

Chapter 3

Physical Properties of Structural Lightweight Aggregate

April 2007

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Appendix 3G “*Water-Vapor Absorption-Desorption Characteristics of Selected Lightweight Concrete Aggregates*”, Landren, PCA Bulletin '78.

Appendix 3H Pages 34-37, 153-155, Extracted from the “*Thermophysical Properties of Masonry and its Constituents*”, R.C. Valore, International Masonry Institute 1988.

Appendix 3I ASTM C 1260-05a “*Test Method for Potential Alkali Reactivity of Aggregates (Mortar Bar Method)*”.

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CHAPTER 3 - PHYSICAL PROPERTIES OF STRUCTURAL LIGHTWEIGHT AGGREGATE

3.0 Introduction

This chapter provides definitions, basic physical properties, ASTM Standards and Specifications. The methodology for determining the fractional parts of an aggregate particle, pores versus solids and interstitial voids in the bulk volume are shown. How these individual parts influence concrete moisture dynamics and aggregate absorption characteristics are analyzed.

This chapter provides specific terminology that is essential for a physical understanding and methodical calculation of various degrees of saturation. Information is also provided on alkali-aggregate reaction test methods and available data on the results of testing programs.

3.1 Definition of Lightweight Aggregates

Lightweight aggregate is the generic name of a group of aggregates having a relative density lower than normal density aggregates (natural sand, gravel, and crushed stone), sometimes and is referred to as low density aggregate.

Structural lightweight aggregate-*Structural aggregate meeting the requirements of ASTM C 330 with bulk density less than 70 lb/ft³ (1120 kg/m³) for fine aggregate and less than 55 lb/ft³ (880 kg/m³) for coarse aggregate.* This includes aggregates prepared by expanding, pelletizing, or sintering products such as blast-furnace slag, clay, fly ash, shale, or slate, and aggregates prepared by processing natural materials such as pumice, scoria or tuff.

Masonry-lightweight aggregate-*Aggregate meeting the requirements of ASTM C 331 with bulk density less than 70 lb/ft³ (1120 kg/m³) for fine aggregate and less than 55 lb/ft³ (880 kg/m³) for coarse aggregate.* This includes aggregates prepared by expanding, pelletizing, or sintering products such as blast-furnace slag, clay, diatomite, fly ash, shale, or slate; aggregates prepared by processing natural materials such as pumice, scoria, or tuff; and aggregates derived from and products of coal or coke combustion.

Insulating aggregate – *Nonstructural aggregate meeting the requirements of ASTM C 332.* This includes Perlite with a bulk density between 7.5 and 12 lb/ft³ (120 and 192 kg/m³), and Vermiculite with a bulk density between 5.5 and 10 lb/ft³ (88 and 160 kg/m³), as well as aggregate that meets the requirements of ASTM C 330 and ASTM C 331.

This chapter primarily addresses structural lightweight aggregates and does not include cellular or foam concrete, where lighter weight is developed primarily by inclusion of large amounts of air or gas through foaming-type agents. Requirements for structural

lightweight aggregates are covered in ASTM C 330 “*Standard Specification for Lightweight Aggregates for Structural Concrete*”, C 331 “*Standard Specification for Lightweight Aggregates for Concrete Masonry Units*”, and C 332 “*Standard Specification for Lightweight Aggregate for Insulating Concrete*”.

3.2 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 (Fig. 3.1 and 3.2). Textures may range from fine pore, relatively smooth skins to highly irregular surfaces with large exposed pores.

Particle shape and surface texture can directly influence the finished products. Shape and texture of aggregates influence workability, coarse-to-fine aggregate ratio, cement content requirements, and water demand in concrete mixtures, as well as other physical aspects.



Figure 3.1 *Lightweight Particle*

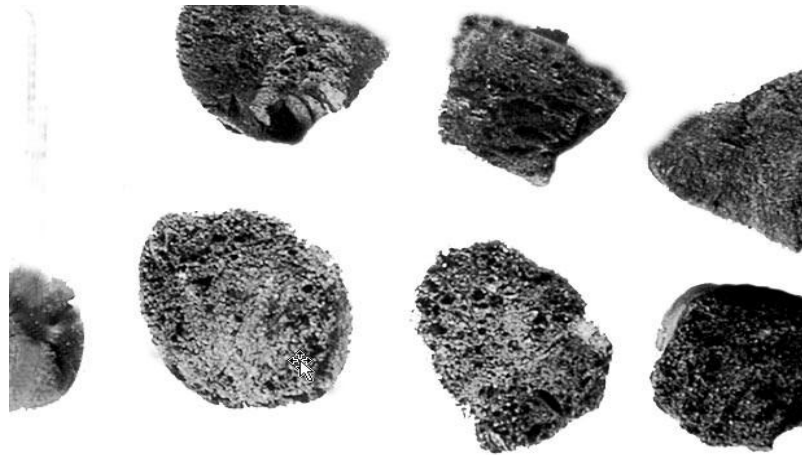


Figure 3.2 *Structural ESCS lightweight aggregate that is composed of a strong, ceramic, vitreous material encapsulating a system of general non-interconnected pores. Although, the particle density is approximately 1/2 of natural aggregates this aggregate when used in concretes and geotechnical application provides the usual structural strengths, stability and durability.*

3.3 Grading Lightweight Aggregate for Concrete

Grading requirements are generally similar to those provided for normalweight 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.

For normalweight aggregates, the relative density of fractions retained on the different sieve sizes are nearly equal. Percentages retained on each size indicated by weight give a true indication of percentages by volume. However, the relative density of the various size fractions of lightweight aggregate usually increases as the particle size decreases. Some coarse aggregate particles may float on water, whereas material passing a No. 100 sieve (0.015 mm) may have a relative density approaching that of normalweight sand. It is the volume occupied by each fraction, and not the weight of material retained on each sieve that determines the void content and influences the workability of the concrete. Percentages retained on each sieve and fineness modulus, by weight and by volume, are computed for comparison in the example illustrated in Table 3.1.

Table 3.1 Comparison of fineness modulus by weight and volume for typical lightweight aggregate.

| Sieve Size No. | Opening in. (mm) | Percent Retained By weight | Cumulative Percent Retained by weight | Relative Density SSD Basis | Percent Retained By Volume | Cumulative Percent Retained by volume |
|----------------|------------------|----------------------------|---------------------------------------|----------------------------|----------------------------|---------------------------------------|
| 4 | 0.187 (4.75) | 0 | 0 | ---- | 0 | 0 |
| 8 | 0.0937 (2.38) | 22 | 22 | 1.55 | 26 | 26 |
| 16 | 0.0469 (1.19) | 24 | 46 | 1.78 | 25 | 51 |
| 30 | 0.0234 (0.59) | 19 | 65 | 1.90 | 19 | 70 |
| 50 | 0.0117 (0.30) | 14 | 79 | 2.01 | 13 | 83 |
| 100 | 0.0059 (0.15) | 12 | 91 | 2.16 | 10 | 93 |
| Pan | ---- | 9 | 100 | 2.40 | 7 | 100 |

Fineness modulus (by weight) 3.03 fineness modulus (by volume) = 3.23

A fineness modulus of 3.23 by volume as shown in Table 3.1 indicates a considerably coarse grading than that normally associated with the fineness modulus of 3.03 by weight. Therefore, lightweight aggregates require a larger percentage of material retained on the finer sieve sizes on a weight basis than do normalweight aggregates to provide an equal size distribution by volume.

The use of normalweight sand usually results in some increased in strength and modulus of elasticity. These increases, however, are made at the sacrifice of increased density. The mixture proportions selected, therefore, should consider these properties in conjunction with the corresponding effects on the overall economy of the structure.

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 the entire fine fraction with normalweight sand, a wide range of concrete densities may be obtained. Aggregates for structural lightweight concrete usually have a top size of minus 3/4 in. or minus 1/2 in. Most lightweight concretes use a lightweight coarse aggregate 3/4 in. to #4 mesh (1/2 - #8) with ordinary sand, minus #4 mesh (minus 4.8 mm), however other combinations of LWA and natural aggregate are used.

Aggregate for lightweight concrete masonry units are normally sized minus 3/8 in. (9.5 mm). This aggregate is usually the crushed variety because of improved machining characteristics and the zero slump concrete mix is drier than that for fresh structural concrete.

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.

3.4

Relative Density of Aggregate Particles

Structural Lightweight Aggregate has a low particle density due to the internal cellular pore system. The cellular structure within the particles is developed by heating certain raw materials to high temperatures to the point of incipient fusion, at which time gases are evolved within the pyroplastic mass, causing expansion that is retained upon cooling. Strong, durable, ceramic lightweight aggregates contain a relatively uniform system of pores that have a size range of approximately 5 to 300 μm enveloped in a high-strength vitreous phase. Pores close to the surface are readily permeable and fill within the first few hours of exposure to moisture. Interior pores, however, fill extremely slowly. A fraction of the interior pores are essentially non interconnected and may remain unfilled after years of immersion.

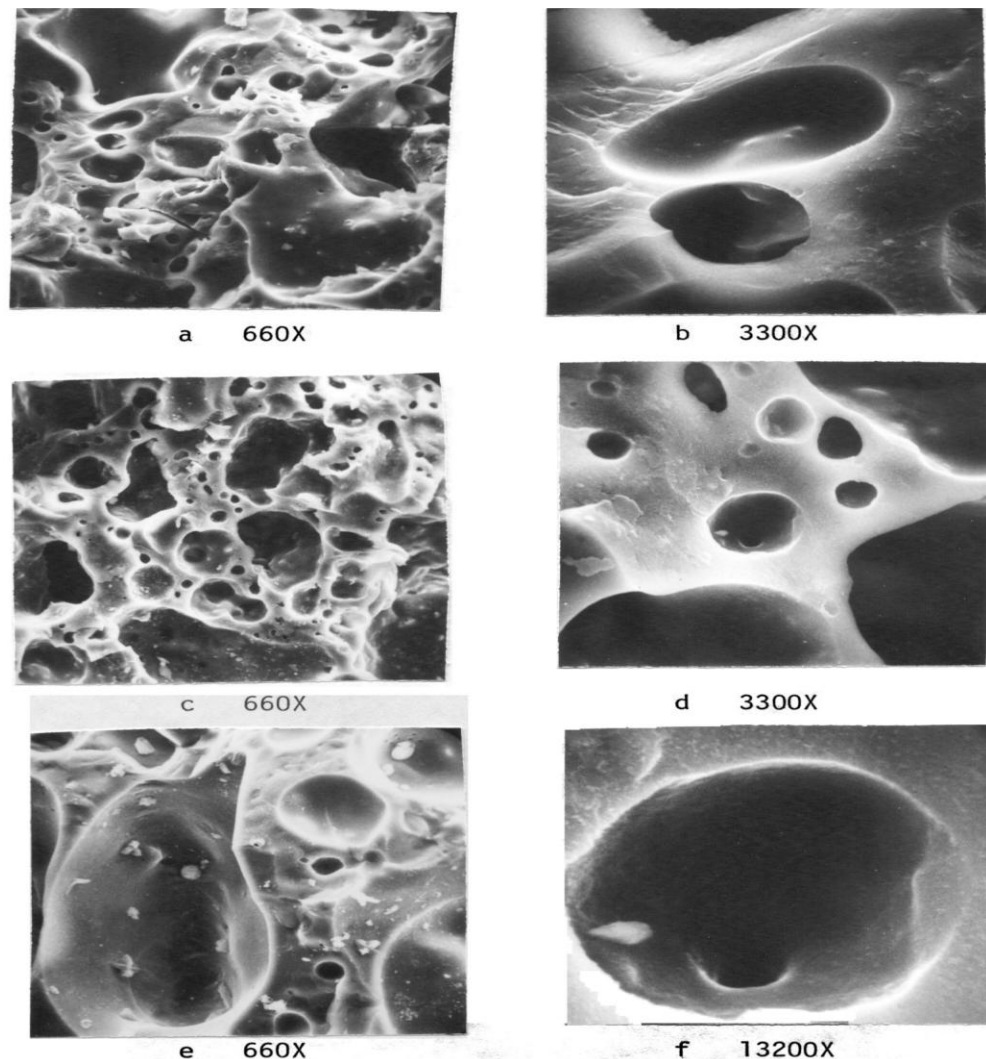


Figure 3.3 Scanning Electron Microscopy of Mature Lightweight Concrete showing the lightweight aggregate particle.
Sample taken from the Cossakie Bridge deck, New York thruway (Holm et. al. 1984).

The particle density of an aggregate is the ratio between the mass of the particle material and the volume occupied by the individual particles. This volume includes the pores within the particle, but does not include voids between the particles (Fig. 3.4). In general, the volume of the particles is determined from the volume displaced while submerged in water. Penetration of water into the aggregate particles during the test is limited by the aggregate's ceramic like matrix which inhibits water absorption particularly to the interior vesicles.

The oven-dry density of an individual particle depends both on the density of the solid vitreous material and the pore volume within the particles, and generally increases when particle size decreases. After pulverizing in a jar mill over an extended period, the relative density of the poreless, solid ceramic material was determined to be 2.60 by methods similar to those used in measuring the relative density of cement.

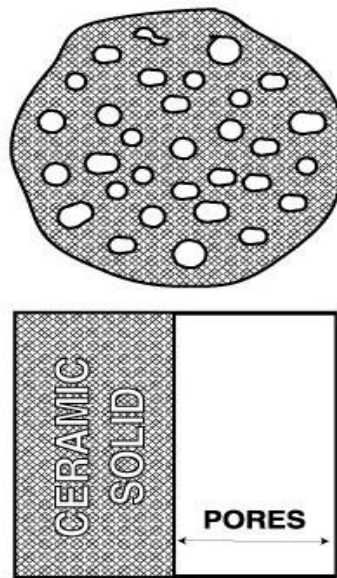


Figure 3.4 Schematic of Dry Lightweight Aggregate

3.5 Aggregate Bulk Density

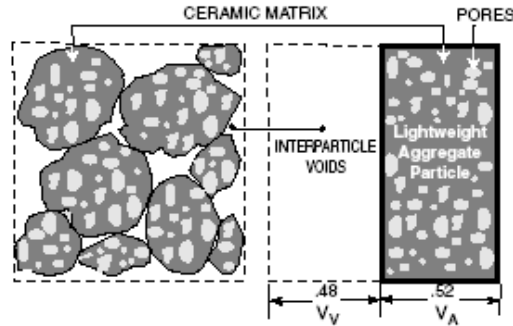
Aggregate bulk density is defined as the ratio of the mass of a given quantity of material and the total volume occupied by it. This volume includes the voids between, as well as the pores within the particles. Bulk density is a function of particle shape, density, size, gradings, and moisture content, 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 3.2 summarizes the maximum bulk density for

lightweight aggregates listed in ASTM C 330 and ASTM C 331. ASTM C 332 provides minimum density requirements for perlite and vermiculite to limit over-expanded, weak particles that would break down in mixing.

TABLE 3.2—*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/m ³ (lb/ft ³) | Minimum Dry Loose Bulk Density kg/m ³ (lb/ft ³) |
|------------------------------------|---|---|
| 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) | ... |

The relationship between the particle relative density and the bulk density of an aggregate sample is illustrated in Fig. 3.5 for a hypothetical lightweight aggregate.



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 pycnometer) 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.

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

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

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

Figure 3.5. Schematic Representation of Bulk Volume, Interparticle Voids and Internal Particle Pores Showing Fractional Volumes of the bulk density of lightweight aggregate

3.6 Moisture Dynamics

The non-steady state exchanges of moisture in and out of particles of lightweight aggregate may be separated into two distinctly different processes. The first is when LWA is immersed in water (or another fluid) and continuously absorbs water initially at a high rate, then at a significantly reduced rate that decreases with time to a rate so slow that it takes years to conclude.

The second mechanism is characterized as “sorption” in which the moisture exchange is between the surface of the lightweight aggregate particle and the surrounding medium (air at differing relative humidity or hydrating cement paste in concrete). ACI 116 defines surface moisture (or adsorbed moisture) as free water retained on the surfaces of aggregate particles and considered to be part of the mixing water in concrete, as distinguished from absorbed water.

Adsorption – “Adsorption is considered to occur when a relatively dry material retains or takes up water in a vapor form from a surrounding atmosphere”. and;

Desorption – “Desorption is the loss of adsorbed water [surface water] to a drying atmosphere” (Landgren, 1964).

If desorption is taking place then the internal (absorbed) moisture will gradually move to the surface and behave like surface moisture to further exchange with the surrounding medium.

The mechanism of the absorption of water into immersed or continuously prewet lightweight aggregate is widely understood and accounted for. The loss of moisture from LWA with an extremely high degree of saturation, when laid on the floor of a laboratory will lose all but a small percentage of its absorbed water within two days, is not equally well known or appreciated. Lightweight aggregate is not significantly hydrophilic (having a strong affinity for water). Water is moved relatively slowly in and out of the aggregate by capillary pores.

When surrounded by a fine pore matrix (hydrating cement paste – smaller pores less than one micron) the large sized pores of a structural lightweight aggregate (typically from 5 to 300 microns) will have their moisture content lowered due to the “wicking” action of the fine capillary pore system because of the hydrophilic action of the hydrating cement paste. The rate of wicking slows as the cement hydrates and the capillaries close off. See appendices F (Valore, 1988) and G (Landgren, 1964) for sorption curves of lightweight aggregate, hydrated cement paste and bricks.

However, soon after set, when the microporous structure of the hydrated cement paste develops, the moisture in the lightweight aggregate will serve as a reservoir for supplying the moisture necessary for providing the curing conditions essential for full

hydration of the cement, this is commonly referred to as internal curing. As shown in Landgren's paper this emptying of water from the LWA will start as soon as the cement paste requires extra water to continue the hydration process. Because the water is in relatively coarse pores it is readily available to be drawn into the significantly finer pores in the cement paste. Capillary forces increase as capillary size decrease, essentially the water inside the lightweight aggregate acts as a readily available source of moisture to extend moist curing. In part or in whole it compensates for moisture lost from the concrete during exposure to air drying. It is extremely beneficial in maintaining longer periods of hydration (Internal Curing) essential to improvements in the aggregate/matrix contact zone. Internal curing will also bring about a significant reduction of permeability by extending the period in which additional products of hydration are formed in the pores and capillaries of the binder.

Absorption Characteristics

Due to their cellular structure, lightweight aggregates absorb more water than their ordinary aggregate counterparts. Based upon a 24-hour absorption test conducted in accordance with the procedures of ASTM C 127 and ASTM C 128, structural-grade lightweight aggregates will absorb from 5 to more than 25 percent moisture by mass of dry aggregate. By contrast, ordinary aggregates generally absorb less than 2 percent of moisture. The important distinction in stockpile moisture content is that with lightweight aggregates the moisture is largely absorbed into the interior of the particles, whereas with ordinary aggregates it is primarily surface moisture. Recognition of this difference is essential in mixture proportioning, batching, and control. Rate of absorption is unique to each lightweight aggregate, and is dependent on the characteristics of pore size, continuity, and distribution, particularly for those pores close to the surface.

When the lightweight aggregate is used in a concrete mixture the internally absorbed water within the particle is not immediately available for chemical interaction with cement as mixing water, and as such, does not enter into water-cement ratio (W/Cm) calculations.

As can be seen in Fig. 3.6 the rate of absorption can be divided into four regimes.

