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Moisture Dynamics in Lightweight Aggregate and Concrete

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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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INTRODUCTION

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.

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

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.

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

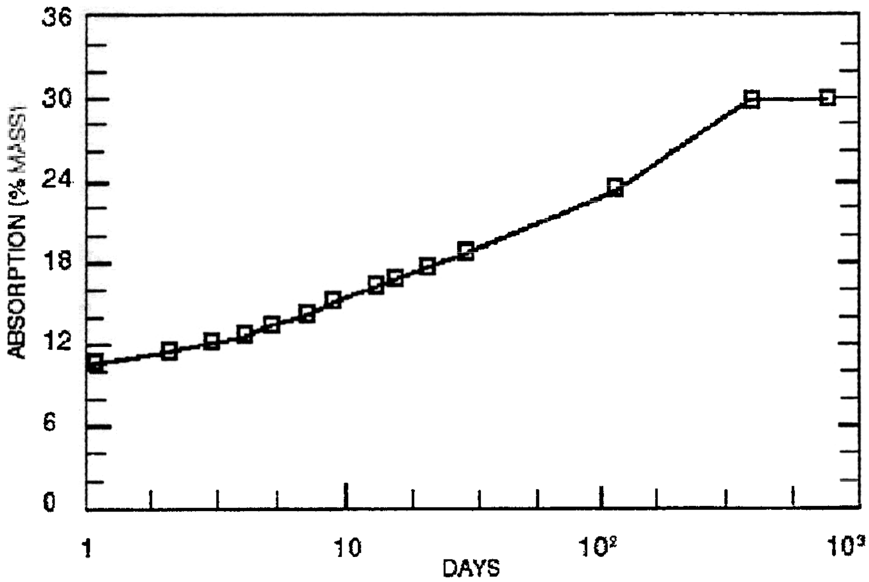


Fig. 1: Water Absorption by Weight of Coarse Lightweight Aggregates during 2 Years of Water Immersion

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%.

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%

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.

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.

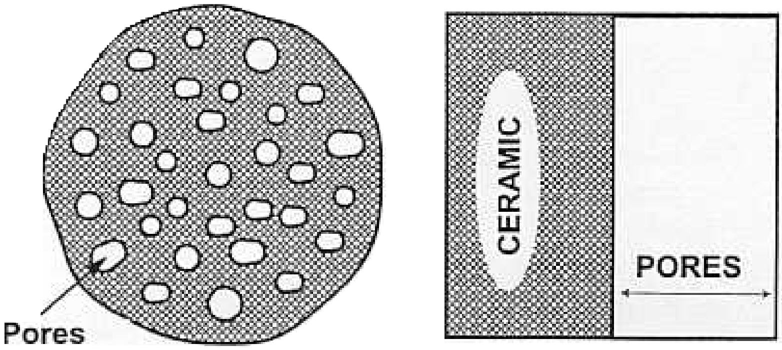


Fig 2. *Schematic of Dry Structural Lightweight Aggregate*

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/Cm) 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.

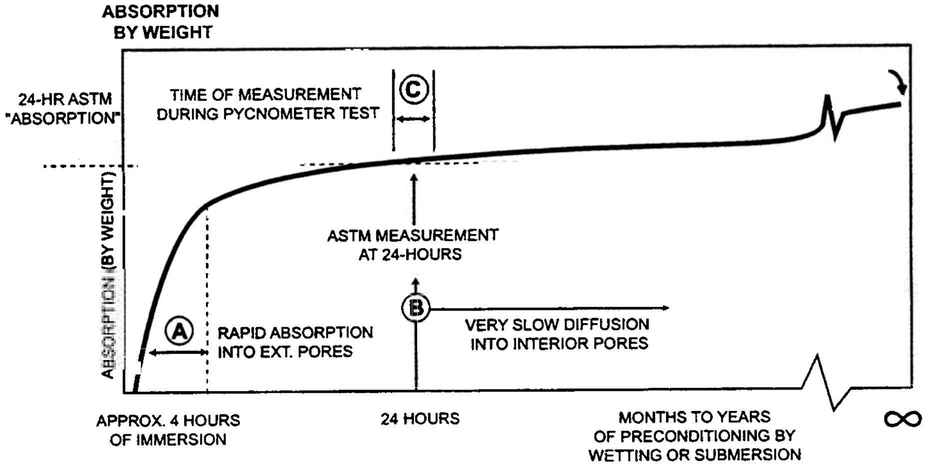
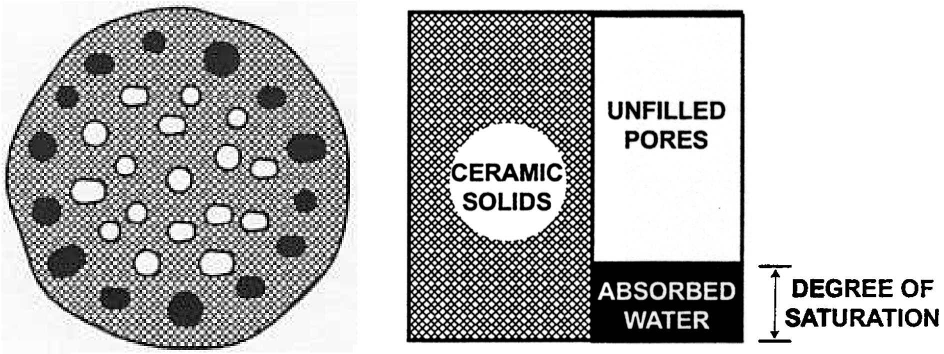


