Chapter 6
Physical Properties of
Structural Lightweight Concrete

The information present in Chapter 6 and 7 is also covered in a more general way in:
ACI 213R-03 "*Guide for Structural Lightweight Aggregate Concrete*" and
ASTM 169 D "*Lightweight Concrete and Aggregates*"
Both are excellent references.

April 2007

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CHAPTER 6 PHYSICAL PROPERTIES OF STRUCTURAL LIGHTWEIGHT CONCRETE

This chapter covers some of the physical properties of lightweight concrete. The information is based on many laboratory studies and records of a large number of existing structures that have provided satisfactory service for more than 85 years. Typically, properties of lightweight concrete have been compared with those of normalweight concrete, and usually the comparison standard has been a single normalweight material. With several million cubic yards of lightweight concrete being placed each year and the fact that normalweight concrete also has an intrinsic variability ; such a comparison of properties is no longer appropriate.

6.0 Definition of Terms

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

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

Concrete, Insulating - Insulating concretes are very light non structural concretes, employed primarily for high thermal resistance, incorporate low-density low-strength aggregates such as vermiculite and perlite. With low densities, seldom exceeding 50 lb/ft^3 (800 kg/m^3), thermal resistance is high. These concretes are not intended to be exposed to the weather and generally have a compressive strength range from about 100 to 500 psi (0.69 to 6.89 MPa).

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

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

Concrete, sand lightweight-Concrete with coarse lightweight aggregate and normalweight fine aggregate.

Concrete, semi-lightweight-Concrete made with a combination of lightweight aggregates (expanded, clay, shale, slag or slate or sintered fly ash) and normalweight aggregates having an equilibrium density of 105-120 lb/ft^3 (1680-1920 kg/m^3) (ACI 216).

Concrete, specified density-Structural concrete having a specified equilibrium density between 50 to 140 lb/ft³ (800 to 2240 kg/m³) or greater than 155 lb/ft³ (2480 kg/m³) (see **concrete, normalweight).** Specified density concrete (SDC) may consist as one type of aggregate or of a combination of lightweight and normalweight aggregate. This concrete is project specific and should include a detailed mixture testing program and aggregate supplier involvement before design.

Concrete, structural/Insulating -Specifications that call for "fill" concretes often require compressive strengths and densities in the intermediate range between structural and insulating concretes. These concretes may be produced with high air mixtures and include structural lightweight aggregate, or sanded insulating lightweight aggregate mixtures, or they may incorporate both structural and insulating lightweight aggregates. Compressive strengths from 500 to 2500 psi (3.4 to 17 MPa) are common with thermal resistance ranging between insulating and structural concrete.

Concrete, structural lightweight-*Structural lightweight-aggregate concrete made with structural lightweight aggregate as defined in ASTM C 330.* The concrete has a minimum 28-day compressive strength of 2500 psi (17 MPa), an equilibrium density between 70 and 120 lb/ft³ (1120 and 1920 kg/m³), and consists entirely of lightweight aggregate or a combination of lightweight and normal-density aggregate.

Structural lightweight concretes generally contain aggregates made from pyroprocessed shale's, clays, slates, expanded slags, expanded fly ash, and those mined from natural porous volcanic sources. Structural lightweight concrete is normally classified by a minimum compressive strength that was jointly established by the ASTM Specification C 330 for Lightweight Aggregates and the Standard Building Code for Reinforced Concrete (ACI 318). The 318 code definition is "Structural concrete made with lightweight aggregate; the equilibrium density at 28 days is usually in the range of 90 to 115 lb/ft³ (1440 to 1850 kg/m³) and the compressive strength is more than 2500 psi (17.2 MPa)". This is a definition, not a specification and project requirements may permit equilibrium densities up to 120 lb/ft³ (1900 kg/m³), most lightweight aggregate concrete used in structures have equilibrium unit weights between 100 and 115 lb/ft³ (1600 to 1792 kg/m³).

These definitions are not specifications. Project specifications vary. While lightweight concrete with an equilibrium density of 70 to 105 lb/ft³ (1120 to 1680 kg/m³) is infrequently used, most lightweight concrete has an equilibrium density of 105 to 120 lb/ft³ (1680 to 1920 kg/m³). Because lightweight concrete is often project-specific, contacting the aggregate supplier before project design is advised to ensure an economical mixture and to establish the available range of density and strength.

Contact zone-The expression "contact zone" includes two distinctly different phenomena (1) the mechanical adhesion of the cementitious matrix to the surface of the aggregate and (2) the variation of physical and chemical characteristics of the transition layer of the cementitious matrix close to the aggregate particle.

Curing, internal-Internal curing refers to the process by which the hydration of cementitious materials continues because of the availability of absorbed water within the pores of the lightweight aggregate particle.

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

Density, oven dry-As defined in ASTM C 567, the density reached by structural lightweight concrete after being placed in a drying oven at 230 $\pm$ 9ºF (110 $\pm$ 5ºC) for a period of time sufficient to reach a density that changes less than 0.5% in a period of 24 hr.

Lightweight-The generic name of a group of aggregates having a relative density lower than normal-density aggregates. The generic name of concrete or concrete products having lower densities than normalweight concrete products.

Lightweight aggregate concretes are broadly divided by ASTM into three groups based upon their use and physical properties, structural, structural/insulating and insulating concrete density, thermal conductivity and compressive strength ranges normally associated with each class of concrete are summarized in Table 6.1.

TABLE 6.1—Lightweight Aggregate Concrete Classified According to Use and Physical Properties according to ASTM C 330 and C 332.

Class of Lightweight Aggregate Concrete	Type of Lightweight Aggregate used in Concrete	Typical Range of Lightweight Concrete Density lb/ft³ (kg/m³)	Typical Range of Compressive Strength Psi (MPa)	Typical Range of Thermal Conductivities Btu · in./h · ft² · °F (W/m • K).
Structural	Structural-grade LWA C 330	90 to 115 (1440 to 1840) at equilibrium	>2500 (> 17)	not specified in C 330
Structural/Insulating	Either structural C 330 or insulating C 332 or a combination of C 330 and C 332	45 to 90 (720 to 1440) at equilibrium	500 to 2500 (3.4 to 17)	C 332 from 0.15 (1.05) to 3.00 (0.43) oven dry
Insulating	Insulating-grade LWA C 332	15 to 50 (240 to 800) oven dry	100 to 500 (0.7 to 3.4)	C 332 from 0.45 (0.065) 1.50 (0.22) oven dry

6.1 Compressive Strength

"Compressive strength levels commonly required by the construction industry for design strengths of cast-in-place, precast, or prestressed concrete are economically obtained with lightweight concrete (Shideler 1957; Hanson 1964; Holm 1980a). Design strengths of 3,000 to 5,000 psi (21 to 35 MPa) are common. In precast and prestressing plants, design strengths above 5,000 psi (35 MPa) are usual. In several civil structures, such as the Heidrun Platform and Norwegian bridges, concrete cube strengths of 8700 psi (60 MPa) have been specified (fib 2000). All aggregates have strength ceilings, and with lightweight aggregates, the strength ceiling generally can be increased by reducing the maximum size of the coarse aggregate. As with normalweight concrete, water-reducing plasticizing and mineral admixtures are frequently used with lightweight concrete mixtures to increase strength and workability as well as to facilitate placing and finishing". ACI 213R-03.

6.2 Density

The fresh density of lightweight concretes is a function of mixture proportions, air contents, water demand, particle density, and moisture content of the lightweight aggregate. Decrease in density of exposed concrete is due to moisture loss that, in turn, is a function of ambient conditions and surface area/volume ratio of the member. Design professionals should specify a maximum fresh density for lightweight concrete, as limits for acceptability that should be controlled at time of placement. The design professional needs to work with the LWA supplier to establish a correlation between fresh density and equilibrium density (self-load used for design).

"Although there are numerous structural applications of lightweight concrete using both lightweight coarse and lightweight fine aggregate, usual commercial practice in North America is to design concrete with natural sand fine aggregates. Long-span bridges using concretes with three-way blends (coarse and fine lightweight aggregates and small supplemental natural sand volumes) have provided long-term durability and structural efficiency (density/strength ratios) (Holm and Bremner 1990). Earlier research reports (Kluge, Sparks, and Tuma 1949; Price and Cordon 1949; Reichard 1964; Shideler 1957) compared concrete containing both fine and coarse LWA with "reference" normalweight concrete, while later studies (Hanson 1964, Pfeiffer 1967) supplemented the early findings with data on lightweight concrete where the fine aggregate was natural sand", ACI 231R-03.

Despite the ACI 213 definition of structural-grade lightweight concrete that has an equilibrium dry density ranging between 90 to 115 lb/ft^3 (1,440 and 1,850 kg/m^3), the report also adds that "it should be understood that this definition is not a specification. Job specifications may, at times, allow density up to 120 lb/ft^3 (1,900 kg/m^3). In the majority of applications in North America, HSLC has been associated with equilibrium densities of about 115 lb/ft³ (1850 kg/m³) and, in some cases, as much as 120 lb/ft³ (1,900 kg/m³).

Density of the Constituents of Concrete Mixtures

The equilibrium density of lightweight concrete is determined by the relative density of the aggregates (lightweight and normalweight) and the density of the cementitious matrix. The relative density of the lightweight aggregates typically range from 1.1 to 1.3 is covered in Chapter three. The relative density of the local normalweight aggregates are usually well established, with the common practice of assuring a value of 2.65 unless otherwise determined.

Surprisingly, even though the relative density of cement is typically 3.15 the relative density of the hardened cementitious matrix fraction (referred to as the hydrated cement paste HCP) of concrete is quite low and closer to that of lightweight aggregates then that of any normalweight aggregates used. Normalweight aggregate is the heaviest component in concrete.

The relative density of the cementitious fraction is best observed in the following simplistic example shown below in Table 6.2 and Fig. 6.1:

Table 6.2. Density of Hydrated Cement Paste (HCP)

Assume a w/cm=0.5 and Non-Air Entrained Concrete				
Relative Density		**Fresh Wet Weight**	**Absolute Volume**	**HCP Dry Weight**
Water	**(1.00)**	**0.5**	**0.5**	**0.2**
Cement	**(3.15)**	**<u>1.0</u>**	**<u>0.32</u>**	**<u>1.0</u>**
	Totals	**1.5**	**0.82**	**1.2**

$$\textbf{Density fresh HCP} = \frac{1.5}{0.82} = 1.83 \text{ (114 pcf)}$$

$$\textbf{Density oven dry} = \frac{1.2}{0.82} = 1.46 \text{ (91 pcf)}$$

$$\textbf{Density, air dry @ 8\%}_{\text{Moisture Content}} = 1.46 \times 1.08 = 1.58 \text{ (98 pcf)}$$

The relative density of the HCP fraction is further reduced by the voids developed by entrapped and deliberately entrained air as shown below in Fig. 6.1.

Assume an air entrained concrete at 6%. When the coarse aggregate is removed the remaining mortar changes to having a 9% air entrained and when the fine aggregate is removed the remaining HCP has about 18% air entrainment. This is always the case as all the air is in the HCP matrix.

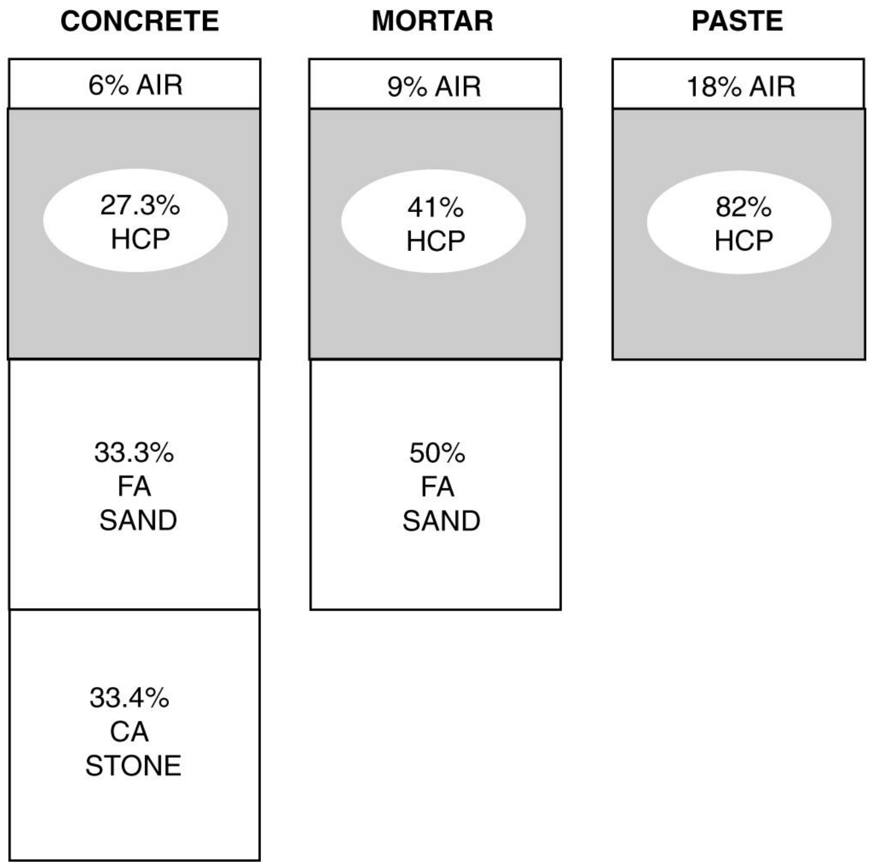

Figure 6.1. ***Density of Air-Entrained Hydrated Cement Paste***

Therefore as shown in the example in Fig. 6.1, a concrete with a W/c ratio of 0.5 and 6% air has a oven dry HCP with a relative density as follows:

$$\text{Oven dry density (HCP)} = \frac{1.46}{1.18} = 1.24 \text{ (77 pcf)}$$

A lightweight aggregate with a 50% pore volume and a relative density of the vitreous ceramic solid equal to 2.60 has an oven dry density of

$$\text{LWA dry density } 2.60 \times .50 = 1.30 \text{ (81 pcf)}$$

When the HCP relative density is compared to lightweight aggregate the fractions are quite similar, and both are significantly lower than that of natural aggregates (typically 2.65 for quartz, 2.3-2.7 limestone and 2.8 to 3.0 for some igneous minerals (diabase)). In other words the HCP is really a lightweight component.

The concept of elastic compatibility is discussed in Chapter 7 and shows how lightweight aggregate is more compatible with the HCP than normalweight aggregate. The compatibility of the lightweight aggregate and high performance concrete fractions minimizes micro-structural strains that result from service loads as well as those developed by thermal gradients.

Equilibrium Density – Self Loads

"Self loads used for design should be based upon equilibrium density that, for most conditions and members, may be assumed to be approached after 90 days. Extensive tests conducted during North American durability studies demonstrated that, despite wide initial variations of aggregate moisture content, equilibrium density was found to be 3.1 lb/ft³ (50 kg/m³) above oven-dry density (Fig. 6.2). European recommendations for in-service density are similar (FIP 1983). Concrete containing high cementitious contents, and particularly those containing efficient pozzolans, will develop densities with less of a difference between fresh and equilibrium density" ACI 213R-03. Unless otherwise specified self loads may be determined by a calculation of equilibrium density using the procedures of ASTM C 567.

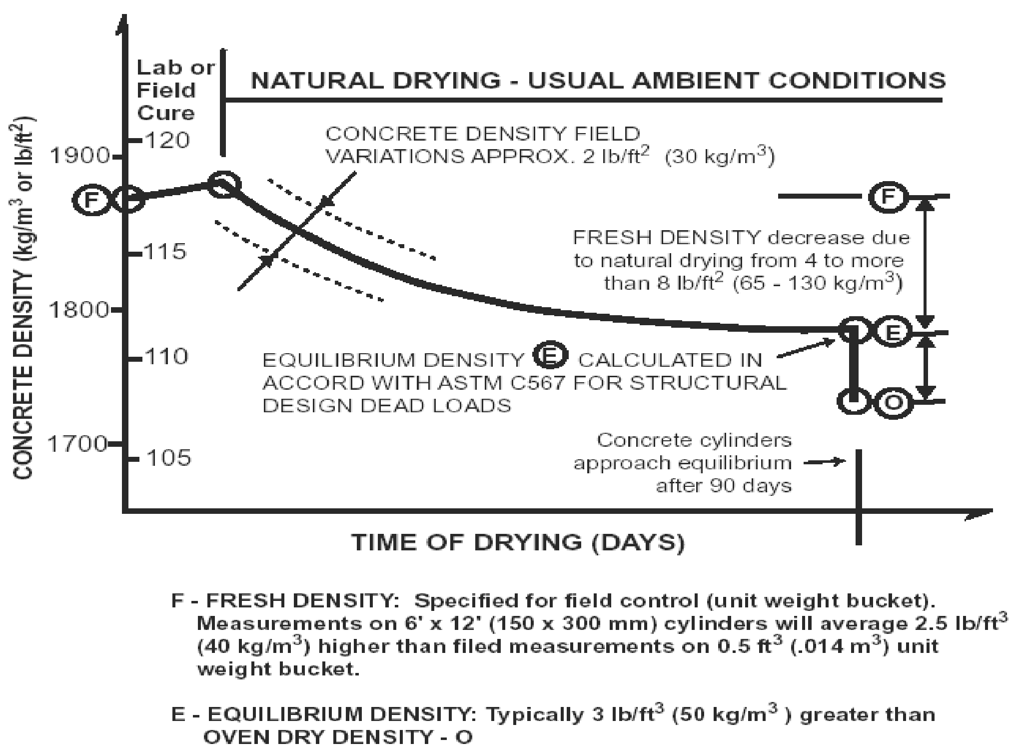

Figure 6.2 ***Concrete density versus time of drying for structural Lightweight concrete ACI 213R-03, ASTM 169 D***

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

$$O = (M_{df} + M_{dc} + 1.2\, M_{ct}) / V$$
$$E = O + 3\ lb/ft^3\ (O + 50\ kg/m^3)$$

where

O	=	calculated oven-dry density, pcf (kg/m³)
M_{df}	=	mass of dry fine aggregate in batch, lb (kg)
M_{dc}	=	mass of dry coarse aggregate in batch, lb (kg)
1.2	=	factor to account for water of hydration
M_{ct}	=	mass of cement in batch, lb (kg)
V	=	volume of concrete produced by the batch, ft³ (m³)
E	=	Calculated equilibrium density, pcf (kg/m³)

Specified Density Concrete

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

The concept of specified density concrete is not new. For more than 20 years precast concrete manufacturers have evaluated trade-offs between the concrete density and transportation costs. Shown in Table 6.3 are the physical properties of concrete in which 25, 50, 75 and 100% of the normalweight limestone coarse aggregate was replaced by an equal absolute volume of lightweight aggregate. This resulted in 5, 11, 15 and 21 percent reductions in density respectively. Fig. 6.3 shows the fresh and equilibrium density and Fig. 6.4 shows the modulus of Elasticity.

By adjusting the density of the concrete, precasters are able to maximize the number of concrete elements on a truck without exceeding highway load limits. This reduces the number of truck loads which lowers transportation and project cost, as well as reducing the environmental consequences of trucking products especially into central cities. Opportunities for increased trucking efficiency also apply when transporting smaller concrete products (hollow core plank, wallboard, precast steps, and other consumer products). Specified density concrete has the added benefit of enhanced cement hydration. See section on "Internal Curing" for more detail", ASTM 169 D, Chapter 48.

Table 6.3. Physical Properties of Concrete Mixtures

Limestone coarse aggregate replaced by varying percentages of structural low density aggregates. Concrete manufactured and tested at U.S. East Coast Prestressed Plant to optimize structural efficiency and reduce transportation costs.

Mixture Number Coarse Aggregate Target Equilibrium Density lb/ft^3 (kg/m^3)	1 Limestone 143 (2300)	2 .75S, .25L 135 (2160	3 .5S, .5L 129 (2050)	4 .25S, .75L 120 (1920)	5 LDA 112 (1800)	M None 125 (2000)
Physical Properties @ 18-24 Hrs.						
Compressive Strength ksi (MPa)	3.50 (24)	3.75 (26)	4.27 (29)	4.10 (28)	3.80 (26)	4.88 (34)
Elastic Modulus (Test) ksi x 10^3 (GPa)	3.42 (24)	3.30 (23)	3.27 (23)	2.97 (20)	2.67 (18)	3.38 (23)
Elastic Modulus (Calc. ACI 318) ksi x 10^3 (GPa)	3.70 (26)	3.49 (24)	2.89 (20)	2.42 (17)	2.17 (15)	2.48 (17)
E (Calc. ACI 318) / E (Test)	1.08	1.06	0.88	0.81	0.81	0.73
Physical Properties @ 29 Days						
Compressive Strength ksi (MPa)	5.60 (39)	5.89 (41)	5.91 (41)	5.95 (41)	6.12 (42)	6.85 (47)
Elastic Modulus (Test) ksi x 10^3 (GPa)	4.28 (30)	4.09 (28)	3.81 (26)	3.53 (24)	3.25 (22)	3.96 (27)
Elastic Modulus (Calc. ACI 318) ksi x 10^3 (GPa)	4.49 (31)	4.10 (28)	4.17 (29)	3.13 (22)	2.92 (20)	4.50 (31)
E (Calc. ACI 318) / E (Test)	1.05	1.00	1.09	0.89	0.90	1.14
Tensile Split Strength @ 29 Days ksi (MPa)	580 (4.0)	615 (4.2)	531 (3.7)	492 (3.4)	498 (3.4)	504 (3.5)

Note: 1. All concrete mixtures contain 752 pcy (446 kg/m^3) Cement, 1190 pcy (706 kg/m^3) Natural Sand.

2. All concrete mixtures, Air 3.5 ± 0.5%, Slump 4" (100 mm)

3. Mortar Mixture "M" contains 1208 pcy (716 kg/m^3) Cement, 1770 pcy (1050 kg.m^3) Natural Sand, Air 5.5%, Slump 5.5" (140 mm).

