on its side in the testing machine. Fracture or "splitting" occurs along the diametral plane. The splitting tensile strength is obtained by use of the following formula:

$$f'_{ct} = \frac{2P}{\pi DL} \qquad \frac{13{,}770\ P}{\pi DL}$$

where

f'_{ct} = splitting tensile strength, psi or Pa

P = total applied load, lb or N

D,L = diameter and length of cylinder, respectively, in. or m

4.10.1 *Moist-cured concrete*-Fig. 4.10.1 indicates a narrow range of this property for continuously moist cured lightweight concretes. The splitting tensile strength of the normal weight reference concrete is nearly intermediate within these ranges. Replacement of lightweight fine aggregate by sand has little or no effect on this property. It thus may be concluded[16,27] that the tensile strength for continuously moist cured lightweight concretes is correlated mainly with the compressive strength and may be considered equal to that of equal compressive strength normal weight concrete.

4.10.2 *Air-dried concrete*-The tensile strength of lightweight concretes which undergo drying is more relevant in respect to 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 probable 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 drying lightweight concrete will be reduced from that indicated by continuously moist cured concrete.[16,27,67] Fig. 4.10.2 indicates this reduced strength for concretes that have been moist cured 7 days followed by 21 days storage at 50 percent relative humidity (ASTM C 330). The splitting tensile strength of all-lightweight concrete varies from approximately 70 to 100 percent that of the normal weight reference concrete when comparisons are made at equal compressive strength.

Replacement of the lightweight fines by sand generally increases the splitting tensile strength of lightweight concrete subjected to drying.[17,27,59] In some cases[27] this increase is nonlinear with respect to the sand content so that with some aggregates partial sand replacement is as beneficial as complete replacement.

Splitting tensile strength is of particular value for estimating the diagonal tension resistance of lightweight concrete in structures. Tests[16] have shown that the diagonal tension strengths of beams and slabs correlate closely with this property of the concrete.

4.11 - Modulus of rupture

The modulus of rupture (ASTM C 78) is also a measure of the tensile strength of concrete. Fig. 4.11 (a) and 4.11 (b) indicate ranges for normally cured and steam-cured concretes, respectively, when tested in the moist condition. Similar to the indications for splitting tensile strength, the modulus of rupture of moist-cured lightweight concrete[13,16,67] appears little different from that of normal weight concrete. A number of studies[16,67] have indicated that modulus of rupture tests of concretes undergoing drying are extremely sensitive to the transient moisture content, and under these conditions may not furnish data that is satisfactorily reproducible.

4.12 - Durability

Freezing and thawing durability and salt-scaling resistance of lightweight concrete are important factors, particularly in horizontally exposed concrete construction such as access ramps, exposed parking floors, or bridge decks. Generally, deterioration is not likely to occur in vertically exposed members such as exterior walls or exposed columns, except in areas where these structures are continually exposed to water. As in normal weight concretes, it has been demonstrated that air entrainment provides a high degree of protection to lightweight concretes exposed to freezing and thawing and salt environments.[31,66,6]

Fig. 4.12 indicates the range of durability factors (similar to that defined in ASTM C 666), for all-lightweight concretes and for sand-lightweight concretes. The durability factor is the percent of the dynamic modulus of elasticity retained after 300 cycles of freezing and thawing. Some of the concretes shown in the Fig. 4.12 had relatively poor freeze-thaw resistance in the lower strength ranges. Generally these concretes have high water-cement ratios, thus the quality of the cement paste is poor. The same concretes had a much improved rating at higher strengths (lower water-cement ratio). Many lightweight concretes, as shown, can perform equivalent to or better than normal weight concretes. Limited salt-scaling tests have indicated similar satisfactory performance. Natural sand provides for additional resistance at all strength levels. However, the difference in the resistance of air-entrained all-lightweight and sand-lightweight concretes having compressive strengths higher than 5000 psi (34.47 MPa) is small.[28]

The use of water-saturated aggregates (approaching the 24 hr water absorption) at the time of mixing generally reduces freezing and thawing resistance of lightweight concrete. Under some conditions air entrainment will improve the durability of concrete made with these saturated aggregates. However, experience has shown that as such concretes are allowed to dry, durability improves considerably. If freezing and thawing resistance is required in lightweight concretes, and if it cannot undergo drying prior to freezing exposure, the moisture content of the aggregate should be minimized.

4.13 - Bond strength (pull out tests)

Field performance has indicated satisfactory behavior of lightweight concrete with respect to bond. The bond strength of lightweight concrete to steel reinforcement, as measured by pullout strength of reinforcing bars [ASTM C 234 top bars, for 0.01 in. (0.25 mm) slip] has usually been measured for all-lightweight concretes.[13,52] Fig. 4.13 indicates the range in results for a somewhat limited number of tests. These tests simulated the conditions of top reinforcing bars in beams and slabs. The bond of bottom bars is generally higher in concrete. Further, this test is made only on a single bar, whereas in actual structures the reinforcement consists of an assemblage. If slip should occur with one bar in this assemblage, stress can be transferred to other bars. Considering the tensile strength of lightweight concrete, precaution should be exercised to investigate the length of reinforcement anchorage in those areas where bond is critical.

4.14 - Ultimate strength factors

4.14.1 *Ultimate strain*-Fig. 4.14.1 indicates a range of values for ultimate compressive strain for all-lightweight concretes. These data were measured on unreinforced specimens eccentrically loaded to simulate the behavior of the compression side of a reinforced beam in flexure.“~** The data indicated for the normal weight reference concrete were obtained in the same manner. This diagram indicates that the ultimate compressive strain of most lightweight concretes (and of the reference normal weight concrete) may be somewhat greater than the value of 0.003, assumed for design purposes.