Fig 3. ***Absorption vs. Time for typical structural grade ESCS lightweight aggregate***

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/Cm 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



ASTM DEFINITION OF ABSORPTION AFTER SUBMERSION FOR 24 HRS
"SATURATED" SURFACE DRY, "SSD"

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 $\mathbf{M_{AD} = M_T - M_{AB}}$.

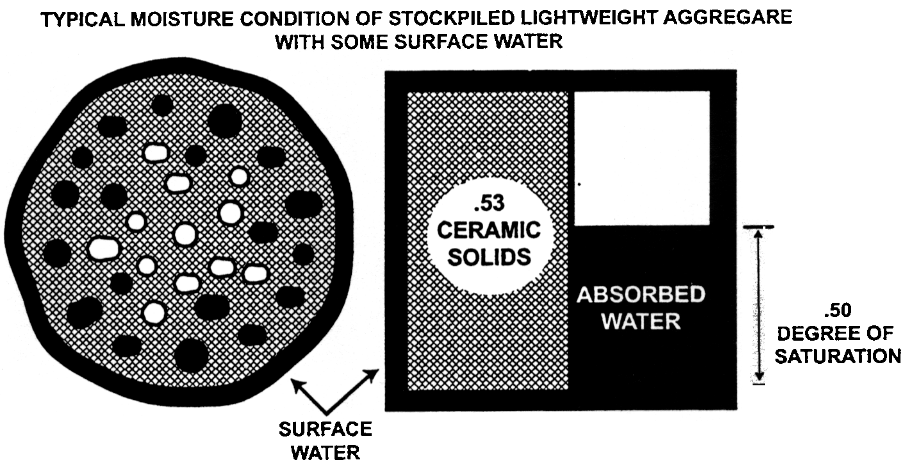


Fig. 5: *"Partially Saturated" Surface Wet*

- Assume for this example that measurements on this LA give the following:
  $\mathbf{M_{Total} = .21,\ M_{AB} = .18,\ \therefore\ M_{AD} = .03.}$
- If this LC contains 800 pcy (474 kg/m^3) of oven-dry LA then the surface moisture will contribute **800 x .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.

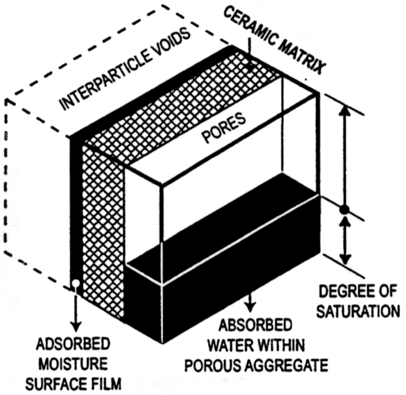


Fig. 6. Schematic showing absorbed water, degree of saturation, and adsorbed surface film water

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.