4. All strength and modulus test conducted on 6" x 12" (152 x 304 mm) cylinders.

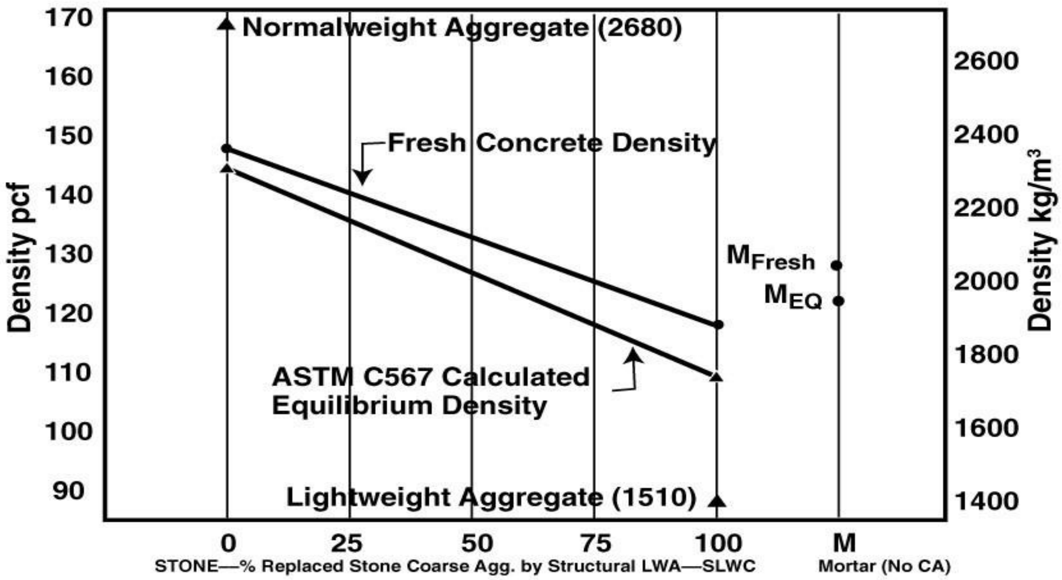

Figure 6.3. ***Fresh and ASTM C 567 Calculated Equilibrium Concrete Density***

MODULUS OF ELASTICITY - Concretes containing LWA have lower modulus of elasticity at both early and later ages. Since exact modulus data at release (18 hrs. ±) is crucial to strand location, camber and deflection control, it is essential to determine the properties directly from the proposed concrete mixture. It is also important to realize that even with normalweight concrete at the same density, the modulus of elasticity can vary considerably. Table 6.3 reveals that for the "control" limestone concrete the tested elastic modulus correlated reasonably well with the computed value using the ACI 318 formula $Ec=33w^{1.5}\sqrt{Fc}$. For the lightweight concrete tested at early age and with a 29 day compressive strength of 6120 psi (42 MPa), the ACI formula clearly over estimates the value of the elastic modulus.

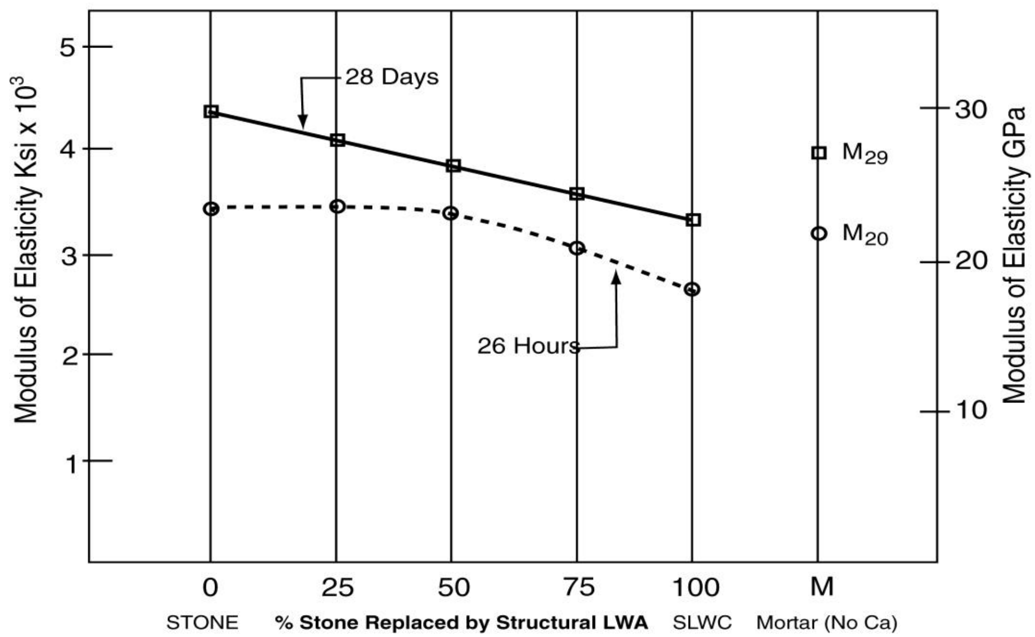

Figure 6.4. ***Modulus of Elasticity 152 x 304 mm (6" x 12") Cylinders with varying replacements of limestone with lightweight aggregate***

6.3 Absorption

Lightweight concrete planned for exposed application will be, of necessity be of high quality. Testing programs have revealed that high-quality lightweight concretes absorbed very little water and thus maintained their low density. This was not unexpected, as Bremner, Holm, and McInerney (1992) and Sugiyama, Bremner, and Holm (1996), in a series of publications, reported that the permeability of lightweight concrete was extremely low and generally equal to or significantly lower than that reported for normalweight concrete that were used as control specimens. Similar results by Russian, Japanese, and English investigators confirmed these findings. All attributed the low permeability to the profound influence of the high-integrity contact zone possessed by lightweight concrete. The zone of weakness demonstrated in concretes containing normalweight aggregate, wherein layers of high w/c at the contact zone combine with bleed-water gaps, can be minimized if not eliminated in concretes containing pozzolanic materials such as silica fume, fly ash, and calcined clays, shales, and slates.

In investigations of high-quality concretes in the Arctic, Hoff (1992) reported that specimens that had a period of drying followed by water immersion at atmospheric pressure did not refill all the void space caused by drying. Pressurization caused an additional density increase of approximately 2.5 lb/ft³ (40 kg/m³). Prior to the introduction of the test specimens into the seawater, all concretes lost mass during the drying phase of their curing, although concrete with a compressive strength of 9,000 psi (62 MPa) did not lose very much due to its very dense matrix

This testing program reported that density changes mixtures containing silica fume, would experience some drying during their initial curing period, and experience long-term density gains of 3 to 4 lb/ft³ (48 to 64 kg/m³) when subjected to hydrostatic pressures equivalent to 200 ft (61 mm) of seawater. The very high-strength lightweight concrete may be on the lower end of this range. At near-surface water depths 0 psi (0 MPa), lightweight concrete will have density increased of less than 1 lb/ft³ (16 kg/m³).

6.4 Internal Curing

Introduction

Lightweight aggregate batched at a high degree of saturation may be substituted for normalweight aggregates to provide "internal curing" in concrete containing a high volume of cementitious materials. High cementitious concretes are vulnerable to self-desiccation and early-age cracking, and benefit significantly from the slowly released internal moisture. Field experience has shown that High Strength Concrete is not necessarily High Performance Concrete and that High Performance Concrete need not necessarily be high strength. A frequent, unintended consequence of high strength concrete is early-age cracking. This application is significantly helpful for vertical members and concretes containing high volumes of pozzolans that are sensitive to curing procedures. In this application, density reduction is a bonus.

Time dependent improvement in the quality of concrete containing pre-wet lightweight aggregate is greater than that with normalweight. The reason is better hydration of the cementitious fraction provided by moisture available from the slowly released reservoir of absorbed water within the pores of the lightweight aggregate. The fact that absorbed moisture in the lightweight was available for internal curing has been known for more than four decades. The first documentation of improved long term strength gains made possible by the use of saturated *normalweight* aggregates, was reported in 1957 by Paul Klieger, who, in addition, commented in detail on the role of absorbed water in lightweight aggregates for extended internal curing.

In his 1965 report, "*Concrete Strength Measurement – Cores vs. Cylinders"*, presented to the National Sand and Gravel Association and the National Ready Mixed Concrete Association, Bloem (1965) states, "Measured strength for lightweight concrete cylinders was not reduced by simulated field curing methods employed. This would tend to support the suggestion that the high absorption of lightweight aggregate may have the beneficial effect of supplying curing water internally." This was confirmed by R. Campbell and Bob Tobin (1967) in their comprehensive program which compared strengths of cores taken from field cured exposed slabs with test results obtained from laboratory specimens cured strictly in accordance with ASTM C 31 procedures. Their tests confirmed that the availability of absorbed moisture in lightweight aggregate produced a more forgiving concrete that was less sensitive to poor field curing conditions.

While providing technical support to a New York City contractor building several twenty-story lightweight concrete frame apartment houses, Holm (2004) reported direct field experience that empirically confirmed the findings of the Bloem and Tobin investigations. "Discussions with a second contractor who was building eight other normalweight multi-story concrete frames visible from our fifteenth floor vantage point, focused on the extensive plastic shrinkage cracking on his project, and the relative absence of the problem on our building. Both projects were exposed to the same ambient conditions that promote plastic shrinkage: *high temperatures, low relative humidity and high wind velocities.* Both projects were furnished from the same readymix concrete supplier with essentially similar mixture ingredients (cement, admixtures, natural sand) with only one differing component: His project used a crushed stone, while ours used a lightweight aggregate batched with a high degree of saturation".

In a paper addressing the long term service performance of lightweight, Holm (1980) cited the improved integrity of the LWA/matrix interface, attributing the improved quality to internal curing, pozzolanic activity at the contact zone, and reduction in stress concentrations resulting from elastic compatibility of the concrete phases. In another paper Holm (1980) documented the long term increase in strength of high strength lightweight concrete incorporating pozzolans.

The benefits of "internal curing" go far beyond any improvements in long-term strength gain, which from some combinations of materials may be minimal or non-existent. The principal contribution of "internal curing" results in the reduction of permeability that develops from a significant extension in the time of curing. Powers (1959) showed that extending the time of curing increased the volume of cementitious products formed which caused the capillaries to become segmented and discontinuous.

It appears that in 1991, Philleo (1991) was the first to recognize the potential benefits to high performance normalweight concrete possible with the addition of lightweight containing high volumes of absorbed moisture. Weber and Reinhardt (1995) have also conclusively demonstrated reduced sensitivity to poor curing conditions in high strength normalweight concrete containing an adequate volume of high moisture content LWA. Since 1995 a large number of papers addressing the role of water entrainment's influence on internal curing and Autogenous shrinkage have been published of which Bentz, et al, is typical (1999).

The benefits of "internal curing" are increasingly important when pozzolans (silica fume, fly ash, metokoalin, calcined shales, clays and slates, as well as the fines of LWA) are included in the mixture. It is well known that the pozzolanic reaction of finely divided alumina-silicates with calcium hydroxide liberated as cement hydrates is contingent upon the availability of moisture. Additionally, "internal curing" provided by absorbed water minimizes the "plastic" (early) shrinkage due to rapid drying of concrete exposed to unfavorable drying conditions (Holm, 1980b).

6.5 Contact Zone

"The expression "contact zone" includes two distinctively different phenomena: (1) the mechanical adhesion of the cementitious matrix to the surface of the aggregate and (2) the variation of physical and chemical characteristics of the transition layer of the cementitious matrix close to the aggregate particle. Collapse of the structural integrity of the concrete conglomerate may come from the failure of either the aggregate or cementitious matrix, or from a breakdown in the contact zone causing a separation of the still intact phases. The various mechanisms that act to maintain continuity, or that cause separation, have not received the same attention as has the air void system necessary to protect the matrix. Aggregates are frequently dismissed as being inert fillers and, as a result, they and the associated contact zone have not received adequate attention.

In order that concrete perform satisfactorily in severe exposure conditions, it is essential that a good bond develop and be maintained between the aggregate and the enveloping mortar matrix. A high incidence of interfacial cracking or aggregate debonding will have a serious effect on durability if these cracks fill with water and subsequently freeze. Deterioration will result, with pieces of apparently sound mortar separating from the bottom of the aggregate, usually with some of the mortar remaining firmly attached to the top side of the aggregate. An equally serious consequence of microcracking is the easy path provided for the ingress for aggressive agents into the mass of the concrete, rendering ineffective the protective layer of concrete over the reinforcing steel. The morphology and distribution of chemical elements at the transition layer in a number of mature structures that have withstood severe exposure were examined and reported by Bremner, et. al.

The contact zone of lightweight aggregate concrete has been demonstrated to be significantly superior to that of normalweight concretes that do not contain supplementary cementitious material (See Fig. 6.5). This profound improvement in the quality, integrity, and microstructure stems from a number of characteristics unique to lightweight concrete that includes:

- The pozzolanic alumina/silicate surface of the fired ceramic aggregate combines with $CaOH_2$ liberated by hydration of the Portland cement.

- Reduced microcracking in the contact zone because of the elastic similarity of the aggregate and the surrounding cementitious matrix.
- Hygral equilibrium between two porous materials (Lightweight aggregate and porous cementitious matrix) as opposed to the usual condition with normalweight aggregate, where bleed-water lenses form around essentially non-absorbent coarse natural aggregates. These lenses have water-to-cementitious materials ratios significantly higher than in the rest of the matrix. When supplementary cementitious materials are added, the high-quality microstructure of the contact zone around lightweight aggregate is moderately enhanced. However, when supplementary cementitious materials are used in concretes containing normalweight aggregate, this zone of weakness is profoundly improved.

While the reduction in compressive and tensile strength due to poor contact zone is important, the significance of increasing permeability is even greater. Increasing permeability inevitable leads to penetration of aggressive agents that accelerate corrosion of embedded reinforcement. The permeability of concrete is greater than the permeability of its constituents. This increase in permeability results from interfacial flaws at the aggregate surface linking up with microcracking in the transition layer.

The phenomenon of bleed water collecting and being entrapped under coarse particles of lightweight aggregate is mitigated if not eliminated. This has been verified in practice by the examination of the contact zone of lightweight concrete tensile splitting cylinders, as well as by visual examination of sandblasted vertical surfaces of building structures. This observation should not be surprising because, with structural lightweight concrete, the aggregate/matrix interface is a boundary between two porous media, while with normalweight concrete there is an abrupt transition at the dense aggregate/porous cementitious matrix interface", ASTM 169D, Chapter 48, (2006).

Implication of Contact Zone on Failure Mechanisms

Exposed concrete must endure the superposition of dynamic forces including variable live loads, rapid temperature changes, moisture gradients, and dilation due to chemical changes. These factors cause a predominantly tensile-related failure. Yet, the uniaxial compressive strength is traditionally considered the preeminent single index of quality, despite the fact that inadequate concrete performance is seldom related to this parameter. The simplicity and ease of compression testing has diverted our focus from life-cycle performance and the development of appropriate measurement techniques that quantify durable concrete characteristics.

In general, weakest link mechanisms are undetected in uniaxial compression tests due to concrete's forgiving load-sharing characteristics in compression, because of localized yielding and the closure of temperature and volume-change cracks.

Weakest link mechanisms, however, are decisive in tensile failures in both dynamic and durability exposure conditions. In most concretes the limiting factor in the long term performance is the integrity of contact zone.

Additionally, a full comprehension has not been developed regarding the accommodation mechanism by which the pores closest to the aggregate/matrix interface provide an accessible space for products that cause deleterious expansion. While research has identified ettringite, alkali-silica gel, marine salts, and corrosion products in these near-surface pores, it is still not fully understood of how these products impact service life (See ASTM 169D).

Micrographs of concretes obtained from mature structural lightweight concrete ships, marine structures, and bridges have consistently revealed minimal microcracking and a limited volume of un-hydrated cement grains. The boundary between the cementitious matrix and coarse aggregates is essentially indistinguishable at the contact zone separating the two phases in all mature high strength lightweight concrete's.

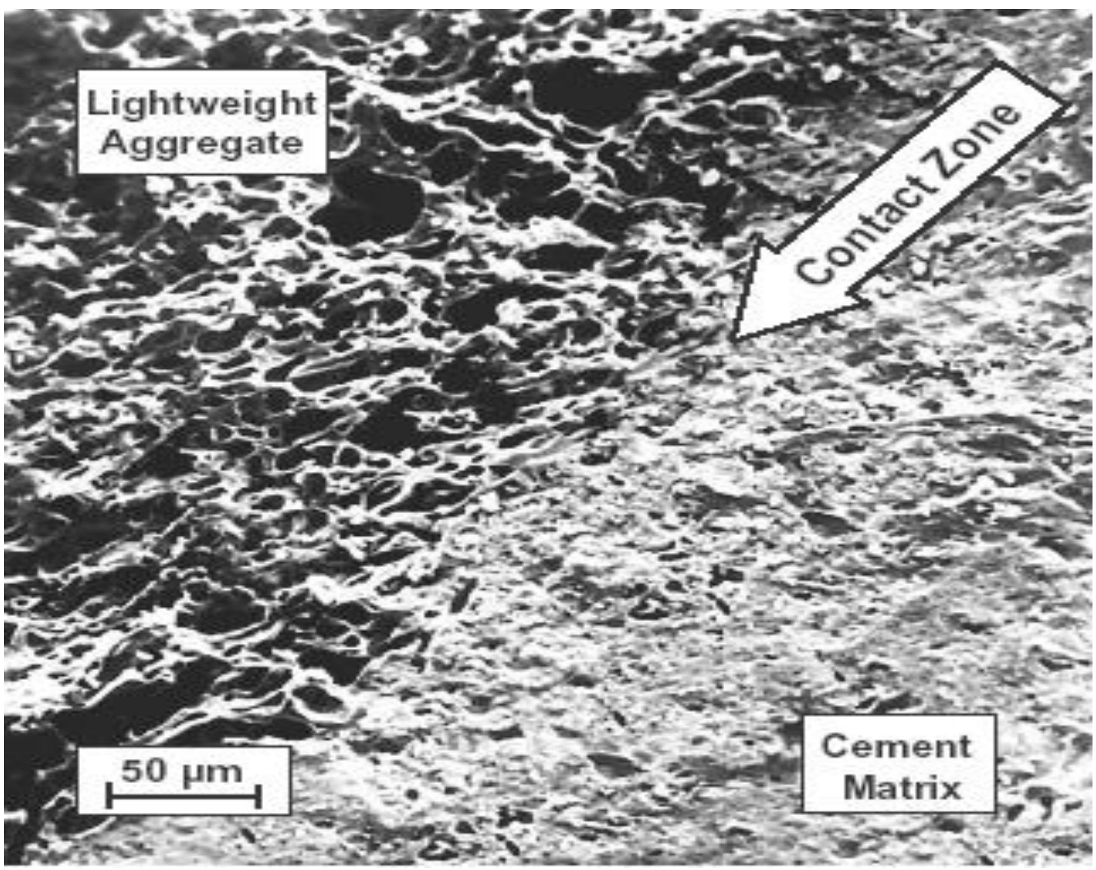

Figure 6.5. ***Contact zone of structural lightweight concrete (W.P. Lane Memorial Bridge over Chesapeake Bay, Annapolis, MD – constructed in 1952) (Holm 1983)***

6.6 Permeability

While technical literature contains numerous reports on the permeability of concrete there is a limited number of papers where structural lightweight and normalweight concrete were tested under the same conditions. Furthermore, almost all studies measuring permeability use test conditions that are static insofar as the concrete is concerned. While this approach is appropriate for dams and water containing structures it is not relevant to bridges and parking garages which are constantly subjected to dynamic stress and strain. Cover concrete is expected to maintain its protective impermeable integrity despite the accumulation of shrinkage, thermal and structural load related strains.

Permeability investigations conducted on lightweight and normalweight concretes exposed to the same testing criteria have been reported by Khokrin, Nishi, Keeton and Bamforth. It is of interest that in every case, despite wide variations in concrete strengths, testing media (water, gas and oil), and testing techniques (specimen size, media pressure and equipment), structural lightweight concrete had equal or lower permeability than its heavier counterpart. Khokrin further reports that the lower permeability of lightweight concrete was attributed to the elastic compatibility of the constituents and the enhanced bond between the coarse aggregate and the matrix. In the Onoda Cement Company tests, concretes with water to cement ratios of 0.55, moist cured for 28 days when tested a 9 kg/cm water pressure had a depth of penetration of 35 mm for normalweight concrete and 24 mm for lightweight concrete. When tested with sea water, penetration was 15 and 12 mm for normalweight and lightweight concretes respectively. The author suggested that the reason for this behavior was, "a layer of dense hardened cement paste surrounding the particles of artificial lightweight coarse aggregate." U.S. Navy sponsored "Permeability Studies of Reinforced Thin Shell Concrete", conducted by Keeton reported the lowest permeability with high strength lightweight concrete. Bamforth incorporated structural lightweight concrete as one of the four concretes tested for permeability to nitrogen gas at 1 MPa pressure level. The normalweight concrete specimens included high strength (90 MPa) concrete as well as concrete with a 25% fly ash replacement. The sanded structural lightweight concrete (50 MPa, 6.4% air) with a density of 1985 kg/m (124 lb/cf) demonstrated the lowest water and air permeability of all mixes tested.

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

In addition, the contact zone in structural lightweight concrete is the interface between two porous medias – the lightweight aggregate particle and the hydrating cement binder. This porous media interface allows for hygral equilibrium to be reach between the two phases, thus eliminating weak zones caused by water concentration. In contrast, the contact zone of normalweight concrete is an interface between a dense, non-absorbent component and a water rich binder. Any accumulation of water at that interface is subsequently lost during drying, leaving voids.