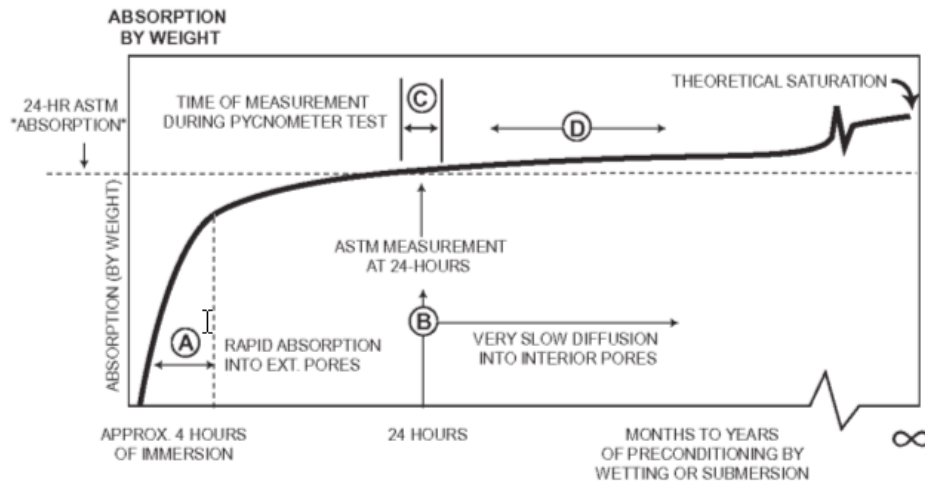


Figure 3.6 Absorption vs. Time for typical structural grade ESCS lightweight aggregate

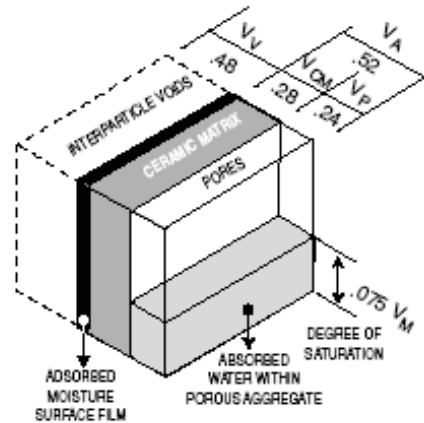
Region A. Rapid entry of water by capillary absorption by close to surface pores within the first few hours.

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 pycnomter 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 \pm) will be very small, and therefore the W/Cm ratio will be *decreased* by an equivalent small amount. Consequently there will be a negligible influence on slump loss if aggregates are batched at a moisture content close to the 24 hour submerged value.

For illustrative purpose the water absorption with time and the resulting degree of saturation for a midrange, typical lightweight aggregate are shown in Figs. 3.7, 3.8 and Table 3.2.



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

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

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

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

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

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

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

Figure 3.7. Schematic representation of volumes occupied By the ceramic matrix, the remaining pores and the degree of saturation of absorbed water.

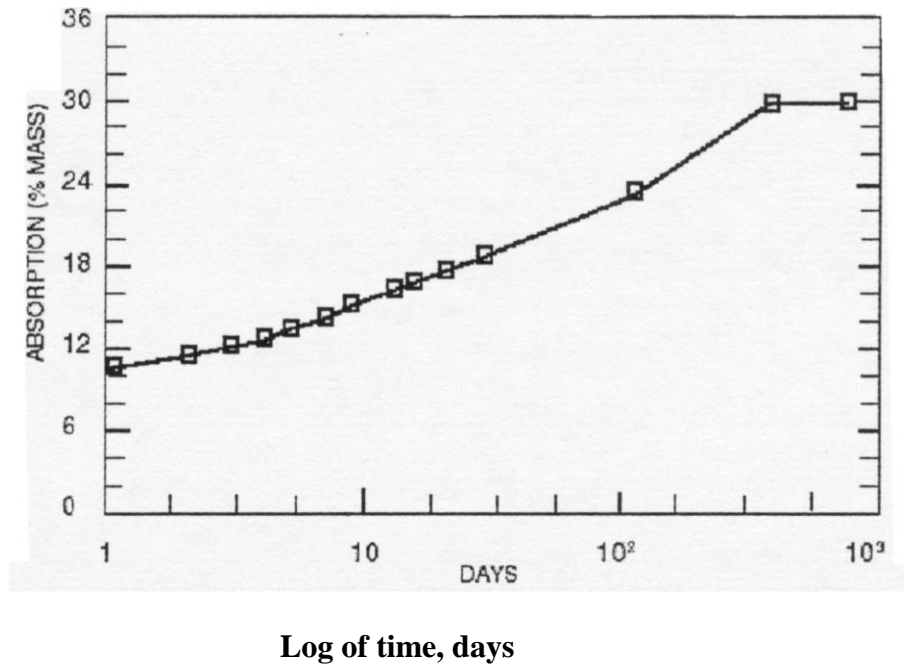


Figure 3.8. Water Absorption by Weight of Coarse Lightweight Aggregates during 2-years of Water Immersion

Table 3.2. Aggregate Absorption and Degree of Saturation (Holm et. al. 2004)

| Immersion Time | Water Absorption (% Mass) | Degree of Saturation | % of 24-Hour Soak | Relative Density Factor |
|----------------|---------------------------|----------------------|-------------------|-------------------------|
| 0 mins | 0 | 0 | 0 | 1.38 |
| 2 mins | 5.76 | .17 | 55 | 1.46 |
| 5 mins | 6.15 | .18 | 59 | 1.46 |
| 15 mins | 6.75 | .20 | 64 | 1.47 |
| 60 mins | 7.74 | .23 | 74 | 1.49 |
| 2 hours | 8.32 | .24 | 79 | 1.49 |
| 1 day | 10.5 | .31 | 100 | 1.52 |
| 3 days | 12.11 | .35 | 115 | 1.55 |
| 28 days | 18.4 | .54 | 175 | 1.63 |
| 4 months | 23.4 | .69 | 223 | 1.70 |
| 1 year | 30 | .88 | 285 | 1.79 |
| 2 years | 30 | .88 | 285 | 1.79 |

Saturated Surface Dry

ASTM C 127 and C 128 procedure prescribe measuring the “saturated” (*inaccurately named in the case of Lightweight Aggregates; partially saturated after a 24-hour soak is more accurate*) particle density in a pycnometer and then determining the absorbed moisture content on the sample that had been immersed in water for 24 hours. After a 24-hour 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 oven-dry particle density may be directly computed. Fig. 3.9 illustrates typical ESCS lightweight aggregate.

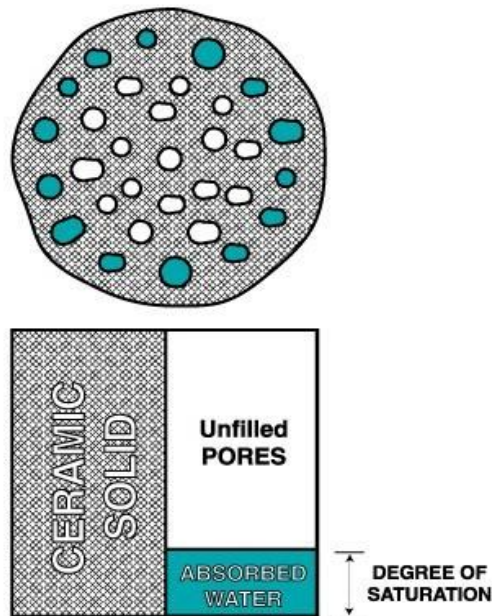


Figure 3.9 Schematic of “Saturated” Surface Dry as defined by ASTM C 127 and C 128 after 24-hour submersion

Following ASTM procedures the measured physical properties of this particular lightweight aggregate are:

Relative Density, $RD_{24} = 1.52$

Moisture Absorption, $M_{24} = 10.5\%$

Relative density solid, $RD_{\text{SOLIDS}} = 2.6$

Bulk Density, $BD = 44.6 \text{ pcf } (714 \text{ kg/m}^3)$

That after 24-hour immersion in a pycnometer, measurements result in a relative density of 1.52 with an “absorption” of 10.5% by mass. The oven-dry particle density (PD_{OD}) may be back calculated to be as follows:

$$PDOD = \frac{1.52}{(1+.105)} = 1.38$$

It follows then that the fractional volume of ceramic solids, $V_s = \frac{1.38}{2.60} = .53$

Fraction Volume of pores, $V_p = 1.00 - .53 = .47$

The degree of saturation (DS: the extent to which the pores are filled)

$$DS = \frac{.105 \times 2.60 \times .53 (\text{volume of absorbed water})}{.47 (\text{Fractional volume of pores})} = .31$$

Following the prescribed ASTM procedures the DS for ESCS lightweight aggregate will generally be in the range of approximately 25 to 35% of the theoretical saturation. The use of the ASTM expression “saturated surface dry” is therefore, inappropriate for lightweight aggregate because it’s theoretically inaccurate and analytically misleading.

Stockpile Moisture Content

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 C 127 procedures (24-hour immersion). In this condition the absorbed (internal) moisture content will be in excess of the 24 hour absorption value defined by ASTM. The degree of saturation (DS) necessary for adequate pumping characteristics, as determined by practical field experience, may be obtained from the ESCS supplier.

Example, assume for this hypothetical lightweight aggregate (Fig. 3.10) that experience has shown that the lightweight concrete will pump efficiently when the lightweight aggregate used has absorption of at least 17% by mass.

At that condition the $DS (\text{Degree of Saturation}) = \frac{.17(2.60 \times .53)}{.47} = .50.$

Due to the continuous pre-wetting, and because of the very slow further tendency to absorb water into the aggregate, there will invariably be a film of surface (adsorbed) water on the surface of the lightweight aggregate. It is essential to evaluate this quantity of surface water for an accurate determination of the “net” mixing water that influences workability and determines the effective w/cm ratio.

Therefore, it is necessary to run the usual moisture test as follows. Measure the weight of the as-received surface moist sample (W_T). After towel drying, measure the weight of the surface dry sample (W_{TD}) and conduct the drying test.

Sample calculations:

Measured Weights(g)

W_T (Totalsample)= 602g

W_{TD} (Toweldried)= 562g

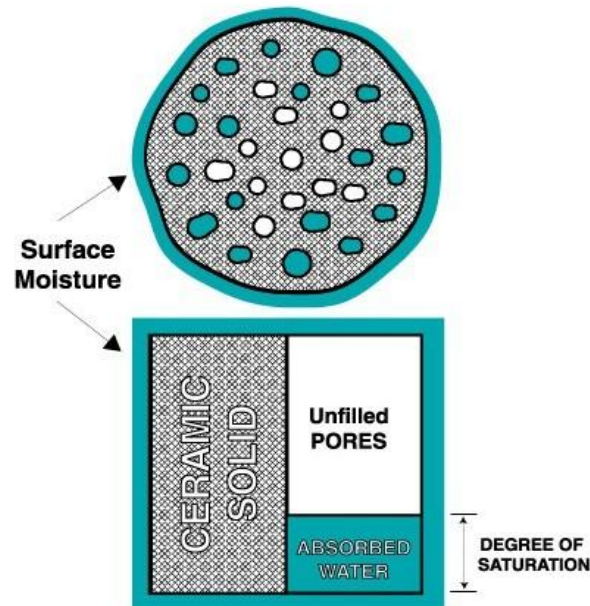
W_{OD} (Ovendried)= 480g

Moisture Content(%)

$$M_T \text{ (TotalSample)} = \frac{602 - 480}{480} \times 100 = 25.4\%$$

$$M_{AB} \text{ (Absorbed)} = \frac{562 - 480}{480} \times 100 = 17.1\%$$

$$M_S \text{ (Surface)} = \frac{602 - 562}{480} \times 100 = 8.3\%$$

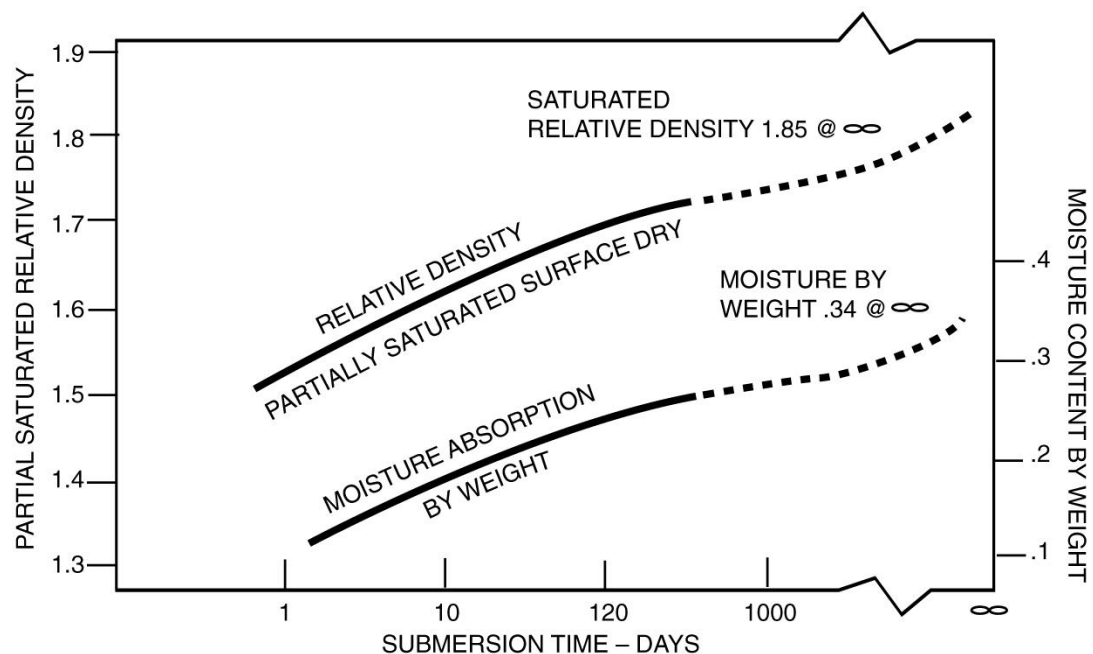


**Figure 3.10 Schematic of “Partially Saturated” Surface Wet
(Moisture Condition of Stockpiled Lightweight
Aggregate with Some Surface Water)**

Full Saturation

Lightweight aggregate exposed to moisture in production plants and/or stored in open stockpiles will contain certain moisture content. Lightweight aggregates that are used alone in geotechnical, horticulture or asphalt applications are exposed to the weather, sprinkled or submerged, will continue to absorb water over time.

In the following LWA investigation, the effective particle density of a submerged LWA sample was measured throughout a two-year period to demonstrate long-term weight gain. Long-term absorption and relative density characteristics are also shown in Table 3.2, and Fig. 3.11 and Fig. 3.12. When moisture absorption-versus-time relationships are extrapolated or theoretical calculations used to estimate the total filling of all the lightweight aggregate pores, it can be shown that for this particular lightweight aggregate, the absorbed moisture content at total saturation ($M@TS$) after an infinite immersion will approach 34% by mass with a totally saturated particle density of 1.85 as can be seen in the following calculations:



e

3.11. Moisture absorption (by weight) and relative density of lightweight aggregate versus time of submersion

$$\text{Moisture content at total saturation } M@_{TS} = \frac{.47 \times 1.0}{.53 \times 2.6} = .34$$

$$\text{Relative density at total saturation } RD@_{TS} = (.53 \times 2.6) + (.47 \times 1.0) = 1.85$$

Complete filling of pores in a structural grade LA is unlikely because the non-interconnected pores are enveloped by a very dense ceramic matrix. However, these calculations do reveal a conservative upper limit for the density in submerged design considerations.

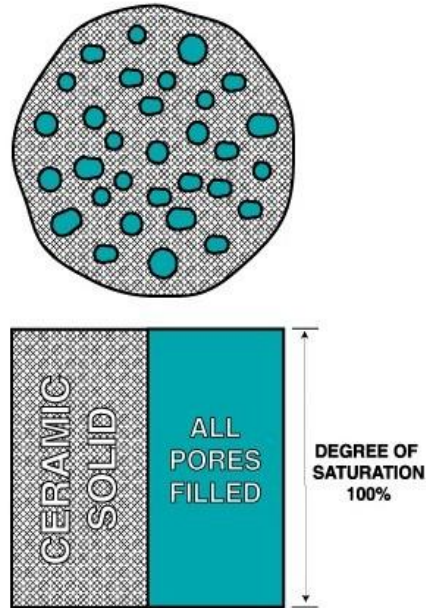


Figure 3.12 Schematic of Total Saturation (TS)
Theoretically All Pores Filled

3.7 Alkali-Silica Reaction in Lightweight Concrete

Aggregates containing certain silica constituents can under certain conditions react with the alkali hydroxide developed during hydration of cement. This reaction may cause a deleterious expansion and potential cracking in concrete members. This mechanism is of great concern to Department of Transportations in states that have experienced shortened service lives in pavements and structures. The issue of alkali silica reactivity has also surfaced when member companies have had a request to supply documentation relating to this mechanism for precast/prestressed manufacturing customers. This need for documentation is generally instigated by a plant certification process initiated by the Prestressed Concrete Institute in Chicago. A number of our member companies have responded to this request with laboratory test programs and references to a historical record of no evidence of deleterious expansion.

Assessing aggregate reactivity by accelerated methods is increasingly common. ASTM C 1260 “*Test Method for Potential Alkali Reactivity of Aggregates (Mortar Bar Method)*” (Appendix I) offers a relatively rapid procedure to supplement other lengthier test methods. This test involves measuring the length change of small mortar bars made with the sample

aggregate when stored in very strong alkali at a high temperature. The total time for conducting the test is 16 days.

The sampling and testing procedures of ASTM C 1260 are inappropriate for measuring the performance of lightweight aggregate concrete and need to be modified..

When preparing laboratory lightweight concrete in accordance with the procedures of ASTM Standard Method of Test for Alkali Silica Tests, it is essential to proportion and prepare the mixture to obtain the same procedures that are commonly used in the production of commercial lightweight concrete. Reasonable correlation of the behavior of the laboratory concrete [Labcrete] with that of commercial concrete [Realcrete] requires:

- Conditioning the lightweight aggregate to an absorbed [internal] moisture content equal to or greater than that achieved after a 24 hour soak [so-called “saturated surface dry”].
- Measuring the moisture content [oven dry and towel dry] to accurately determine the values of the surface [adsorbed] moisture and the absorbed [internal] moisture contents.
- Following the procedures requires computation of a lesser mass of lightweight aggregate that provides the SAME ABSOLUTE VOLUME as that occupied by normalweight aggregate is used in the standard testing procedures.
- The mass of lightweight aggregate used to replace the specified normalweight aggregate is calculated as follows:

Abs volume of LWA used in test = Abs volume of NWA specified for test

$$V_{LWA} = V_{NWA}$$

$$\text{Mass}_{LWA} / (\text{Relative density @ test})_{LWA} = (\text{Mass}_{NWA} / 2.65)$$

$$\text{Mass}_{LWA} \text{ used in test} = 990\text{g} \frac{(\text{ASTM C 1260}) \times \text{RD}_{LWA}}{2.65}$$

If for example the measured density factor of the LWA tested is 1.60 at the absorbed moisture content as tested, then when following the requirements of section 7.4.3 of ASTM C 1260 “Standard Test Method for Potential Alkali Reactivity [Mortar Bar method] then the mass of LWA used in the test should be:

$$990 \text{ grams} \times 1.60 / 2.65 = 598 \text{ grams}$$

This approach would assure that the results of the tests on the labcrete specimens would more closely correlate with the performance of commercial concrete. Additionally, this would result in a more realistic comparison between the behavior of LWC and NWC and a more realistic comparison between LWA’s of differing relative densities and differing moisture characteristics.

A non-mandatory appendix to C 1260 classifies an expansion of 0.10% or less at 14 days as innocuous behavior. Expansions of more than 0.20% are indicative of potentially deleterious expansion. Between 0.10 and 0.20% aggregates may exhibit either innocuous or deleterious behavior in field performance. Several state DOT's conduct or require this test to be conducted on lightweight aggregates used in bridge members. In one state, an expansion above 0.10% but below 0.20% triggers a requirement (for all aggregates, natural and lightweight) for the concrete supplier to provide supplementary cementitious materials (fly ash, silica fume, natural pozzolons, slag cement) in the mixture submitted for approval by the DOT.

The percent expansion results of tests conducted on various expanded shale, clay and slate in accordance with the principles if not the exact ASTM 1260 procedure are shown in Table 3.3. The tests samples A1-A2, B1-B3 and C1-C2 were conducted on ESCS aggregates from the same source but with separate samples submitted at different times. These results show the repeatability of the test results.