4.14.2 *Stress block factors*-Fig. 4.14.2 presents coefficients relating to an assumed curvilinear stress block at ultimate flexural load.1’*‘2 These values were obtained simultaneously with the ultimate strains discussed in Section 4.14.1. The factor $\boldsymbol{k_1 k_3}$ represents the ratio of the average stress in the stress block to the cylinder strength of the concrete, and $\boldsymbol{k_2}$ is the ratio of the depth to the stress block centroid and the depth to the neutral axis. For general design purposes individual values of these coefficients may have little significance.

4.15 - Water absorption of concrete

Generally, lightweight concretes have considerably higher water absorption values than do normal weight concretes. High absorption, however, does not necessarily indicate that concretes will have poor durability or high permeability. Various investigations have failed to reveal any consistent relationship between water absorption of concrete and its durability.[22] The durability of lightweight concrete, as with normal weight concrete, is primarily a function of the cement paste quality and the amount of well-distributed, discrete air bubbles entrained in the cement paste. Permeability depends primarily on the quality of the cement paste.

4.16 - Alkali-aggregate reaction

Laboratory studies[5,13] concerning potential alkali-aggregate reactivity of structural lightweight aggregates have indicated little or no detrimental reaction between the alkalis in the concrete and silica in the aggregates. At least half of a typical shale, for example, is silica (a) but occurs as well crystallized silicates and free quartz rather than the nearly amorphous forms of silica such as (b) opal and chalcedony known to be reactive.

4.17 - Thermal expansion

Only a few determinations[5,34,42] have been made of linear thermal expansion coefficients for structural lightweight concrete. Approximate values are 4 to 6 × 10^{-6} in/in/F (7 to 11 × 10^{-6} mm/mm/C) depending on the amount of natural sand used.

Ranges for normal weight concretes are 5 to 7 × 10^{-6} in./in./F (9 to 13 × 10^{-6} mm/mm/C) for those made with siliceous aggregates and 3.5 to 5 × 10^{-6} in./in./F (6 to 9 × 10^{-6} mm/mm/C) for those made with limestone aggregate[62] the values in each case depending upon the mineralogy of specific aggregates.

4.16 - Heat flow properties

4.18.1 *Thermal conductivity*-The value of thermal conductivity, $\boldsymbol{k}$, 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 one degree:

U.S. units, k = Btu/hr ft² (deg F/in.)

(S.I. units, k = W/m • K)

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

Thermal conductivity has been determined for concretes ranging in oven-dry density from less than 20 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 k values for concretes having a wide range of densities are plotted against oven-dry density, best-fitting curves show a general dependence of $\boldsymbol{k}$ on density, as shown in Fig. 4.18.1, originally published in 1956.[63] Also shown is the fact that different investigators have provided different relationships. These differences are accounted for by differences in materials, particularly in aggregate mineralogical type and microstructure, and in gradation. Differences in cement content, and matrix density and pore structure also occur. Some differences in test methods and specimen sizes also existed.

Valore[64] plotted over 400 published test results of density against the logarithm of conductivity and suggested the equation:

$$\boldsymbol{k = 0.5\ e^{0.02w}\ (k = 0.072\ e^{0.00125w})}$$

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*See References 3, 4, 5, 25, 38, 39, 43, 63, 64, 65

Existing data in the ASHRAE Handbook of Fundamentals 1977[65] compares very closely with the suggested formula. An accurate ***k*** value for a given concrete, based on testing by the method of ASTM C 177 is preferable to an estimated value, but for purposes of estimation, 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*-It is generally acknowledged that increasing the free moisture content of hardened concrete causes an increase in thermal conductivity. In Reference 64, a rule of thumb was stated that ***k*** increases by 6 percent for each one percent increment in free or evaporable moisture, by weight in relation to oven-dry density. ***k*** (corrected) =

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

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

Data on the effect of moisture on ***k*** of lightweight aggregate concretes are mostly of European origin and have been summarized by Valore.[64]

4.18.3 *Equilibrium moisture content of concrete*-Concrete in a wall is not in an oven-dry condition; it is in an air-dry condition. Since *k* values shown are for ovendry 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. While relative humidity within masonry units in a wall will vary with type of occupancy, geographical location, exposure, and with the seasons, it may be assumed to be a constant relative humidity of 50 percent. It is further assumed that exterior surfaces of single-wythe walls are "protected" by paint (of a "breathing" type), stucco or surface-bonding fibered cement plaster. For single-wythe walls, such protection is necessary to prevent 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 structural sand-gravel and expanded shale concretes, and for lowdensity insulation concretes have been summarized in References 63, 64, 65, and 69. Average long-term moisture contents for structural concretes are in good agreement with data for concrete masonry units.

It is recognized that, under certain conditions, condensation within a wall can cause high moisture contents, and that temperature gradients within the wall cause moisture to migrate to the cold side. Nevertheless, the assumed average values appear to form a reasonable basis for estimating average effects of moisture on *k*.