Fully hydrated portland cement paste has the potential to form an essentially impermeable matrix that should render concretes impermeable to the flow of liquids and gases. In practice, however, this is not the case, as microcracks form in concrete during the hardening process as well as later due to shrinkage, thermal and applied stresses. In addition, excess water added to concrete for easier placing will evaporate leaving pores and conduits in the concrete. This is particularly true in exposed concrete decks where concrete has frequently provided inadequate protection for steel reinforcement. To evaluate this behavior several series of thick walled cylindrical specimens were tested with flow of nitrogen gas being measured radially as the axial load was increased. In this way flow rate could be measured normal to the compressive stress as is the case of containment vessels and bridge decks.

To evaluate the influence of stress level on permeability normalweight and structural lightweight concrete specimens were tested with increasing loads in a nitrogen gas cell shown in Fig. 6.6. Nitrogen was chosen because the concrete's permeability would not be affected by this inert gas. The results were reported by Sugiyama et. al (1996).

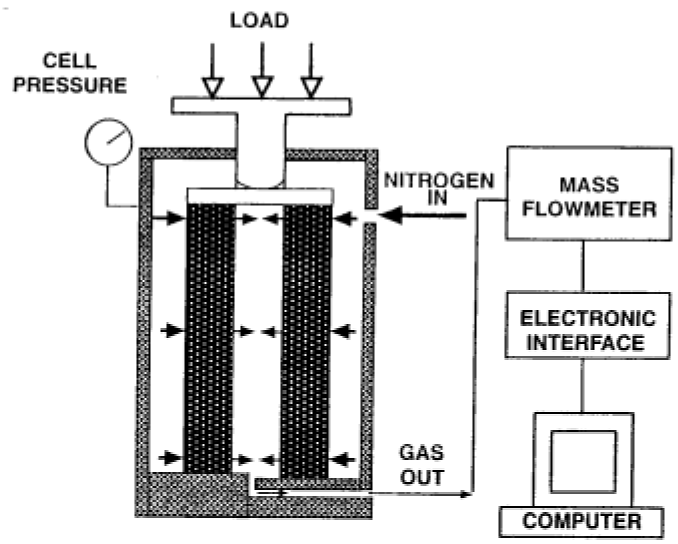

Figure 6.6. ***Flowchart of nitrogen permeability apparatus***

The test results indicate that the permeability of both types of concrete are relatively insensitive to applied stress levels up to the critical level at which extensive stress induced microcracking would be expected to occur. At approximately 54% to 62% of the stress to strength ratio for normalweight concrete and about 72% to 82% for structural lightweight concrete, permeability increases significantly. These levels at which a rapid increase in permeability was noted correspond to the stress levels at which others have observed that the incidence of microcracking starts to increase rapidly and the interconnection between the microcracks becomes significant. The close match between the stiffness of the expanded lightweight aggregate and the cement past matrix minimizes internal stress concentration and explains the delayed onset of microcracking as compared to normalweight concrete.

6.7 Pozzolonic Characteristics

History

There is a long history of successfully blending calcined clays and shale's to cementitious materials to improve performance. The pozzolanic properties of burnt clays were well known to the Romans, who utilized ground clay bricks and tiles. Addition of burnt clay to lime mortars to obtain hydraulic properties also were known in ancient concrete produced in India and Egypt (Vitruvius, Lea). In 1950 Meissner reported that a California cement company had been producing for two decades a portland-pozzolan cement containing Monterey Shale. It was used in 1932 by the California Division of Highways in several structures and in a stretch of an experimental concrete highway. Observations on these trial installations, together with laboratory studies on the properties of concrete made with the blended cement, caused the authorities of the Golden Gate Bridge and San Francisco-Oakland Bay Bridge to permit its use on these bridges. The San Francisco anchorage of the Bay Bridge and the San Francisco pier and fender of the Golden Gate Bridge utilized large quantities of this cement type. The main reasons for recommending the use of this cement in these structures was its proven resistance to alkali soils and sulfate waters together with the favorable heat generation characteristics it possessed for these massive blocks of concrete. The advantages attributed to cements composed of a blend of portland cement and siliceous materials had been amply demonstrated by investigations conducted at the engineering Materials Laboratory of the University of California, as well as the Corps of Engineers reported in ASTM STP-99, (Pepper).

Improvements in the physical properties and chemical resistance of concrete by the addition of rotary kiln produced calcined clays and shale's have been documented in a number of comprehensive reports (Barger).

Pozzolonic Terminology and Properties

ASTM 618 classifies calcined clay and shale as natural pozzolans of class N. Natural pozzolans are grouped with fly ash in the chemical requirements. ASTM 618 also provides requirement for physical characteristics.

The definition of a pozzolan is stated in ACI 116R-00 "Cement and Concrete Terminology": "Pozzolans – a siliceous or siliceous and aluminous material that in itself possess little or no cementitious value but that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds having cementitious properties; there are both natural and artificial pozzolans".

Three characteristics of a pozzolon make it reactive and therefore effective. Firstly and of prime importance is a high silica content because silica participates in the reaction with the calcium hydroxide liberated in the hydration process of cements.

Table 6.6 shows the percentage composition from tests conducted on commercial rotary kiln produced expanded shale's, clays and slates. The summation of the percentages of S_1O_2, AL_2O_3 and Fe_2O_3 is 91% with a range of approximately $\pm$ 6%. Table 6.7 shows that, despite the small test sample size, the location in the quarry and the vagaries of testing procedures, that the range of compositional percentages of multiple tests on the same material is relatively small.

Table 6.6. Percentage Composition of Rotary Kiln Produced Expanded Shale's, Clays and Slates from North America and Europe

Pozzolon Element	A	B	C	D	E	F	G	H	I	J	K
S_1O_2	66	65	52	71	53	78	60	66	54	63	61
Al_2O_3	23	20	22	17	20	15	18	16	38	20	23
Fe_2O_3	7	9	11	4	14	4	8	6	2	7	12
CaO	2	1	2	1	4	1	2	2	1	2	1
MgO	1	2	4	4	2	1	3	3	1	2	1

Note: Results do not add up to 100%, because of variation in reporting techniques used by various testing labs.

Table 6.7. Uniformity of Composition of Two Selected Rotary Kiln Produced Expanded Shale, Clay and Slate.

Pozzolon Element	A_1	A_2	A_3	B_1	B_2	B_3
S_1O_2	66	66	64	65	58	65
Al_2O_3	23	18	19	20	27	20
Fe_2O_3	7	6	9	9	11	9
CaO	2	7	1	1	1	1
MgO	1	1	3	2	3	3

The second requirement is a high degree of amorphous structure. When cooled slowly silica tends to a crystalline state, but when cooled rapidly it does not have sufficient time to organize into crystals and solidifies into an amorphous structure (glassy) or into an intermediate structure between crystalline and amorphous. The results of petrography tests conducted at the laboratory of the Portland Cement Association on a commercial rotary kiln produced lightweight aggregate are shown in Table 6.8.

Table 6.8. Petrography tests

Particle Shape	Particle Surface Texture	Micro Structural Character of Air Void System	Mineralogy
Coarse Aggregate			Mineralogy was similar for all samples examined. The following constituents were present 50 to 70% glass. Refractive index 1.540 to 1.565 10 to 30% quartz 1 to 10% feldspar 1 to 10% unidentified microcrystalline material Less than 1% iron oxides
Tabular to ellipsoidal, subangular to rounded.	Dense. Few voids greater than 1000 microns diameter were exposed.	Uniform structure with few or no bedding plane separations. Most voids were nearly spherical and isolated, but if connected showed no directional preference for such connection. Totaled voids were from 5 to 25 microns diameter, a few up to 100 microns. 50 to 100 micron voids uniformly and closely space. Largest void less area observed was 900 square micron	
Fine Aggregate			
Tabular to ellipsoidal. Progressively more angular with decreasing particle size.	Very dense, smooth. Few voids at surface were larger than 100 microns	Voids were similar to those described for coarse aggregate. Maximum dimensions of air voids limited by particle size.	

(Reference PCA)

The third characteristic of a reactive pozzolon is a high specific surface which will provide a greater surface to which the material can react. Highly reactive ESCS pozzolans with Blaine fineness considerably greater than commercial cements have performed well in laboratory testing programs and commercial applications. Inadequately ground or improperly fired material may reduce pozzolanic behavior.

Influence on Properties of Concrete

Pozzolans made from ESCS's have been used commercially as both:

- A separate mineral admixture addition or
- As part of a blended cement.

When used as a mineral admixture the properties of concrete are improved in both the fresh, and hardened states. ESCS pozzolans have been shown to impart a high degree of workability in both non-air entrained and air entrained concretes that also demonstrated improved pumping characteristics. ESCS pozzolans do not contain carbon or other contaminants that affect air entrainment in concrete. The air entrained admixture dosage rates have been shown to be comparable to that of straight Portland cement mixtures. ESCS pozzolans do not retard setting time.

During calcining the silica and alumina minerals are unlocked and made available for combination with the calcium hydroxide liberated during the hydration reaction of Portland cement. This results in the development of greater amounts of calcium silicate hydrate (CSH) (the inorganic glue) than would be available in straight Portland cement concrete mixtures. Additionally, because of the increased amount of the insoluble CSH, the permeability of the mixture is significantly reduced, thus increasing resistance to both sulfate attack and alkali-silica reactions.

There are three mechanisms by which pozzolans improve the resistance of concrete to sulfate attack.

- Simple dilution by replacing Portland cement, there is less C_3A present in the paste.
- The pozzolanic hydration reaction consumes a portion of the calcium hydroxide resulting in a lower amount available to react with sulfates to form gypsum.
- Pozzolonic hydration products contribute to a reduced permeability, thus limiting the ingress of the sulfate solution.

Recent tests conducted on a ground rotary kiln expanded shale, clay and slate in accordance with the procedures of ASTM C 1012 "*Standard Test Method for Length Change of Hydraulic Cement Mortars Exposed to Sulfate Solution",* showed reductions of approximately 80% when mixtures containing 15, 20 and 25% rotary kiln produced pozzolans were compared with a straight Portland control mixture.

In a similar fashion, comparison of expansion measured in accordance with ASTM C 441 "*Standard Test Method for Effectiveness of Mineral Admixtures or Ground-Based Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction",* showed expansion of mixtures with 15, 20 and 25% additions of RK ESCS to be less than one half that of straight Portland cement mixtures, (Lehigh Lightweight 2005 private communication).

Pozzolonic Reaction in the Contact Zone

All of the earlier commentary of this section report the proven performance (laboratory and field) when ESCS materials are manufactured to the requirements of pozzolans, particularly in relation to surface area criteria. Less evident is the contribution of the significant enhancement of the critical contact zone developed by modest amounts of reaction between the extremely limited surface area of large (comparatively) aggregate particles used in the production of structural lightweight concrete.

The contact zone is the transition layer of material connecting the coarse aggregate particle with the enveloping continuous mortar matrix. Analysis of this linkage layer requires consideration of more than the adhesion developed at the interface and should include the transitional layer that forms between the two phases. Collapse of the structural integrity of a conglomerate may come from the failure of one of the two phases or from a breakdown in the contact zone causing a separation of the still intact phases. The various mechanisms that act to maintain continuity or that causes separation have not received the same attention as has the air void system necessary to protect the paste. Aggregates are frequently dismissed as being "inert" fillers and as a result they and the associated transition zone have received very modest attention.

In order that concrete perform satisfactorily in severe exposure conditions it is essential that a good bond develop and be maintained between the aggregate and the enveloping continuous mortar matrix. A high incidence of interfacial cracking or aggregate debonding will have a serious effect on durability if these cracks fill with water and subsequently freeze. A serious consequence of microcracking is the easy path provided for the ingress of salt water into the mass of the concrete where it can react with the products of hydration and render ineffective the protective layer of concrete over the reinforcing steel. To provide an insight into the performance of different types of concrete, a number of mature structures that have withstood severe exposure were examined. The morphology and distribution of chemical elements at the interface were studied so that those factors associated with good performance could be identified.

Specimens taken from severely exposed mature concrete bridge decks and ships were prepared from these cores for examination in a Cambridge S4-10 scanning electron microscope equipped with a Tracor Northern NS-880 energy dispersive X-ray analyzer (For details see "*Aggregate-Matrix Interaction in Concrete Subject to Severe Exposure"*, Bremner T.W., Holm T.A. and DeSouza H., FIP-CPCI International Symposium on Concrete Sea Structure in Arctic Regions, Aug. 29, 1984, Calgary, Canada). The data indicates that the silicon content increases at a reasonably constant rate as the aggregate interface is approached suggesting that the aggregate acts as source of reactive silica.

Reductions in mechanical properties are inevitable as a result of the interface flaws as they limit interaction between the two distinctly different phases. However significant the reduction in compressive and tensile strength, the effect on permeability is even greater. Increasing permeability inevitably leads to ingress of water carrying aggressive agents that accelerate frost damage and corrosion of embedded reinforcement.

The permeability of concrete is magnitudes greater than the permeability of its two constituents. A plausible explanation could be the effect of the interface flaws linking up with mirocracking in the mortar phase of the matrix.

6.8 Heat Flow Characteristics

Thermal Conductivity

Thermal conductivity is a property of a material and is a measure of the rate at which energy (heat) passes linearly through a unit area of homogeneous material of unit thickness for a temperature gradient of 1 deg. Thermal conductivity of concrete depends mainly on its density and moisture content but is also influenced by the size and distribution of the pores, the chemical composition of the solid components, their internal structure (crystalline or amorphous), and the test temperature Crystalline materials (e.g. quartz) conduct heat better than amorphous materials (calcined clays, ceramics, etc.).

Lightweight Concrete

Thermal conductivity is generally measured on oven-dry samples in a guarded hot-plate assemblage according to ASTM C 177. Fig. 6.8 shows the results of the analysis of conductivity tests on concretes with densities from 20 – 200 lb/ft³ (320 to 3,200 kg/m) (Valore 1980), which suggest the equation

$$k = 0.5e^{0.02\omega}$$

where k is the thermal conductivity (Btu • in./hr • ft² • ºF) and ω is the density (lb/ft³)

$$k = 0.072e^{0.00125\omega}$$

where k is the thermal conductivity in, W m^{-1}•K, and ω is the density, kg/m³.

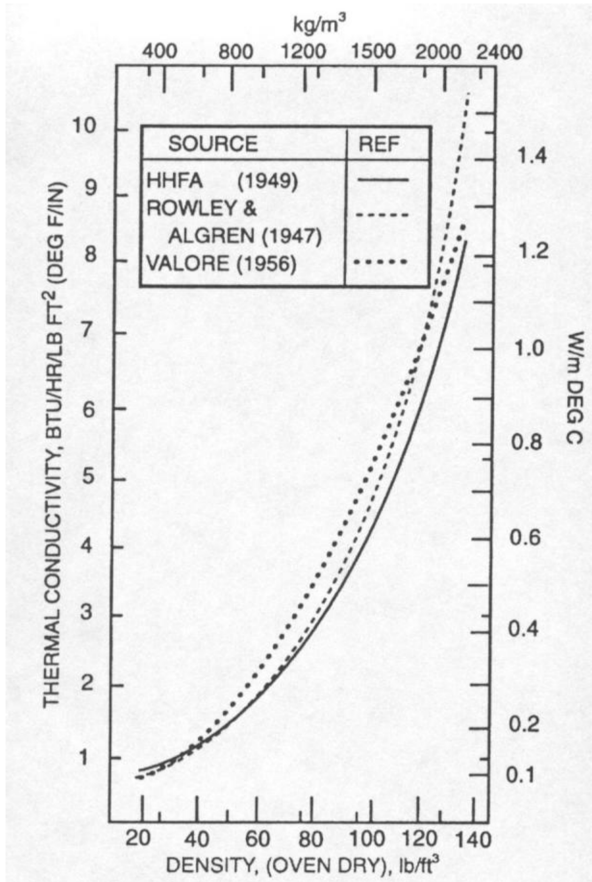

Figure 6.8 ***Relation of Average Thermal Conductivity k Values of Concrete in an Oven-Dry Condition to Density, (Valore 1980).***

The Valore equation (Valore 1980) is accurate for concretes composed entirely of lightweight aggregate up to a density of 100 lb/ft³ (1,600 kg/m³) but becomes increasingly non-conservative for higher density concrete containing highly crystalline normalweight aggregate. That being the case, it becomes essential to measure the thermal conductivity in a guarded hot plate for specified-density concrete aggregate combination.

For a given concrete, an accurate value of the thermal conductivity based upon tests in a guarded hot plate (for oven-dry specimens) or a heat flow meter (for rapid testing when specimens contain moisture) is preferable to an estimated value. However, the formula provides guidance for estimating the thermal conductivity in an oven-dry condition and, in addition, may readily be revised for air-dry conditions. When thermal resistance values are part of the project specifications, the addition of crystalline natural aggregates should be avoided, as the resulting thermal conductivity of the mixture will increase at a rate faster than that predicted by density alone (Schule and Kupke 1972).

Increasing the free-moisture content of hardened concrete causes an increase of thermal conductivity. As most conductivity data are reported for oven-dry concrete, it is essential to know the moisture contents of the concrete in equilibrium with its in-service environment, and then apply a modification factor for estimating the conductivity under service conditions. Valore (1980) reported long-term moisture contents for concretes with the average for lightweight concrete being 4 percent by volume. As a practical matter, after considering the many variations of density, mixture composition, and in-service ambient conditions, Valore (1980) suggested that a reasonable approximation would be to increase the in-place thermal conductivity by 20 percent over test oven-dry values.

Thermal conductivity values for moist concretes were reported by Scanlon and MacDonald in ASTM 169C (1994). CRD-C 44 (U.S. Army Corps of Engineers 1998b) provides a procedure for calculating thermal conductivity from the results of test of thermal diffusivity and specific heat.

High-strength lightweight concrete

With the exception that, in general, high-strength concretes have greater density (low w/c, low air content), there is only a modest increase in thermal conductivity with increased strength. The low porosity developed by the fully hydrated, rich cementitious fraction increases the thermal conductivity of the continuous matrix that encapsulates the aggregate fractions. The thermal conductivities of the oven-dried concretes reported by Hoff (1992) were 5.64 to 6.24 Btu • in./hr • lb/ft^3 ºF (0.814 to 0.900 W/m • ºK) for 120.0 lb/ft^3 (1,922 kg/m^3) concrete, and 7.66 to 7.45 Btu • in./hr • lb/ft^2 • ºF (1.10 to 1.07 W/m ºK) for 128.0 lb/ft^3 (2,051 kg/m^3) high-strength concrete. These values compare well with the results estimated by the Valore equation (Valore 1980).

$$k = 0.072e^{0.00125 \times 1922} = 0.80 \; (k = 0.5e^{0.02 \times 120} = 5.5)$$

$$k = 0.072e^{0.00125 \times 2057} = 0.93 \; (k = 0.5e^{0.02 \times 128} = 6.5)$$

High-Strength Specified-density concrete

The thermal conductivity of concrete is fundamentally influenced by the thermal conductivity of the aggregates that are used in the specified-density concrete mixtures. While the thermal conductivity of the differing lightweight aggregate does not differ significantly at any particular porosity, the thermal conductivity of normalweight aggregate varies over a wide range that is principally determined by the degree of crystallinity. As reported by Scanlon and McDonald (1994) and shown in Table 6.9, there exists a wide range of conductivity of concrete depending on aggregate type and moisture content.

Holm and Bremner (1987) reported the results of measurements of the thermal conductivity of lightweight concrete over a wide range of temperatures. Also included were measurements of the thermal conductivity of lightweight, expanded aggregates alone that averaged 3.3 Btu • in./hr • ft² (0.47 W/m • ºC) over a temperature range of 70 to 1,400 ºF (42 to 760 ºC).

Table 6.9
Effect of Aggregate Type on Conductivity of Moist Concrete at Normal Temperatures

	Density		Conductivity	
Aggregate Type	**Kg/m³**	**lb/ft³**	**W/m • K**	**Btu • un./hr • ft² • ºF**
Hermatite	**3,040**	**190**	**4.1**	**28**
Quartzite	**2,400**	**150**	**4.1**	**28**
Quartzite	**2,440**	**152**	**3.5**	**24**
Dolomite	**2,500**	**156**	**3.3**	**23**
Quartzite	**...**	**...**	**3.3**	**23**
Limestone	**2,450**	**153**	**3.2**	**22**
Quartzite	**2,350**	**147**	**3.1**	**21**
Sandstone	**2,130**	**133**	**2.9**	**20**
Sandstone	**2,400**	**150**	**2.9**	**20**
Granite	**2,420**	**151**	**2.6**	**18**
Limestone	**2,420**	**151**	**2.6**	**18**
Marble	**2,440**	**152**	**2.2**	**15**
Limestone	**2,420**	**152**	**2.2**	**15**
Basalt	**2,520**	**157**	**2.0**	**14**
Rhyolite	**2,340**	**146**	**2.0**	**14**
Barite	**3,040**	**190**	**2.0**	**14**
Dolerite	**2,350**	**147**	**2.0**	**14**
Basalt	**2,350**	**158**	**2.0**	**13**
Expanded Shale	**1,590**	**99**	**0.85**	**5.9**

(Scanlon and McDonald Chapter 24, ASTM 169C, 1994)

Specific Heat

The definition of specific heat is "the ratio of the amount of heat required to raise a unit mass of material 1 deg to the amount of heat required to raise an equal mass of water 1 deg". In systems of units in which the heat capacity of water is 1.0 (either cal/g ºC or Btu/lb ºF), the specific heat values are the same. In SI units, specific heat is expressed in Joules per kilogram kelvin, which can be obtained from customary values by multiplying by 4.1868 x 10^3. Tests for specific heat are generally carried out according to the procedures specified in the U.S. Army Corps of Engineers Test Method CRD-C124 (USACE 1998c).

ACI 122R-02 reports that the specific heat of concretes with a density range of 80 to 140 pcf varies from 0.21 to 0.22, ACI 122, 2002.