Table 3.3. Percent Expansion Results of tests conducted according to the principles of ASTM C 1260.

| LWA | Commercial Laboratory | DOT State #1 | DOT State #2 |
|-----|-----------------------|--------------|--------------|
| A1 | .06 | .08 | --- |
| A2 | --- | .12 | --- |
| B1 | .07 | .11 | .07 |
| B2 | --- | --- | .11 |
| B3 | --- | --- | .06 |
| C1 | .05 | --- | .05 |
| C2 | --- | --- | .04 |
| D | .04 | --- | --- |
| E | .04 | --- | --- |
| F | .04 | --- | --- |
| G | --- | .09 | .10 |
| H | --- | .08 | --- |
| I | --- | .07 | --- |

Average of 18 tests .07

3A

ASTM C 330-05

**“Standard Specification for Lightweight Aggregate
for Structural Concrete”**

Visit www.ASTM.org for document

3B

ASTM C 331-05

**“Standard Specification for Lightweight Aggregate
for Concrete Masonry Units”**

Visit www.ASTM.org for document

3C

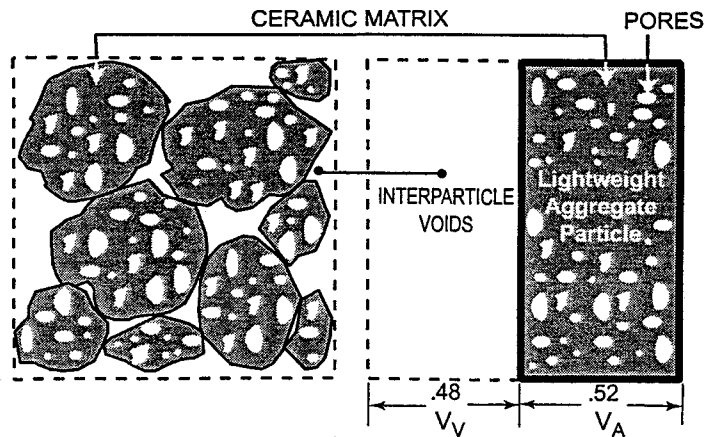
ASTM C 332-99

**“Standard Specification for Lightweight Aggregate
for Insulating Concrete”**

Visit www.ASTM.org for document

3D

**ESCSI Worksheet for Calculating
Aggregate Properties**

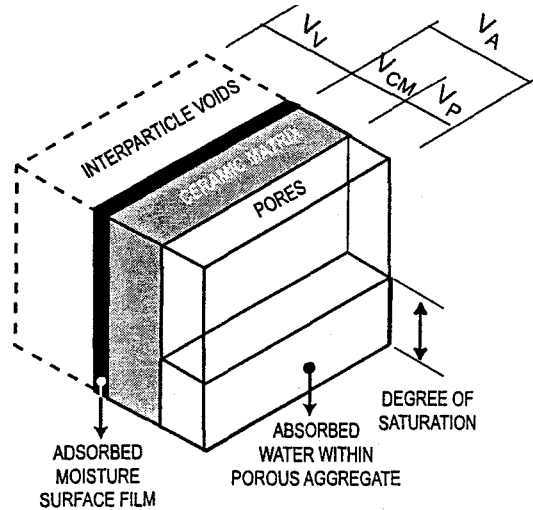


The following calculations are based on a hypothetical lightweight aggregate sample (illustrated above) that has a bulk loose dry density of 44.6 lb/ft³ (714 kg/m³) and a relative density (SSD pycnometer) of 1.50 after a 24-hour soak resulting in a moisture content of 8.5% by weight. The relative density of the ceramic matrix was measured to be 2.60.

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

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

$$V_V \left[\begin{array}{c} \text{Fractional Part of Bulk} \\ \text{Volume Occupied by Voids} \\ \text{between Particles} \end{array} \right] = 1.0 - V_A =$$



$$\text{Fractional Part of Lightweight Aggregate Particle (V}_A\text{) occupied by the solid ceramic Matrix} = \frac{RD_D}{RD_{CM}} \left[\frac{\text{Relative Dry Density}}{\text{Relative Density of the Solid Ceramic Matrix}} \right] = \text{---} =$$

Fractional Part of Lightweight Aggregate Particle Occupied by Pores =

$$V_{CM} \left[\text{Fractional Part of Bulk Volume occupied by the Solid Ceramic Matrix} \right] = V_A \times \left[\text{Fractional Part of Aggregate Particle (V}_A\text{) occupied by the Solid Ceramic Matrix} \right] =$$

$$\therefore V_P \left[\text{Fractional Part of Bulk Volume Occupied by Pores in Aggregate} \right] =$$

$$V_M \left[\text{Fractional Volume of Bulk Loose Sample Occupied by Moisture} \right] = \frac{\left[\text{Moisture Content by Weight} \right] \left[\text{Bulk Loose Dry Density of Sample} \right]}{1000 \left[\text{Density of Water} \right]} = \text{---} =$$

$$DS \left[\text{Degree of Saturation of the Pores Occupied by Moisture} \right] = \text{---} = *$$

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

3E

**“Procedures for Determination of Density
Factors of Structural Lightweight Aggregate”**

Procedure for Determination of Density Factors of Structural Lightweight Aggregate

Procedure for determining the density factors of lightweight aggregates containing absorbed water.

Pycnometer method for fine and coarse lightweight aggregates:

- a. A pycnometer consisting of a narrow-mouthed 2-quart mason jar with a pycnometer top (Soil test G-335, Humboldt H-3380, or equivalent).
- b. A balance or scale having a capacity of least 5 kg and a sensitivity of 1 g.
- c. A water storage jar (about 5-gallon capacity) for maintaining water at room temperature.
- d. Isopropyl (rubbing) alcohol and a medicine dropper.

Calibration of Pycnometer

The pycnometer is filled with water and agitated to remove any entrapped air. Water is added to “top off” the jar. The filled pycnometer is dried and weighed and the weight (weight *B* in grams) is recorded. (Regarding this method, a review of ASTM C 128 may be helpful).

Sampling Procedure

Representative samples of about 2 to 3 ft³ (.06 to .09m³) of each size aggregate should be obtained from the stockpile and put through a sample splitter or quartered until the correct size of the sample desired has been obtained. During this operation with damp aggregates, extreme care is necessary to prevent the aggregate from drying. The aggregate sample should occupy one-half to two-thirds the volume of the 1-quart pycnometer.

Test Procedure

Two representative samples should be obtained of each size of lightweight aggregate to be tested. The first is towel dried to remove surface (absorbed) water, weighed, placed in an oven at 105° C and dried to a constant weight. “Frying pan drying” to constant mass is an acceptable field expedient. The dry aggregate weight is recorded, and the aggregate moisture content (percentage of aggregate dry mass) is calculated.

The second aggregate sample is also towel dried, weighed (mass *C* in grams). The sample is then placed in the empty pycnometer and water is added until the jar is three-quarter full. The time of water addition should be noted.

The air entrapped between the aggregate particles is removed by rolling and shaking the jar. During agitation, the hole in the pycnometer tip is covered with the operator’s finger. The jar is then filled and agitated again to eliminate any additional entrapped air. If foam appears during the agitation and prevents the complete filling of the pycnometer with water at this stage, a minimum amount of isopropyl alcohol should be added with a medicine dropper to eliminate the foam. The water level in the pycnometer must be adjusted to full capacity and the exterior surfaces of the jar must be dry before weighing.

The pycnometer, thus filled with the sample and water, is weighed (mass A in grams) after 5, 10, and 30 minutes of sample immersion to obtain complete data, and the weights at these times are recorded after each “topping off”.

Calculation

The pycnometer relative density factor S , after any particular immersion time, is calculated by the following formula. In general the relative density and the absorption moisture content is reported after immersion for 24 hours.

$$S = C / (C + B - A)$$

Where:

A = mass of pycnometer charged with aggregate and then filled with water, g

B = mass of pycnometer filled with water, g

C = mass of moist aggregate tested, g

| <u>Relative Density Factor</u> | <u>Absorbed Moisture Percent by Dry Weight</u> |
|--------------------------------|--|
| 1.34 | 0 |
| 1.50 @ 24 hours | 12 |
| 1.61 | 20 |

Example of the measured relationship between pycnometer relative density and moisture content for lightweight aggregate.

Rationale:

Currently the only source of information on determining the relative density (specific gravity) factor for lightweight aggregate is ACI 211.2. This proposed appendix is a modified version of ACI 211.2. This information will be very useful to the users of this specification.

3F

**“Moisture Dynamics of Lightweight
Aggregate and Concrete”**

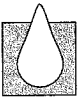
Moisture Dynamics in Lightweight Aggregate and Concrete

T.A. Holm, P.E., FACI • O.S. Ooi, P. Eng. • T.W. Bremner, Ph.D., P.Eng, FACI

Synopsis: This paper evaluates the moisture dynamics in lightweight aggregates and structural lightweight concrete. The time related changes in the moisture contents of aggregate and matrix fractions in the lightweight concrete were investigated while exposed to moist-curing and air-drying.

Methodology and terminology essential for the determination of the particle density, the porosity and the absorption characteristics of structural lightweight aggregate are presented. The effects of these properties on the batching and freezing and thawing resistance of lightweight concrete are reported.

When tested by the procedures of ASTM C666, concretes exposed to seven days of moist-curing and provided with five days of air-drying at 23°C and 50% RH developed a relative durability factor of over 100% after 300 cycles of freezing and thawing.



Keywords: absorption, air-drying, freezing and thawing, lightweight aggregate, lightweight concrete, moisture, pore structure, saturation

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This paper was presented at the Professor T.W. Bremner Symposium on High Performance Lightweight Concrete at the Sixth International Conference on the Durability of Concrete, Thessaloniki, Greece, June 2003

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Physical inspection of mature lightweight concretes which have been exposed to severe environments have shown that structural lightweight concrete has performed extremely well in marine and freezing and thawing environments (1-4). This successful performance of lightweight concrete has been attributed to the elastic compatibility between the lightweight aggregate and the cement paste, the improved "contact zone" between the aggregate and cement paste, and the extended curing derived from the internal moisture in the lightweight aggregates (5-7).

To fully understand the role of absorbed water in the enhancement of hydration, it is essential to use terms that unambiguously define the amount and location of the water. As with all densities of concrete, absorbed water is useful for extended internal curing and the reduction of autogenous and plastic shrinkage. For precise determination of the W/Cm ratio, it is essential to evaluate the amount of adsorbed water on the surface of the aggregate. Technical papers should use caution when using the expression "saturated" lightweight aggregates, to avoid the lack of precision existing in those cases where the lightweight aggregate used, in fact, has a moderate degree of saturation. Additionally, the aggregate may also have carried an unknown volume of adsorbed surface water that contributed to the "net" mixing water.

This paper presents the results of experimental studies that investigate the moisture dynamics between the lightweight aggregates and cementitious matrix during moist-curing and air-drying, and the effects of air-drying on the freezing and thawing durability of lightweight aggregate concrete produced with aggregates batched at a high degree of saturation.

STRUCTURAL LIGHTWEIGHT AGGREGATES

Structural grade lightweight aggregates of nominal 20 mm maximum size, manufactured by the Solite Corporation, Richmond, Virginia, were used in this research. Expanded shales, clays and slates (ESCS) aggregates have been used for more than 80 years in the United States in structural lightweight concrete, structural concrete masonry units and geotechnical fill. ESCS aggregates are produced by heating selected raw materials at high temperatures in a rotary kiln. Aggregates are produced to meet the requirements of ASTM C330, ASTM C331, and AASHTO M195.

TEST PROGRAM

Aggregate Absorption

Starting from an oven-dried condition, lightweight coarse aggregates were immersed in water at atmospheric pressure for a period of two years. The moisture content and particle density of the aggregates were measured at various ages of water immersion.

Table 1
Aggregate Absorption and Degree of Saturation

| Immersion Time | Water Absorption (% Mass) | Degree of Saturation | % of 24-Hour Soak |
|----------------|---------------------------|----------------------|-------------------|
| 0 mins | 0 | 0 | 0 |
| 2 mins | 5.76 | .17 | 55 |
| 5 mins | 6.15 | .18 | 59 |
| 15 mins | 6.75 | .20 | 64 |
| 60 mins | 7.74 | .23 | 74 |
| 2 hours | 8.32 | .24 | 79 |
| 1 day | 10.5 | .31 | 100 |
| 3 days | 12.11 | .35 | 115 |
| 28 days | 18.4 | .54 | 175 |
| 4 months | 23.4 | .69 | 223 |
| 1 year | 30 | .88 | 285 |
| 2 years | 30 | .88 | 285 |

Fig. 1 shows the results of absorption tests, and Table 1 provides the degree of saturation of the aggregates at various ages of immersion.

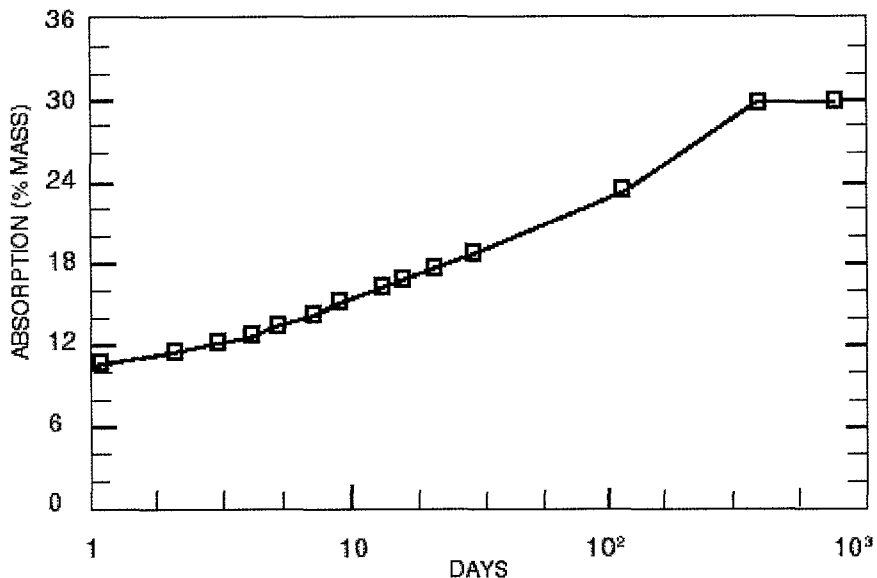


Fig. 1: Water Absorption by Weight of Coarse Lightweight Aggregates during 2 Years of Water Immersion

Concrete Mixture Proportions

Lightweight aggregate concrete mixtures were produced from ESCS that was conditioned to a high degree of saturation and used with normalweight fine aggregate. The moisture content of the lightweight aggregate was 24%.

The concrete mixtures were cast into 75 mm x 150 mm cylinders for the

moisture dynamic tests, and 75 mm x 100 mm x 400 mm prisms for the freezing and thawing tests. The concrete mixture proportions are shown in Table 2.

Table 2

Concrete Mixture Proportions

| | Lightweight Concrete Mixture Proportions [kg/m ³ (pcy)] |
|------------------------------|---|
| Type 10 Cement | 363 kg/m ³ (612) |
| Added Mixing Water | 130 kg/m ³ (219) |
| Solite Coarse Aggregate @ 24 | 582 kg/m ³ (981) |
| Fine Aggregate @ 4 | 763 kg/m ³ (1,287) |
| Fresh Density | 1,838 kg/m ³ (114.9 pcf) |
| Slump mm (in) | 72 mm (2.8) |
| Air Content (%) | 7.0% |

Method of Determining Moisture Content

The moisture dynamics in the lightweight aggregate concrete were investigated by measuring the moisture content of the aggregates and matrix fractions in the concretes following various ages of moist-curing and air-drying. The procedure used was as follows:

- The 75 mm x 150 mm concrete cylinders were crushed using a sledgehammer;
- The broken pieces of concrete were sieved using an ASTM # 10 sieve(1.68 mm sieve opening) to obtain the matrix fraction of concrete.

This matrix fraction could also include traces of crushed lightweight aggregate which passed through the sieve, thus limiting the precision of the analysis;

- The coarse aggregates were manually separated from the remaining concrete pieces using a 14 oz. hammer;
- The matrix and coarse aggregate fractions and the remaining concrete mixture were each weighed and oven-dried separately to determine their moisture contents.

Any free water present on the surface of the concrete cylinders was towel-dried prior to crushing. The entire crushing and separation procedure took approximately 15 minutes to complete. Precautions were taken to prevent the specimens from drying during this time.

PHYSICAL PROPERTIES OF STRUCTURAL LIGHTWEIGHT AGGREGATE

Particle Density

Structural Lightweight Aggregates (LA) have a low particle density due to their internal cellular pore system. The cellular structure within the particles is developed by heating certain raw materials to high temperatures to the point of incipient fusion, at which time gases are evolved within the pyroplastic mass, causing expansion that is retained upon cooling. Strong, durable, ceramic lightweight aggregates contain a relatively uniformly distributed system of pores that have a size range of approximately 5 to 300 μm enveloped in a high-strength vitreous phase. Pores close to the surface are readily permeable and fill within the first few hours of exposure to moisture. Interior pores, however, fill extremely slowly, with many months of submersion necessary for complete saturation. A fraction of the interior pores are essentially non interconnected and may remain unfilled after years of immersion.

The particle density of an aggregate is the ratio between the mass of the particle material and the volume occupied by the individual particles. This volume includes the pores within the particle, but does not include voids between the particles. In general, the volume of the particles is determined from the volume displaced while submerged in water. Penetration of water into the aggregate particles during the test is limited by the aggregate's previous degree of saturation.

The oven-dry density of an individual particle depends both on the density of the solid vitreous material and the pore volume within the particles, and generally increases when particle size decreases. After pulverizing in a jar mill over an extended period, the relative density of the poreless, solid ceramic material was determined to be 2.60 by methods similar to those used in measuring the relative density of cement.

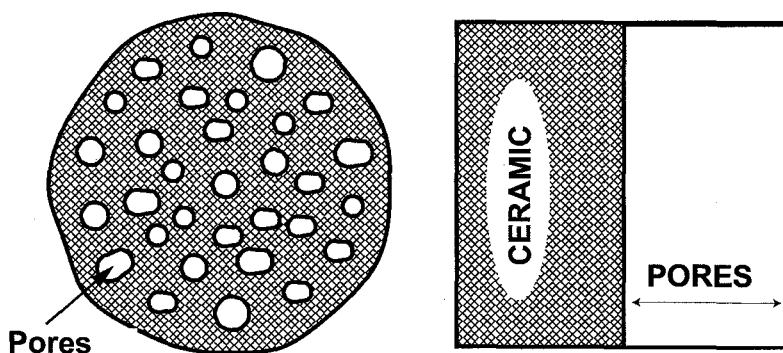


Fig 2. Schematic of Dry Structural Lightweight Aggregate

Absorption Characteristics

Due to their cellular structure, lightweight aggregates absorb more water than their ordinary aggregate counterparts. Based upon a 24-hour absorption test conducted in accordance with the procedures of ASTM C 127 and ASTM C 128, structural-grade lightweight aggregates will absorb from 5 to more than 25 percent moisture by mass of dry aggregate. By contrast, ordinary aggregates generally absorb less than 2 percent of moisture. The important distinction in stockpile moisture content is that with lightweight

aggregates the moisture is largely absorbed into the interior of the particles, whereas with ordinary aggregates it is primarily surface moisture. Recognition of this difference is essential in mixture proportioning, batching, and control. Rate of absorption is unique to each lightweight aggregate, and is dependent on the characteristics of pore size, continuity, and distribution, particularly for those pores close to the surface. (Fig. 3) Internally absorbed water within the particle is not immediately available for chemical interaction with cement as mixing water, and as such, does not enter into water-cement ratio (W/C_m) calculations. However, it is extremely beneficial in maintaining longer periods of hydration essential to improvements in the aggregate/matrix contact zone. Internal curing will also bring about a significant reduction of permeability by extending the period in which additional products of hydration are formed in the pores and capillaries of the binder.

As can be seen in Fig. 3, the rate of absorption can be divided into several regimes.

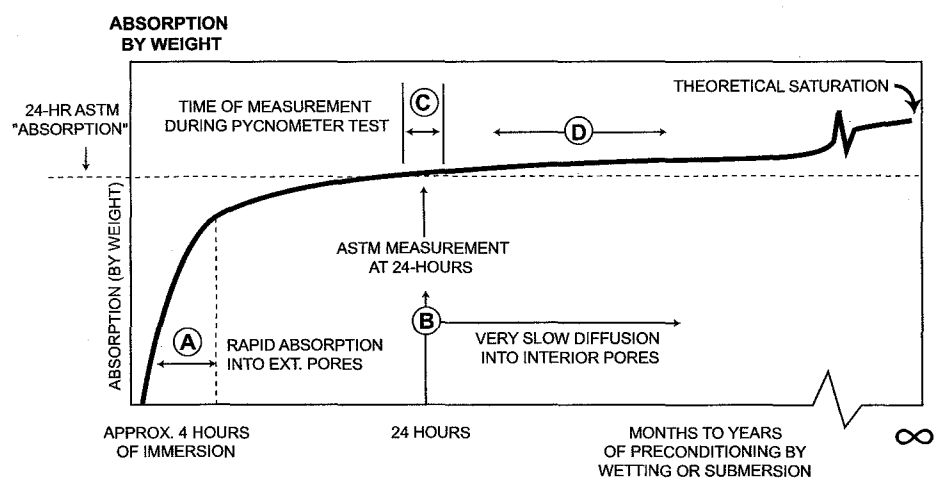


Fig 3. Absorption vs. Time for typical structural grade ESCS lightweight aggregate

- 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/C_m ratio will be decreased by an equivalent small amount (see the hypothetical example in Fig.6).