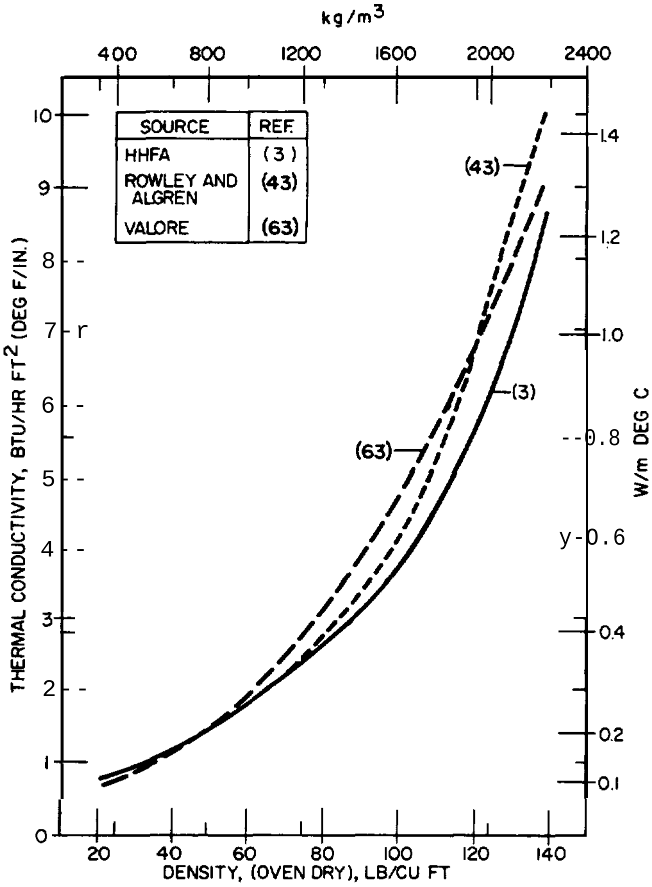

Fig. 4.18.1-Relation of average thermal conductivity, k, values of concrete in oven-dry condition to density

4.18.4 *Recommended moisture factor correction for thermal conductivity*-Moisture factors of 6 and 9 percent increase in *k* per 1 percent of moisture, by weight, are recommended for lightweight aggregate concretes (of all types) and normal weight 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 percent, for normal concrete, and 4 percent (by volume) for lightweight concrete.

As a practical matter, a simple constant factor can be used for masonry unit and structural concretes, under conditions of normal protected exposure. The recommended factor to be multiplied by *k* values of ovendry concrete is 1.2; i.e., *k* values corrected for equilibrium moisture in normal protected exposure are to be increased by 20 percent over standard values for ovendry concrete. This correction factor is recommended for application to the Valore equation of Fig. 4.18.2, which now becomes: $k = 0.6e^{0.02w}$, *in* Btu/hr **ft²** (deg F/in.) ($k = 0.0865e^{0.00125w}$, in W/m K), in that figure, where $e = 2.71828$ and w is the density of concrete, ovendry in lb/ft³ and kg/m³, respectively.

4.18.5 *Cement paste as insulating material*-The ovendry density of mature portland cement paste ranges from 100 Ib/ft³ (1600 kg/m³) for a water-cement weight ratio of 0.4, to 67 lb/ft³ (1075 kg/m³) for a w/c ratio of 0.8. This range for w/c ratio encompasses structural concretes. Campbell-Allen and Thorne[70] and Lentz and Monfore[34] have studied the influence of cement paste on *k* of concrete. The former study provided theoretical *k* values for ovendry and moist pastes and the latter reported measured *k* values of water-soaked pastes. Other data on moist-cured neat cement cellular concretes (aerated cement pastes) permit us to de-

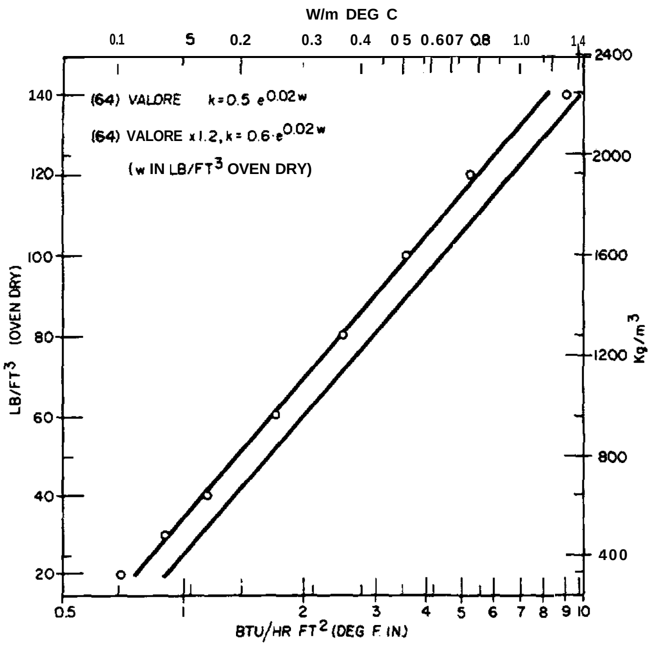

Fig. 4.18.2-Relation of average k values of concrete to dry density

velop k-density relationships for ovendry, air-dry and moist pastes[63] 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/hr ft^2 deg F, (U = W/m^2 · K).

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:

$$U = \frac{1}{R_1 + R_2 + R_3 + \ldots\ldots R_n}$$

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 = deg F/(Btu/hr ft^2), (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

Structural lightweight concretes are more fire resistant than normal weight concretes because of their lower thermal conductivity, lower coefficient of thermal expansion and the inherent fire stability of an aggregate already burned to over 2000 F (1100 C).*

4.19.1 *Heat transmission*-Recent research on fire endurance comparing lightweight aggregate concrete with normal weight concrete all with f_c' = 4000 psi (27.58 MPa)[32] yielded the data shown in Fig. 4.19.1. In these tests the lightweight aggregate concrete would be classified as sand-lightweight.