Thermal Diffusivity

Thermal diffusivity is defined as thermal conductivity divided by the product of specific heat and density and relates to the rate at which temperature changes take place within a mass of material. Tests are generally conducted in accordance with CRD-C36 (U.S. Army Corps of Engineers 1998a). The low value for expanded shale concrete shown in Table 6.10 is caused by the fact that thermal conductivity in the numerator has been shown to be exponentially influenced by density.

Hoff (1992) reported diffusivity results of 0.0197 and 0.0224 ft^2/hr (0.00183 and 0.00281 m^2/hr) for concrete densities of 119.4 and 127.5 lb/ft^3 (1,913 and 2,043 kg/m^3), respectively. These values are in line with those given in Table 4.10 and are consistent with values reported by other researchers (Fig. 6.9).

Table 6.10
Typical Thermal Diffusivity Values (after Scanlon and McDonald 1994)

Type of Aggregate in Concrete	Thermal Diffusivity	
	m^2 / hr	ft^2 / hr
Quartz	0.0079	0.085
Quartzite	0.0061	0.065
Limestone	0.0055	0.059
Basalt	0.0025	0.027
Expanded shale	0.0015	0.016

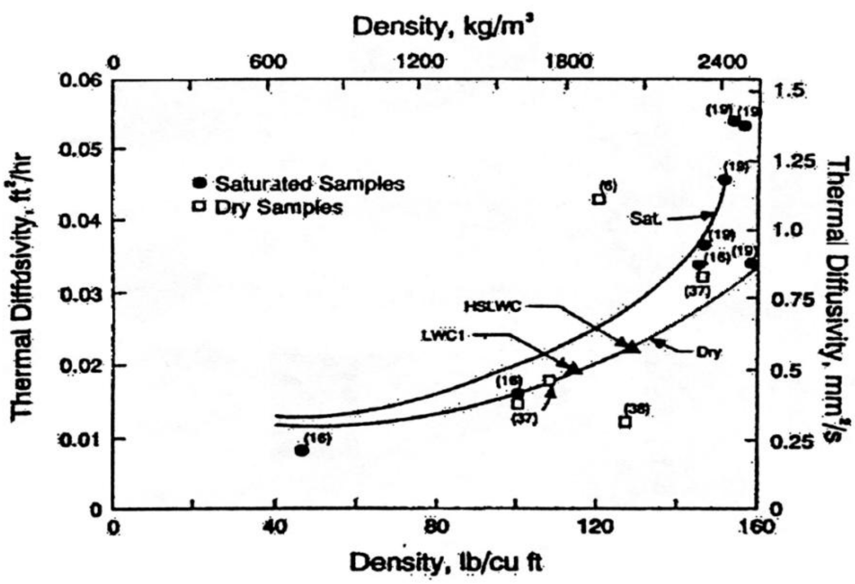

Figure 6.9 ***Thermal diffusivity of concrete as a function of density (from Hoff 1992, with permission of ACI)***

6.9 Fire Resistance

General

When tested according to the procedures of ASTM E 119, structural lightweight concrete slabs, walls, and beams have demonstrated greater fire-endurance periods than equivalent-thickness members made with concretes containing ordinary aggregate. Superior performance is, according to ACI 213, due to a combination of lower thermal conductivity (lower temperature rise on unexposed surfaces), lower coefficient of thermal expansion (lower forces developed under restraint), and the inherent thermal stability developed by aggregates that have already been exposed to temperatures greater than 2,000 ºF (1,093 ºC) during Pyroprocessing (see Fig. 6.10).

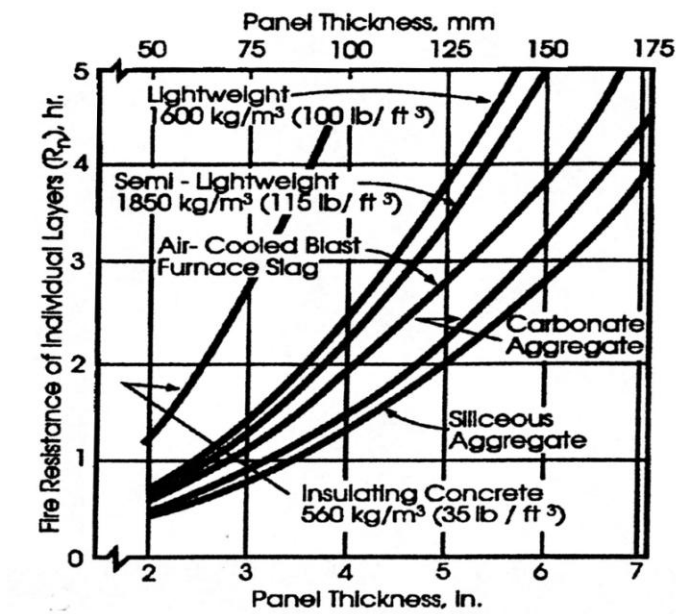

Figure 6.10. ***Effect of slab thickness and aggregate type on fire resistance of concrete slabs based on 250 deg F (139 deg C) rise in temperature of unexposed surface (ACI 216.1)***

High-strength lightweight concrete

While there is more than 50 years experience and a multitude of fire tests conducted on lightweight concrete of strength levels appropriate for commercial construction of strength 2,900 to 5,080 psi, (20 to 35 MPa), the availability of data on high strength lightweight concrete has, until recently, been very limited.

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

Several reports have documented the beneficial influence of adding small quantities of polypropylene fibers to high strength lightweight concrete, as demonstrated by exposure to fire testing that was more intense than the exposure conditions (time-temperature criteria) specified by ASTM E 119. Jensen et al. (1995) reported the results of tests conducted at the Norwegian Fire Research Laboratories, Trondheim, Norway. These studies included the determination of mechanical properties at high temperature, the improvement of spalling resistance through material design and the verification of fire resistance and residual strength of structural elements after exposure to fire.

Conclusion offered by the authors included the following:

a. A considerable reduction in compressive strength and elastic modulus, even at relatively low temperatures between 212 to 572 ºF (100 and 300 ºC), was documented.
b. Spalling is highly dependent on moisture content.
c. The addition of 0.1 to 0.2 percent polypropylene fibers in the lightweight concrete mixture provided significant reduction of spalling. This was later confirmed by structural beam test.
d. Fire tests on beams confirmed earlier findings that severe spalling (exposed reinforcement) occurred on reinforced and prestressed lightweight concrete beams. Reduced spalling occurred on normalweight concrete beams. Reduced or no spalling occurred on lightweight concrete beams with polypropylene fibers. No spalling was observed on lightweight concrete beams with passive fire protection (a special cement-based mortar with expanded polystyrene balls).

Bilodeau et al. (1995) also commented on the behavior of several lightweight concrete exposed to hydrocarbon fires. This comprehensive report primarily, focused on the determination of mechanical properties, e.g. compressive, flexural and splitting tensile strengths, Young's modulus, drying shrinkage, and durability measurements. However, it also concluded that "all concretes without fibers were almost completely destroyed during the hydrocarbon fire. Based on the visual appearance, the use of polypropylene fibers improved considerably the fire resistance of the concrete". Apparently, the fibers melt and provide conduits for release of the pressure developed by the conversion of moisture to steam.

High-strength specified-density concrete

To a certain degree, the findings of these earlier tests have been paralleled by results from tests jointly sponsored by CANMET, Ottawa, Canada; Mobil, Dallas, TX; Synthetic Industries-Fibermesh, Chattanooga, TN; Headed Reinforcement Canada, Mt. Pearl, Newfoundland; and Health and Safety Executive, London, U.K. These tests used 19.7 by 39.4 by 39.4 in. (500 by 1,000 by 1,000 mm) reinforced prisms (Bilodeau, Malhotra, and Hoff 1998).

In tests conducted on normalweight concrete, lightweight concrete and specified density concrete the authors reported the following:

a. The amount of spalling increased with the increase in the amount of lightweight aggregate.
b. Use of polypropylene fibers significantly reduced the spalling of concrete exposed to hydrocarbon fires.
c. Reduced spalling resulted in a lower temperature increase in the core of the concrete and enhanced protection to the reinforcing steel.
d. The properties of the concrete inside the block were not seriously affected by the fire exposure. However, the residual properties were slightly better for the concrete with fibers due to a smaller increase in temperature.
e. The amount of fibers used in the concrete containing lightweight aggregate was not fully adequate to prevent spalling. More research is needed to determine the optimum amount of fibers for the fire protection of different types of concrete.

6.10 Refractory Concrete

Structural lightweight concrete made with ESCS aggregates, which were manufactured in a Pyroprocessing process at approximately 2000ºF have more than a half century of proven performance in refractory applications. These uses include the lining of major smoke stacks, the total construction of fire training centers, fireplace liners, fireplace logs and many high temperature industrial applications.

Another refractory application included an investigation of jet exhaust damaged airport runways. Based on the performance under simulated F/A-18APU exhaust and accelerated tests, the following was the ranking of the candidate pavement systems evaluated, from best to worst performers:

1. Magnesium ammonium phosphate cement with ESCS aggregate (least damaged).
2. Portland cement with ESCS aggregate (performed 3.7 times better than control).

3. Magnesium ammonium phosphate cement with ASTM C 33 Size No. 8 (2.36 mm) aggregate (cracked).
4. Magnesium aluminum phosphate binder system (very short set time, cracks and spalls).
5. Portland cement with ASTM C 33 Size No. 57 (4.75 mm) aggregate (control airfield pavement).

The first candidate is about 9 times more expensive than the control (#5), but should last about 15 times longer. The second candidate is about 80 percent more expensive than the control but should last 3.7 times longer.

Based on analytical modeling and laboratory testing of candidate pavement systems under simulated F/A-18 APU jet exhaust conditions, several candidate pavement systems superior to standard Navy airfield pavement constructed with ordinary Portland cement have been developed. The two recommended candidate systems were magnesium ammonium phosphate cement with 3/8 in. (9.5 mm) ESCS aggregate and PCC with ESCS aggregate. Alternatively, removing the spilled oils from the surface of existing pavements would significantly extend their service life.

Lightweight refractory concrete (LWRC) is effective because of:

a. Aggregate already fire tested.
b. High thermal insulation.
c. High compressive strength
d. Low tendency towards spalling
e. Low transportation costs for LWRC
f. Immediate, widespread availability
g. No combustible or corrosive material

Technical service representatives of refractory cement companies are an excellent source of practical information regarding mixture properties, placing and curing. For a sample of cement company technical literature see Appendix C.

6.11 Abrasion Resistance

Abrasion resistance of concrete depends on the strength, hardness, and toughness characteristics of the cement paste and the aggregates, and on the bond between these two phases. Most lightweight aggregates suitable for structural concretes are composed of solidified vitreous material comparable to quartz on the Mohs scale of hardness. Due to its pore system, however, the net resistance to shearing forces may be less than that of a solid particle of most natural aggregates. Lightweight concrete bridge decks that have been subjected to more than 100 million vehicle crossings, including truck traffic, show wearing performance similar to that of normalweight concrete. Limitations are necessary in certain commercial applications where steel-wheeled industrial vehicles are used, but such surfaces generally receive specially prepared surface treatments.

Hoff (1992) reports that specifically developed testing procedures that measured ice abrasion of concrete exposed to arctic conditions demonstrated essentially similar performance for lightweight concrete and normalweight concrete (ACI 213R-03). In these tests, directed towards high strength concretes for the severe Arctic environment, two lightweight and one normalweight were evaluated by five distinctly different test methods, two of which are standard ASTM test procedures. Table 6.11 from Hoff (1992) compares the results of four of the test methods, the relative wear test results are not included as no useful data were obtained from that testing procedure. The conclusions reached were:

1. The evaluation of the ice abrasion resistance of the concrete is greatly influenced by the type of test method used.
2. High-strength lightweight concrete (greater than 7000 lb/sq. in. (48 MPa) compressive strength) has acceptable resistance to ice abrasion.
3. High quality lightweight aggregate from both the USA and Japan gave comparable results.

Table 6.11. Relative Performance of Concretes for Abrasion Resistance

Test Method	Concrete Mixture Designation Ranking of Abrasion Values. in. (mm) 1	2	3	4
Revolving Disk Test				
Contact Pressure				
71 psi (0.49 MPa)	**NWC** 0.008-0.009 (0.212-0.231)	**LWC2** 0.007-0.011 (0.179-0.271)	**--**	**--**
142 psi (0.98 MPa)	**NWC** 0.007-0.012 (0.180-0.294)	**LWC1** 0.017-0.023 (0.442-0.593)	**LWC2** 0.017-0.025 (0.444-0.626)	
ASTM C779, Procedure A				
USA Tests	**LWC2** 0.044 (1.12)	**LWC1** 0.055 (1.40)	**NWC** 0.061 (1.55)	**--**
Japan Tests	**NWC** 0.020 (0.517)	**LWC1** 0.022 (0.569)	**LWC2** 0.023 (0.596)	**--**
Tumbler Test				
Rough Surface	**NWC** 0.075 (1.90)	**LWC1** 0.095 (2.41)	**LWC2** 0.114 (2.90)	**HSLWC** 0.132 (3.35)
Smooth Surface	**NWC** 0.084 (2.13)	**HSLWC** 0.087 (2.21)	**LWC1** 0.102 (2.59)	**LWC2** 0.105 (2.67)
Sliding Contact Wear Test	**LWC1** 0.081 (2.06)	**LWC2** 0.096 (2.45)	**NWC** 0.124 (3.16)	**--**

Note: Ranking of 1 is least abrasion observed.
Ranking of 4 is most abrasion observed.

6A

ASTM D 567-05

"Standard Test Method for Determining Density of Structural Lightweight Concrete"

Visit www.ASTM.org for document

6B
"Jet Exhaust Damaged Concrete"

Jet Exhaust Damaged Concrete

by Melvin C. Hironaka and L. Javier Malvar

Concrete parking aprons deteriorate when exposed to F/A-18 jet aircraft auxiliary power unit (APU) exhaust (Fig. 1). Observations indicate that failures occur in the form of progressive delamination at some shallow depth (about 1/4 to 1/2 in. [6 to 13 mm]) beneath the surface. This "scaling" of the pavement surface can occur as early as 8 months after construction, due to cyclic thermal stresses caused by repeated exposure to high thermal gradients and strength degradation caused by spilled aircraft fluids.

Previous studies have addressed the effect of high temperatures and thermal gradients on concrete surfaces.[1] The British RAF conducted tests for vertical takeoff and landing (VTOL) aircraft where the main turbine exhaust was directed toward the concrete pavement.[2] It was found that all-lightweight concrete (i.e., concrete in which both fine and coarse aggregates are lightweight) provided "exceptional spall resistance."[2] A joint U.S./U.K. study between Tyndall Air Force Base and British Aerospace on advanced short takeoff and vertical landing (ASTOVL) aircraft concrete pavements concluded that concretes made with lightweight concrete aggregates "appear to resist spalling" when subjected to the high exhaust temperatures (around 1400 F [760 C]).[3]

These previous studies involved pavement temperatures usually higher than those produced by the F/A-18 APU exhaust, which are in the 300 to 400 F (150 to 200 C) range. However, several studies did focus specifically on the F/A-18 APU.

Research conducted at the South Dakota School of Mines and Technology recognized the existence of high horizontal compressive stresses and vertical tensile stresses near the pavement surface due to the high thermal gradients.[4,5] Main factors affecting thermal resistance were reported to be thermal expansion, conductivity, moisture, air content, high vapor pressure, and the loss of strength (up to 50 percent) due to spilled engine fluids.

Lightweight concrete, with a low thermal expansion coefficient, was reported as a good candidate, and using all-lightweight concrete reduces thermal expansion incompatibilities.[4,6,7] For typical normal weight portland cement concretes (PCC), numerical analyses showed the resulting cracking at the relatively weak cement paste-aggregate interface.[7] However, if a lightweight aggregate is used, this problem is mitigated since lightweight aggregates have a rough, porous surface that adheres well to the paste.

Preliminary numerical analyses assuming a homogeneous material showed that the use of all-lightweight concrete would substantially reduce the thermal stress problem.[8] Finally, chemical analyses of the damaged airfield concrete aprons also point toward strength degradation due to hydraulic fluid and lubricating oils.[9,10] Neutral pH concretes were recommended to prevent calcium hydroxide breakdown.

Several investigations also attempted to assess pavement surface temperatures versus time due to F/A-18 APU exhaust exposure. The aircraft manu-

Fig. 1 — F/A-18 APU exhaust profile

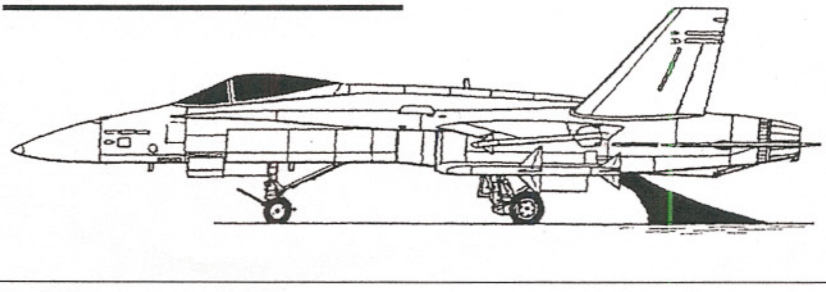

Table 1 — Typical proportions used for test slabs

Constituents	Ordinary portland cement concrete	Portland cement / expanded shale concrete	Magnesium ammonium phosphate concrete	Magnesium ammonium phosphate/expanded shale concrete	Magnesium aluminum phosphate concrete
Cement (lbs)	146.2 (Type II)	152.2 (Type II)	350	550	1 Bag with 1 Activator
Water (lbs)	55.6	76.6	29.4	46.2	
Fine aggregate (lbs)	210.4	242.6			
Coarse aggregate (lbs)	449.8	168.1	210	138.6	

resistance to Heat Flux Type II cycles. To reproduce the worst-case thermal gradients, the test slabs were cooled down to just above freezing before each exposure cycle. Measured and predicted heat-up profiles were used for input to the numerical model.

Numerical model

The 24 in. diameter, 6 in. thick slabs were modeled using a homogeneous two-dimensional axisymmetric model. The model was simplified by excluding shrinkage. If shrinkage were included, this would reduce the stress state.[7] Thermal loading was assumed to be applied to a 2 in. (50 mm) diameter area in the specimen center. A thermo-isotropic material model was used, with a temperature-dependent modulus of elasticity and specific heat. The model allowed vertical translation of the slab center and lateral translation to capture the bending of the slab when heated on the top. In the finite element model, due to the large discrepancy between the compressive and tensile stresses, the latter may present large relative errors, and/or result in values that oscillate about the exact solution.[15] Therefore, the stresses in tension were obtained by averaging values at all four Gaussian distribution points in each element.

For NWC, horizontal compression stresses reached about 7500 psi (52 MPa), in excess of the expected model biaxial strength of 6900 psi (48 MPa), so that superficial scaling failure in compression was likely down to a depth of about 1/16 in. (2.0 mm). These maximum stresses occur along the vertical axis of symmetry. At a small radial distance the stress state decreases, so that the numerical model predicts failure along a circular area. Thermal cycling would increase both the predicted failure area and its depth. Vertical tensile stresses reach about 125 psi (0.9 MPa). Although large, these stresses are not critical since they are well below the expected tensile strength. However, the combination of both sets of stresses would accelerate in-plane buckling and scaling. The compressive stresses themselves can result in cracking parallel to the compression (i.e., horizontal cracking). For the lightweight concrete, neither the vertical tensile stresses nor the horizontal compressive stresses would result in any failure, so most of the thermal stress problem is mitigated.

Test results

Test specimens exposed to the simulated jet exhaust failed in two basic modes: scaling and progressive external and internal damage. Failure of a test specimen was considered to have occurred if any of the following was observed or was detected by nondestructive testing with an impact-echo instrument: delamination, scaling, popouts, and vertical cracks.

Normal weight PCC

The normal weight PCC specimens failed in scaling similar to that observed in the field (Fig. 4). This type of failure was about 1/4 in. (6 mm) deep and, in one case, the failure surface did not show any presence of oil. Five series of tests were conducted with this material under different test conditions. The specimens tested with oil and water withstood an average of 17.3 Heat Flux Type II cycles. The specimens treated with trisodium phosphate (TSP) detergent on alternate cycles withstood 85 to 100 Heat Flux Type II cycles.

Lightweight PCC

All of the structural lightweight concrete specimens treated with water and oil failed in scaling, somewhat similar to the normal weight PCC specimens. However, these specimens resisted an average of 63.2 Type II cycles. This is 3.7 times higher than normal PCC under the same test conditions. In a couple of cases, and after many thermal cycles, the specimens split vertically through the center, as the analyses had predicted.

Neutral pH concretes

The magnesium ammonium phosphate cement with ASTM C 33 Size No. 8 (2.36 mm) aggregate mix and the magnesium aluminum phosphate binder mix were recommended by the Air Force as their best candidates for resisting chemical deterioration.[9] These two candidates had been placed at McConnell Air Force Base (AFB), Wichita, Kansas, and at the Beaufort Marine Corps Air Station (MCAS) in South Carolina in 1992.

Field observations at McConnell AFB in June 1994 indicated that the magnesium ammonium phosphate cement inlay exposed to the APU showed cracking, debonding, and spalling.[16] The magnesium aluminum phosphate binder inlay showed cracking, debonding, and shrinkage cracks.[16] Although the inlays at Beaufort MCAS received much less exposure, the magnesium aluminum phosphate binder also showed some cracking and debonding.