ASTM procedures prescribe measuring the “saturated” (*inaccurately named in the case of LA’s; partially saturated after a 24-hour soak is more accurate*) particle density in a pycnometer and then determining the absorbed moisture content on the sample that had been immersed in water for 24 hours. After a 24-hour 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 oven-dry particle density may be directly computed.

The example illustrated in Fig. 4 shows a typical ESCS structural lightweight aggregate (LA) of mid-range porosity and 24-hour absorption characteristics. Assume, following ASTM procedures, that after 24-hour immersion in a pycnometer, measurements result in a relative density of 1.52 with an associated

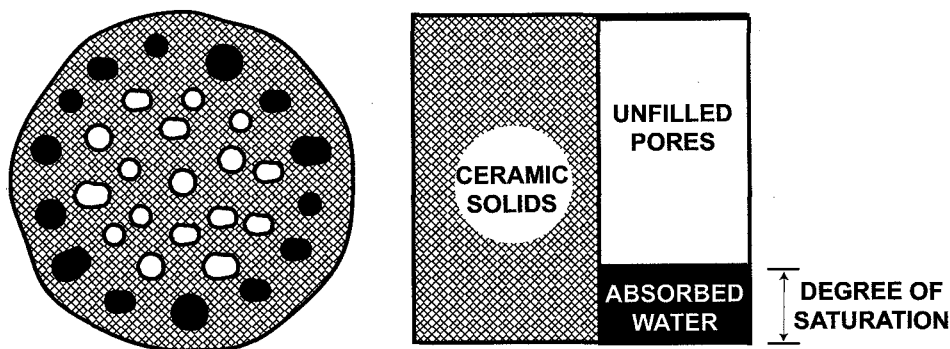


Fig. 4. "Saturated" Surface Dry as defined by ASTM C 127 and C 128 – after 24-hour submersion

ASTM "absorption" of 10.5% by mass. Then, the oven-dry particle density (PD_{OD}) may be back calculated to be as follows:

$$PD_{OD} = \frac{1.52}{(1 + .105)} = 1.38$$

It follows then that the fractional volume of ceramic solids, $V_s = \frac{1.38}{2.60} = .53$

Fraction Volume of pores, $V_p = 1.00 - .53 = .47$

The degree of saturation (DS: the extent to which the pores are filled)

$$DS = \frac{.105 \times 2.60 \times .53 \text{ (Volume of absorbed water)}}{.47 \text{ (Fractional volume of pores)}} = .31$$

Following the prescribed ASTM procedures the DS for ESCS LA will generally be in the range of approximately 25 to 35% of the theoretical saturation. The use of the ASTM expression "saturated surface dry" is therefore, inappropriate for LA, theoretically inaccurate and analytically misleading.

From a practical perspective and considering the fact that most LC is placed by pumping, the usual practice is to batch the LA at a moisture condition greater than the "Absorption Value" defined by ASTM procedures (24-hour immersion). In this condition the absorbed (internal) moisture content will be in excess of the arbitrarily defined ASTM "absorption" value. The degree of saturation (DS) necessary for adequate pumping characteristics, as determined by practical field experience, may be obtained from the ESCS supplier. Assume for this hypothetical LA that experience has shown that the LC will pump efficiently when the LA used has an absorption of at least 17% by mass.

At that condition the $DS = \frac{.17(2.60 \times .53)}{.47} = .50$.

Due to the continuous pre-wetting, and because of the very slow further tendency to absorb water into the aggregate, there will invariably be a film of surface (adsorbed) water on the surface of the LA. It is essential to evaluate this quantity of surface water for an accurate determination of the "net" mixing water that influences workability and determines the effective W/Cm ratio.

Therefore, it is necessary to run the usual moisture test twice. Measure the weight of the as-received 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 M_{AB} . The surface water M_{AD} (adsorbed) on the LA is then determined by $M_{AD} = M_T - M_{AB}$.

TYPICAL MOISTURE CONDITION OF STOCKPILED LIGHTWEIGHT AGGREGARE WITH SOME SURFACE WATER

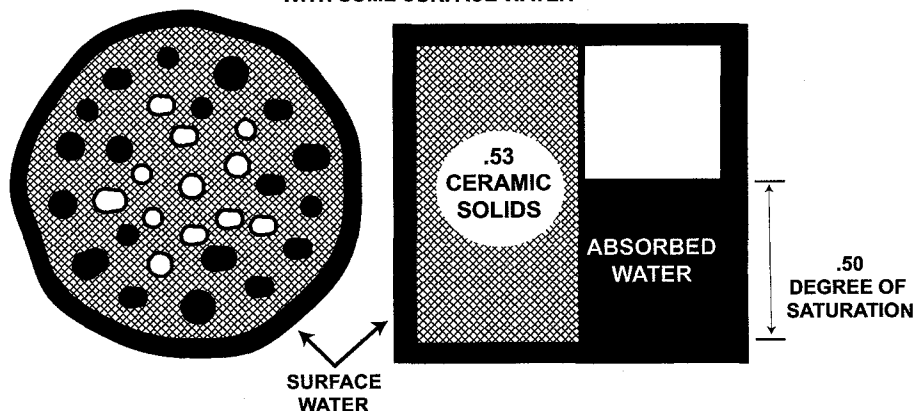


Fig. 5: "Partially Saturated" Surface Wet

- Assume for this example that measurements on this LA give the following:
 $M_{Total} = .21$, $M_{AB} = .18$, $\therefore M_{AD} = .03$.
- If this LC contains 800 pcy (474 kg/m^3) of oven-dry LA then the surface moisture will contribute $800 \times .03 = 24$ additional lbs/cy (14 kg/m^3) of net mixing water.
- If a w/c of .45 is specified with a cementitious content of 600 pounds, then an amount of $24/600 = .04$ must be part of the mixing water in the batch procedure.

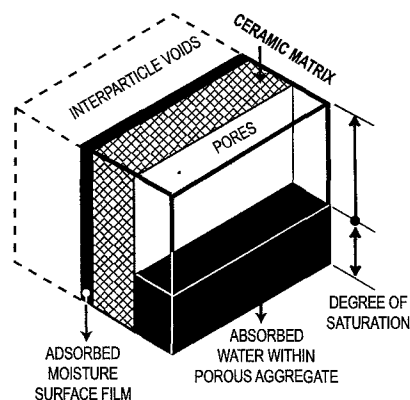


Fig. 6. Schematic showing absorbed water, degree of saturation, and adsorbed surface film water

Structural grade LA exposed to moisture in production plants and stored in open stockpiles will contain an equilibrium moisture content. Unbonded LA's are frequently used alone in geotechnical applications (eg. behind marine sheet piling, over tunnels, etc.) that are continuously sprinkled or submerged, will, however, continue to absorb water over time. In this investigation, the effective particle density of a submerged LA sample was measured throughout a two-year period to demonstrate long-term weight gain. Long-term absorption and relative density characteristics are also shown in Table 1, and Fig. 1 and Fig. 8

for an LA sample. When moisture absorption-versus-time relationships are extrapolated or theoretical calculations used to estimate the total filling of all the LA pores, it can be shown that for this particular LA, the absorbed moisture content at total saturation (M@TS) after an infinite immersion will approach 34% by mass with a totally saturated particle density of 1.85.

Complete filling of pores in a structural grade LA is unlikely because the non-interconnected pores are enveloped by a very dense ceramic matrix. However, these calculations do reveal a conservative upper limit for the density in submerged design considerations.

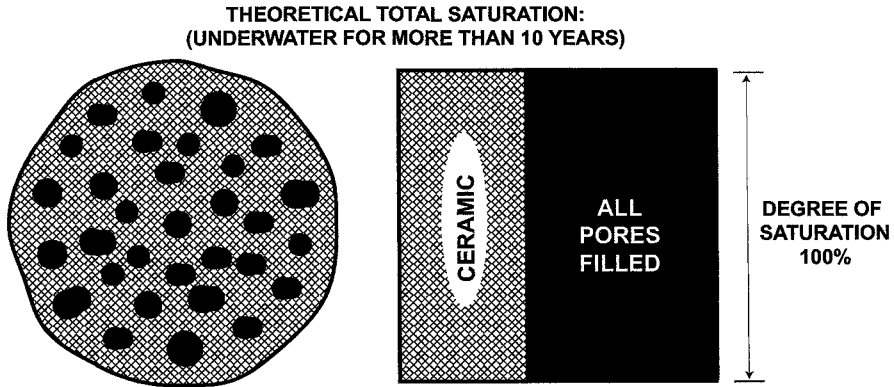


Fig. 7. Total Saturation (TS), theoretically all pores filled

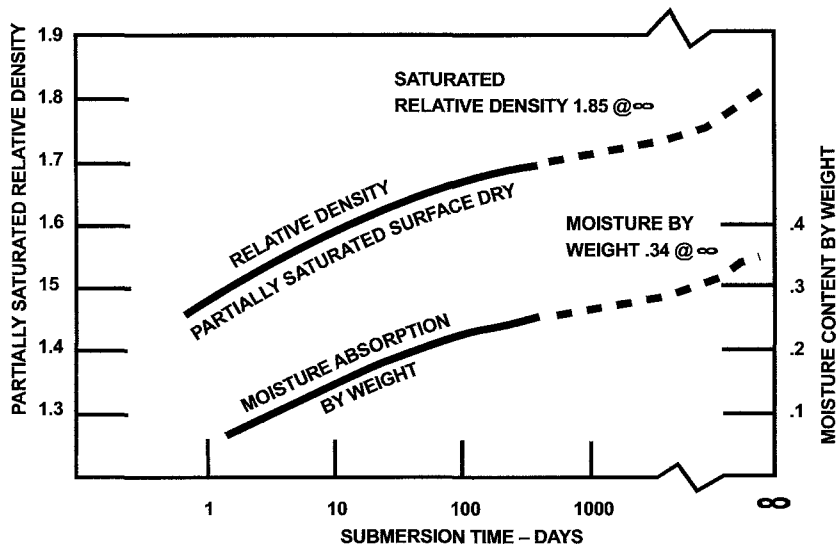


Fig. 8. Moisture absorption (by weight) and relative density of lightweight aggregate versus time of submersion

Moisture Content at Total Saturation

$$M@TS = \frac{.47 \times 1.0}{.53 \times 2.6} = .34$$

Relative Density at Total Saturation

$$\text{Relative Density @ TS} = (.53 \times 2.6) + (.47 \times 1.0) = 1.85$$

Moist-Curing and Air-Drying

As discussed previously, the hardened lightweight concrete was crushed and separated into aggregate and matrix, and the moisture content of each was determined. The moisture content of the aggregates rapidly decreased from 24% to 12% by aggregate mass within the first 24 hours in concrete.

Fig. 9 shows the decrease in the moisture contents of the lightweight aggregates during both moist-curing and when exposed to air-drying. It is noted that moisture dynamics during air-drying depend on the permeability of the concrete, area-to-volume ratio, and ambient conditions.

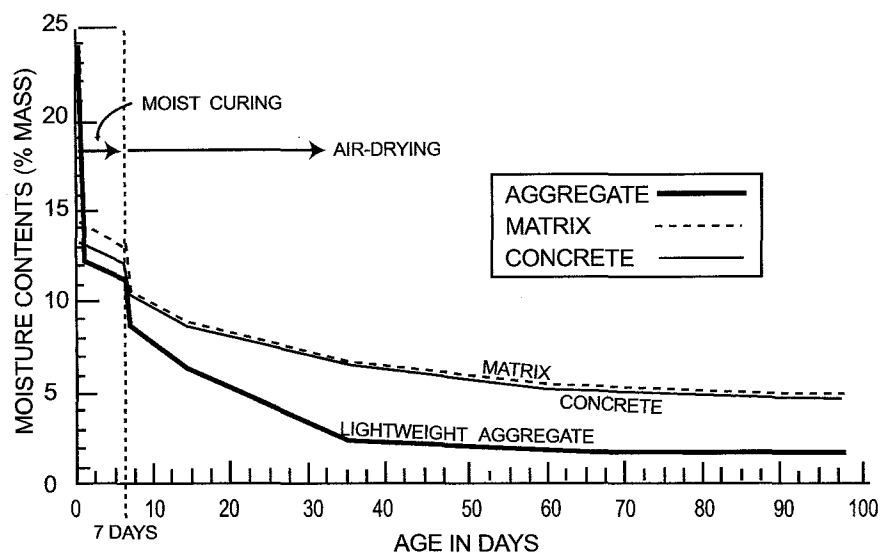


Fig. 9: Moisture content vs. Time for concrete containing lightweight aggregate batched with an absorbed moisture content of 24% by weight

INTERNAL CURING

LA batched at a high degree of saturation may be substituted for normalweight aggregates (NA) 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 as shown to be occurring in Fig. 9. We have learned that High Strength Concrete (HSC) is not necessarily High Performance Concrete (HPC), that HPC need not necessarily be HSC, and that a frequent, unintended consequence of HSC 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 LA is greater than that with NA. 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. This process of “internal curing” is particularly effective when the moisture content of LA at the time of mixing is in excess of that achieved in a 24-hour soak. The fact that absorbed moisture in the LA batched with a high degree of saturation (percent of internal pore volume occupied by water) 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 (8), 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 (9) 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 (10)(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 procedures. Their tests confirmed that the availability of absorbed moisture in LA 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, the first author of this paper had 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, focussed 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 one 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 1980 paper addressing the long term service performance of LC, Holm (11) cited the improved integrity of the LA/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 (12)(1980) documented the long term increase in strength of high strength LC incorporating pozzolons.

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 (13) 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 (14) was the first to recognize the potential benefits to high performance NC possible with the addition of LA containing high volumes of absorbed moisture. Weber and Reinhardt (15)(1995) have also conclusively demonstrated reduced sensitivity to poor curing conditions in high strength normalweight concrete containing an adequate volume of high moisture content LA. 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 (16).

The benefits of "internal curing" are increasingly important when pozzolans (silica fume, fly ash, metakolin, calcined shales, clays and slates, as well as the fines of LA) 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.

Freezing and Thawing Resistance

After seven days of moist-curing, the concrete prisms were air-dried for one, two three, five and seven days at 23°C and 50% R.H. Following air-drying, the prisms were subjected to freezing and thawing in an environmental chamber in accordance with Procedure A of ASTM C666. The prisms were tested at regular intervals of freezing and thawing cycles by measuring the resonant transverse frequency of the prism in accordance with ASTM C215 to obtain the relative dynamic modulus of elasticity.

Figure 10 indicates that lightweight aggregate concrete produced from aggregates with a high degree of saturation can be made durable to freezing and thawing with proper curing.

In this study, it was found that concrete produced from lightweight aggregates with an original moisture content of 24% by aggregate mass passed the ASTM C666 tests after seven days of moist-curing and five days of air-drying at 23°C and 50% RH.

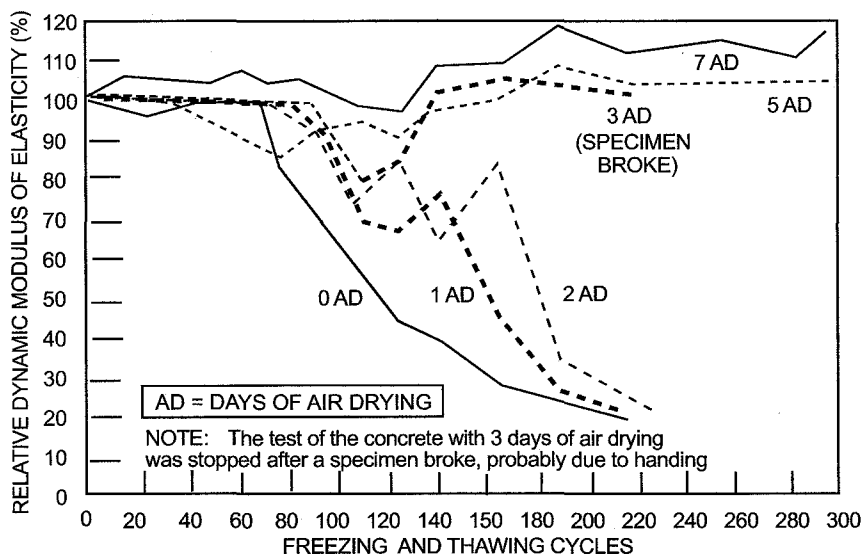


Fig. 10. Relative Dynamic Modulus of Elasticity for the Lightweight Concrete Containing Aggregates with a High Degree of Saturation in the Freezing and Thawing Experiments

CONCLUSIONS AND RECOMMENDATIONS

1. Each LA has a unique pore system that controls the rate and amount of water absorbed. In order to accurately proportion concrete mixtures, the water absorption vs. time of moisture preconditioning must be established by a testing program.
2. Attention to testing procedures and unambiguous terminology are essential in evaluating the amount and location of the water in/on the LA at the time of batching.
3. Water absorbed within the lightweight aggregate does not contribute to the W/Cm ratio; however, it reduces plastic shrinkage and enhances hydration through extended internal curing.
4. The amount of surface (adsorbed) water must be determined by a moisture measurement on an additional "towel dried" sample, and added to the "net" mixing water in the determination of the W/Cm ratio.
5. During air drying the small sized pore system in the matrix ($< 1 \mu\text{m}$) will wick out the moisture from the larger sized pores (5 to 300 μm) of the LA, thus providing for an extended period of internal curing.
6. A simple testing methodology for determination of the amount of water in the aggregate and matrix fractions during curing and drying was developed and provided results that provide insight into the process of internal curing.
7. Lightweight concrete produced with aggregates with a high degree of saturation were shown to be freeze-thaw durable when the concrete was properly protected prior to exposure to freezing and thawing cycles.

In this study, lightweight concrete batched with aggregates having 24% moisture content developed durability factors in excess of 100% when tested by the procedures of ASTM C666 after seven days of moist-curing followed by five days of air-drying at 23°C and 50% RH.

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**“Water-Vapor Adsorption-Desorption
Characteristics of Selected Lightweight Aggregates”**

**Research and Development Laboratories
of the
Portland Cement Association**

RESEARCH DEPARTMENT

Bulletin 178

**Water-Vapor Adsorption-Desorption
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By

Robert Landgren

**Authorized Reprint from the Copyrighted Proceedings
of the**

AMERICAN SOCIETY FOR TESTING AND MATERIALS

Philadelphia, Pa. 19103

Volume 64, pp. 830-845 (1964)

WATER-VAPOR ADSORPTION-DESORPTION
CHARACTERISTICS OF SELECTED
LIGHTWEIGHT CONCRETE AGGREGATES

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WATER-VAPOR ADSORPTION-DESORPTION CHARACTERISTICS OF SELECTED LIGHTWEIGHT CONCRETE AGGREGATES

BY ROBERT LANDGREN¹

SYNOPSIS

Water-vapor adsorption-desorption isotherms were determined for 15 typical lightweight concrete aggregates which have been used either in lightweight structural concrete or in load-bearing concrete masonry construction. Internal surface areas of the lightweight aggregates were calculated. Although of high porosity, the lightweight aggregates had surface areas comparable to the surface areas of equal weights of dense concrete aggregate.

The amount of sorbed water held by these lightweight aggregates, when dried to equilibrium at relative humidities less than 75 per cent, is extremely small compared to the amounts of water absorbed by the same aggregates when immersed in water. Applications of these adsorption-desorption data to the problems of drying lightweight concrete materials, fire resistance of lightweight structural concretes, and freezing-and-thawing durability are discussed.

Water-vapor adsorption-desorption characteristics have been determined for a group of typical lightweight concrete aggregates. Such characteristics relate the amount of moisture held by an aggregate to the relative humidity of the aggregate environment.

Adsorbed water is defined (1)² as "Water held on surfaces in a material by physico-chemical forces and having physical properties substantially different from those of absorbed water..." while *absorbed* water is "moisture held mechanically in a material and having physical properties not substantially different from ordinary water at the same temperature and pressure." Here, an elemental distinction will be made

between the processes of adsorption and absorption. *Adsorption* is considered to occur when a relatively dry material retains or takes up water in vapor form from a surrounding atmosphere. *Desorption* is the loss of adsorbed water to a drying atmosphere. *Absorption* occurs when a material imbibes moisture as it is immersed in or wetted by liquid water.