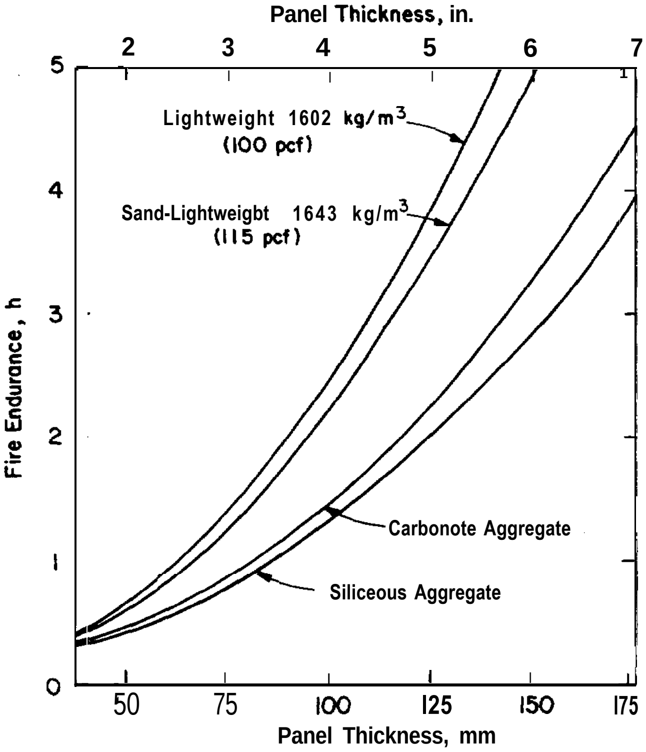

Fig. 4.19.1-Fire endurance (heat transmission) of concrete slabs as a function of thickness for naturally dried specimens[32]

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 simply supported slabs, beams and columns, fire endurance is dependent largely on cover. For fire ratings, the reinforcing steel cover requirements for lightweight concrete are lower than those for normal weight concrete.

4.19.3 *Strength retention* - Abrams[33]reported that carbonate aggregate concrete and lightweight concrete tested hot without prior loading retained about 75 percent of their original strengths (strengths prior to heating) at 1200 F (649 C). The sanded lightweight concrete had strength characteristics at high temperatures similar to carbonate concrete.

4.20 - Abrasion resistance

Tests indicating abrasion resistance have been conducted on a limited number of slabs using several commercially available lightweight aggregates. The method of test[73] and the degree of abrasion simulated the wear encountered in public, commercial, and industrial environments. Among other results, these tests confirmed that abrasion resistance of structural lightweight concrete varies with compressive strength in a manner similar to normal weight concrete.

Most lightweight aggregates, acceptable for structural concrete were at one time molten, and on cooling resulted in

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*References 32, 33, 35, 36, 37, 39, 40

a vesicular particle having an adequate gross strength. The composition of the solidified material is such that it ranks high on Moh's scale of hardness, often comparable or superior to that of glass, and the equal of quartz, feldspar, or volcanic minerals. However, because of its vesicular structure, the net resistance to load and/or impact may be low compared to a solid particle of similar composition. Therefore, the abrasion resistance of "all-lightweight" concrete may not be suitable for steel-wheeled or exceptionally heavy industrial traffic in commercial establishments. As the severity of wear becomes less, i.e., in light warehousing, markets, public buildings, schools, churches, residences, etc., the abrasion resistance should be as satisfactory as that of normal weight concrete.

The abrasion resistance of structural lightweight concrete can be improved in several ways. First, the relatively soft lightweight coarse aggregate can be combined with a hard fine aggregate to resist abrasive wear in a manner similar to combinations of hard fine aggregates and soft natural coarse aggregates such as limestone.

Another approach is to apply a natural sand-portland cement dry shake to the surface of the concrete. Thus, the benefit of low weight of an all-lightweight aggregate concrete is combined with the abrasion resistance of a hard fine aggregate. Further, iron-aggregate shakes have similarly been employed in heavy industrial applications of structural lightweight concrete.

CHAPTER 5-DESIGN OF STRUCTURAL LIGHTWEIGHT AGGREGATE CONCRETE

5.1 - Scope

The availability of quality lightweight aggregates, capable of providing satisfactory structural concrete has led to economical design of lightweight buildings, bridges, and other structures since World War II. During much of this period, designs were based on the fundamental properties of concrete, properly evaluated by the structural engineers, but without the guidance and control of building codes or recommended practices specifically pertaining to structural lightweight concrete. With the adoption of the 1963 ACI Building Code, lightweight aggregate concrete received full recognition as an acceptable structural medium. Some general guidelines for the structural engineer and for the construction industry, in general, were presented.

This chapter of the guide is intended to interpret the ACI 318 requirements for structural lightweight concrete. At the same time it condenses many practical design aspects pertaining to lightweight concrete and provides the structural engineer with additional information on which to base engineering judgment.

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

5.2 - General considerations

Lightweight aggregate concrete has been shown by test and performance (see Chapter 4) to behave structurally in much the same manner as normal weight concrete, but at the same time to provide some improved concrete properties, notably reduced weight and better insulation. For certain properties of concrete, the differences in performance are those of degree. The recent editions of ACI 318 attempt to modify structural designs in lightweight concrete to achieve the same load factors as for normal weight concrete design. Generally those properties that include tensile strength (see Section 4.10) and modulus of elasticity (see Section 4.6) are sufficiently different from those of normal weight 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 unit weight 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 in Section 5.12. Depending on how critically the values E_c will affect the nature of the design, the engineer should decide whether the values determined by formula are sufficiently accurate, or whether he should call for determination of E_c values from tests on the specified concrete.