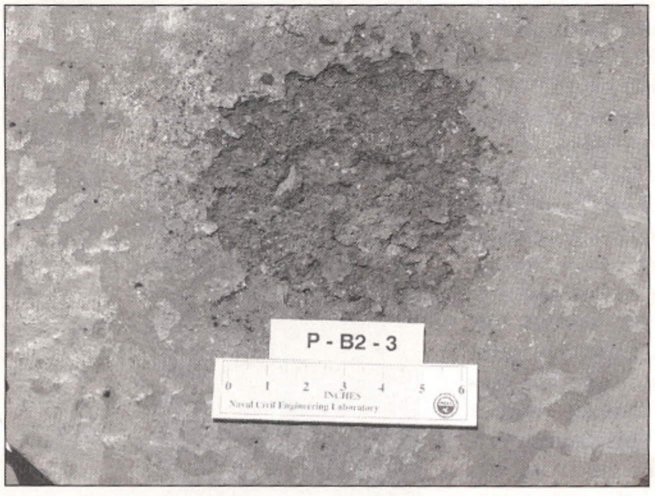

Fig. 4 — Standard Navy airfield PCC at heat cycle 50

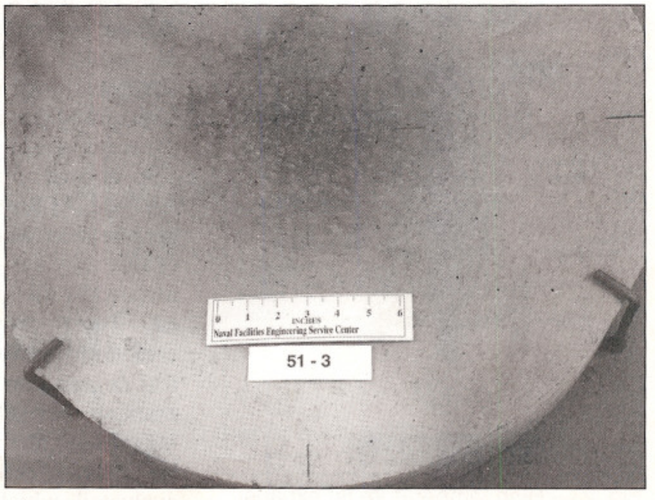

Fig. 5 — Magnesium ammonium phosphate cement with expanded shale aggregate at cycle 351

In the laboratory tests, both magnesium ammonium phosphate cement and magnesium aluminum phosphate binder showed early signs of internal deterioration as detected by the impact-echo device, after exposure to 40.0 and 23.3 average cycles of Heat Flux Type I, respectively. External damage in the form of hairline cracking was observed beginning about the 75th cycle. It should be noted that the magnesium ammonium phosphate cement mix had a low modulus of elasticity (2800 ksi [19 GPa]) and the magnesium aluminum phosphate binder mix had a low coefficient of thermal expansion, properties which may also explain their improved behavior. However, since both mixes eventually failed, the neutral pH concretes, as formulated, are still susceptible to the thermal stress problem.

Lightweight neutral pH concrete

To address both the thermal stresses and chemical deterioration, an all-lightweight concrete with magnesium ammonium phosphate cement was designed. This concrete had a compressive strength of 6170 psi (43 MPa), a modulus of rupture of 1010 psi (7 MPa), and a modulus of elasticity of 3600 ksi (25 GPa). This was one of the longer lasting candidates under thermal cycling in the presence of oils. When tests were terminated at 351 cycles, visible damage to the specimen surface was minor (Fig. 5).

Effects of oil

To evaluate the degradation due to the oil (MIL-L-23699), some samples were tested without oil, with oil only, and others with TSP detergent. Tests showed that the normal weight PCC Type II cycles increased to 100 (versus 17.3) when detergent was applied. Tests also showed that the expanded shale specimens could resist more than 500 cycles when oil was not added (versus 63.2 in the presence of oil).

Ranking of systems

Based on the performance under simulated F/A-18 APU exhaust and accelerated tests, the following is a ranking of the candidate pavement systems evaluated, from best to worst performers:

1. Magnesium ammonium phosphate cement with expanded shale aggregate (least damaged).
2. Portland cement with expanded shale aggregate (performed 3.7 times better than control).
3. Magnesium ammonium phosphate cement with ASTM C 33 Size No. 8 (2.36 mm) aggregate (cracked).
4. Magnesium aluminum phosphate binder system (very short set time, cracks and spalls).
5. Portland cement with ASTM C 33 Size No. 57 (4.75 mm) aggregate (control airfield pavement).

The first candidate is about 9 times more expensive than the control, but should last about 15 times longer. The second candidate is about 80 percent more expensive than the control but should last 3.7 times longer.

Conclusions

Based on analytical modeling and laboratory testing of candidate pavement systems under simulated F/A-18 APU jet exhaust conditions, several candidate pavement systems superior to standard Navy airfield pavements constructed with ordinary portland cement have been developed. The two recommended candidate systems were magnesium ammonium phosphate cement with 3/8 in. (9.5 mm) expanded shale aggregate, and PCC with expanded shale aggregate. Alternatively, removing the spilled oils from the surface of existing pavements would significantly extend their service life.

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Selected for reader interest by the editors.

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6C
Refractory Concrete Papers

ATLAS LUMNITE & REFCON

Calcium-Aluminate Cements

Refractory Concrete

LUMNITE: Expanded Shale, Clay or Slate

LUMNITE cement is often used with lightweight aggregates described by the broad term expanded shale, clay or slate (ESCS) to produce refractory concrete.

ESCS aggregates are produced, from the indicated raw materials, after being crushed, in either a rotary kiln process or the traveling grate-type sintering process. In either case the burning temperature is generally in the range of 2000-2200F (1095-1205C) which results in the removal of combustible and foreign waste matter. The heat also expands the raw material producing a cellular mass. After cooling it is crushed, screened and graded to size. The aggregates are usually available in at least two sizes, fine and coarse, but some producers grade into two coarse sizes and some provide a combined fine and coarse gradation.

Typical Lumnite ESCS Application

ESCS aggregates are manufactured by a number of firms across the United States under a variety of trade names. While the chemistry of these may vary somewhat they generally have an oxide analysis comparable to that shown below.

SiO_2	60.5%	MgO	2.4 %
Al_2O_3*	20.8	MnO	0.01
Fe_2O_3	8.0	K_2O	4.4
CaO	2.6	Na_2O	0.95

*Includes TiO_2 of 1.12% and P_2O_5 of 0.12%

The above chemical analysis is presented only as information and should not be considered as a criteria for acceptance or the ability of any given ESCS aggregate to perform satisfactorily with LUMNITE. While many of these aggregates display good volume stability when exposed to temperatures of 2000F (1095C) and higher; some of them may exhibit a high degree of volume change at temperatures below 2000F. In the absence of recent proven records of satisfactory performance in refractory concrete, tests may be required on a particular aggregate to determine its suitability for use at the anticipated service temperature.

LUMNITE in combination with ESCS aggregates has over the years produced refractory concretes with good strength, satisfactory resistance to abrasion and corrosion and good insulating properties. The data in the following tables are presented as an example of the properties that can be achieved, under laboratory conditions, from a LUMNITE:ESCS concrete. These data were developed using a particular ESCS aggregate. Other ESCS aggregates may produce different results depending on their gradation, method of manufacture, etc.

Aggregate Gradation & Bulk Density* (Cumulative Percent Retained on Each Sieve)

Tyler (Mesh) U.S. (Alternate)	0.371 in ⅜ in (9.5 mm)	4 4 (4.75 mm)	8 8 (2.36 mm)	14 16 (1.18 mm)	28 30 (600 µm)	48 50 (300 µm)	100 100 (150 µm)	Bulk Density lb/ft³ (g/cm³)
Size "A"	0	0.1	20.1	50.2	68.7	78.4	85.4	54.5 (0.87)
Size "B"	0	45.8	96.1					38.8 (0.62)

*The chemical composition of the aggregate is that shown in the above Oxide Analysis.

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A review of this data reveals that while the 1:6 mix has significantly lower strengths it also has somewhat lower unit weight. This reduced unit weight provides improved insulating properties. While the insulating properties of LUMNITE:ESCS concretes are not as good as could be achieved by using some of the very lightweight aggregates such as perlite or vermiculite, they combine good strength as well as corrosion and abrasion resistance with their insulating value and are used for lining stacks, ducts and breechings, as well as in and around process vessels in petroleum and petrochemical industries.

The data were developed on specimens made from small size batches under laboratory conditions where temperature, humidity, and curing were closely controlled. Actual field conditions may produce variable results.

For additional information, contact the District Sales Office nearest you or Lehigh Cement Company, 718 Hamilton Mall, Allentown, PA 18105, Telex: 5106511020, LEHPORCEM.

Typical Stack Lining Application

[illegible]

Aggregate:	1 Part Size "B"; 2 Parts Size "A" by Weight Bulk Density = 52.6 lb/ft³ (0.84 g/cm³)
Mix Proportions:	1:4 by dry, loose volume Water Solids (W/S) = 20.0% by weight
Consistency:	Wet "Ball-in-Hand"

Temperature Exposure F (C)	Linear Change %	Unit Weight lb/ft³ (g/cm³)	Compressive Strength psi (MPa)	Modulus of Rupture psi (MPa)
72 (22)*	—	102.4 (1.64)	4410 (30.4)	610 (4.2)
220 (105)	—	92.1 (1.48)	3780 (26.1)	680 (4.7)
500 (260)	−0.07	86.4 (1.38)	2620 (18.1)	350 (2.4)
1000 (540)	−0.12	84.1 (1.35)	2430 (16.8)	350 (2.4)
1500 (815)	−0.03	83.1 (1.33)	2360 (16.3)	360 (2.5)
2000 (1095)	−0.06	85.1 (1.36)	1680 (11.6)	405 (2.8)

*Moist Cure

PCE (Pyrometric Cone Equivalent)—9—10

Load Deformation Test—[2000 F (1095C) and 10 psi (69kPa) Load]—Deformation =2.6%

[illegible]

Aggregate:	1 Part Size "B"; 2 Parts Size "A" by Weight Bulk Density = 52.6 lb/ft³ (0.84 g/cm³)
Mix Proportions:	1:6 by dry, loose volume Water Solids (W/S) = 19.5% by weight
Consistency:	Wet "Ball-in-Hand"

Temperature Exposure F (C)	Linear Change %	Unit Weight lb/ft³ (g/cm³)	Compressive Strength psi (MPa)	Modulus of Rupture psi (MPa)
72 (22)*	—	84.0 (1.35)	1540 (10.6)	315 (2.2)
220 (105)	—	77.8 (1.25)	1680 (11.6)	365 (2.5)
500 (260)	−0.08	78.6 (1.26)	1480 (10.2)	245 (1.7)
1000 (540)	−0.11	77.2 (1.24)	1460 (10.1)	240 (1.7)
1500 (815)	−0.03	78.4 (1.26)	1460 (10.1)	265 (1.8)
2000 (1095)	+0.25	72.3 (1.16)	740 (5.1)	195 (1.3)

*Moist Cure

PCE (Pyrometric Cone Equivalent)=7

Load Deformation Test—[2000 F (1095C) and 10 psi (69kPa) Load]—Deformation =3.5%

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ATLAS LUMNITE & REFCON

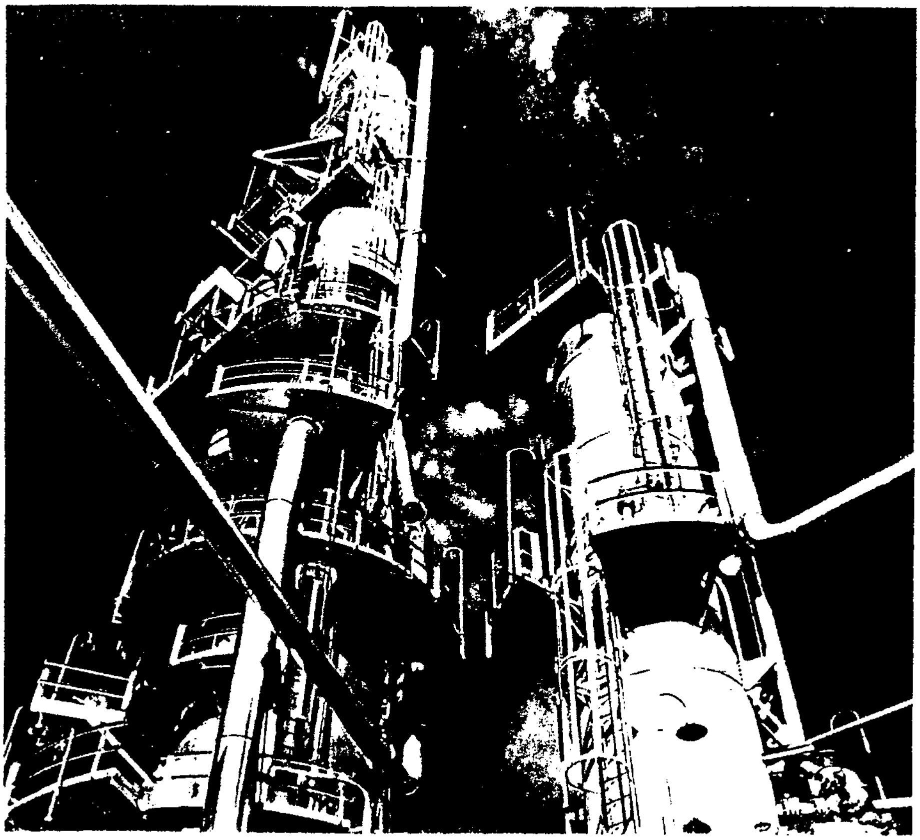
Calcium-Aluminate Cements

Refractory Concrete

LUMNITE: Expanded Shale, Clay, Slate: Vermiculite

In Bulletin No. 2-02 we discussed the properties of LUMNITE: expanded shale, clay, slate (ESCS) concretes and mortars. Mixtures of this type provide high strength, good resistance to abrasion and corrosion, and good insulating properties. For some installations, strength and abrasion and corrosion resistance are of secondary importance, and the major function of the refractory lining is that of insulation. In these cases, very lightweight aggregate such as vermiculite (exfoliated mica) may be used in conjunction with LUMNITE and ESCS aggregates.

Vermiculite is a form of mica that was long considered to be practically valueless. In its crude state, a piece of vermiculite consists of thousands of paper-thin sheets. Trapped between these sheets and within the mineral are molecules of water. The raw ore, which is comparatively soft, is crushed, cleaned, dried and sized before being directly exposed to open heat at about 2000F (1095C) which turns the entrapped water to steam, causing the sheets to separate and move apart. At the same time, the granules expand from 12 to 15 times their original size, forming in the process thousands of tiny cells of dead air. It is these cells that provide most of the insulating properties of the ex-



Refractory Insulating Concrete Used in the Petroleum Industry

Aggregate Gradation & Bulk Density (Cumulative Percent Retained on Each Sieve)

Tyler (Mesh) U.S. (Alternate)	0.371 in ⅜ in (9.5 mm)	4 4 (4.75 mm)	8 8 (2.36 mm)	14 16 (1.18 mm)	28 30 (600 μm)	48 50 (300 μm)	100 100 (150 μm)	Bulk Density lb/ft³ (g/cm³)
ESCS—Size "A"	0	0.1	20.1	50.2	68.7	78.4	85.4	54.5 (0.87)
Vermiculite	—	2.3	17.8	37.2	67.6	90.5	97.5	9.6 (0.15)

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panded vermiculite. The remainder comes from the shiny surfaces of the particles, which reflect radiant heat somewhat as a mirror will reflect light.

The particles of finished aggregate are relatively soft and the color varies from brown to buff with a characteristic pearly luster.

Data on a LUMNITE: ESCS: vermiculite mix are shown in the table. These data are presented as an example of the properties that can be achieved under laboratory conditions. They were developed using a specific ESCS aggregate and vermiculite with the gradation shown. Other ESCS aggregates or different aggregate gradations may produce different results.

The data were developed on specimens made from small size batches under laboratory conditions where temperature, humidity, and curing were closely controlled. Actual field conditions may produce variable results.

Aggregates:		
	ESCS:	Size "A" (2 Parts by volume) Bulk Density—54.5 lb/ft³ (0.87 g/cm³)
	Vermiculite:	4 Parts by volume Bulk Density = 9.6 lb/ft³ (0.15 g/cm³)
Mix proportions:		1:2:4 LUMNITE: ESCS: Vermiculite by dry, loose volume Water Solids (W/S) = 56.1% by weight
Consistency:		Wet "Ball-In-Hand"

Note: Aggregate presoaked (15 minutes) with approximately 2/3 of required water.

Temperature Exposure F (C)	Linear Change %	Unit Weight lb/ft³ (g/cm³)	Compressive Strength psi (MPa)	Modulus of Rupture psi (MPa)
72 (22)*	—	91.7 (1.47)	120 (0.83)	65 (0.45)
220 (105)	—	67.2 (1.08)	370 (2.55)	130 (0.90)
500 (260)	−0.43	62.5 (1.00)	270 (1.86)	75 (0.52)
1000 (540)	−0.46	62.1 (0.99)	280 (1.93)	70 (0.48)
1500 (815)	−0.54	61.0 (0.98)	250 (1.72)	75 (0.52)
2000 (1095)	−1.35	61.7 (0.99)	110 (0.76)	45 (0.31)

*Moist Cure

A comparison of the data on 1:2:4 LUMNITE: ESCS: vermiculite with that shown in Bulletin No. 2-02 on 1:6 LUMNITE: ESCS shows that the use of 4 parts vermiculite instead of 4 parts ESCS reduces the unit weight of the concrete after drying. This reduction in weight reduces the thermal conductivity (k) of the concrete, providing improved insulating properties. A further improvement in insulation can be achieved by using all vermiculite or other very lightweight aggregates. Data along these lines are presented in another bulletin.

It must also be noted that the substitution of vermiculite or other very lightweight aggregates for ESCS aggregate drastically reduces the strength of the concrete. The very lightweight aggregates (vermiculite, perlite, calcined diatomaceous earth) should only be used in applications where insulation is the prime consideration and strength and abrasion and corrosion resistance are of little or no significance.

Since vermiculite and the other very lightweight aggregates are highly absorbent, the amount of water required to produce a plastic workable concrete or mortar containing these aggregates is naturally very high. This high water content is partially responsible for the very low strengths, and also results in rather large volume changes when the concrete or mortar is dried and fired.

For additional information, contact the District Sales Office nearest you or Lehigh Cement Company, 718 Hamilton Mall, Allentown, PA 18105, Telex: 5106511020, LEHPORCEM.

Typical Lumnite ESCS: Vermiculite Application

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LEHIGH Calcium Aluminate Cements and Mortars

LUMNITE® and **REFCON®** calcium aluminate cements are manufactured by the Lehigh Portland Cement Company. Bauxite and limestone are the basic raw materials used in the patented "Shock Sintering" manufacturing process, which is the first of its kind in the world for calcium aluminate cements. Variations of these cements designated RS (Rapid Set) are also available. Further detail on these cements is noted under "Quick Setting Mixes" and in separate bulletins.

The raw materials are pelletized and heated to high temperatures in the solid state rather than melted as has been practiced previously. Because the pellets are heated very rapidly from a calcining temperature to a maximum reaction temperature, the most desirable cement compounds are formed.

In the manufacturing process, finely powdered raw meal is compounded from precisely controlled raw materials. The raw meal is then pelletized on a disc pelletizer and transported to a drier-preheater. There the moisture is removed and the pellets preheated before being fed into the kiln for sintering. A specially designed rotary kiln produces the required solid state reaction in the sinter with a high degree of uniformity. The sintered pellets are then ground into cement. Calcium aluminate cements are not portland cements (calcium silicate), but like portland cements they set and harden when mixed with water.

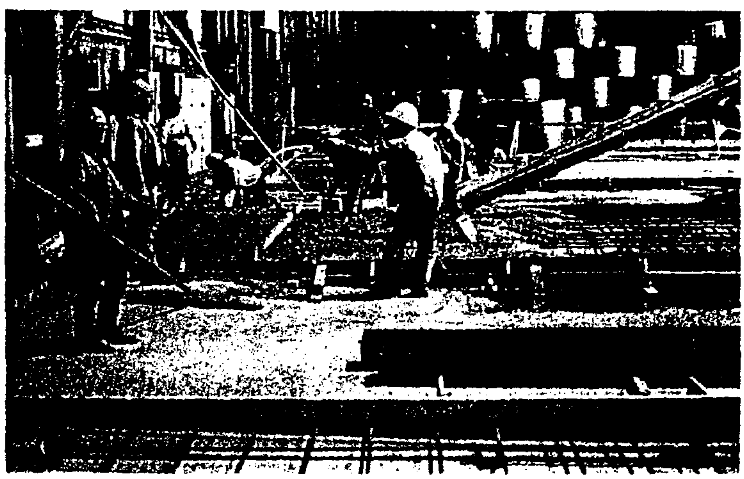
The high alumina content of both cements contributes to increased refractoriness in various concrete and mortar mixes. Low iron contents, expressed as Fe_2O_3 also enhance refractory properties and provide increased resistance to CO disintegration.

Physical Characteristics: Typical

Properties	LUMNITE	REFCON
BULK DENSITY		
kg/m³ (lb/ft³)	(94)1500	(94)1500
SPECIFIC GRAVITY	3.02	3.02
SPECIFIC SURFACE		
Blaine - m²/kg	350	350
SETTING TIME, ASTM C-403		
hours:min	4:00	4:30
COMPRESSIVE STRENGTH		
1 day Mpa	35	45
psi, ASTM C-109	5000	6500

Chemical Analysis: Typical Percent

Oxide	LUMNITE	REFCON
$Al_2O_3+TiO_2$	48.0 %	59.0 %
Fe_2O_3 (Total Iron)	6.0 %	1.2 %
CaO	34.5 %	34.2 %
SiO_2	8.5 %	5.0 %
MgO	0.7 %	0.0 %
SO_3	0.5 %	0.3 %



Both LUMNITE and REFCON cements are manufactured at Buffington (near Gary), Indiana, and are available for shipment in bulk and in 42.6 kg (94 lb.) (1 cu. ft.) bags. These products are readily available for shipment from most of our other cement producing and distribution facilities.