Knowledge of the adsorption-desorption properties of lightweight aggregates has a number of applications. For example, desorption data are of interest to producers of concrete masonry products who are sometimes required by specifications (2) to dry their products to weight equilibrium with air at a definite relative humidity before use. Information on the amount of moisture to be removed during the drying of different aggregate-cement combinations is needed

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² The boldface numbers in parentheses refer to the list of references appended to this paper.

if economies are to be realized. The amount of water to be removed is the difference between the water absorbed by the aggregate and the residual moisture in the aggregate after drying, this being obtained from the desorption data.

A knowledge of the residual moisture content of the concrete aggregates when concrete is "dried" is also useful in relation to the fire resistance of concrete and in establishing fire resistance building standards. Ashton and Bate (3)

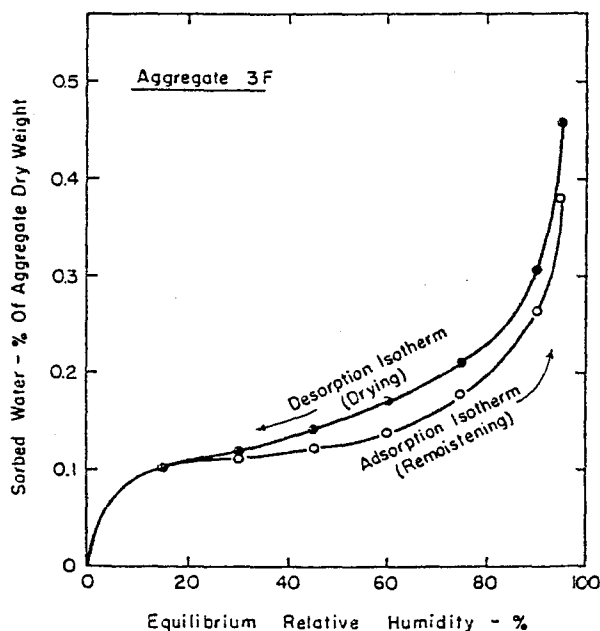


FIG. 1—The Adsorption-Desorption Isotherms of Aggregate 3F Show That More Water is Retained During the Drying Process Than Will be Adsorbed During Remoistening.

state: "The fire resistance of a beam is affected to a marked extent by the amount of free water in the concrete . . ." Concrete members are dried to a predetermined relative humidity before being tested for fire resistance, and the quantity of water in the concrete aggregate at this relative humidity is an important factor.

The amount of water present in an aggregate in concrete also influences the ability of the concrete to withstand the effect of freezing (4,5). Water-vapor adsorption-desorption characteristics are

helpful in evaluating the degree of water saturation of concrete aggregates used in freezing-and-thawing studies.

Detailed descriptions of the adsorption process are given elsewhere, (6,7,8). Here, it is sufficient to recognize that porous materials contain a small amount of adsorbed water, even when they are dried to constant weight at low hu-

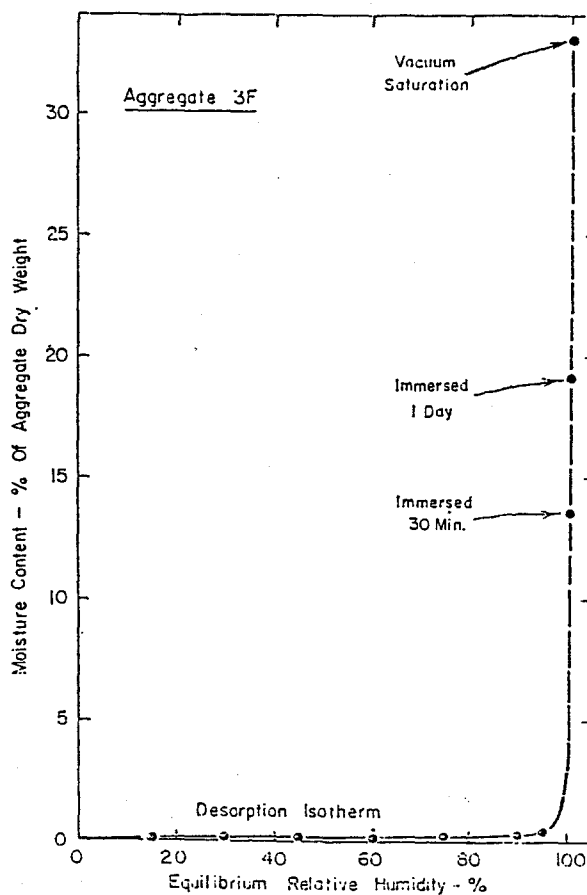


FIG. 2—The Water Retained at Normal Relative Humidities Is Small When Compared with the Water Absorbed by the Aggregate.

midities. Surface-adsorbed water is present because water-vapor molecules coat the internal surfaces of the porous material and are strongly held by these surfaces. At low relative humidities, the amount of water-vapor adsorbed by porous materials is related directly to the total area of solid surface coated by the adsorbed water-vapor. Surfaces capable of adsorbing water are not confined to the visible, external portions of a

particle. Such internal surfaces as the boundaries of individual grains or pores and microcracks in the grains may also adsorb water-vapor.

The amount of sorbed water in a

the adsorption and desorption isotherms of the aggregate. (The word "isotherm" indicates that all measurements were made at one temperature.) In Fig. 1, equilibrium moisture contents obtained

TABLE 1—LIGHTWEIGHT AGGREGATES INVESTIGATED.

| Sample No., Sieve Size | | Aggregate Description |
|------------------------|------------------------------------|---|
| No. 4 to 8 | $\frac{3}{8}$ to $\frac{1}{4}$ in. | |
| 1F ^a | 1C | Volcanic cinders, particles crushed to subangular form and have a fairly coarse texture. |
| 2F..... | 2C | Volcanic cinders, particles crushed to subangular form and have a fairly coarse texture. |
| 3F ^a | 3C | Crushed pumice, very fine-grain subangular particles. Large amounts of dense volcanic glasses and obsidian. |
| 4F ^a | 4C | Crushed pumice, very fine-grain subangular particles. Little obsidian or other dense glasses. |
| 5F ^a | 5C | Expanded shale, half of the particles rounded with a poorly developed shell and half blocky crushed particles with a very coarse texture. |
| 6F..... | 6C Shideler (No. 3) | Well rounded expanded shale with a smooth fine-grain shell. |
| 7F..... | 7C Shideler (No. 9) | Experimental expanded shale, fairly well rounded with a well-sealed shell. |
| 8F..... | 8C Klieger and Hanson (No. 10) | Sealed and rounded expanded shale. |
| 9F..... | Shideler (No. 5) | Crushed expanded slate with a medium texture. |
| | 9C Shideler (No. 5) | Subangular particles of expanded slate, some of which are exfoliated. |
| 10F..... | Shideler (No. 2) | Crushed, fine-grain material with no appreciable fired shell. Expanded shale designated as Haydite. |
| | 10C Shideler (No. 2) | Rounded material with a fine-grain fairly dense shell. Haydite expanded shale. |
| 11F..... | 11C Klieger and Hanson (No. 11) | Lumpy, striated particles of Haydite expanded shale. Has fine-grain surface with very small internal pores. |
| 12F ^a | 12C | Crushed soft coal cinders, angular in shape. |
| 13F..... | 13C | Coarse textured expanded slag crushed to a subangular form. |
| 14F..... | 14C | Very coarse-textured expanded slag crushed to a subangular form. |
| 15F..... | 15C Shideler (No. 6) | Crushed expanded slag with all particles quite porous and angular in shape. |

^a Insufficient No. 4 to No. 8 material was present in the sample of fine material received, so the sample of coarse material was separated into the desired sizes.

material increases as the relative humidity of the atmosphere surrounding the material increases. Figure 1 shows the relationships between the moisture contents of a lightweight aggregate equilibrated at various relative humidities. This figure, typical of such relationships for most porous materials, shows both

while drying the aggregate (desorbing water) or while remoistening the aggregate (adsorbing water) coincide through the range of 0 to 25 per cent relative humidity (RH), the range where physical adsorption on solid surfaces is predominant and is a reversible process. However, above 25 per

cent RH the drying and remoistening (desorption and adsorption) curves in Fig. 1 differ. This is generally believed to be caused by the filling of small pores with water through the process of capillary condensation. In this humidity range, capillary forces should cause a porous material to retain more water when dried to constant weight at a given humidity than it could regain if dried further and then remoistened to the same humidity level.

Figure 2 contrasts desorption values obtained during drying with the water absorption of an aggregate, Aggregate 3F, after 30 min of water soaking, 1 day of soaking, and after vacuum saturation. This figure shows that the amount of water remaining in this aggregate after drying to normal humidity levels is small compared to the total water absorption of the aggregate.

Aggregates Studied:

All of the lightweight aggregates studied have been used in structural concrete or in load-bearing masonry units. In the group of 15 aggregates were volcanic cinders, pumices, soft coal cinders and expanded clays, shales, slate, and slags.

Some of the fine- and coarse-aggregate samples were obtained from suppliers especially for this work. Additional samples were obtained from the same aggregate stocks used by Shideler (9) and Klieger and Hanson (10) in their work on the properties and durability of concrete. The aggregates are identified in Table 1.

Samples of each fine and coarse aggregate, with the exceptions noted in Table 1, were studied. The fine aggregate was represented by material passing No. 4 and retained on No. 8 sieves, and the coarse aggregate was represented by material passing $\frac{3}{8}$ -in. and retained on $\frac{1}{4}$ -in. sieves. Aggregates of these sizes

are large enough to be surface-dried with a towel during absorption measurements, yet small enough to be readily dried or remoistened during adsorption-desorption determinations.

Procedure:

A sample weighing approximately 20 g was obtained from the No. 4 to No. 8 and $\frac{3}{8}$ to $\frac{1}{4}$ in. size of each aggregate. All samples were vacuum-dried (at 2 cm Hg absolute pressure and a temperature of 40 C) to constant weight over flake calcium chloride. The aggregates were then "vacuum saturated" by evacuation for 2 hr at an absolute pressure less than 1 mm Hg, followed by inundation in air-free distilled water while still under vacuum. The aggregates were stored under water until they had reached a very high degree of saturation, this requiring from 5 to 7 weeks.

Water was desorbed from the samples by exposing them in a desiccator over solutions of sulfuric acid. Different relative humidities were obtained in the desiccator by the use of different acid concentrations. The aggregates were dried stepwise to weight equilibrium at relative humidities of 95, 90, 75, 60, 45, 30, and 15 per cent and finally redried to 0 per cent RH by the vacuum procedure previously described. The aggregates were remoistened stepwise through the same humidity levels to 95 per cent RH, vacuum-dried, and finally oven-dried at 105 C. Oven drying was specifically deferred to this time so that any possible physical changes in the aggregates induced by high temperatures would not occur before the adsorption-desorption work was completed.

Tests to determine the absorption and specific gravity of the aggregate samples were then made using the "selective toweling procedure" (11). This procedure is essentially that of ASTM Method C

TABLE 2—TEST RESULTS FOR LIGHTWEIGHT AGGREGATES.

| Aggregate Type..... | | Volcanic Cinders | | | | Pumices | | | | Expanded Shales | | | | | | | |
|---|-------------|------------------|-----------------|------|------|---------|------|------|------|-----------------|------|------|------|------|------|------|------|
| Sample Number..... | | 1F ^a | 1C ^a | 2F | 2C | 3F | 3C | 4F | 4C | 5F | 5C | 6F | 6C | 7F | 7C | 8F | 8C |
| Bulk specific gravity (dry basis). | | 1.36 | 1.29 | 1.62 | 1.81 | 1.27 | 1.33 | 0.93 | 0.96 | 1.37 | 1.29 | 1.53 | 1.49 | 1.60 | 1.38 | 1.32 | 1.27 |
| WATER ABSORPTION (% OF AGGREGATE DRY WEIGHT) | | | | | | | | | | | | | | | | | |
| 30-min water immersion..... | | 13.6 | 14.0 | 6.4 | 6.0 | 13.6 | 10.9 | 25.9 | 21.8 | 9.5 | 8.4 | 8.1 | 6.4 | 4.3 | 3.3 | 6.3 | 3.5 |
| 1-day water immersion..... | | 14.1 | 14.2 | 10.6 | 7.8 | 19.1 | 14.0 | 34.0 | 26.3 | 12.6 | 11.7 | 10.9 | 9.3 | 5.9 | 5.4 | 12.9 | 7.8 |
| Vacuum saturation..... | | 29.9 | 32.5 | 22.5 | 16.5 | 33.0 | 30.4 | 63.2 | 60.4 | 23.9 | 27.5 | 21.4 | 23.6 | 15.3 | 21.5 | 30.6 | 30.9 |
| SORBED WATER-VAPOR (% OF AGGREGATE DRY WEIGHT) ^b | | | | | | | | | | | | | | | | | |
| Drying (desorbing water) | 95% RH..... | 0.75 | 0.89 | 0.63 | 0.68 | 0.46 | 0.49 | 2.38 | 4.16 | 0.61 | 0.70 | 0.71 | 1.09 | 0.89 | 1.13 | 1.21 | 0.68 |
| | 90%..... | 0.52 | 0.53 | 0.45 | 0.38 | 0.31 | 0.31 | 1.57 | 1.44 | 0.33 | 0.36 | 0.27 | 0.54 | 0.61 | 0.79 | 0.59 | 0.36 |
| | 75%..... | 0.35 | 0.30 | 0.23 | 0.18 | 0.21 | 0.24 | 1.08 | 0.98 | 0.18 | 0.17 | 0.14 | 0.25 | 0.21 | 0.27 | 0.18 | 0.11 |
| | 60%..... | 0.28 | 0.24 | 0.16 | 0.16 | 0.17 | 0.20 | 0.94 | 0.85 | 0.12 | 0.11 | 0.10 | 0.21 | 0.18 | 0.22 | 0.09 | 0.08 |
| | 45%..... | 0.24 | 0.20 | 0.12 | 0.13 | 0.14 | 0.16 | 0.82 | 0.74 | 0.10 | 0.09 | 0.09 | 0.16 | 0.15 | 0.19 | 0.06 | 0.07 |
| | 30%..... | 0.18 | 0.16 | 0.07 | 0.09 | 0.12 | 0.15 | 0.72 | 0.65 | 0.06 | 0.05 | 0.07 | 0.12 | 0.13 | 0.17 | 0.05 | 0.07 |
| | 15%..... | 0.13 | 0.12 | 0.05 | 0.07 | 0.10 | 0.13 | 0.62 | 0.56 | 0.04 | 0.04 | 0.06 | 0.11 | 0.12 | 0.15 | 0.04 | 0.06 |
| Remoistening (adsorbing water) | 15% RH..... | 0.13 | 0.11 | 0.05 | 0.08 | 0.10 | 0.13 | 0.59 | 0.53 | 0.06 | 0.03 | 0.04 | 0.10 | 0.11 | 0.14 | 0.05 | 0.06 |
| | 30%..... | 0.16 | 0.13 | 0.07 | 0.09 | 0.11 | 0.14 | 0.66 | 0.59 | 0.07 | 0.03 | 0.07 | 0.12 | 0.12 | 0.15 | 0.06 | 0.07 |
| | 45%..... | 0.18 | 0.15 | 0.08 | 0.10 | 0.12 | 0.15 | 0.73 | 0.66 | 0.09 | 0.04 | 0.07 | 0.13 | 0.13 | 0.17 | 0.07 | 0.07 |
| | 60%..... | 0.21 | 0.18 | 0.10 | 0.12 | 0.14 | 0.16 | 0.79 | 0.71 | 0.10 | 0.06 | 0.08 | 0.14 | 0.15 | 0.18 | 0.08 | 0.08 |
| | 75%..... | 0.25 | 0.21 | 0.13 | 0.14 | 0.18 | 0.20 | 0.89 | 0.81 | 0.12 | 0.07 | 0.09 | 0.16 | 0.17 | 0.21 | 0.09 | 0.09 |
| | 90%..... | 0.33 | 0.28 | 0.20 | 0.19 | 0.26 | 0.29 | 1.13 | 1.03 | 0.18 | 0.12 | 0.13 | 0.22 | 0.22 | 0.27 | 0.12 | 0.11 |
| | 95%..... | 0.42 | 0.37 | 0.30 | 0.24 | 0.38 | 0.40 | 1.40 | 1.29 | 0.25 | 0.18 | 0.22 | 0.29 | 0.26 | 0.31 | 0.15 | 0.12 |
| PERMANENT GAIN IN WEIGHT (% OF AGGREGATE DRY WEIGHT) | | | | | | | | | | | | | | | | | |
| During drying..... | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.04 | 0 | 0.05 | 0 | 0 | 0 | 0.03 |
| During adsorption..... | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.09 | 0.03 | 0.04 | 0.02 | 0 | 0.07 | 0.06 | 0.03 |

| Aggregate Type..... | Expanded Slate | | Haydites | | | | Soft Coal Cinders | | Expanded Slags | | | | | |
|------------------------------------|----------------|------|----------|------|------|------|-------------------|------|----------------|------|------|------|------|------|
| Sample Number..... | 9F | 9C | 10F | 10C | 11F | 11C | 12F | 12C | 13F | 13C | 14F | 14C | 15F | 15C |
| Bulk specific gravity (dry basis). | 1.65 | 1.44 | 1.18 | 1.36 | 1.49 | 1.45 | 1.99 | 1.93 | 1.76 | 1.71 | 1.68 | 1.80 | 1.59 | 1.54 |

WATER ABSORPTION (% OF AGGREGATE DRY WEIGHT)

| | | | | | | | | | | | | | | |
|-----------------------------|------|------|------|------|------|------|-----|-----|------|------|------|------|------|------|
| 30-min water immersion..... | 5.2 | 4.9 | 15.2 | 12.6 | 10.3 | 10.6 | 3.5 | 3.8 | 7.4 | 10.5 | 14.7 | 13.2 | 3.6 | 3.5 |
| 1-day water immersion..... | 9.9 | 8.7 | 21.9 | 16.6 | 15.3 | 15.5 | 4.5 | 4.3 | 10.3 | 11.5 | 16.8 | 14.4 | 8.1 | 5.3 |
| Vacuum saturation..... | 20.2 | 28.3 | 39.6 | 30.4 | 23.3 | 24.4 | 7.7 | 8.3 | 17.6 | 20.4 | 23.4 | 20.3 | 18.2 | 15.1 |

SORBED WATER-VAPOR (% OF AGGREGATE DRY WEIGHT)^b

| | | | | | | | | | | | | | | | |
|--------------------------------------|------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Drying (desorbing water) | 95%RH..... | 0.47 | 0.22 | 1.60 | 1.21 | 3.12 | 3.22 | 0.19 | 0.25 | 1.15 | 1.18 | 3.69 | 3.20 | 0.48 | 0.69 |
| | 90%..... | 0.14 | 0.12 | 0.97 | 0.56 | 1.90 | 1.64 | 0.15 | 0.16 | 0.89 | 0.83 | 3.09 | 2.45 | 0.29 | 0.54 |
| | 75%..... | 0.07 | 0.07 | 0.50 | 0.13 | 0.48 | 0.34 | 0.11 | 0.13 | 0.64 | 0.42 | 1.60 | 1.21 | 0.21 | 0.40 |
| | 60%..... | 0.05 | 0.07 | 0.39 | 0.11 | 0.42 | 0.29 | 0.09 | 0.11 | 0.47 | 0.37 | 1.42 | 1.08 | 0.15 | 0.28 |
| | 45%..... | 0.05 | 0.06 | 0.29 | 0.06 | 0.31 | 0.22 | 0.08 | 0.10 | 0.37 | 0.29 | 1.09 | 0.85 | 0.13 | 0.21 |
| | 30%..... | 0.04 | 0.06 | 0.24 | 0.04 | 0.19 | 0.13 | 0.06 | 0.07 | 0.25 | 0.22 | 0.79 | 0.61 | 0.10 | 0.14 |
| | 15%..... | 0.04 | 0.06 | 0.22 | 0.04 | 0.16 | 0.11 | 0.05 | 0.06 | 0.16 | 0.17 | 0.61 | 0.50 | 0.08 | 0.11 |
| Remoistening (adsorbing water) | 15%RH..... | 0.04 | 0.06 | 0.20 | 0.06 | 0.16 | 0.12 | 0.05 | 0.05 | 0.21 | 0.24 | 0.66 | 0.55 | 0.08 | 0.10 |
| | 30%..... | 0.04 | 0.06 | 0.21 | 0.07 | 0.19 | 0.13 | 0.06 | 0.06 | 0.28 | 0.27 | 0.78 | 0.63 | 0.09 | 0.12 |
| | 45%..... | 0.05 | 0.07 | 0.24 | 0.08 | 0.23 | 0.15 | 0.07 | 0.07 | 0.33 | 0.31 | 0.90 | 0.71 | 0.10 | 0.13 |
| | 60%..... | 0.05 | 0.07 | 0.27 | 0.09 | 0.27 | 0.18 | 0.08 | 0.08 | 0.41 | 0.35 | 1.04 | 0.81 | 0.10 | 0.15 |
| | 75%..... | 0.06 | 0.08 | 0.32 | 0.12 | 0.36 | 0.23 | 0.09 | 0.09 | 0.50 | 0.47 | 1.56 | 1.31 | 0.12 | 0.18 |
| | 90%..... | 0.07 | 0.09 | 0.49 | 0.20 | 0.53 | 0.36 | 0.12 | 0.11 | 0.69 | 0.69 | 2.46 | 2.16 | 0.16 | 0.23 |
| | 95%..... | 0.09 | 0.11 | 0.68 | 0.30 | 0.66 | 0.45 | 0.14 | 0.13 | 0.84 | 0.81 | 2.96 | 2.61 | 0.20 | 0.28 |

PERMANENT GAIN IN WEIGHT (% OF AGGREGATE DRY WEIGHT)

| | | | | | | | | | | | | | | |
|------------------------|------|------|---|------|------|------|------|------|------|------|------|------|------|------|
| During drying..... | 0 | 0.03 | 0 | 0.02 | 0.21 | 0.17 | 0.04 | 0.04 | 0.78 | 0.44 | 2.69 | 2.13 | 0.47 | 0.66 |
| During adsorption..... | 0.03 | 0.01 | 0 | 0.01 | 0.08 | 0.04 | 0.07 | 0.05 | 0.36 | 0.26 | 0.94 | 1.01 | 0.10 | 0.09 |

^a F = Fine fraction (No. 4 to No. 8 sieve size).C = Coarse fraction ($\frac{3}{8}$ to $\frac{1}{4}$ " sieve size).^b All values are percentages of the calculated oven-dry aggregate weights determined during the interval between drying and remoistening of the aggregates.