A lower E_c value for lightweight concrete means essentially that it is less stiff, since 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 normal weight 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

Tensile strength of lightweight concrete, for equal compressive strength, is comparable to that of normal weight concrete when continuously moist-cured specimens are tested. Although the mechanisms of drying and the effects of moisture gradients are not fully understood, it is generally recognized that air drying reduces the tensile strength of lightweight concrete (see Section 4.10). For this reason test values for the diagonal tension resistance of lightweight concrete are generally lower, and hence shear design formulas in ACI 318 are modified accordingly. There are a few other instances where tensile strength is important, for example, in allowable cracking stress for prestressed members and determining when deflection calculations should be based on a cracked section instead of a homogeneous section.

5.5 - Development length

Basic development length factors of ACI 318 reflect the lower tensile splitting strength of structural lightweight concrete. Provisions for modification of development length for all-lightweight and sanded lightweight concretes are similar

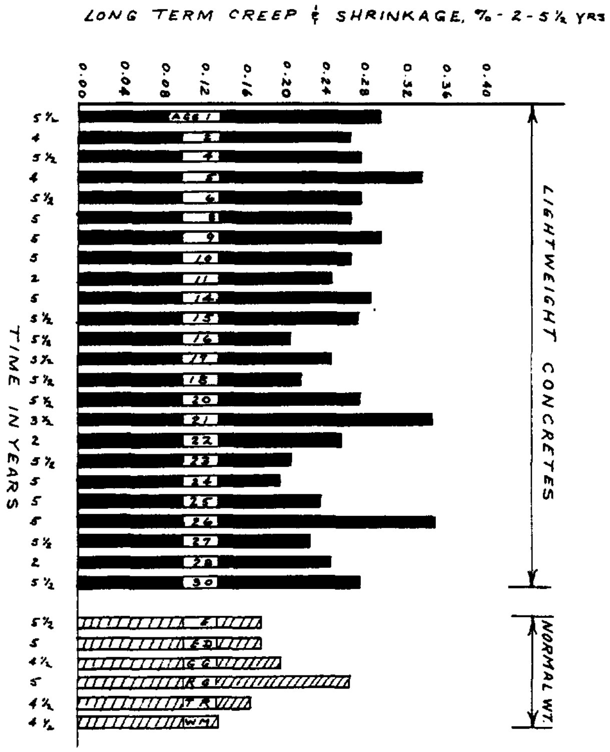

Fig. 5.6.1-Long-term creep and shrinkage

to the tensile strength sections of ACI 318. For a full explanation of use of modification factors see Section 5.8 of this guide.

5.8 - Creep and shrinkage

Values for creep and shrinkage show sufficient range for concretes made with both normal weight and lightweight aggregates so that average, minimum, or maximum values can be used only with qualifying phrases.

Fig. 5.6.1 and 5.6.2 are a summary from NBS Monograph # 74,[41] after a five-year study of high-strength concretes highly stressed at early ages. It should be noted that the overlapping of data indicates the "regular" normal weight aggregates do not have the standard properties that lightweights are often compared against. Designs that are based on creep properties or that recognize shrinkage performance fall into this category. Therefore, when these properties are included in design considerations, generalities given in ACI 318 and in other guides to design are subject to engineering judgment, and specific data or performance of job materials are the preferred basis for design. Furthermore, it should be recognized that the effects of creep and shrinkage are moderated by internal stress redistribution. Creep and shrinkage of concrete account for the greater portion of prestressing losses in post-tensioned concrete, but an engineer may be in error by 50 or 100 percent by using an arbitrary stress loss in any given location, whether his aggregate is normal or lightweight. Since creep and shrinkage loss is significant in prestressing design, calculations should be based on test data for specific materials being used. In other design considerations, such as sustained load deflection, the accuracy of assumed creep and shrinkage values is overshadowed by other variables so that they become less significant and the general ACI 318 requirements may be adequate.

Investigations into the difference in behavior of structural lightweight and normal weight concrete in columns caused by the effect of creep and shrinkage are covered in detail in Section 5.11.

5.7 - Deflection

5.7.1 *Initial deflection*-Section 9.5 of ACI 318 specifically includes the modifications of formulas and minimum thickness requirements that reflect the lower modulus of elasticity, lower tensile strength and lower modulus of rupture of lightweight aggregate concretes.

Table 9.5 of ACI 318 listing minimum thickness of beams or one-way slabs unless deflections are computed, requires a minimum increase of 9 percent in thickness for lightweight members over normal weight. Thus, using the values in this table, lightweight structural members with increased thickness are not expected to deflect more than normal weight 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 which occur from creep and shrinkage. Final deflection can then be compared with the initial deflection due to elastic strains only. Comparative studies of lightweight and normal weight concrete show that the creep values are approximately the same for both lightweight and normal weight concrete. Comparative shrinkage values for concrete vary appreciably with variations in component materials, and may even be less for concrete made with a high-quality lightweight aggregate than for concrete made with marginal normal weight aggregate (see Section 4.9). In typical cases, however, the shrinkage of lightweight concrete may be somewhat greater than normal weight concrete of the same strength. The effect of shrinkage on deflection arises from the restraint of shrinkage due to steel reinforcement. Tests have shown that for usual amounts of reinforcements, the effect of shrinkage on deflection is quite small regardless of type of concrete. Thus, the difference between the shrinkage deflection of lightweight and normal weight members of comparable design is quite small. An analysis of deflection due to elastic strain, creep and shrinkage, leads to the same factor given in Section 9.5.2.5 of ACI 318 and it is recommended that this factor for obtaining long-term deflections be used for both types of concrete. More refined approaches to estimating deflections are, in general, not warranted.