Maximum Service Temperature

Aggregate	LUMNITE	REFCON
Diabase Traprock	980° C 1800° F	980° C 1800° F
Exfoliated Mica (Vermiculite)	1090° C 2000° F	1090° C 2000° F
Expanded Clay or Shale	1150° C 2100° F	1150° C 2100° F
Crushed Firebrick	1370° C 2500° F	1570° C 2850° F
Calcined Flint Clay	1370° C 2500° F	1570° C 2850° F
Mullite, Kyanite or Bauxite	1370° C 2500° F	1570° C 2850° F

Applications

Refractory Concrete & Mortars

The primary use of LUMNITE and REFCON cements are to produce refractory concretes and mortars. LUMNITE and suitable aggregates are used in applications where service temperatures up to 1372° C (2500° F) are encountered. Because of its higher alumina and lower iron content, REFCON is similarly used in applications up to 1570° C (2850° F). In addition, the low iron content of REFCON makes it especially suitable with low iron bearing aggregates to combat the effects of reducing atmospheres (carbon monoxide) on concrete and/or mortar linings. The table shows the maximum service temperatures of selected aggregates mixed in combination with cement under optimum conditions.

Many refractory producers market prepared castable mixes containing LUMNITE or REFCON cements and selected aggregates. Castables are convenient to use, as they have controlled cement/aggregate ratios, aggregate quality and gradation. The castable producer should be consulted to obtain the proper product for a particular application.

Raw pellets being processed

Corrosion-Resistant Concrete & Mortars

LUMNITE hydrates to produce an alumina gel in the concrete or mortar that makes it resistant to the corrosive effects of many industrial wastes and certain mild acids. It is also highly resistant to sulfate attack. The aggregate as well as the cement must be resistant to corrosion. Keeping density high and porosity low is critical to good corrosion-resistant concrete.

Overnight & Structural Concrete

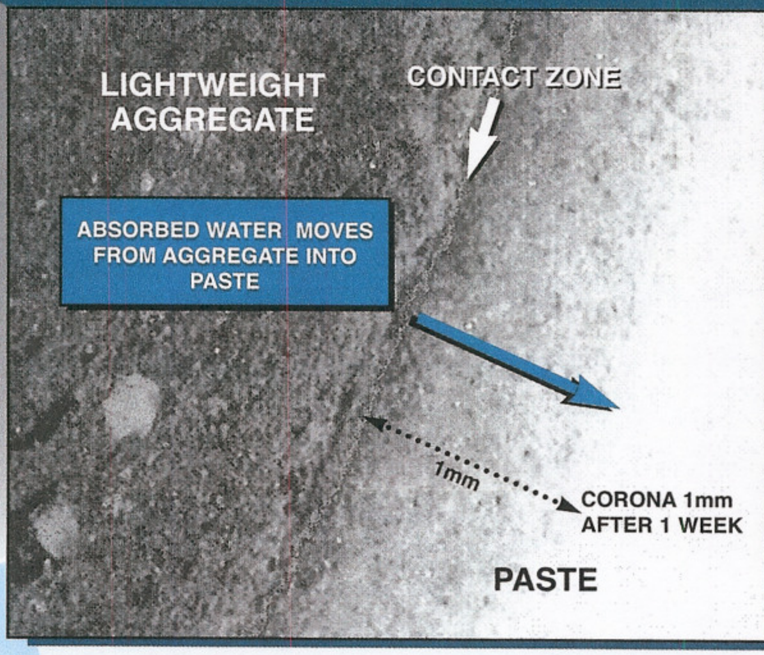
Because of the rapid strength devel-

6D

ESCSI Publication #4362

“Internal Curing Using Expanded Shale, Clay and Slate Lightweight Aggregate”

INTERNAL CURING
Using Expanded Shale, Clay and Slate Lightweight Aggregate



ESCSI

Internal Curing
Using Expanded Shale, Clay and Slate Lightweight Aggregate

The text and references are from ASTM 169D *Significance of Test and Properties of Concrete and Concrete Making Materials*, Chapter 46 – "Lightweight Concrete and Aggregate," American Society of Testing Materials, West Conshohocken, PA 2006. The figure (I) was developed by ESCSI and is not in Chapter 46.

Internal Curing

Lightweight aggregate batched at a high degree of absorbed water may be substituted for normalweight aggregates to provide "internal curing" in concrete containing a high volume of cementitious materials. High cementitious concretes are vulnerable to self-desiccation and early-age cracking, and benefit significantly from the slowly released internal moisture. Field experience has shown that high strength concrete is not necessarily high performance concrete and that high performance concrete need not necessarily be high strength. A frequent, unintended consequence of high strength concrete is early-age cracking. Blending lightweight aggregate containing absorbed water is significantly helpful for concretes made with a low ratio of water-to-cementitious material or concretes containing high volumes of supplementary cementitious materials that are sensitive to curing procedures. This process is often referred to as water entrainment.

Time dependent improvement in the quality of concrete containing prewet lightweight aggregate is greater than with normalweight aggregate. The reason is better hydration of the cementitious materials provided by moisture available from the slowly released reservoir of absorbed water within the pores of the lightweight aggregate. The fact that absorbed moisture in the lightweight aggregate is available for internal curing has been known for more than four decades. The first documentation of improved long term strength gains made possible by the use of saturated normalweight aggregates, was reported in 1957 by Paul Klieger [2], who, in addition, commented in detail on the role of absorbed water in lightweight aggregates for extended internal curing.

In his 1965 report, "Concrete Strength Measurement – Cores vs. Cylinders," presented to the National Sand and Gravel Association and the National Ready Mixed Concrete Association, Bloem [3] states, "Measured strength for lightweight concrete cylinders was not reduced by simulated field curing methods employed. This would tend to support the suggestion that the high absorption of lightweight aggregate may have the beneficial effect of supplying curing water internally." This was confirmed by Campbell and Tobin [4] in their comprehensive program which compared strengths of cores taken from field cured exposed slabs with test results obtained from laboratory specimens cured strictly in accordance with ASTM C 31. Their tests confirmed that the availability of absorbed moisture in lightweight aggregate produced a more forgiving concrete that was less sensitive to poor field curing conditions. Addressing the long term service performance of lightweight concrete, Holm [5] cited the improved integrity of the contact zone between the lightweight aggregate and the matrix. The improved quality was attributed to internal curing, and better cement hydration and pozzolanic activity at the interface, and reduction in stress concentrations resulting from elastic compatibility of the concrete constituents.

The benefits of internal curing go far beyond any improvements in long-term strength gain, which from some combinations of materials may be minimal or non-existent. **The principal contribution of internal curing results in the reduction of permeability that develops from a significant extension in the time of curing.** Powers [6] showed that extending the time of curing increased the volume of cementitious products formed which caused the capillaries to become segmented and discontinuous.

It appears that in 1991, Philleo (7) was the first to recognize the potential benefits to high performance normalweight concrete possible with the addition of lightweight aggregate containing high volumes of absorbed moisture. Reduced sensitivity to poor curing conditions in concretes containing an adequate volume of prewet lightweight aggregate has also been reported [8]. Since 1995 a large number of papers addressing the role of water entrainment's influence on internal curing and autogenous shrinkage have been published of which Bentz, et al, is typical [9].

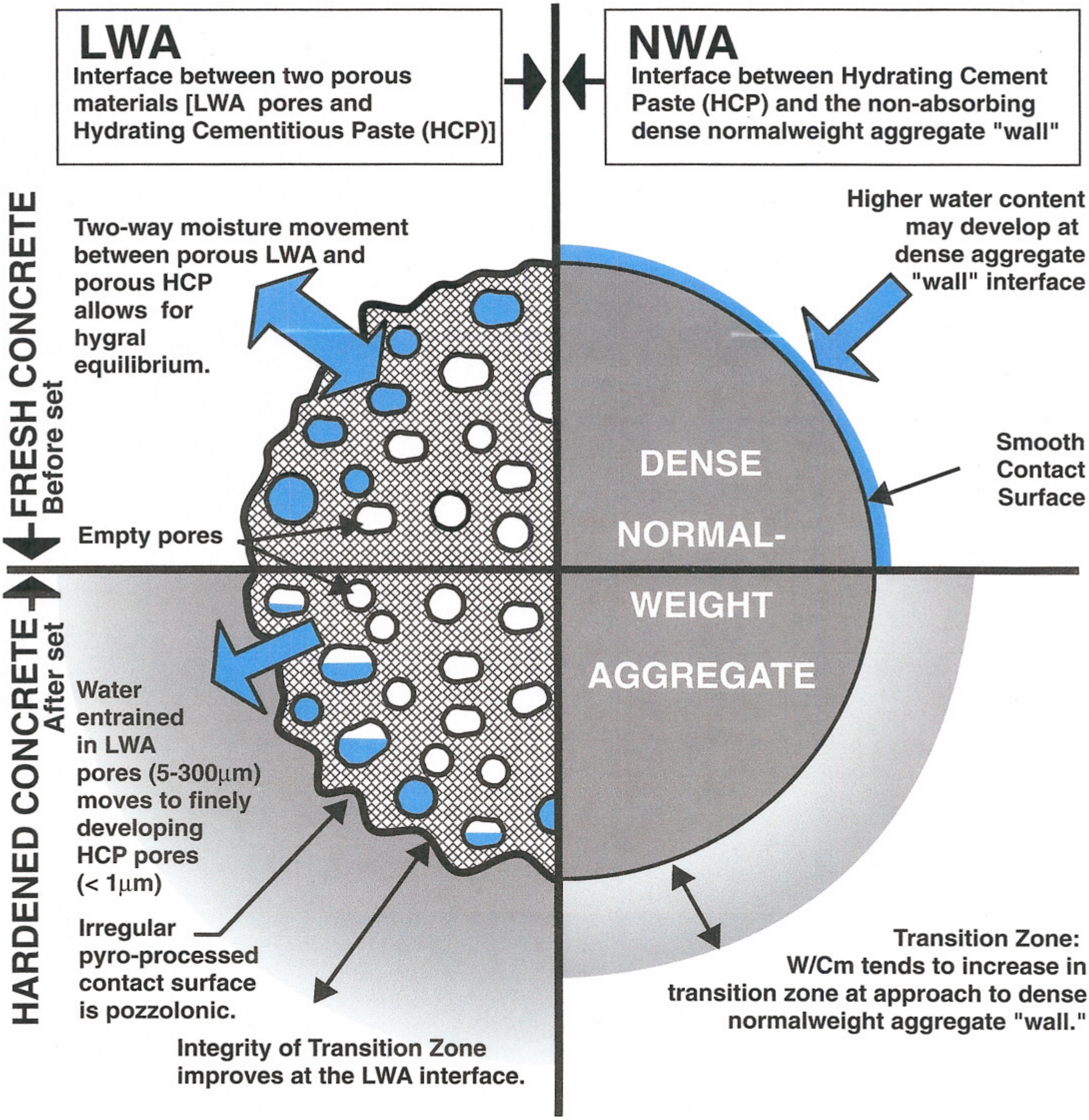
The benefits of internal curing are increasingly important when supplementary cementitious materials, (silica fume, fly ash, metokaolin, calcined shales, clays and slates, as well as the fines of lightweight aggregate) are included in the mixture. It is well known that the pozzolanic reaction of finely divided alumina-silicates with calcium hydroxide liberated as cement hydrates is contingent upon the availability of moisture. Additionally, internal curing provided by absorbed water minimizes the "plastic" (early) shrinkage due to rapid drying of concretes exposed to unfavorable drying conditions. [10]

Contact Zone

The expression "contact zone" includes two distinctively different phenomena: (1) the mechanical adhesion of the cementitious matrix to the surface of the aggregate and (2) the variation of physical and chemical characteristics of the transition layer of the cementitious matrix close to the aggregate particle. Collapse of the structural integrity of the concrete conglomerate may come from the failure of either the aggregate or cementitious matrix, or from a breakdown in the contact zone causing a separation of the still intact phases. The various mechanisms that act to maintain continuity, or that cause separation; have not received the same attention as has the air void system necessary to protect the matrix. Aggregates are frequently dismissed as being inert fillers and, as a result, they and the associated contact zone have not received adequate attention.

In order that concrete perform satisfactorily in severe exposure conditions, it is essential that a good bond develop and be maintained between the aggregate and the enveloping mortar matrix. A high incidence of interfacial cracking or aggregate debonding will have a serious effect on durability if these cracks fill with water and subsequently freeze. Deterioration will result, with pieces of apparently sound mortar separating from the bottom of the aggregate, usually with some of the mortar remaining firmly attached to the top side of the aggregate. An equally serious consequence of microcracking is the easy path provided for the ingress for aggressive agents into the mass of the concrete, rendering ineffective the

Internal Curing at the Contact Zone



IMPROVING THE TRANSITION ZONE

"Internal curing" refers to the process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water (ACI 213-03R).

"Contact Zone" refers to two distinctly different phenomena: (1) the mechanical adhesion of the cementitious matrix to the surface of the aggregate; (2) the variation of physical and chemical characteristics of the transition layer of the cementitious matrix close to the aggregate particle (ASTM STP 169 D [2006] Chapter # 46 Holm & Ries) protective layer of concrete over the reinforcing steel. The morphology and distribution of chemical elements at the transition layer in a number of mature structures that have withstood severe exposure were examined and reported by Bremner, et. al. [23].

The contact zone of lightweight aggregate concrete has been demonstrated to be significantly superior to that of normalweight concretes that do not contain supplementary cementitious material [19, 24]. This profound improvement in the quality, integrity, and microstructure stems from a number of characteristics unique to lightweight concrete that includes:

- The pozzolanic alumina/silicate surface of the fired ceramic aggregate combines with $CaOH_2$ liberated by hydration of the Portland cement.

- Reduced microcracking in the contact zone because of the elastic similarity of the aggregate and the surrounding cementitious matrix. [25]

- Hygral equilibrium between two porous materials (Lightweight aggregate and porous cementitious matrix) as opposed to the usual condition with normalweight aggregate, where bleed-water lenses form around essentially non-absorbent coarse natural aggregates. These lenses have water-to-cementitious materials ratios significantly higher than in the rest of the matrix. When supplementary cementitious materials are added, the high-quality microstructure of the contact zone around lightweight aggregate is moderately enhanced. However, when supplementary cementitious materials are used in concretes containing normalweight aggregate, this zone of weakness is profoundly improved.

While the reduction in compressive and tensile strength due to poor contact zone is important, the significance of increasing permeability is even greater. Increasing permeability inevitably leads to penetration of aggressive agents that accelerate corrosion of embedded reinforcement. The permeability of concrete is greater than the permeability of its constituents. This increase in permeability results from interfacial flaws at the aggregate surface linking up with microcracking in the transition layer.

The phenomenon of bleed water collecting and being entrapped under coarse particles of lightweight aggregate is mitigated if not eliminated. This has been verified in practice by the examination of the contact zone of lightweight concrete tensile splitting cylinders, as well as by visual examination of sandblasted vertical surfaces of building structures. This observation should not be surprising because, with structural lightweight concrete, the aggregate/matrix interface is a boundary between two porous media, while with normal-weight concrete there is an abrupt transition at the dense aggregate/porous cementitious matrix interface.

Implication of Contact Zone on Failure Mechanisms

Exposed concrete must endure the superposition of dynamic forces including variable live loads, rapid temperature changes, moisture gradients, and dilation due to chemical changes. These factors cause a predominantly tensile-related failure. Yet, the uniaxial compressive strength is traditionally considered the preeminent single index of quality, despite the fact that inadequate concrete performance is seldom related to this parameter. The simplicity and ease of compression testing has diverted our focus from life-cycle performance and the development of appropriate measurement techniques that quantify durable concrete characteristics.

In general, weakest link mechanisms are undetected in uniaxial compression tests due to concrete's forgiving load-sharing characteristics in compression, because of localized yielding and the closure of temperature and volume-change cracks. **Weakest link mechanisms, however, are decisive in tensile failures in both dynamic and durability exposure conditions. In most concretes the limiting factor in the long term performance is the integrity of contact zone.**

Cover photo of the movement of absorbed water from aggregate to paste is from the Ph.D Thesis, *Autogenous Deformation and Internal Curing of Concrete*, P. Lura 2003

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Publication # 4362
July '06

6E

Chapter 46 "*Lightweight Concrete and Aggregates*", Significance of Tests and Properties of Concrete and Concrete-Making Materials ASTM Special Technical Publication 169D

Chapter 46

Lightweight Concrete And Aggregates

Significance of Tests and Properties of Concrete and Concrete-Making Materials ASTM Special Technical Publication 169D

Thomas A. Holm and John P. Ries

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Lightweight Concrete and Aggregates

Thomas A. Holm[1] and John P. Ries[1]

Preface

THE GENERAL PRESENTATION OF THIS EDITION IS similar to previous editions, with additional information on structural properties of lightweight aggregates, as well as strength making, durability, and placement characteristics of lightweight concrete to reflect the current state of the art. This edition also includes new discussions relative to the moisture dynamics and the enhanced hydration of cementitious materials brought about by internal curing when using water-entraining lightweight aggregates. Specified density concrete, concrete with densities between traditional lightweight and normal-weight concretes, is also discussed. In *ASTM STP 169* this chapter was authored by R. E. Davis and J. W. Kelly. *ASTM 169A* and *ASTM 169B* were authored by D. W. Lewis. *ASTM 169C* was authored by T. A. Holm.

Classification of Lightweight Aggregates and Lightweight Aggregate Concretes

Lightweight aggregate concretes are broadly divided into three groups based upon their use and physical properties: structural, structural/insulating, and insulating. Bulk density, thermal conductivity, and compressive strength ranges normally associated with each class of concrete are summarized in Table 1.

This chapter primarily addresses structural concretes where weight reduction is achieved through the use of lightweight aggregates. Cellular concrete is covered in a separate chapter in this volume, where lighter weight is developed primarily by inclusion of large amounts of air or gas through the use of foaming-type agents.

Structural

Structural lightweight concretes generally contain aggregates made from pyroprocessed shales, clays, slates, expanded slags, expanded fly ash, and those mined from natural porous volcanic sources. Structural lightweight concrete is normally classified by a minimum compressive strength that was jointly established by the ASTM Specification for Lightweight Aggregates (C 330) and the Standard Building Code for Reinforced Concrete (ACI 318) [1]. The 318 code definition is structural concrete made with lightweight aggregate; the equilibrium density as determined by ASTM Test Method for Determining Density of Structural Lightweight Concrete (C 567) not exceeding 115 lb/ft^3 and the compressive strength is more than 17.2 MPa (2500 psi). This is a definition, not a specification and project requirements may permit higher equilibrium densities. Although structural concrete with equilibrium densities from 1450 to 1920 kg/m^3 (90 to 120 lb/ft^3) are often used, most lightweight aggregate concrete used in structures have equilibrium densities between 1760 to 1840 kg/m^3 (110 and 115 lb/ft^3).

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

Structural lightweight aggregates can be manufactured from raw materials such as, for example, soft shales and clays that have limited structural applications in their natural state. This is an environmentally sound practice as it minimizes demands on finite resources of quality natural sands, stones, and gravels.

Structural/Insulating

Industrial applications that call for "fill" concretes often require compressive strengths and densities in the intermediate between structural and insulating concretes. These concretes may be produced with high air contents and include structural lightweight aggregate, or sanded insulating lightweight aggregate mixtures, or they may incorporate both structural and insulating lightweight aggregates. Compressive strengths from 3.4 to 17 MPa (500 to 2500 psi) are common with thermal resistance ranging between insulating and structural concrete.

Insulating

Insulating concretes are very light nonstructural concretes, employed primarily for high thermal resistance, that incorporate low-density low-strength aggregates such as vermiculite and perlite. With low densities, seldom exceeding 800 kg/m^3 (50 lb/ft^3), thermal resistance is high. These concretes are not intended to be exposed to weather and generally have a compressive strength range from about 0.69 to 3.4 MPa (100 to 500 psi).

[1] Director of Engineering and President, respectively, Expanded Shale Clay and Slate Institute, Salt Lake City, UT 84117.

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

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

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

Properties of Lightweight Aggregate

Internal Structure of Lightweight Aggregates

Lightweight aggregates have a low particle density because of the cellular structure. The cellular structure within the particles is normally developed by heating certain raw materials to incipient fusion, at which temperature gases are evolved within the pyroplastic mass causing expansion that is retained upon cooling. Strong, durable, lightweight aggregates contain a uniformly distributed system of pores that have a size range of approximately 5 to 300 μm (0.000040 in.) and which are developed in a relatively crack-free, high-strength vitreous matrix (Fig. 1).

Particle Shape and Surface Texture

Depending on the source and the method of production, lightweight aggregates exhibit considerable differences in particle shape and texture. Shapes may be cubical, rounded, angular, or irregular. Textures may range from fine pore, relatively smooth skins to highly irregular surfaces with large exposed pores. Particle shape and surface texture directly influence workability, coarse-to-fine aggregate ratio, cement content requirements, and water demand in concrete mixtures, as well as other physical properties.

Relative Density

The relative density of an aggregate is the ratio between the mass of the material and the volume occupied by the individual particles contained in that sample. This volume includes the pores within the particles but does not include the voids between the particles. Relative density of individual particles depends both on the relative density of the poreless vitreous material and the pore volume within the particles, and generally increases when particle size decreases. The relative density of the pore-free vitreous material may be determined by pulverizing the lightweight aggregate in a jar mill and then following procedures used for determination of the relative density of cement.

Bulk Density

Aggregate bulk density is defined as the ratio of the mass of a given quantity of material and the total volume occupied by it. This volume includes the voids between, as well as the pores within, the particles. Bulk density is a function of particle shape, density, size, gradings, and moisture content, as well as the method of packing the material (loose, vibrated, rodded), and varies not only for different materials, but for different sizes and gradations of a particular material. Table 2 summarizes the maximum bulk density for lightweight aggregates listed in ASTM (C 330) and ASTM Specification for Lightweight Aggregates for Concrete Masonry Units (C 331). ASTM Standard Specification for Lightweight Aggregates for Insulating Concrete (C 332) provides minimum density requirements for perlite and vermiculite to limit over-expanded, weak particles that would break down in mixing. The relationship between the particle relative density and the bulk density of a sample is illustrated in Fig. 2 for a hypothetical lightweight aggregate.