LANDGREN ON WATER-VAPOR ADSORPTION IN AGGREGATES

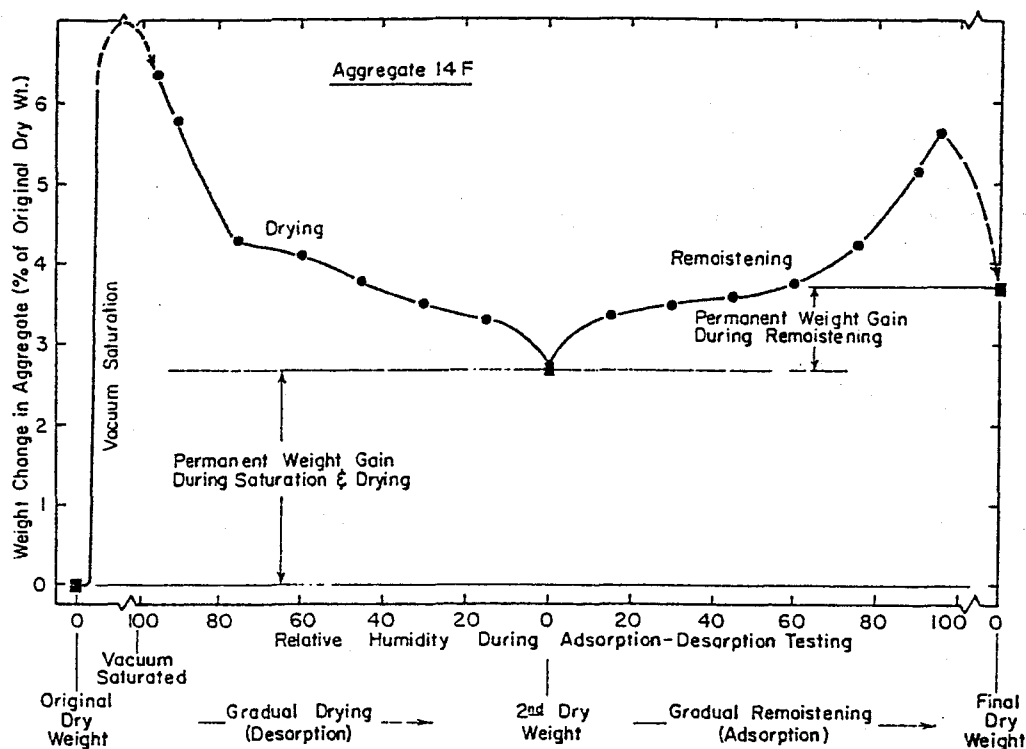


FIG. 3—Changes in Vacuum Dry Weight of Aggregate 14F During Adsorption-Desorption Testing Reflect the Permanent Weight Gains Occurring in the Aggregates.

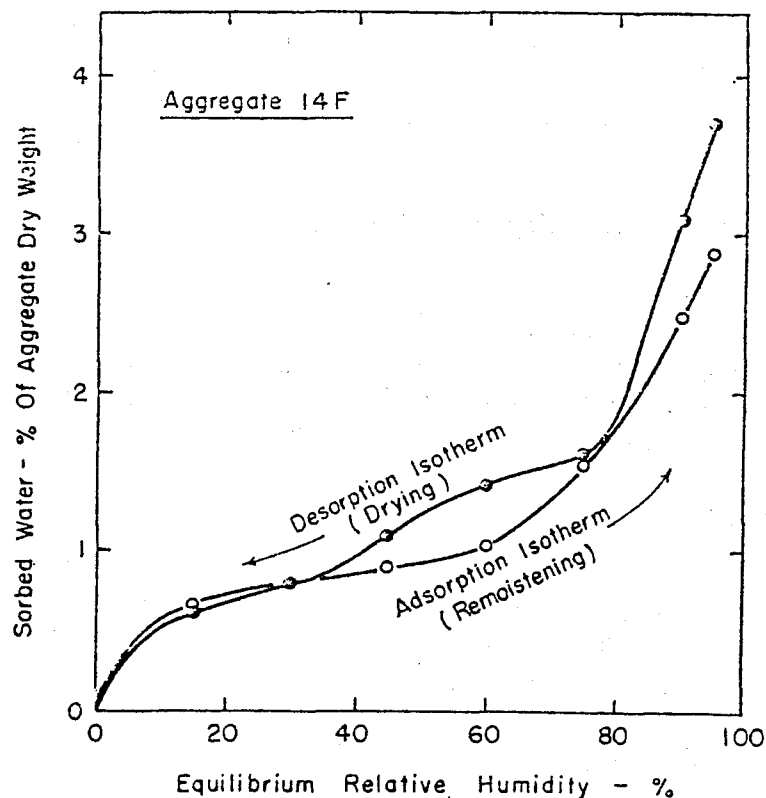


FIG. 4—For Some Aggregates, Permanent Weight Changes During Test Change the Shape of the Adsorption-Desorption Isotherms.

127,³ except that small samples of aggregates were tested, and particular care was taken to ensure that the aggregates were not overdried as they were towed to surface-dryness. An analytical balance was used for all weight measurements. Water absorption of the lightweight aggregates was determined after immersion in water for 30 min, after one day of water immersion, and for the

aggregate solid during the time when determinations of sorbed water contents are made. Many of these lightweight aggregates however, did change during study. Figure 3 compares the weight changes of aggregate 14F, from its original dry condition through desorption and adsorption to the final dry weight determination. It shows that the dry weight of this aggregate increased during

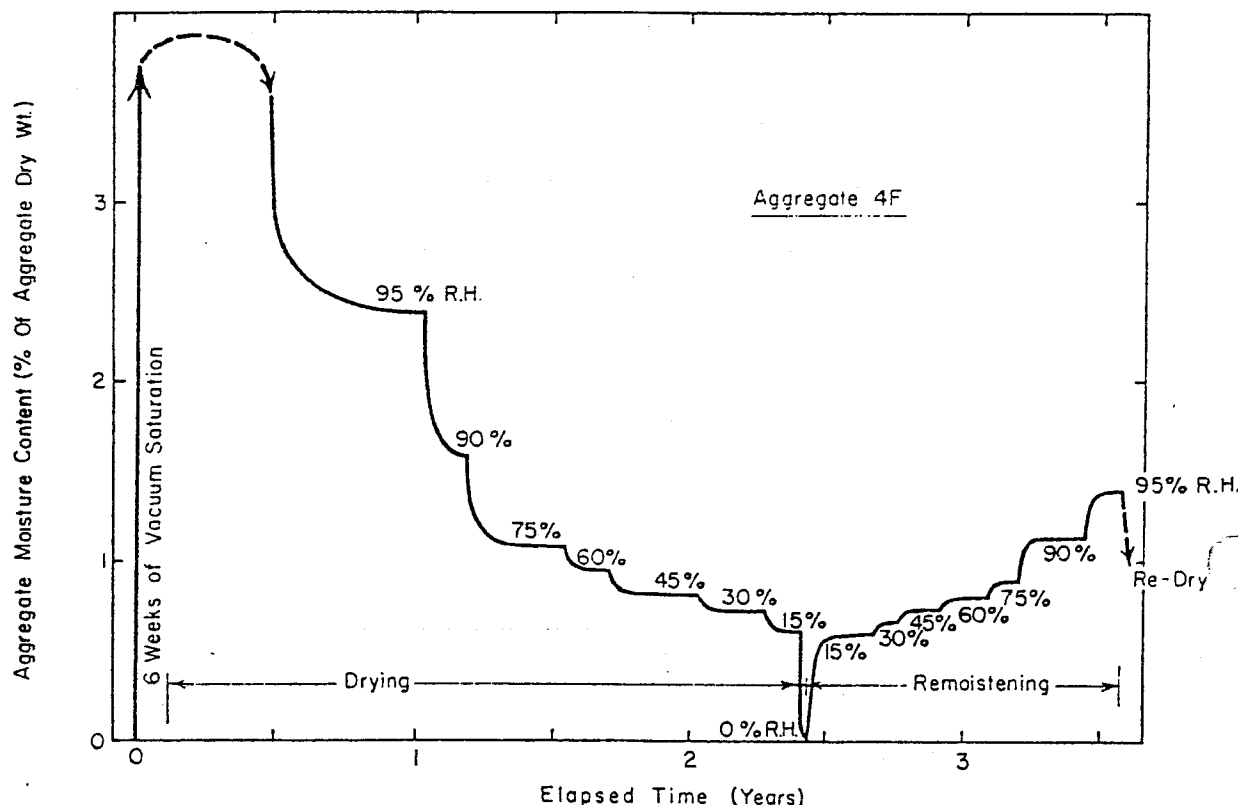


FIG. 5—Moisture Content—Exposure Time Relationships for Stepwise Desorption-Adsorption Tests.

vacuum saturated condition. Water absorptions, aggregate bulk specific gravities, and all adsorption-desorption results are given in Table 2.

Lightweight Aggregate Adsorption-Desorption Data:

In order that physical adsorption-desorption data be precise, there must be no change in the properties of the ag-

gregate. After vacuum saturation and the slow drying cycle, the redried aggregate weighed almost 3 per cent more than it did in the original dry condition. Another weight increase of about 1 per cent occurred during the period of remoistening and subsequent redrying.

Such increases in permanent weight complicate the interpretation of the data. This is demonstrated by Fig. 4, which shows the adsorption-desorption isotherm for aggregate 14F. The unusual shape of the drying and remoistening

³ Method of Test for Specific Gravity and Absorption of Coarse Aggregate, 1964 Book of ASTM Standards, Part 10.

curves and their crossing at 30 per cent RH may be attributed to a small permanent weight gain during testing. The permanent increases in dry weight of the specimens could be caused by either the hydration or the oxidation of aggregate solids. Tests made by soaking various aggregates in water at 100 C and drying them in an inert nitrogen atmosphere showed that the aggregates having the largest cumulative weight gain during the adsorption-desorption testing also had the largest weight gain during the 100 C water storage. This strongly indicates that hydration of some component of the aggregates occurred during the adsorption-desorption determinations. Oxidation should not have been an important factor in the weight increase of the aggregates during these determinations, since the work was conducted in such a way as to minimize the exposure of the aggregates to atmospheric oxygen.

Exposure of the aggregates to water vapor was necessarily prolonged in order that weight equilibrium could be achieved. Figure 5 compares time of exposure to water vapor and weight for one of the aggregates during stepwise drying and remoistening. The possibility of hydration cannot be avoided during the determination of sorbed water contents, particularly at high relative humidities. Therefore, the only alternative is to correct data obviously affected by such hydration effects.

Permanent gains in weight of aggregates during the saturation-desorption period and the adsorption period are given in Table 2. These permanent weight changes are small and appear to be of practical importance only in their effect upon the accuracy of the surface area determinations for some of the lightweight aggregates. There is no evidence that such weight increases produce adverse effects on concretes made from these aggregates. Expanded

slag aggregates, for example, have been successfully used in concrete for many years, yet the slags showed a greater permanent hydration weight change during the sorption determinations than the other aggregates investigated. The natural lightweight aggregates showed the least tendency to hydrate during test. This is probably because the aggregates had already been exposed for a very long time to atmospheric conditions before they were studied.

The sorbed water content values tabulated are expressed as percentages by weight of the second "oven" dry weight of the aggregate which was determined in the interval between drying and remoistening of the specimens. This dry weight gives a more accurate basis for calculation of low humidity moisture contents than either the original or final dry weights of the specimens which had permanent weight increases.

Since the aggregates were vacuum-dried, not oven-dried, at the time of the first and second dry weight determination, the oven-dry weights for the first and second determinations were calculated with the assumption that their oven-dry and vacuum-dry weights were proportional to such weights actually measured at the end of the adsorption process.

Internal Surface Areas of Lightweight Aggregates from Water-Vapor Adsorption Data:

Two equations were used to calculate the internal surface areas of the lightweight aggregates. The BET equation (based on the multimolecular-adsorption theory of Brunauer, Emmett, and Teller) (6) is the more universally accepted method for calculating internal surface areas, but can only be applied to adsorption values in the low partial pressure or relative humidity range (for water vapor

TABLE 3—INTERNAL SURFACE AREAS OF LIGHTWEIGHT AGGREGATES
FROM WATER-VAPOR ADSORPTION ISOTHERMS.

| Sample No. | Aggregate Type | Internal Surface Area, sq m/g of oven-dry aggregate | |
|------------|-------------------|--|------------------|
| | | Hüttig Equation | BET Equation |
| 1F..... | volcanic cinders | 5.8 | 4.1 |
| 1C..... | volcanic cinders | 3.9 | 3.1 |
| 2F..... | volcanic cinders | 3.4 | 2.5 |
| 2C..... | volcanic cinders | 2.5 | 2.1 |
| 3F..... | pumice | 3.3 | 2.7 |
| 3C..... | pumice | 3.8 | 3.1 |
| 4F..... | pumice | 18 | 15 |
| 4C..... | pumice | 17 | 14 |
| 5F..... | expanded shale | 2.7 to 1.1 ^a | 1.0 |
| 5C..... | expanded shale | 1.1 to 1.0 ^a | 0.8 |
| 6F..... | expanded shale | 2.1 ^b | 2.1 ^b |
| 6C..... | expanded shale | 3.3 ^a to 2.9 | 2.7 |
| 7F..... | expanded shale | 3.6 | 2.7 |
| 7C..... | expanded shale | 4.8 to 3.3 ^a | 2.9 |
| 8F..... | expanded shale | 2.0 ^b | 1.4 ^b |
| 8C..... | expanded shale | 1.8 ^a to 1.3 | 1.5 |
| 9F..... | expanded slate | 1.2 ^a to 0.7 | 1.0 |
| 9C..... | expanded slate | 1.6 ^a to 1.4 | 1.4 |
| 10F..... | haydite | 6.8 | 4.8 |
| 10C..... | haydite | 1.9 ^a to 1.7 | 1.5 |
| 11F..... | haydite | 5.8 | 4.6 |
| 11C..... | haydite | 3.9 ^a to 3.5 | 3.1 |
| 12F..... | soft coal cinders | 2.0 ^b | 1.5 ^b |
| 12C..... | soft coal cinders | 2.0 ^b | 1.7 ^b |
| 13F..... | expanded slag | 12.3 to 5.4 ^a | 4.3 |
| 13C..... | expanded slag | 7.7 to 4.5 ^a | 4.4 |
| 14F..... | expanded slag | 23 to 11 ^a | 11 |
| 14C..... | expanded slag | 18 to 11 ^a | 10 |
| 15F..... | expanded slag | 2.5 ^a to 1.5 | 2.1 |
| 15C..... | expanded slag | 3.5 ^a to 2.2 | 3.0 |

^a Preferred value chosen because it fit the Hüttig equation better than the alternate value for the same sample. Actual internal surface areas are probably closer to the preferred value than the alternate value.

^b Specimens with slight permanent weight change during adsorption but for which no prorated or minimum correction may be made.

roughly 5 to 35 per cent RH). Since only two experimental points in this range were available for surface area calculation, the Hüttig equation (12,8) was also used to calculate surface areas. This

equation applies to a wider adsorption range (0 to about 70 per cent RH) and usually gives slightly larger internal surface area values than the BET equation.

Surface areas for those aggregates which showed no permanent weight change during adsorption are shown as single values in Table 3. For aggregates having permanent weight changes during adsorption, Hüttig and BET surface areas were first calculated directly from the observed adsorption values. This process gives the maximum possible surface area of the aggregate, since adsorption data for such materials comprise true adsorption weight gains in the aggregate and some small weight gains due to hydration.

The minimum surface areas of those aggregates showing permanent weight gains during sorption testing were

surface area values are reported for the BET equation, and these surface areas are considered to be the most reliable that can be obtained from the data. Only a single value is reported for Aggregates 6F, 8F, 12F, and 12C, since the uncorrected data gave the only acceptable results when tested by the Hüttig equation.

No one type of lightweight aggregate studied has surface areas consistently higher or lower than any of the other aggregate types. The surface areas of Expanded Slag 14 and Pumice 4 are appreciably larger than the other aggregates, but Slag 15 and Pumice 3 have only moderate surface areas. The

TABLE 4—PHYSICAL PROPERTIES OF SOME DENSE CONCRETE AGGREGATES.

| Aggregate Type | BET Surface Area, sq m/g | Absorption, weight per cent | | Bulk Specific Gravity (Dry) |
|---------------------|--------------------------|-----------------------------|------------------|-----------------------------|
| | | 1-day immersion | vacuum saturated | |
| Orthoquartzite..... | 0.1 | 0.15 | 0.2 | 2.63 |
| Granite..... | 3 | 0.4 | 0.5 | 2.60 |
| Gabbro..... | 4 | 0.1 | 0.2 | 2.99 |
| Dolomite No. 2..... | 4 | 2.8 | 3.3 | 2.56 |
| Graywacke..... | 6 | 1.7 | 2.4 | 2.51 |
| Dolomite No. 1..... | 7 | 5.5 | 7.0 | 2.35 |

calculated with both equations using adsorption values obtained by subtracting permanent weight gains, equally prorated between the adsorption steps, from the adsorption data. Since most hydration occurs at high humidities, this proration gives low adsorption weights in the low humidity ranges, making internal surface areas calculated by this method minimum values.

The surface area ranges reported in Table 3 for the Hüttig equation represent both the maximum and minimum values discussed above. Either the maximum or minimum value usually fitted the Hüttig equation plot more closely. This test, by the Hüttig equation, was considered to give the "preferred" surface area value in the table. Only "preferred"

internal surface areas of the three expanded slags appear to increase as the susceptibility of the slags to hydration weight change increases. Pumice surface area and absorption should increase when the amount of dense, glassy obsidian present in the aggregate decreases, and this may explain the differences noted between Pumices 3 and 4.

The surface areas of the lightweight materials may be compared with surface areas of some natural dense aggregates. These dense aggregates, the physical properties of which are given in Table 4, represent a broad range of aggregate types and service records. The majority of the lightweight aggregates investigated have surface areas comparable to the surface areas of the dense materials

on a weight-for-weight basis. Because of their low specific gravity, the lightweight aggregates studied have a lower surface area per unit volume than these dense coarse aggregates.