5.8 - Shear and diagonal tension

Lightweight concrete members, subject to shear and diagonal tension, behave in fundamentally the same manner as normal weight concrete members. In both cases, the shear and diagonal tension capacity of the concrete member is determined primarily on the tensile capacity of an unreinforced web. Since most concrete in construction is subjected to air drying, lightweight concrete will generally have lower tensile strength than normal weight concrete of equal compressive strength (see Section 4.10). ACI 318 provides two alternate approaches by which the permissible shear capacity in a lightweight concrete member may be deter-

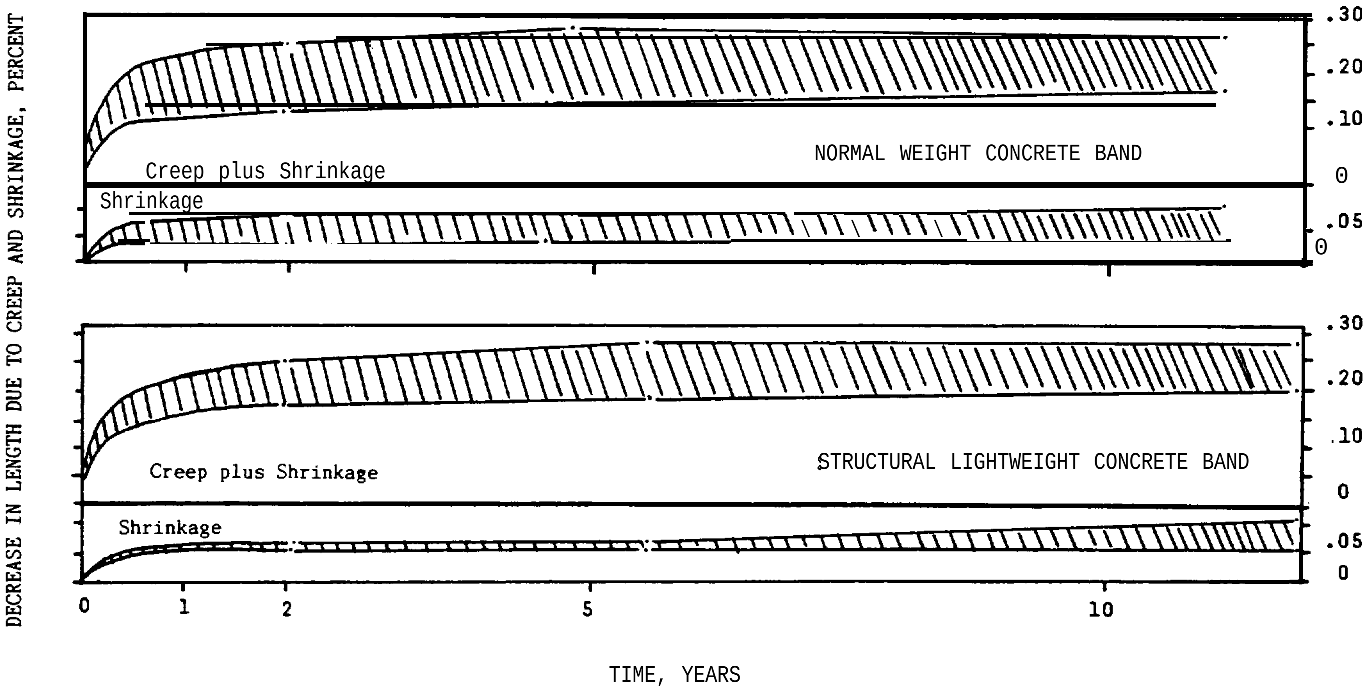

Fig. 5.6.2-Sample data showing results to date for ESCSI creep program

mined. The permissible shear capacity may be determined by utilizing the splitting tensile strength f_{ct} for the specific aggregate to be used or by using a fixed percentage of a similar-strength normal weight 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 Chapter 11 of ACI 318. A few lightweight aggregates develop high tensile strength[16,27] so that the shear performance of concrete members using these aggregates is comparable to similar members of normal weight concrete. The possible shear capacity for lightweight concrete members, however, should never exceed that of the normal weight concrete of the same strength.

Most structural lightweight aggregate producers have sufficient data available to realistically estimate the range off, values which can be achieved using all-lightweight coarse and natural fine aggregates. A realistic value off, for design purposes should be established for each desired compressive strength and composition of concrete. It is not realistic, for example, to specify f_{ct} = 425 psi (2.9 MFa) for most structural lightweight concretes with a compressive strength of 4000 psi (27.6 MPa) since this is comparable to design values of normal weight concretes. 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 mixes similar to those proposed for the project. These tests should be performed in accordance with ASTM C 330. 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 which may be used to determine the shear of lightweight or natural sand lightweight concrete as a fixed percentage of normal weight concrete shear. Research[27] on the splitting tensile strength of lightweight concrete shows some improvement in tensile strength when natural sand is used in place of the lightweight fine aggregate. Two reduction factors have, therefore, been established: 75 percent of normal weight values for all-lightweight aggregates; and 85 percent of normal weight values for combinations of natural sand fine aggregates and lightweight coarse aggregates.

Since reduction in dead weight leads to a substantial reduction in total load on lightweight concrete members, shear capacity, reduced to as much as 75 percent that of normal weight concrete, does not necessarily lead to an increase in web reinforcement, or for that matter, a decrease in relative structural efficiency.

5.9 - Strength design

The strength design requirements in ACI 318 for flexural computations and for combined axial compression and bending apply to structural lightweight concrete. Where the code requires a differentiation due to the reduced modulus the equations are suitably modified.