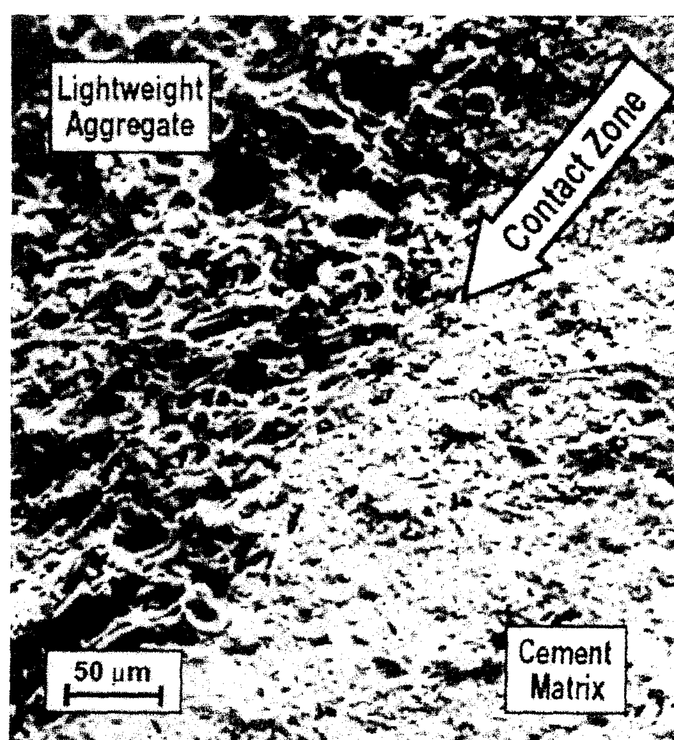


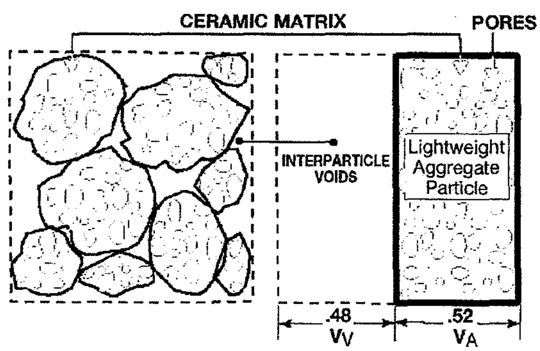
Fig. 1—Contact zone—structural lightweight concrete from 30-year-old bridge deck, W. P. Lane Memorial Bridge over the Chesapeake Bay, Annapolis, Maryland: compression strength 24 MPa (3500 psi); density 1680 kg/m^3 (105 lb/ft^3).

TABLE 2—Requirements of ASTM C 330, C 331, and C 332 for Dry Loose Bulk Density of Lightweight Aggregates

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

Grading

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



The following calculations are based on a hypothetical lightweight aggregate sample (illustrated above) that has a bulk loose dry density of 44.6 lb/ft³ (714 kg/m³) and a relative density (SSD pychnometer) of 1.52 after a 24-hour soak resulting in a moisture content of 10.5% by weight. The relative density of the ceramic matrix was measured to be 2.60.

$$RD_D \left[\begin{array}{c}\text{Relative}\\ \text{Density,}\\ \text{Dry}\end{array}\right] = \frac{RD_{24}}{(1+M)} \left[\frac{\text{Pychnometer Relative Density after 24-Hour Soak}}{\text{Moisture Content by Weight after 24-hour Soak}}\right] = \frac{1.52}{1+.105} = 1.38\ (1380)$$

$$V_A \left[\begin{array}{c}\text{Fractional Part of Bulk}\\ \text{Volume Occupied by}\\ \text{Aggregate Particles}\end{array}\right] = \frac{D_B}{RD_D} \left[\frac{\text{Measured Bulk Dry Loose Density}}{\text{Relative Density of Dry Particle}}\right] = \frac{714}{1380} = 0.52$$

$$V_V \left[\begin{array}{c}\text{Fractional Part of Bulk}\\ \text{Volume Occupied by Voids}\\ \text{between Particles}\end{array}\right] = 1.00 - 0.52 = 0.48$$

Fig. 2—Schematic representation of lightweight aggregate bulk volume, interparticle voids, and internal particle pores.

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

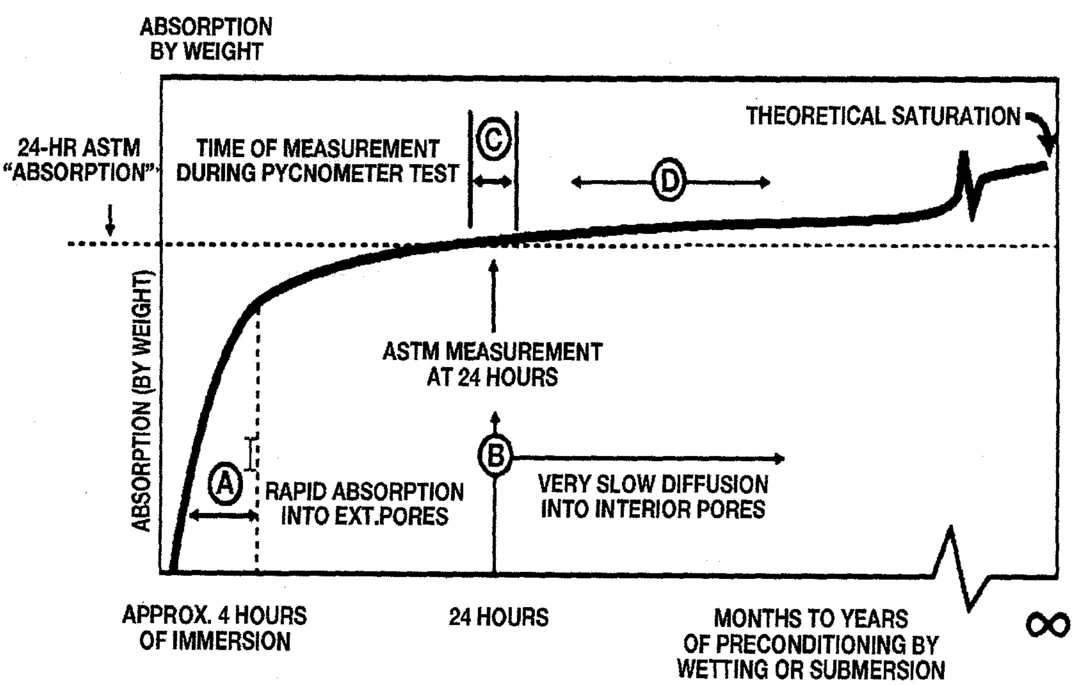
Absorption Characteristics

Due to their porous structure, lightweight aggregates absorb more water than their normal-weight aggregate counterparts. Based upon a 24-h absorption test, conducted in accordance with the procedures of ASTM Test Method Specific Gravity and Absorption of Coarse Aggregate (C 127) and ASTM Test Method Density, Relative Density and Absorption of Fine Aggregate (C 128), lightweight aggregates will absorb from 5 to more than 25 % by weight of dry aggregate. By contrast, normal-weight aggregates generally absorb less than 2 %. The important difference in measurements of stockpile moisture contents is that with lightweight aggregates the moisture is largely absorbed into the interior of the particles whereas in normal-weight aggregates it is primarily adsorbed, surface moisture. Recognition of this essential difference is important in mixture proportioning, batching, and field control. Rate of absorption of lightweight aggregates is dependent on the characteristics of pore size, connection, and distribution, particularly those close to the surface. Pores close to the surface are readily permeable and fill within the first few hours of exposure to moisture. Interior pores, however, fill slowly, with many months of submersion necessary. A fraction of the interior pores are essentially non-interconnected and remain unfilled after years of immersion.

Internally absorbed water within the particle is not immediately available for chemical interaction with cement and mixing water, but is extremely beneficial in maintaining longer periods of curing essential to improvements in the hydration of cement and the aggregate/matrix contact zone.

ASTM C 127 procedures prescribe measuring the "saturated" particle density in a pycnometer and then determining the absorbed moisture content on the sample that had been immersed in water for 24 h. With lightweight aggregate it is more accurate to report partially saturated after a 24-h soak because the particle is not fully saturated yet. After a 24-h immersion in water, the rate of moisture absorption into the lightweight aggregate will be so low that the partially saturated particle density will be essentially unchanged during the time necessary to take weight measurements in the pycnometer. After the moisture content is known, the over-dry particle density may be directly computed. As can be seen in Fig. 3, the rate of absorbtion can be divided into several regions.

Following the prescribed procedures, the degree of saturation, that is, the fractional part of the pore volume occupied by water, will generally be in the range of approximately 25 to 35 % of the theoretical total saturation of all pores for



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

Fig. 3—Absorption vs. time for typical structural grade expanded shale, clay, or slate (ESCS).

structural lightweight aggregates. The use of the ASTM expression "saturated surface dry" for lightweight aggregates is theoretically inaccurate, analytically misleading, and, therefore, inappropriate.

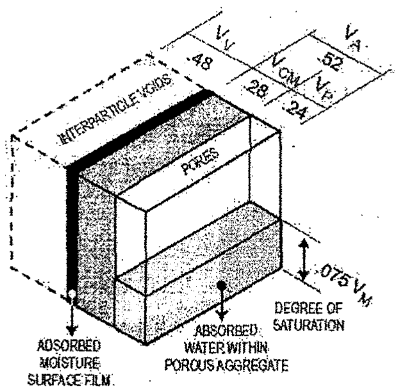
From a practical perspective and considering the fact that most lightweight concrete is placed by pumping, the usual practice is to batch the lightweight aggregate at a moisture condition greater than the "Absorption Value" defined by ASTM procedures (24-h immersion). In this condition the absorbed (internal)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

Due to pre-wetting, there will invariably be a film of surface water on the lightweight aggregate. As with normal-weight concrete it is essential to evaluate this quantity of surface water for an accurate determination of the "net" mixing water to achieve the desired workability and to determine the effective water-to-cementitious materials ratio.

To accurately determine the amount of absorbed water and the amount of surface water it is necessary to run the usual moisture test as follows. Measure the weight of the wet, ready-to-batch surface moist sample. After towel drying, measure the weight of the surface dry sample. Conduct the drying test to calculate the moisture content absorbed within the sample. The surface water (adsorbed) on the lightweight aggregate is then determined by the difference between the as-received and the absorbed moisture contents. (Fig. 4)

Proportioning Lightweight Concrete

Proportioning procedures used for ordinary concrete mixes apply to lightweight concrete with added attention given to



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

$$\text{Fractional Part of Lightweight Aggregate Particle Occupied by Pores} = 1.00 - 0.53 = 0.47$$

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

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

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

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

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

Fig. 4—Schematic representation of volumes occupied by the ceramic matrix, the internal pores, and the degree of saturation of absorbed water (see Fig. 2).

concrete density and the water absorption characteristics of the lightweight aggregate, Standard Practice for Selecting Proportions for Structural Lightweight Concrete, ACI 211.2. Structural lightweight concretes are generally proportioned by absolute volume methods in which the fresh concrete produced is considered equal to the sum of the absolute volumes of cement, aggregates, net water, and entrained air. Proportioning by this method requires the determination of absorbed and surface moisture contents and the aggregate's relative density factor.

When lightweight aggregates have been preconditioned to levels of absorbed moisture greater than that developed after a one-day immersion, the rate of further absorption will be very low and the water-to-cementitious materials ratios can be established with precision. Thus, lightweight concrete can meet water-to-cementitious materials specification requirements with the same facility as normal-weight concrete. Water absorbed within the lightweight aggregate prior to mixing is not used for calculating the water-to-cementitious materials ratio at the time of setting. This absorbed water is available, however, for internal curing and the continued cement hydration after external curing has ended.

Air Content

As with normal-weight concrete, air-entrained lightweight concrete significantly improves durability and resistance to scaling, reduces density, and improves workability. With 4 to 6 % air contents, bleeding and segregation are reduced and mixing water requirements are lowered while maintaining optimum workability. Because of the elastic compatibility of the lightweight aggregate and mortar matrix, strength reduction penalties due to high air contents will be lower for structural lightweight concrete than for normal-weight concretes.

Air content of lightweight aggregate concretes is determined in accordance with the procedures of ASTM Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method (C 173). Volumetric measurements assure reliable results while the pressure method, Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method (ASTM C 231), will provide erratic data due to the influence of aggregate porosity.

Air contents higher than required for durability considerations are frequently developed for high thermal resistance, or for lowering density of semi-structural "fill" concrete, with reduced compressive strength as a natural consequence.

Admixtures

Use of water reducers, retarders, and superplasticizers will result in improved lightweight concrete characteristics in a manner similar to that of normal-weight concretes; however, superplasticizers, while effective, will slightly increase the density of lightweight concrete.

Mixing, Placing, and Curing

Properly proportioned structural lightweight concrete can be mixed, delivered, and placed with the same equipment as normal-weight concretes. The most important consideration in handling any type of concrete is to avoid segregation of coarse aggregate from the mortar fraction. The basic principles required to secure a well-placed concrete also apply to lightweight concrete:

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

Well-proportioned structural lightweight concretes can be placed and screeded with less physical effort than that required for ordinary concrete. Excessive vibration should be avoided, as this practice serves to drive the heavier mortar fraction down from the surface where it is required for finishing. On completion of final finishing, curing operations similar to normal-weight concrete should begin as soon as possible. Lightweight concretes batched with pre-wet aggregates carry their own internal water supply for curing and as a result are more forgiving to unfavorable ambient conditions and poor curing practices.

Prewetting

Lightweight aggregates may absorb part of the mixing water when exposed to increased pumping pressures. To avoid loss of workability, it is essential to properly prewet the lightweight aggregates prior to pumping. Prewetting is often done at the aggregate production plant and continued at the concrete plant or can be done entirely at the concrete plant by wetting stockpile with sprinkler systems. It is essential to consult the aggregate supplier on methods and duration of prewetting.

Prewetting will significantly reduce the lightweight aggregates' rate of absorption, minimizing water transfer from the mortar fraction that, in turn, causes slump loss during pumping. Prewetting will result in an increased relative aggregate density factor that, in turn, develops higher fresh concrete density. The higher water content due to prewetting will eventually diffuse out of the concrete, developing a longer period of internal curing as well as a larger differential between fresh and equilibrium density than that associated with normal-weight concretes. Aggregate suppliers should be consulted for mixture proportion recommendations necessary for consistent pumpability.

Internal Curing

Lightweight aggregate batched at a high degree of absorbed water may be substituted for normal-weight aggregates to provide "internal curing" in concrete containing a high volume of cementitious materials. High cementitious concretes are vulnerable to self-desiccation and early-age cracking, and benefit significantly from the slowly released internal moisture. Field experience has shown that high strength concrete is not necessarily high performance concrete and that high performance concrete need not necessarily be high strength. A frequent, unintended consequence of high strength concrete is early-age cracking. Blending lightweight aggregate containing absorbed water is significantly helpful for concretes made with a low ratio of water-to-cementitious material or concretes containing high volumes of supplementary cementitious materials that are sensitive to curing procedures. This process is often referred to as water entrainment.

Time-dependent improvement in the quality of concrete containing prewet lightweight aggregate is greater than that of concrete containing normal-weight aggregate. The reason is better hydration of the cementitious materials provided by moisture available from the slowly released reservoir of absorbed water within the pores of the lightweight aggregate. The fact that absorbed moisture in the lightweight aggregate is available for internal curing has been known for more than four decades. The first documentation of improved long term strength gains made possible by the use of saturated *normal-weight* aggregates was reported in 1957 by Paul Klieger [2], who, in addition, commented in detail on the role of absorbed water in lightweight aggregates for extended internal curing.

In his 1965 report, "Concrete Strength Measurement–Cores vs. Cylinders," presented to the National Sand and Gravel Association and the National Ready Mixed Concrete Association, Bloem [3] states, "Measured strength for lightweight concrete cylinders was not reduced by simulated field curing methods employed. This would tend to support the suggestion that the high absorption of lightweight aggregate may have the beneficial effect of supplying curing water internally." This was confirmed by Campbell and Tobin [4] in their comprehensive program which compared strengths of cores taken from field-cured exposed slabs with test results obtained from laboratory specimens cured strictly in accordance with ASTM C 31. Their tests confirmed that availability of absorbed moisture in lightweight aggregate produced a more forgiving concrete that was less sensitive to poor field curing conditions. Addressing the long-term service performance of lightweight concrete, Holm [5] cited the improved integrity of the contact zone between the lightweight aggregate and the matrix. The improved quality was attributed to internal curing, and better cement hydration and pozzolanic activity at the interface, and reduction in stress concentrations resulting from elastic compatibility of the concrete constituents.

The benefits of internal curing go far beyond any improvements in long-term strength gain, which from some combinations of materials may be minimal or nonexistent. The principal contribution of internal curing results in the reduction of permeability that develops from a significant extension in the time of curing. Powers [6] showed that extending the time of curing increased the volume of cementitious products formed which caused the capillaries to become segmented and discontinuous.

It appears that in 1991, Philleo [7] was the first to recognize the potential benefits to high performance normal-weight concrete possible with the addition of lightweight aggregate containing high volumes of absorbed moisture. Reduced sensitivity to poor curing conditions in concretes containing an adequate volume of prewet lightweight aggregate has also been reported [8]. Since 1995 a large number of papers addressing the role of water entrainment's influence on internal curing and autogenous shrinkage have been published, of which Bentz et al. is typical [9].

The benefits of internal curing are increasingly important when supplementary cementitious materials (silica fume, fly ash, metokaolin, calcined shales, clays and slates, as well as the fines of lightweight aggregate) are included in the mixture. It is well known that the pozzolanic reaction of finely divided alumina-silicates with calcium hydroxide liberated as cement hydrates is contingent upon the availability of moisture. Additionally, internal curing provided by absorbed water minimizes the "plastic" (early) shrinkage due to rapid drying of concretes exposed to unfavorable drying conditions [10].

Sampling and Field Adjustments

Changes in lightweight aggregate moisture content, grading, or relative density, as well as usual job site variation in entrained air, suggest frequent checks of the fresh concrete to facilitate adjustments necessary for consistent concrete characteristics. Standardized field tests for slump, ASTM C 143; fresh density, ASTM C 138; and entrained-air content, ASTM C 173 are used to verify conformance of field concretes with the project specification. Sampling should be conducted in accordance with ASTM Practice Sampling Freshly Mixed Concrete (C 172). ASTM Test Method for Density of Structural Lightweight Concrete (C 567) describes methods for calculating the in-service, equilibrium density of structural lightweight concrete. When variations in fresh density exceed $\pm$ 4 lb/ft^3, an adjustment in batch weights may be required to restore specified concrete properties. To avoid adverse effects on durability, strength, and workability, air content should not vary more than $\pm$ 1.5 % from target values.

Properties of Lightweight Concrete

Comprehensive information detailing the properties of lightweight concretes and lightweight aggregates has been published by Shideler [11], Holm [12], Carlson [13], and Valore [14]. The first two deal with structural-grade concretes, Carlson reported on lightweight aggregate for concrete masonry units, and Valore covered both structural and insulating concretes. In most instances, test procedures for measuring properties of lightweight concretes were the same as commonly used for normal-weight concretes. In limited cases, different procedures particularly suited to measure lightweight concrete characteristics were developed.

Density

Although there are numerous structural applications for all lightweight concretes (coarse and fine lightweight aggregate), usual commercial practice in North America is to design lightweight concretes where part or all of the fine aggregate used is natural sand. Long-span bridges using concretes with three-way blends (coarse and fine lightweight aggregates and small supplemental natural sand volumes) have provided long-term durability and structural efficiency by increasing the density/strength ratios [15]. Normal-weight sand replacement will typically increase unit weight from about 80 to more than 160 kg/m^3 (5 to 10 lb/ft^3). Using increasing amounts of cement to obtain high strengths above 35 MPa (5000 psi), concrete will increase equilibrium density, ASTM C 567, from 32 to 96 kg/m^3 (2 to 6 lb/ft^3).

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

Unless otherwise specified, the dead loads used for design should be based upon the calculated equilibrium density that, for most conditions and structural members, may be assumed to be reached after 90 days. Extensive tests reported in ACI 213, Structural Lightweight Concrete, conducted during North American durability studies, demonstrated that despite wide initial variations of aggregate moisture content, equilibrium density was found to be about 50 kg/m^3 (3.1 lb/ft^3) above oven-dry density (Fig. 5). When weights and moisture contents of all the constituents of the batch of concrete are known, an approximate calculated equilibrium density may be determined.

Specified Density Concrete

The use of specified density concrete is based on engineers' decisions to improve structural efficiency by optimizing concrete

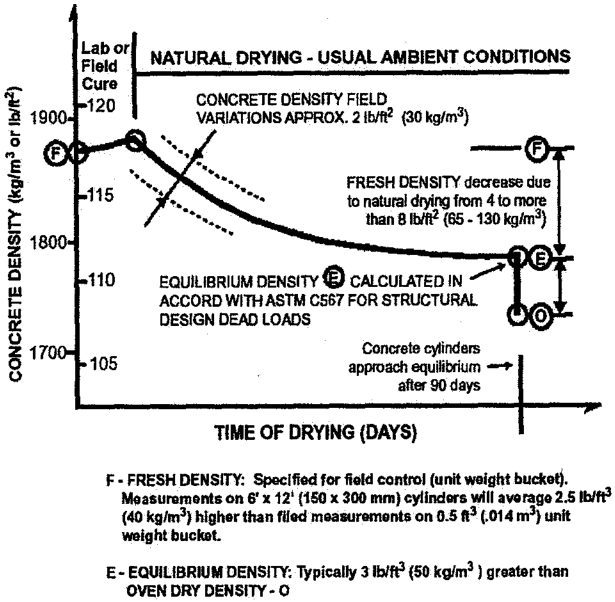


Fig. 5—Concrete density versus time of drying for structural lightweight concrete.

density. Specified density concrete is defined as concrete with a range of density less than what is generally associated with normal-weight concrete, 2320–2480 kg/m^3 (145–155 lb/ft^3), and greater than the code-defined maximum density for lightweight concrete, 1840 kg/m^3 (115 lb/ft^3). Specified density concrete is achieved by replacing part of the ordinary normal-weight aggregate (Relative Density >2.60) with either coarse or fine lightweight aggregate (Relative Density generally < 1.60).