It may be noted that some lightweight aggregates with high absorption have a lower surface area than low-absorption, dense aggregates. This may be explained

found in aggregates and is the reason why dense aggregates with limited volumes of fine pores may have higher surface areas than lightweight aggregates with large pores and a higher absorption. No correlation has been established between the water absorption and the internal surface areas of the various lightweight aggregates.

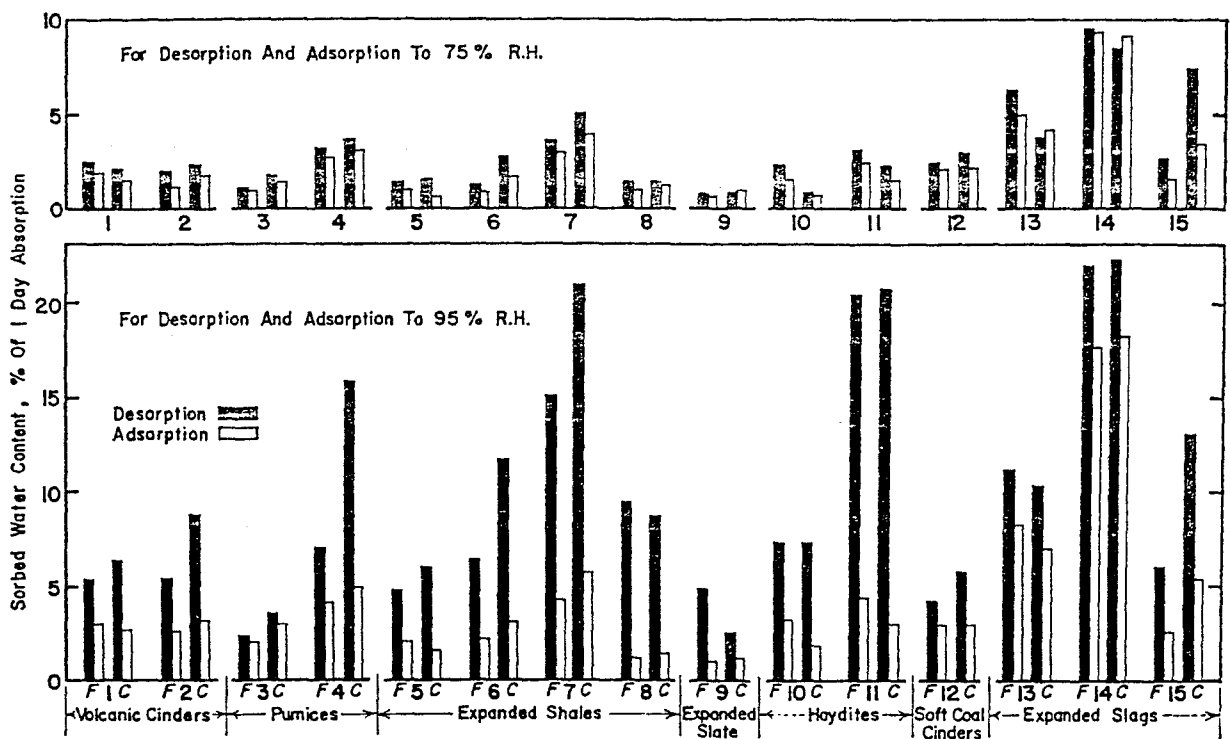


FIG. 6—Relationship Between the 1-Day Absorption of the Lightweight Aggregates and the Sorbed Water Content at High Humidities.

by considering the relationships between the pore volume and surface area of a porous material. Most of the water absorbed by a lightweight aggregate occupies relatively large pores in the aggregate, while water absorbed by a normal dense aggregate is held in a system of much smaller pores. The geometry of very simple pore configurations, such as spheres or cylindrical capillaries, is such that the ratio of pore wall surface area to pore volume increases as the radius of the pore decreases. The same general relationship applies to more complex pore networks

Lightweight Aggregate Water Absorption and Moisture Loss Upon Partial Drying:

To know how much water must be removed from a water-saturated lightweight aggregate particle while drying it to a particular relative humidity condition requires desorption data for residual water content at that particular relative humidity and data on the amount of water absorbed by the aggregate in the saturated condition.

Direct comparisons of water-vapor adsorption and water-absorption values

are of interest. Figure 6 shows the relationships between the one-day absorption of the aggregates and the equilibrium amounts of sorbed water in the aggregates at 95 and 75 per cent RH. Quantities of sorbed water, expressed as percentages of the one-day aggregate absorption,

Half of the aggregates retained 8 per cent or less of their one-day absorption water content when dried to this same humidity, while the minimum sorbed water retention at 95 per cent RH amounted to about $2\frac{1}{2}$ per cent of the one-day absorption of the aggregate.

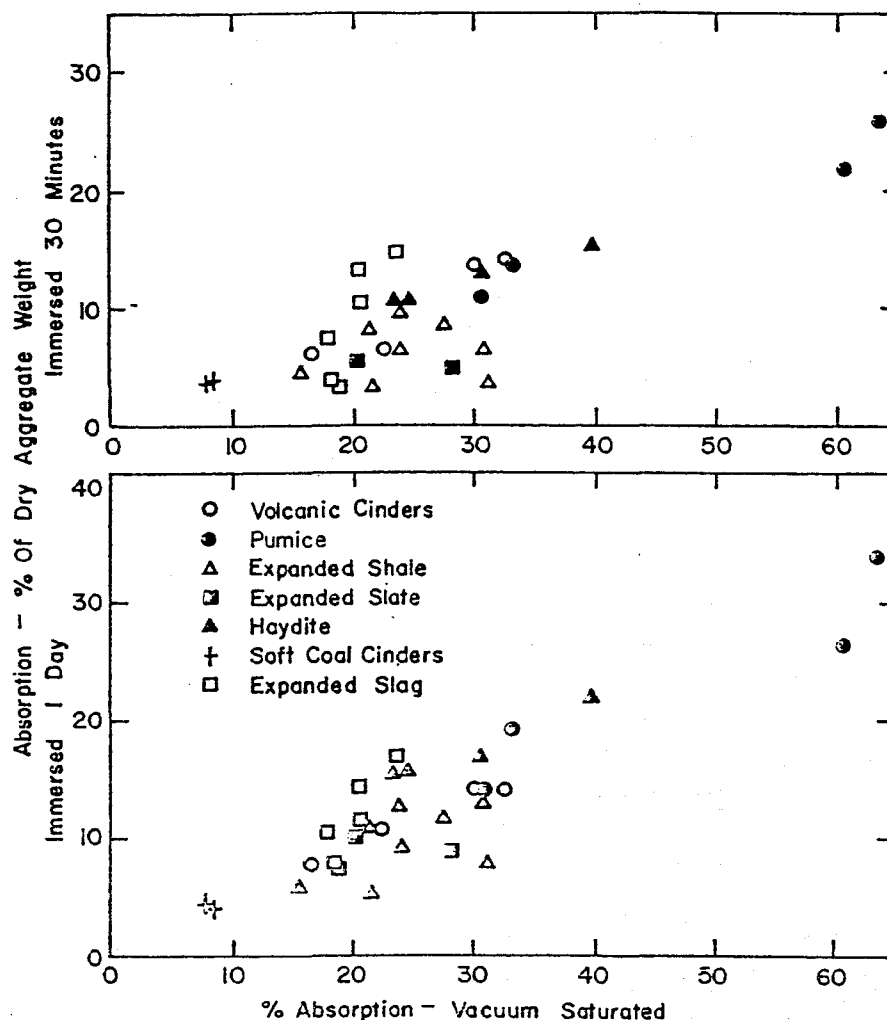


FIG. 7—Relationships Between Absorptions by Vacuum Saturation and by Immersion for Different Periods of Time.

are given for both the desorption and adsorption condition. The left portion of each bar represents the drying or desorption portion of the isotherm, while the right side of the bar is the value for adsorption or remoistening at the same humidity.

When dried to equilibrium at 95 per cent RH, some of the lightweight aggregates retained slightly over 20 per cent of their one-day absorbed water content.

For the lightweight aggregates dried to weight equilibrium at 75 per cent RH, the maximum, median, and minimum percentages of one-day absorbed water retained as sorbed water were 9, $2\frac{1}{2}$, and 0.7 per cent, respectively. Corresponding maximum, median, and minimum percentages for aggregates dried to 60 per cent RH were 8, 2, and 0.5 per cent.

No general relationship was observed between the type of aggregate studied

and the portion of the absorbed water that the aggregate retained when dried to a desired relative humidity level.

The lightweight aggregates studied could be expected to lose about 80 per cent or more of their total absorbed water if they were soaked in water for one day and then dried to weight equilibrium at 95 per cent RH and would lose 90 per cent or more of their total absorbed water if further dried to 75 per cent RH. Such losses are a very large portion of the total water absorbed by one day of water soaking, and very little of the absorbed water is retained by the aggregate upon drying to moderate relative humidities.

Absorption Observations:

Figure 7 shows the relationships between absorption determined by vacuum saturation of the lightweight aggregates and absorption after 30 min and one day of soaking in water. The observed dispersion of the points indicates that the lightweight aggregates had different fractions of their available pore space filled with water during the 30-min and one-day periods of water immersion. Some of the aggregates were comparatively well saturated after a short time in water. Several shales with smooth, well-developed surface shells, as well as the expanded slate and Slag 15, had a relatively small percentage of their available pore volume filled by water after 30 min of immersion. Correlation of aggregate surface texture and absorption rates is not possible from the data, since the surfaces of these aggregates with low "absorption rates" varied from the smooth shells of the expanded shales to the highly vesicular surface of the expanded slag.

Aggregate Drying Rates:

Efforts were made to evaluate the relative rates of drying of the lightweight aggregates, the rate of drying of an aggre-

gate presumably being a function of the desorption characteristics, total porosity, and permeability of the aggregate. The results were quite inconclusive and failed to show that any aggregate consistently came to weight equilibrium during drying much faster or slower than any of the other aggregates under the relatively slow drying conditions used in these studies.

While the aggregate drying rates appeared similar when the aggregates were in a loose condition, drying rates for these same aggregates in concrete need not be similar. Aggregates when used in concrete are coated with a cement paste which is relatively impermeable to water. The paste should greatly retard loss of moisture from the aggregate in the concrete during drying. For concretes containing aggregates coated with a fixed thickness and quality of cement paste, drying to any specific relative humidity will occur more rapidly if less pore water must be removed from the aggregates during the drying process.

Strictly interpreted, the amount of water that must be removed from the aggregate during the drying process would be the amount of absorbed water minus the sorbed water remaining in the aggregate when it is at equilibrium at the desired relative humidity. For the specific aggregates in this investigation, however, reasonably good estimates of the amount of water to be removed from the aggregates during drying to or below 75 per cent RH equilibrium could be made from absorption values alone, since the quantity of sorbed water in these aggregates at these humidities is quite low compared to the aggregate absorption.

Applications of the Moisture Content Data:

Knowledge of the amount of water that must be removed from different concrete aggregates during drying to a pre-

determined relative humidity is of value in the production of concrete masonry products which can be most easily dried. Selection of lightweight aggregates with low moisture absorption and use of appropriate mixing techniques to minimize the initial absorption during mixing would result in more easily dried lightweight masonry units.

A knowledge of the absorption and the adsorption-desorption characteristics of an aggregate may be of value as regards the fire resistance of concrete.

Information on the moisture contents of aggregates, when saturated and partially dry, is useful in studies of freezing-and-thawing durability of concrete. Durability is closely related to the moisture content of the cement pastes and aggregates at the time that freezing-and-thawing action occurs (4,5). Investigations (10) show that lightweight-aggregate concretes can be quite durable. Lightweight concretes are especially resistant to freezing-and-thawing disruption in laboratory tests if the test specimens are allowed to dry for only short periods of time before freezing-and-thawing testing is started.

The large differences between sorbed water contents and estimated absorption during soaking of the lightweight aggregates show that considerable drying of the aggregate, in concrete can occur, thereby alleviating distress due to freezing and thawing of pore water in the lightweight-concrete aggregate.

Summary:

The internal surface areas of different lightweight aggregates differ considerably. For the group of lightweight aggregates tested, surface areas ranged from about 1 to about 15 sq m/g of dried lightweight aggregate.

The internal surface areas of lightweight aggregates are within the same range as the surface areas of normal dense aggregates when compared on a weight basis.

The weight of sorbed water remaining in lightweight aggregates after drying to weight equilibrium at moderate humidities is a very small portion of the amounts of water that the lightweight aggregate is capable of absorbing after short periods of water immersion.

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PCA.R&D.Ser.1116-1

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**Pages 34-37, 153-155, "Thermophysical Properties of
Masonry and its Constituents"**

R.C. Valore, International Masonry Institute, 1988

Water Vapor Sorption.

The microstructure of hardened portland cement paste was studied by Powers and Brownyard (1946) and Sereda, et al (1966) to evaluate pore sizes by using water vapor adsorption as a measure of surface area of pore walls. These studies showed that adsorption increased as cement hydration progressed. Landgren (1964) used similar methods to determine the surface area of expanded clay, shale and slate, and cinders, pumice, scoria, and expanded slag lightweight aggregates. Water adsorption data of Powers and Brownyard, and of Sereda, et al for hardened portland cement pastes expressed as moisture content versus equilibrium relative humidity, are shown in Fig. B1.1a and B1.1b. Values in these Figures were converted from the desiccant-dry basis used by the authors to the oven-dry zero moisture basis by the present writer. Landgren's adsorption data for lightweight aggregates are shown in Fig. B1.2a and B1.2b. Comparison of Figures B1.1 and B1.2, noting differences in moisture content scales, shows that that equilibrium moisture contents of cement paste are many times greater than that of lightweight aggregates and clay bricks when compared at the same relative humidity. At 60 percent relative humidity, for example, moisture contents for cement pastes hydrated for 130 days were virtually constant at about 10 percent for a practical range of water-cement weight ratios of 0.5 to 0.7; Powers and Brownyard's data were similar at equal age. It is more realistic for present purposes to use shorter-term hydration periods of 7 to 28 days for concrete masonry in structures. Accordingly, the equilibrium moisture content of portland cement paste is given in Table 1.3 as 8 percent at 60 percent

PAGES 34-37, 153-156 EXTRACTED FROM "THE THERMOPHYSICAL PROPERTIES OF MASONRY AND ITS CONSTITUANTS" R.C. VALORE
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relative humidity. In Fig. B1.1a it is about 12 percent at 80 percent relative humidity.

Adsorbed moisture for clay bricks and for expanded clay and shale lightweight aggregates in Fig. B1.2a generally did not exceed 0.5 percent, even at 80 percent relative humidity. Cinders and scoria behaved similarly. For concretes based on these aggregates, then, the moisture sorption is essentially that of the cement paste constituent alone. Landgren's data showed that one of two domestic pumices and two of three expanded slags also showed less than 0.5 percent moisture contents at 80 percent relative humidity. However, one pumice (the lower in density of the two) had almost one percent, and one expanded slag more than 1.5 percent adsorbed moisture at 80 percent relative humidity. Shideler's (1955) data shown in Fig. B1.2 were obtained on concrete blocks and took about two years to complete with each humidity step requiring up to 4 months. The bottom values in Fig. B1.3 are Shideler's actual data. The top curves were calculated by the present writer for the cement paste components of the block concretes by dividing the bottom values by the cement paste weight fractions shown in the upper graph. Increases in paste weight fractions for lightweight aggregate concretes result from decreases in aggregate weight fractions in concrete as aggregate density decreases. Calculated paste moisture contents are in reasonable agreement with Powers and Brownyard's 7-day values in Fig. B1.1a.

From this discussion of sorbed moisture of cement pastes and aggregates it can be stated that:

- a. For concretes of the same density and age the equilibrium moisture content is proportional to the cement content only, expressed as the cement paste weight fraction, at constant relative humidity.
- b. For concretes having the same cement content the equilibrium moisture content, expressed in percent by weight, is inversely proportional to density of the concrete; the moisture content in percent by volume is the same for all densities when the cement content is constant.
- c. For clay bricks, equilibrium moisture contents are low but not negligible. The value 0.5 percent is given in the British CIBS Guide (1980) and codes of other European countries use similar values. The value 0.5 percent is given for brick masonry in Table 1.3 for "protected" exposure.

Returning to earlier discussion of Toennies' high moisture contents for pumice concrete blocks, it is seen that one of Landgren's (1964) pumice aggregates had somewhat higher equilibrium moisture contents than other lightweight aggregates. Kalousek and Selden's (1953) data for pumice blocks indicate higher than average equilibrium moisture contents for equilibration times of 35 days. Considering the sorption data and the fact that pumice block concretes are usually lower in density and often require higher cement contents than other lightweight aggregate concretes, moisture contents in Table 1.3 have been set at 5.5 and 7 percent for protected and unprotected exposures, respectively.

For concretes the method of curing affects the microstructure and consequently the equilibrium moisture content of the cementitious binder matrix. The effect is small for atmospheric pressure

steam-cured precast or block concretes; for these materials equilibrium moisture contents may be about 10 percent lower than for moist-cured concretes. High-pressure steam (autoclave) curing produces a marked reduction in moisture contents. Autoclaved cellular (aerated) concretes, which contain no aggregates in the usual sense, have relatively low equilibrium moisture contents, equivalent to those of many nonautoclaved lightweight aggregate concretes, despite the fact that they are virtually all "binder" materials, as shown in Table B1.1. The equilibrium moisture content is set, in Table 1.3, conservatively at 4.5 percent for protected exposure.

Practical Thermal Conductivity.

The practical thermal conductivities in Table 1.4 are based on the "practical conductivity multipliers" of Table 1.3 and small variability factors of one to 3 percent. As a result, and neglecting differences among groups of materials of less than 5 percent, practical conductivities are the same for perlite, vermiculite, expanded polystyrene beads, and expanded glass insulating concretes. Similarly, practical conductivities are the same for expanded clay, shale, and slate, for pumice, cinder and sintered fly ash, and for scoria concretes. This may cause over-estimates of conductivity for scoria and sintered fly ash concretes but we simply do not have adequate amounts of consistent data for these materials. It is suggested that these materials be given adequate study to learn if they can provide consistent conductivity-density relationships and well-defined conductivity-moisture factors.