For example, the code assumes the maximum compressive strain in the extreme fiber to be 0.003. Tests[11,12] have shown this to be a reasonably conservative assumption for both normal weight and lightweight concrete. In a similar manner, certain of the basic coefficients can he shown to apply to both lightweight and normal weight concrete.[12]

The basic philosophy in the design for flexural capacity is that failure will occur by yielding of the steel rather than by crushing of the concrete. The formulas have been prescribed to insure this type of performance, and hence the properties of the concrete, once adequate strength is maintained, are not of major importance to ultimate safety of structures. Tests of lightweight concrete members to failure have verified the ultimate strength design of the members.[36,46]

5.10 - Working stress design

While ACI 318 has essentially de-emphasized what was originally titled working stress design, it still includes this approach as an alternate design method. The difference in concretes caused by the differences in modulus are suitably accounted for.

5.11 - Columns

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

Extensive **tests**[74,75,76] comparing the time-dependent behavior of structural lightweight and normal weight columns developed the following facts.

1. 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 normal weight column due to the lower modulus of elasticity of lightweight concrete.
2. Tie-dependent shortenings of lightweight and normal weight concretes may differ when small unreinforced specimens are compared. However, these differences are minimixed when large reinforced concrete columns are tested; both increasing size and longitudinal reinforcements reduce time-dependent shortenings. Measured time-dependent shortenings were compared with those predicted by theory and satisfactory correlations were found.
3. Measured ultimate strengths were compared with theory and good correlations were found. Both concrete type and previous loading had no effect on this correlation.
4. The lightweight concrete columns generally had slightly greater ultimate strain capacity when they were unreinforced. When reinforced, the strain capacities were closely similar

5.12 - Prestressed lightweight concrete applications

5.12.1 *Applications*-In recent years prestressed lightweight aggregate concrete has been widely used in both North America and Europe. The new material has been found particularly useful in certain building applications and, to some extent, in nearly every application for which prestressed normal weight concrete has been employed. The most beneficial applications are those in which the unique properties of prestressed lightweight aggregate concrete are fully utilized. It is selected not merely as a lightweight substitute for prestressed normal weight concrete but as a new material in its own right.

Restressed lightweight concrete has been used extensively in roofs, walls, and floors of buildings. Particularly in flat plate construction, prestressed lightweight aggregate concrete has found extensive use. For these uses, the reduced dead weight with its lower structural, seismic and foundation loads, the better thermal insulation and better fire resistance have usually been the determining factors in the selection of prestressed lightweight concrete.[72]

Several newer applications of the material appear promising. Many of these are based on its energy-absorption properties and reduced modulus of elasticity, others on its thermal properties, and still others on its greatly reduced submerged weight.

Prestressed lightweight concrete has been used in composite action with normal weight concrete. Many combinations have been tried and have proved successful structurally. These combinations are:

1. Prestressed lightweight aggregate concrete joists and beams with deck slab of normal weight concrete cast-in-place.
2. Prestressed lightweight aggregate concrete joists and beams with deck slab of lightweight aggregate concrete cast-in-place.
3. Prestressed normal weight concrete beams with cast-in-place lightweight aggregate concrete.

In general, combinations 1 and 2 are most efficient because of the relative moduli of elasticity. However, combination 3 has proved suitable in many cases including bridge structures.

5.12.2 *Properties*-When lightweight aggregate concrete is used with prestressing, it must possess two important properties; the aggregates must be of high quality, and the concrete mix must have high strength. All the properties of lightweight aggregate concrete are affected to some extent by the moisture conditions of the concrete.

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

Unit weight-The range is between 100 to 120 lb/ft^3 (1600 to 1920 kg/m^3).

Compressive Strength-Only high-strength concrete can be used with prestressing. In general, the commercial range of strengths is between 4000 and 6000 psi (27.58 and 41.36 MPa).

Modulus of Elasticity-An approximate formula for evaluating the modulus of elasticity of lightweight aggregate concrete in high-strength prestressed applications can be achieved by a modification of the formula listed in Section 8.5 of ACI 318.

The above formula relates E_c values to the strength and unit weight of the concrete. In general, the ACI formula for evaluating E_c tends to overestimate E_c values at high concrete strengths.

When accurate values of E_c are required, it is suggested that either (1) a laboratory test or (2) the following modified formula be used (see Reference 51):

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

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.[71]

C = 31 when f_c' = 5000 psi (C = .040 when f_c' = 34.47 MPa)

C = 29 when f_c' = 6000 psi (C = .038 when f_c' = 41.36 MPa)

Combined loss of prestress-This is about 110 to 115 percent of the total losses for normal weight concrete when both are subjected to normal curing; 124 percent of the total losses for normal weight concrete when both are subjected to steam curing.

Steam curing reduces the total prestress loss by 30 to 40 percent compared with normal curing.

Thermal insulation-The much greater thermal insulation of lightweight aggregate concrete has a decided effect on prestressing applications, because of the following factors:

(a) Greater temperature differential in service between the side exposed to sun and the inside may cause greater camber
(b) Better response to steam curing
(c) Greater suitability for winter concreting
(d) Better fire resistance

Dynamic, shock, vibration and seismic resistance-Prestressed lightweight concrete appears at least as good as normal weight concrete and might even be better due to its greater resilience and lower modulus of elasticity.

Cover Requirements-Where fire requirements dictate the cover requirements, the insulating effects developed by the lower density, as well as the fire stability offered by a preburned aggregate may be used to considerable advantage.

5.13 - Thermal design considerations

In concrete elements exposed to environmental conditions, the choice of lightweight concrete will provide several distinct advantages over natural aggregate concrete.[80, 81] These physical properties covered in detail in Chapter 4 are:

- The lower conductivity 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 contribution of the lower coefficient of thermal expansion of the lightweight aggregate itself is a fundamental design consideration in exposed members. The expansion and contraction of exposed columns of tall buildings induces shearing forces and bending moments into floor frames that are connected to interior members that are subject to unchanging interior structural members. The architectural decision to locate glass window lines must of necessity take into account the conductivity and the expansion of coefficients of the exposed concretes.
- The lower modulus of expansion will develop lower stress changes in members exposed to thermal strains.