Specified density concrete has been used on bridges, marine structures, precast elements, and consumer products in North America, Europe, and several other parts of the world [16].

The concept of specified density concrete is not new. For more than 20 years precast concrete manufacturers have evaluated trade-offs between the concrete density and transportation costs. Shown in Table 3 are the physical properties of concrete in which 25, 50, 75, and 100 % of the normal-weight limestone coarse aggregate was replaced by an equal absolute volume of lightweight aggregate [10]. This resulted in 5, 11, 15, and 21 % reductions in density, respectively.

By adjusting the density of the concrete, precasters are able to maximize the number of concrete elements on a truck without exceeding highway load limits. This reduces the number of truck loads which lowers transportation and project cost, as well as reducing the environmental consequences of trucking products, especially into central cities. Opportunities for increased trucking efficiency also apply when transporting smaller concrete products (hollow core plank, wallboard, precast steps, and other consumer products). Specified density concrete has the added benefit of enhanced cement hydration. See section on "Internal Curing" for more detail.

Compressive Strength

While most structural lightweight aggregates are capable of producing concretes with compressive strengths in excess of 35 MPa (5000 psi), a limited number of lightweight aggregates can be used in concretes that develop cylinder strengths from 48 to >69 MPa (7000 to >10 000 psi) [17].

While compressive strengths of 21 to 35 MPa (3000 to 5000 psi) are common for cast-in-place lightweight concretes, higher strengths are presently being specified for precast bridge mem-

TABLE 3—Physical Properties of Concrete Mixtures

Limestone Coarse Aggregate replaced by varying percentages of structural Lightweight Aggregate.
Concrete manufactured and tested at Prestressed Plant to optimize structural efficiency and reduce transportation costs.

Mixture Number Coarse Aggregate Target Equilibrium Density kg/m^3 (lb/ft^3)		1 Limestone 2300 (143)	2 .75S,.25L 2160 (135)	3 .5S 5L 2050 (128)	4 .25S,.75L 1920 (112)	5 LWA 1800 (112)	M NONE 2000 (125)
Physical Properties @ 18–24 h							
Compressive Strength	MPA (ksi)	24 (3.50)	26 (3.75)	29 (4.27)	28 (4.10)	26 (3.80)	34 (4.88)
Elastic Modulus (Test)	GPa (ksi × 10^3)	24 (3.42)	23 (3.30)	23 (3.27)	20 (2.97)	18 (2.67)	23 (3.38)
Elastic Modulus (Calc. ACI 318)	GPA(ksi × 10^3)	26 (3.70)	24 (3.49)	20 (2.89)	17 (2.42)	15 (2.17)	17 (2.48)
E (Test) / E (Calc. ACI 318)		1.08	1.06	0.61	0.81	0.81	0.73
Physical Properties @ 29 Days							
Compressive Strength	MPA (ksi)	39 (5.60)	41 (5.89)	41 (5.91)	42 (6.12)	42 (6.12)	47 (6.85)
Elastic Modulus (Test)	GPa (ksi × 10^3)	30 (4.28)	28 (4.09)	26 (3.81)	24 (3.25)	22 (3.25)	27 (3.96)
Elastic Modulus (Calc. ACI 318)	GPA(ksi × 10^3)	31 (4.49)	28 (4.10)	29 (4.17)	20 (2.92)	20 (2.92)	31 (4.50)
E (Test) / E (Calc. ACI 318)		1.05	1.00	1.09	0.89	0.9	1.14
Tensile Split Strength @ 29 Days	MPa (psi)	4.0 (580)	4.2 (615)	3.7 (531)	3.4 (492)	3.4 (498)	3.5 (504)

Note: 1. All concrete mixtures contain 446 kg/m^3 (752 pcy) cement, 708 kg/m^3 (1190 pcy) Natural Sand.
2. All concrete mixtures, Air 3.5 ± 0.5 %, Slump 100 mm (4 in.)
3. Mortar Mixture "M" contains 716 kg/m^3 (1208 pcy) Cement, 1050 kg/m^3 (1770 pcy) Natural Sand, Air 5.5 %, Slump 140 mm (5.5 in.)
4. All strength and modulus tests conducted on 152 × 304 mm (6 in. × 12 in.) cylinders.

bers and offshore applications. Lightweight aggregate concrete will demonstrate a strength "ceiling" where further additions of cementitious materials will not significantly raise the maximum attainable strength. Strength ceilings differ for each lightweight aggregate source and are the result of pore size and distribution as well as the strength characteristics of the vitreous material surrounding the pores. The strength ceiling of a particular lightweight aggregate may be increased by reduction of the top size in a particular grading formulation.

Tensile Strength

Shear, torsion, development length, bond strengths, and crack resistance are related to tensile strength, which is, in turn, dependent upon tensile strength of the coarse aggregate particle and the mortar and the degree to which the two phases are securely bonded. Traditionally, tensile strength has been defined as a function of compressive strength, but this is known to be only a first approximation that does not reflect aggregate particle strength, surface characteristics, nor the concrete's moisture content and distribution. The splitting tensile strength, as determined by ASTM Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (C 496), is used throughout North America as a simple, practical design criterion that is known to be a more reliable indicator of tensile-related properties than beam flexural tests. Splitting tests are conducted by applying diametrically opposite compressive line loads to a concrete cylinder laid horizontally in a testing machine. A minimum tensile splitting strength of 2.0 MPa (290 psi) is a requirement for structural lightweight aggregates conforming to the requirements of ASTM C 330. As tensile splitting results vary for different combinations of materials, the specifier should consult with the aggregate suppliers for laboratory-developed splitting strength data. Tensile splitting strength test data should be developed prior to the start of special projects where development of early-age tensile-related forces occur, as in handling precast or tilt-up members.

Tensile splitting strength tests on structural lightweight concrete specimens that are allowed to dry correlate better with the behavior of concrete in actual structures. Moisture loss progressing slowly into the interior of concrete members will result in the development of outer envelope tensile stresses that balance the compressive stresses in the still-moist interior zones. ASTM C 496 requires a 7-day moist and 21-day laboratory air drying at 23°C (73.4°F) and 50 % relative humidity prior to conducting splitting tests. Structural lightweight concrete splitting-tensile strengths vary from approximately 75 to 100 % of normal-weight concretes of equal compressive strength. Replacing lightweight fine aggregate with normal-weight fine aggregate will normally increase tensile strength.

Modulus of Elasticity

The modulus of elasticity of concrete is a function of the modulus of each constituent (mortar, lightweight, and normal-weight aggregates) and their relative mixture proportion. The modulus of normal-weight concretes is higher because the moduli of the natural aggregate particles are greater than those of lightweight aggregate particles. For practical design conditions, the modulus of elasticity of concretes with densities between 1400 to 2500 kg/m^3 (90 to 155 lb/ft^3) and within normal strength ranges may be assumed to follow the ACI 318 formula

$$E = 33 w_c^{1.5} \sqrt{f_c'} \qquad E = 0.04 \sqrt{w_c^3 f_c'}$$

where

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

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

Shrinkage

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

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

Aggregate characteristics influence the quantity of cementitious materials (the shrinking fraction) necessary to produce a required strength at a given water content. Particle strength, shape, and grading influence water demand and directly determine the fractional volume and quality of the cement paste necessary to meet specified strength levels. When structural lightweight aggregate concretes are proportioned with cementitious material quantities similar to that required for normal aggregate concretes, the shrinkage of lightweight concrete is generally, but not always, slightly greater than that of normal-weight concrete due to the lower aggregate stiffness. The time rate of shrinkage strain development in structural lightweight concrete is slower, and the time required to reach a plateau of equilibrium is longer when the as-batched, lightweight-aggregate absorbed moisture is high [10].

Creep

Time-related increases in concrete strain due to sustained stress can be measured according to the procedures of ASTM Test Method for Creep of Concrete in Compression (C 512). Creep and shrinkage characteristics of any concrete type are principally influenced by water and cementitious materials (paste volume fraction), aggregate characteristics, age at time of loading, type of curing, and applied stress/strength ratio. As creep and shrinkage strains will cause an increase in long-time deflections, loss of prestress, a reduction in stress concentration, and changes in camber, it is essential for design engineers to have an accurate assessment of these time-related characteristics as a necessary design input. ACI 213 [10] demonstrates wide envelopes of one-year specific creep values for all lightweight, normally cured concretes. Test results for higher-strength, steam-cured concretes with a blend of lightweight and normal-weight aggregates have a range of values that narrows significantly and closely envelopes the performance of the normal-weight "reference" concrete. These values are principally based upon the results of the comprehensive testing program of Shideler [12]. Long-term investigations by Troxell [18] on normal-weight concretes report similarly wide envelopes of results for differing natural aggregate types, so comparisons with "reference" concretes should be based upon data specific to the concretes considered.

Durability

Numerous accelerated freezing and thawing testing programs conducted on structural lightweight concrete studying the influence of air-void system, cement content, aggregate moisture content, specimen drying times, and testing environment have arrived at similar conclusions: air-entrained lightweight concretes proportioned with proper air-void systems provide good durability results. Observations of the resistance to deterioration in the presence of deicing salts on mature bridges indicate similar performance between structural lightweight and normal-weight concretes [19]. Several comprehensive investigations into the long-term weathering performance of bridge decks [20] and marine structures [21] exposed for many years to severe environments support the findings of laboratory investigations and demonstrate that properly proportioned and placed lightweight concretes perform equal to or better than normal-weight concretes.

Core samples taken from hulls of 70-year-old lightweight concrete ships as well as 40-year-old lightweight concrete bridges have demonstrated concretes with a high integrity contact zone between aggregate/matrix with low levels of microcracking [5]. This proven record of high resistance to weathering and corrosion is due to physical and chemical mechanisms that include: (a) a higher resistance to macrocracking; (b) superior aggregate/matrix adhesion; and (c) the reduction of internal stresses due to elastic matching of coarse aggregate and the cementitious matrix. Micro-cracking is mitigated by the high ultimate strain capacity provided when concretes have a high strength/modulus ratio. The ratio at which the disruptive dilation of concrete starts is higher for lightweight concrete than for equal strength normal-weight concrete. Near-surface pores provided by the lightweight fine aggregates have been shown to accommodate etringite [15].

Long-term pozzolanic action developed at the surface of the pyroprocessed silica/alumina-rich lightweight aggregate will combine with the calcium hydroxide liberated during cement hydration. This will reduce overall concrete permeability, minimize leaching of soluble compounds, and further improve the integrity of the contact zone.

It is widely recognized that while ASTM Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666) provides a useful comparative testing procedure, there remains an inadequate correlation between the results of this accelerated laboratory test and the observed behavior of mature concretes exposed to natural freezing and thawing. When lightweight concrete is tested, ASTM C 330 "Standard Specification for Lightweight Aggregates for Structural Concrete" requires modification of the procedures of ASTM C 666 to provide 14 days of drying in laboratory air after 14 days of moist curing. Durability of any concrete, both normal-weight and lightweight, is significantly influenced by the resistance to macro and micro-cracking. It is imperative that permeability and strain capacity characteristics of the concrete be sufficient to protect reinforcing steel from corrosion, which is clearly the dominant form of structural deterioration observed in current construction.

The matrix protective quality of insulating type concretes proportioned for thermal resistance by using high volumes of entrained air and low cement contents will be significantly reduced. Very low density, non-structural concretes will not provide adequate resistance to the intrusion of chlorides and carbonation, etc. [21].

Field Tests

For more than 25 years, field exposure testing programs have been conducted by the Canadian Department of Minerals, Energy and Technology (CANMET) on various types of concretes exposed to the extremely harsh marine environment at the Treat Island Severe Weather Exposure Station maintained by the U.S. Army Corps of Engineers at Eastport, Maine. Concrete specimens placed on a mid-tide wharf experience alternating conditions of seawater immersion followed by cold air exposure at low tide. In typical winters, the specimens experience over 100 cycles of freezing and thawing. Starting in 1980, five sets of specimens incorporating lightweight aggregate have been placed at this site. Kondratova listed several websites that could be used to examine the performance of these specimens, and reported that the deterioration rate was similar for the lightweight and normal-weight concretes. After more than 25 years of exposure to a severe marine environment, properly proportioned concretes of both types were providing durable performance [22].

Contact Zone

The expression "contact zone" includes two distinctively different phenomena: (1) the mechanical adhesion of the cementitious matrix to the surface of the aggregate, and (2) the variation of physical and chemical characteristics of the transition layer of the cementitious matrix close to the aggregate particle. Collapse of the structural integrity of the concrete conglomerate may come from the failure of either the aggregate or cementitious matrix, or from a breakdown in the contact zone causing a separation of the still-intact phases. The various mechanisms that act to maintain continuity, or that cause separation, have not received the same attention as has the air void system necessary to protect the matrix. Aggregates are frequently dismissed as being inert fillers and, as a result, they and the associated contact zone have not received adequate attention.

In order that concrete performs satisfactorily in severe exposure conditions, it is essential that a good bond develop and be maintained between the aggregate and the enveloping mortar matrix. A high incidence of interfacial cracking or aggregate debonding will have a serious effect on durability if these cracks fill with water and subsequently freeze. Deterioration will result, with pieces of apparently sound mortar separating from the bottom of the aggregate, usually with some of the mortar remaining firmly attached to the top side of the aggregate. An equally serious consequence of microcracking is the easy path provided for the ingress for aggressive agents into the mass of the concrete, rendering ineffective the protective layer of concrete over the reinforcing steel. The morphology and distribution of chemical elements at the transition layer in a number of mature structures that have withstood severe exposure were examined and reported by Bremner et al. [23].

The contact zone of lightweight aggregate concrete has been demonstrated to be significantly superior to that of normal-weight concretes that do not contain supplementary cementitious meterial [19,24]. This profound improvement in the quality, integrity, and microstructure stems from a number of characteristics unique to lightweight concrete that includes:

- The pozzolanic alumina/silicate surface of the fired ceramic aggregate combines with $CaOH_2$ liberated by hydration of the portland cement.
- Reduced micro-cracking in the contact zone because of the elastic similarity of the aggregate and the surrounding cementitious matrix [25].
- Hygral equilibrium between two porous materials (lightweight aggregate and porous cementitious matrix) as opposed to the usual condition with normal-weight aggregate, where bleed-water lenses form around essentially nonabsorbent coarse natural aggregates. These lenses have water-to-cementitious materials ratios significantly higher than in the rest of the matrix. When supplementary cementitious materials are added, the high-quality microstructure of the contact zone around lightweight aggregate is moderately enhanced. However, when supplementary cementitious materials are used in concretes containing normal-weight aggregate, this zone of weakness is profoundly improved.

While the reduction in compressive and tensile strength due to poor contact zone is important, the significance of increasing permeability is even greater. Increasing permeability inevitably leads to penetration of aggressive agents that accelerate corrosion of embedded reinforcement. The permeability of concrete is greater than the permeability of its constituents. This increase in permeability results from interfacial flaws at the aggregate surface linking up with micro-cracking in the transition layer.

The phenomenon of bleed water collecting and being entrapped under coarse particles of lightweight aggregate is mitigated if not eliminated. This has been verified in practice by the examination of the contact zone of lightweight concrete tensile splitting cylinders, as well as by visual examination of sandblasted vertical surfaces of building structures. This observation should not be surprising because, with structural lightweight concrete, the aggregate/matrix interface is a boundary between two porous media, while with normal-weight concrete there is an abrupt transition at the dense aggregate/porous cementitious matrix interface.

Implication of Contact Zone on Failure Mechanisms

Exposed concrete must endure the superposition of dynamic forces including variable live loads, rapid temperature changes, moisture gradients, and dilation due to chemical changes. These factors cause a predominantly tensile-related failure. Yet, the uniaxial compressive strength is traditionally considered the preeminent single index of quality, despite the fact that inadequate concrete performance is seldom related to this parameter. The simplicity and ease of compression testing has diverted our focus from life-cycle performance and the development of appropriate measurement techniques that quantify durable concrete characteristics.

In general, weakest link mechanisms are undetected in uniaxial compression tests due to concrete's forgiving load-sharing characteristics in compression, because of localized yielding and the closure of temperature and volume-change cracks. Weakest link mechanisms, however, are decisive in tensile failures in both dynamic and durability exposure conditions. In most concretes the limiting factor in the long-term performance is the integrity of contact zone.

Additionally, a full comprehension has not been developed regarding the accommodation mechanism by which the pores closest to the aggregate/matrix interface provide an accessible space for products that cause deleterious expansion. While research has identified ettringite, alkali-silica gel, marine salts, and corrosion products in these near-surface pores, it is still not fully understood how these products impact service life.

Resistance to Alkali-Aggregate Deleterious Expansion

ACI 201 "Guide to Durable Concrete" reports no documented instance of in-service distress caused by alkali reactions with lightweight aggregate [26]. No evidence of alkali-lightweight aggregate distress was observed in tests conducted on samples from a 70-year-old marine structure and several lightweight concrete bridge decks that were more than 30 years old [27]. The pyroprocessing of the aggregates tends to activate the particles' surfaces such that they act as a source of silica to react with the alkalis from the cement at an early age to counteract any potential long-term disruptive expansion. As maintained earlier, another factor that enables lightweight aggregate to reduce disruptive expansion is the availability of space within the expanded aggregate for reactive material to precipitate in a benign manner. Precipitation of alkali-rich material in the pores of an expanded aggregate was observed in concrete made with a well-known reactive normal-weight coarse aggregate in which some of the nonreactive fine aggregates were replaced with lightweight fine aggregates [28].

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

Many lightweight concrete mixtures designed for an equilibrium density in the range of 110 lb/ft^3 (1760 kg/m^3) and above are produced using either natural sand or a naturally occurring coarse aggregate. In either case, these natural aggregates should be considered a potential source to develop alkali-aggregate reaction until they have been demonstrated by an appropriate ASTM test procedure or by having an established service history to be of negligible effect.

Abrasion Resistance

Abrasion resistance of concrete depends on strength, hardness, and toughness characteristics of the cement matrix and the aggregates, as well as on the bond between these two phases. Most lightweight aggregates suitable for structural concretes are composed of solidified vitreous ceramic comparable to quartz on the Mohs Scale of Hardness. Structural lightweight concrete bridge decks that have been subjected to more than 100 million vehicle crossings, including truck traffic, show wearing performance similar to that of normal-weight concretes. Hoff [29] reported that specially developed testing procedures that measured ice abrasion of concrete exposed to arctic conditions demonstrated essentially similar performance for lightweight and normal-weight concretes.

Fire Resistance

When tested according to the procedures of ASTM Method for Fire Tests of Building Construction and Materials (E 119), structural lightweight aggregate concrete slabs, walls, and beams have demonstrated greater fire endurance periods than equivalent-thickness members made with normal-weight aggregates (Fig. 6). Superior performance is due to a combination of lower thermal conductivity (lower temperature rise on unexposed surfaces), lower coefficient of thermal expansion (lower forces developed under restraint), and the inherent thermal stability developed by aggregates that have been already exposed to temperatures greater than 1093°C (2000°F) during pyroprocessing.

Specifications

Specifications for structural lightweight concrete usually require minimum values for compressive and tensile splitting strength, maximum limitations on slump, specified range of air content, and a limitation on maximum fresh density. The density of lightweight concrete depends primarily on the relative density factor of the lightweight aggregates, and it is also influenced to a lesser degree by cementitious materials, water, air contents, and proportions of coarse-to-fine aggregate.

Conclusion

Structural lightweight concrete is a unique construction material that should be specified, designed, and constructed in a manner that recognizes and takes advantage of its unique physical and mechanical properties (ASTM C 330, C 496, C 567).

Acknowledgments

The principal sources of information for this chapter include the *Guide for Structural Lightweight Aggregate Concrete* (ACI 213) [14], ACI 318 Building Code Requirements for Reinforced Concrete [1], and the "State-of-the-Art Report on High-Strength High-Durability, Structural Low Density Concrete for Applications in Severe Marine Environments" [15].

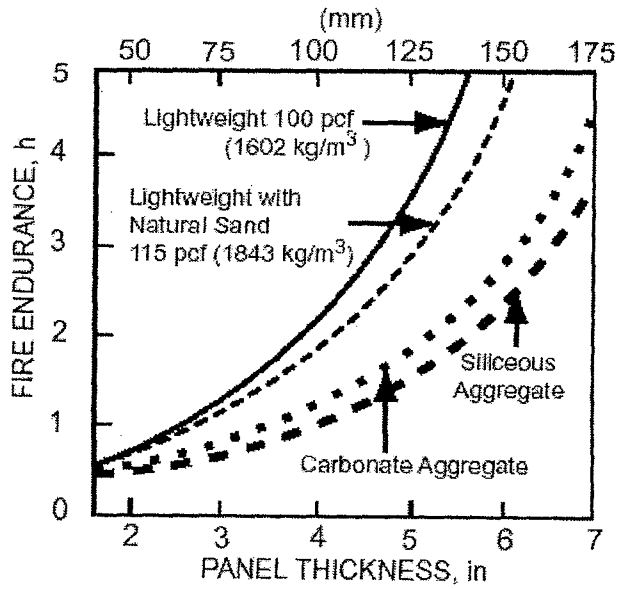


Fig. 6—Fire endurance (heat transmission) of concrete slabs as a function of thickness for naturally dried specimens [10].

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