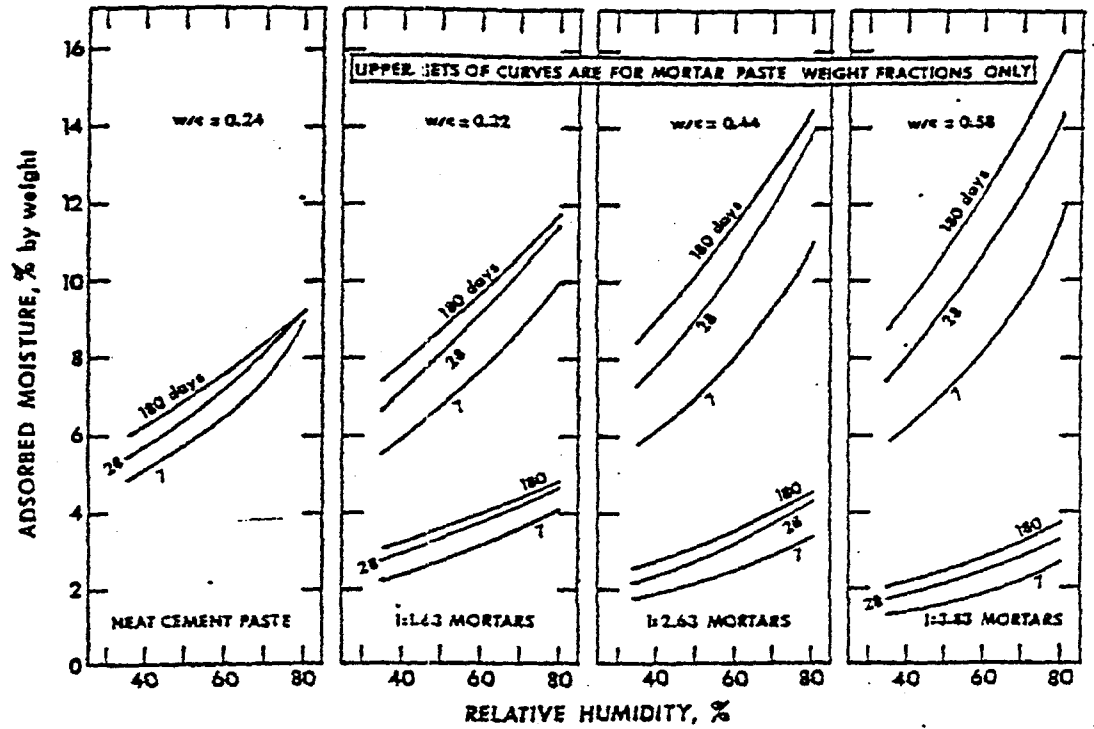


FIG. B1.1a

Adapted from Powers & Brownhard (1946)

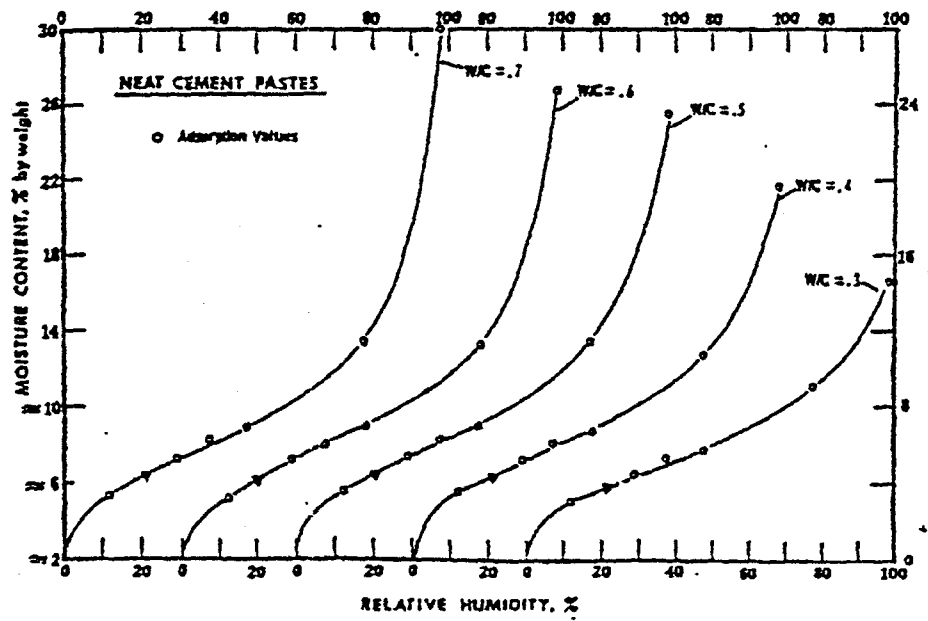


FIG. B1.1b

(Adapted from Sweda, et al, 1966)

FIG. B1.2a

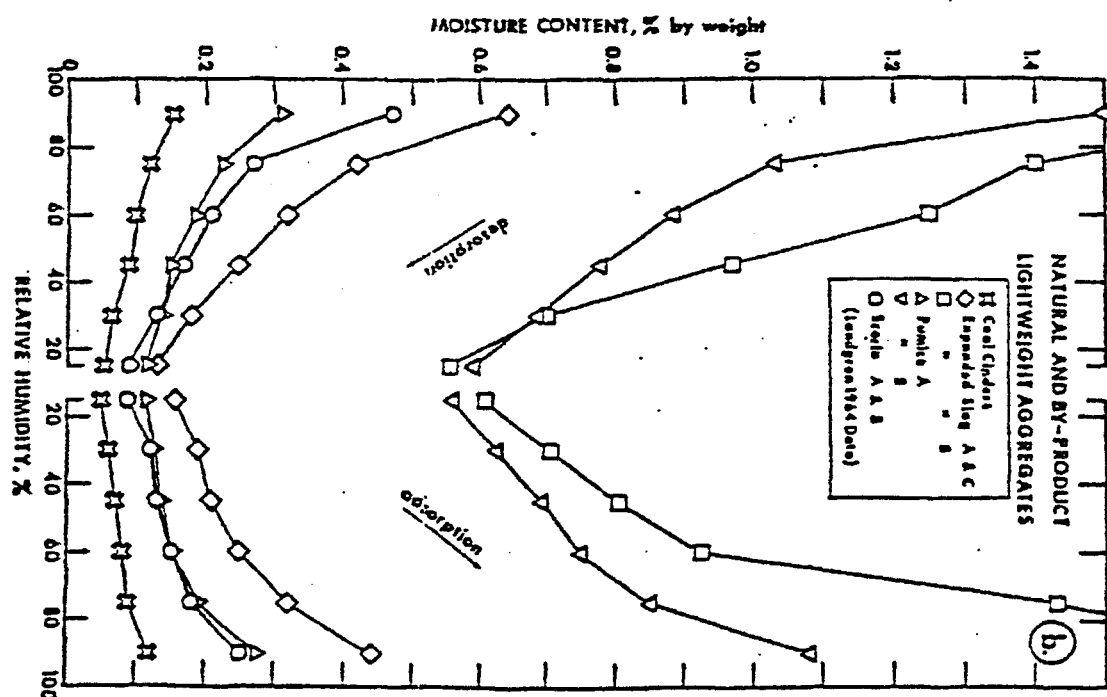
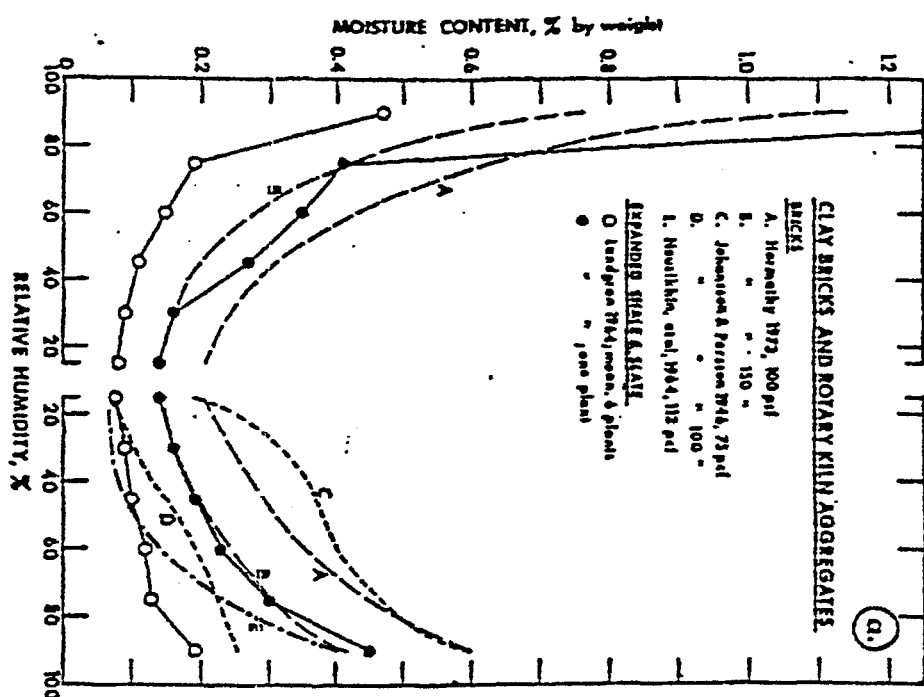


FIG. B1.2b

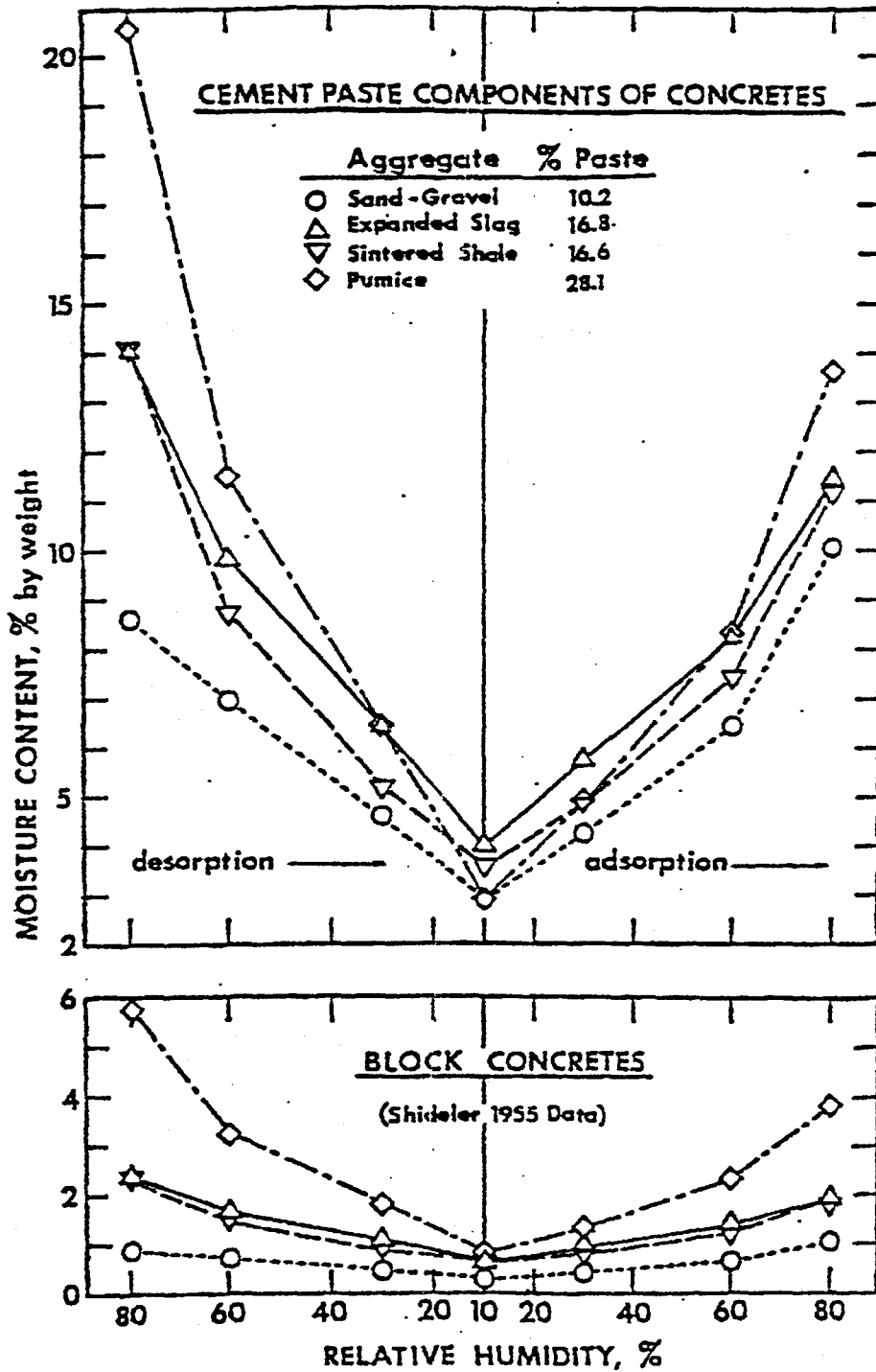


FIG. B1.3

3I

ASTM C 1260 “Test Method for Potential Alkali Reactivity of Aggregates (Mortar Bar Method)”

Visit www.ASTM.org for document

3J

**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. Holm¹ and John P. Ries¹

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/ft³ 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/m³ (90 to 120 lb/ft³) are often used, most lightweight aggregate concrete used in structures have equilibrium densities between 1760 to 1840 kg/m³ (110 and 115 lb/ft³).

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/m³ (50 lb/ft³), 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/m³ (lb/ft³), compressive strengths in MPa (psi), and thermal conductivity in W/m · °K (Btu · in./h · ft² · °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.

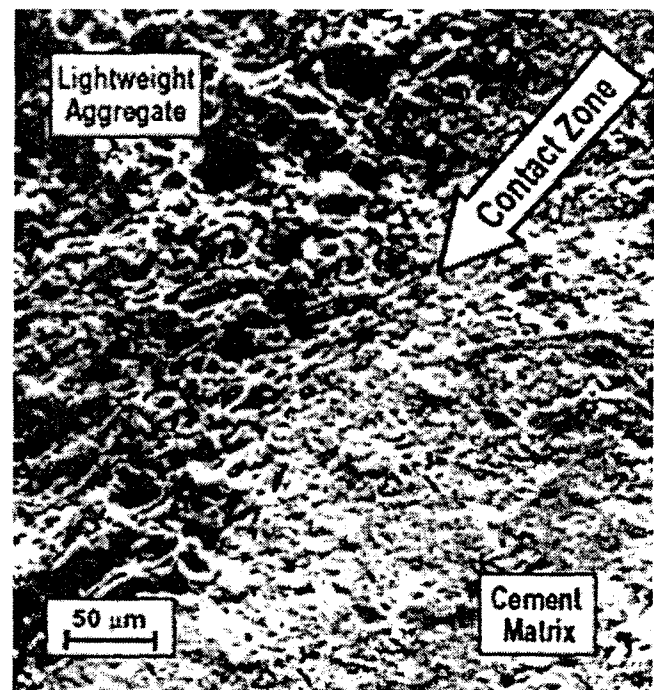


Fig. 1—Contact zone—structural lightweight concrete from 30-year-old bridge deck, W. P. Lane Memorial Bridge over the Chesapeake Bay, Annapolis, Maryland: compression strength 24 MPa (3500 psi); density 1680 kg/m³ (105 lb/ft³).

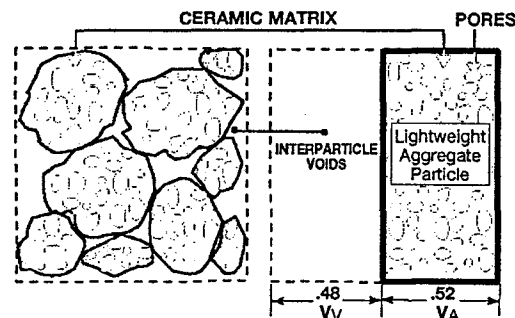
TABLE 2—Requirements of ASTM C 330, C 331, and C 332 for Dry Loose Bulk Density of Lightweight Aggregates

| Aggregate Size and Group | Maximum Dry Loose Bulk Density kg/m ³ (lb/ft ³) | | Minimum Dry Loose Bulk Density kg/m ³ (lb/ft ³) | |
|------------------------------------|---|------|---|-------|
| | | | | |
| 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 pycnometer) 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.

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

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

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

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

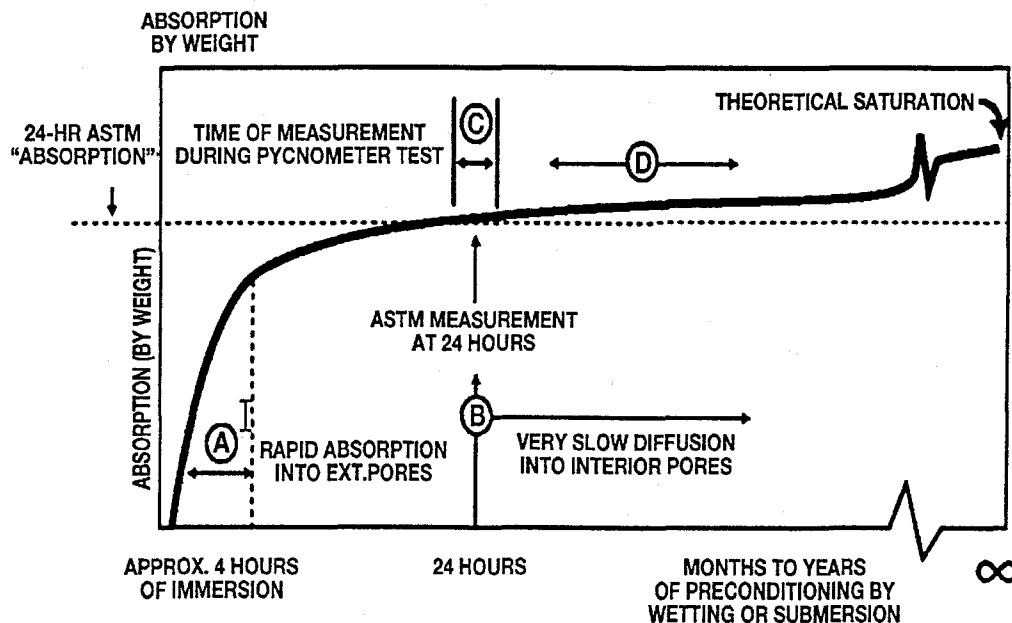
Due to their porous structure, lightweight aggregates absorb more water than their normal-weight aggregate counterparts. Based upon a 24-h absorption test, conducted in accordance with the procedures of ASTM Test Method Specific Gravity and Absorption of Coarse Aggregate (C 127) and ASTM Test Method 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 absorption 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 \pm) will be very small, and consequently the W/C_m 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.

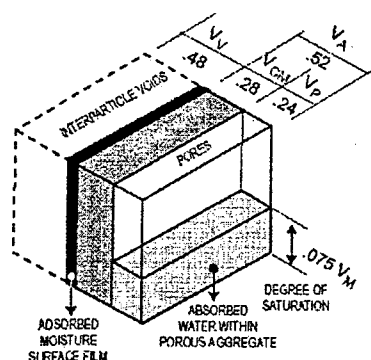
Due to pre-wetting, there will invariably be a film of surface water on the lightweight aggregate. As with normal-weight concrete it is essential to evaluate this quantity of surface water

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



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

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

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

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

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

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

* "Saturated Surface Dry" 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, metakaolin, 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 speci-

fication. 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 $\pm 4 \text{ lb/ft}^3$, 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

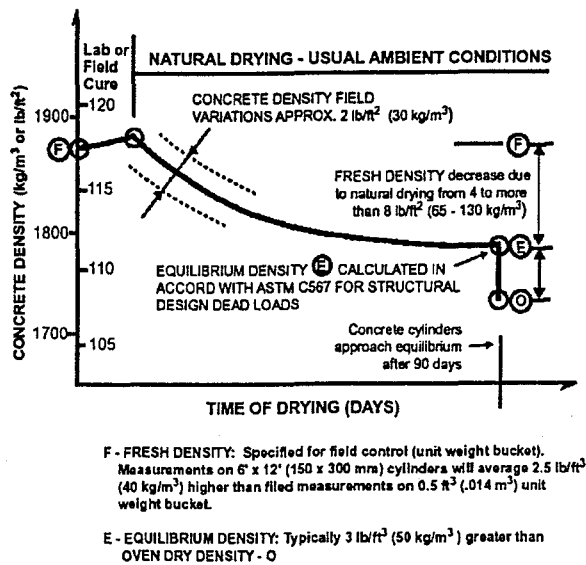


Fig. 5—Concrete density versus time of drying for structural lightweight concrete.

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/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 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 .55 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/m³ (752 pcy) cement, 708 kg/m³ (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/m³ (1208 pcy) Cement, 1050 kg/m³ (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 modulus 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/m³ (90 to 155 lb/ft³) and within normal strength ranges may be assumed to follow the ACI 318 formula

$$E = 33w_c^{1.5} \sqrt{f'_c} \quad E = 0.04 \sqrt{w_c^3 f'_c}$$

where

E = the secant modulus in MPa (psi),

w_c = the density in kg/m³ (lb/ft³), 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

- shrinkage characteristics of the cement paste fraction,
- internal restraint provided by the aggregate fraction,
- the relative absolute volume fractions occupied by the shrinkage medium (cement paste fraction) and the restraining skeletal structure (aggregate fraction), and
- 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 ettringite [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 web-sites 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 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 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 sand-blasted 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 pyro-processing 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 non-reactive 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].

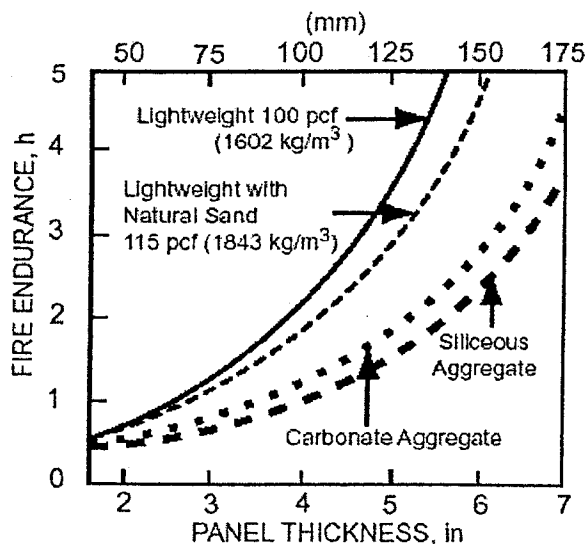


Fig. 6—Fire endurance (heat transmission) of concrete slabs as a function of thickness for naturally dried specimens [10].

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