A comparative thermal investigation[81] 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 percent smaller for structural lightweight concrete and the stresses due to restrained bowing were about 35 percent less with structural lightweight concrete than with normal weight concretes. The analysis, conducted on a 20-story concrete frame, used the following assumptions:

	Normal weight	Structural lightweight concrete
Thermal conductivity	12.0	5.0
Coefficient of linear thermal expansion	5.5×10^{-6}	4.5×10^{-6}
Modulus of elasticity (4.0 ksi) (27.58 MPa)	3.6×10^{6} (24,840 MPa)	2.5×10^{6} (17,250 MPa)

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

Numerous practical examples demonstrating isotherms and average temperatures developed in both lightweight and normal weight concrete exposed columns are fully shown” including the practical considerations of how the thermal inertia of structural lightweight concrete serves to minimize condensation.

5.14 - Seismic design

Structural lightweight concrete is particularly adaptable to seismic design and construction because of the significant reduction in dead weight. A large number of multistory buildings as well as bridge structures have effectively utilized lightweight concrete in areas subject to earthquakes principally along the West Coast of the U.S. and in those countries bordering the Pacific Ocean Rim.

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

For detailed information on design, refer to ACI 318, Appendix A and/or special provision for seismic design in the Uniform Building Code, Section 2312.

5.15 - Specifications

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

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

It should be observed that 28 day compressive strength tests are based on the methods of ASTM C 39 which requires that the test cylinders be continuously moist-cured. One reason for confusion on this point with lightweight concrete is that ASTM C 330 specifies that tests for the 28 day compressive strength to determine the concrete-making properties of a lightweight aggregate be done on test cylinders that are air dried for the final 21 days at 50 percent relative humidity. Since there is some slight improvement in apparent compressive strength when the specimens are tested air-dried, the standard test method leads to conservative test values. Cylinders continuously moist-cured should not be weighed and measured and used to determine the 28-day density of the concrete.

Lightweight aggregate concrete that, after curing, will be exposed to freezing shall have a specified compressive strength f_c' of at least 3000 psi (20.68 MPa) and have entrained air in accordance with ACI 318.

Lightweight aggregate concrete that is intended to be watertight shall have a specified compressive strength f_c' of at least 3750 psi (25.84 MPa) for exposure to fresh water and 4000 psi (27.58 MPa) for exposure to sea water.

Lightweight aggregate concrete that will be exposed to injurious concentrations of sulfate-containing solutions shall be made with sulfate-resisting cement and have a specified compressive strength f_c' of at least 3750 psi (25.84 MPa

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

The analysis of the load-carrying capacity of a lightweight concrete structure either by cores or load tests shall be the same as for normal weight concrete.

In general, most structural lightweight aggregate suppliers have suggested specifications pertaining to their material.

CHAPTER 6 - REFERENCES

6.1-Specified and/or recommended references

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation, including year of adoption or revision. The documents listed were the latest effort at the time this document was revised. Since some of these documents are revised frequently, generally in minor detail only, the user of this document should check directly with the sponsoring group if it is desired to refer to the latest revision.

American Concrete Institute

211.1-81 (Revised 1985)	Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
211.2-81	Standard Practice for Selecting Proportions for Structural Lightweight Concrete
212.1R-81 (Revised 1986)	Admixtures for Concrete
212.2R-81 (Revised 1986)	Guide for Use of Admixtures in Concrete
221R-84	Guide for Use of Normal Weight Aggregates in Concrete
225R-85	Guide to the Selection and Use of Hydraulic Cements
301-84 (Revised 1985)	Specifications for Structural Con-Crete for Buildings
302.1R-80	Guide for Concrete Floor and Slab Construction
304R-85	Guide for Measuring, Mixing, Transporting, and Placing Concrete
304.5R-82	Batching, Mixing, and Job Control of Lightweight Concrete
308-81 (Revised 1986)	Standard Practice for Curing Concrete
318-83 (Revised 1986)	Building Code Requirements for Reinforced Concrete
318R-83 (+ 1986 supplement)	Commentary on Building Code Requirements for Reinforced Concrete (ACI 318-83)

ASTM

C 31-85	Standard Method of Making and Curing Concrete Test Specimens in the Field
C 33-86	Standard Specification for Concrete Aggregates
C 39-86	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 78-84	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
C 94-86a	Standard Specification for Ready-Mixed Concrete
C 143-78	Standard Test Method for Slump of Portland Cement Concrete
C 144-84	Standard Specification for Aggregate for Masonry Mortar
C 150-85a	Standard Specification for Portland Cement
C 172-82	Standard Method of Sampling Freshly Mixed Concrete
C 173-78	Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
C 177-85	Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus
C 234-71 (Reapproved 1977)	Standard Test Method for Comparing Concretes on the Basis of the Bond Developed with Reinforcing Steel
C 330-85	Standard Specification for Lightweight Aggregates for Structural Concrete
C 469-83	Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
C 496-85	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
C 512-82 (Reapproved 1983)	Standard Test Method for Creep of Concrete in Compression

C 567-85	Standard Test Method for Unit Weight of Structural Lightweight Concrete
C 595-86	Standard Specification for Blended Hydraulic Cements
C 666-84	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing

International Conference of Building Officials

UBC-85	Uniform Building Code, 1985 Edition

The above publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 19150
Detroit, MI 48219-0150

ASTM
1916 Race Street
Philadelphia, PA 19103

International Conference of Building Officials
5360 South Workman Mill Road
Whittier, CA 90601

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This report was submitted to letter ballot of the committee and was approved in accordance with ACI balloting requirements.