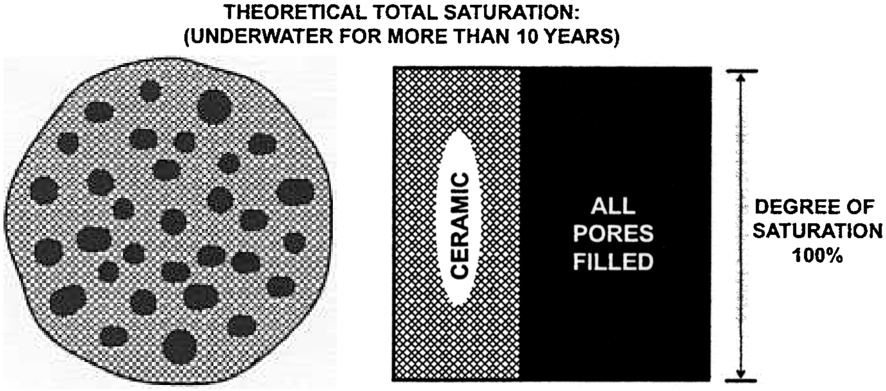


Fig. 7. *Total Saturation (TS), theoretically all pores filled*

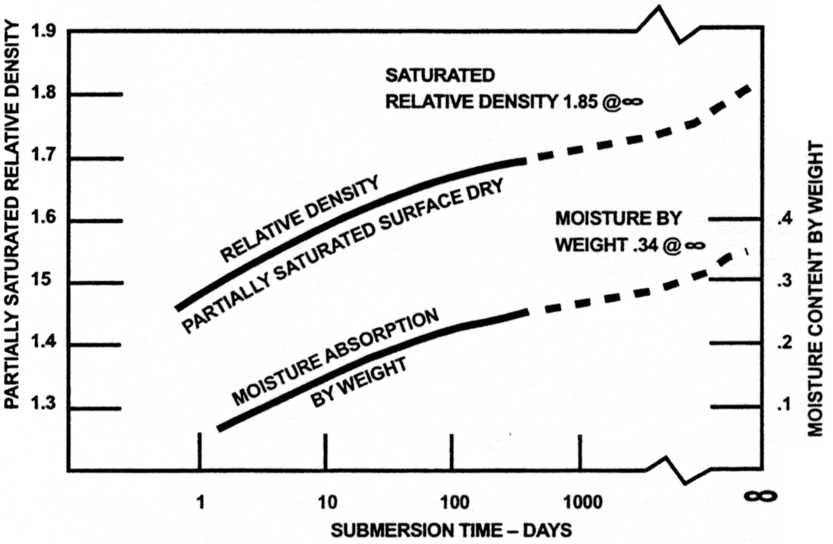


Fig. 8. ***Moisture absorption (by weight) and relative density of lightweight aggregate versus time of submersion***

Moisture Content at Total Saturation	***Relative Density at Total Saturation***
$\mathrm{M@}_{TS} = \frac{.47 \times 1.0}{.53 \times 2.6} = .34$	$\text{Relative Density @}_{TS} = (.53 \times 2.6) + (.47 \times 1.0) = 1.85$

MOISTURE DYNAMICS IN LIGHTWEIGHT 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.

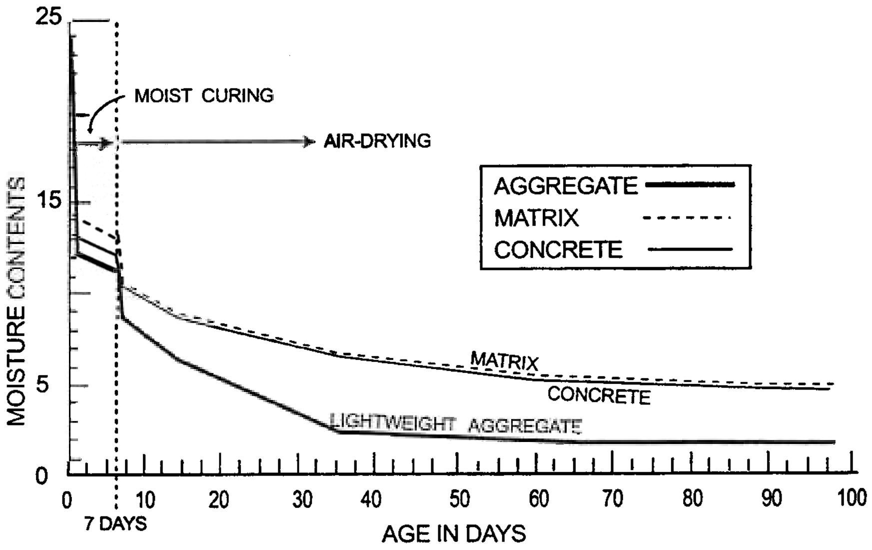


Fig. 9: Moisture content vs. Time for concrete containing lightweight aggregate batched with an absorbed moisture content of 24% by weight

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, metokoalin, 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.

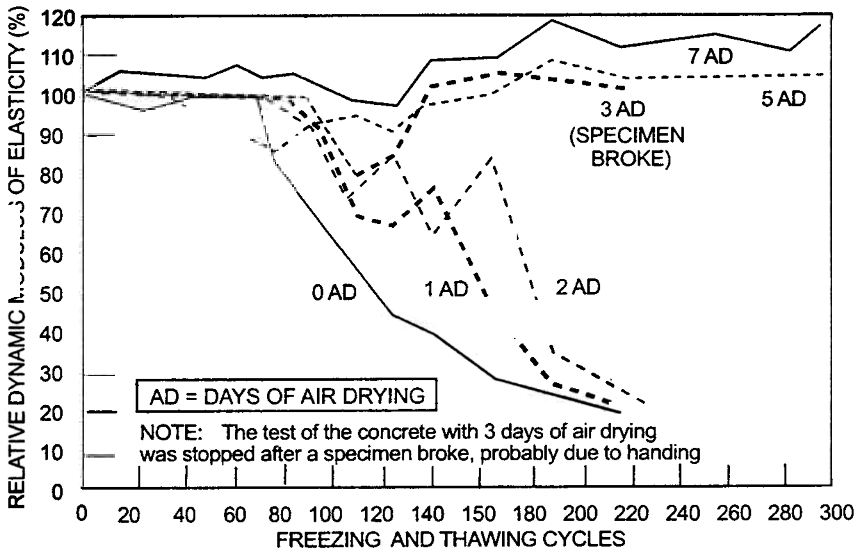


Fig. 10. ***Relative Dynamic Modulus of Elasticity for the Lightweight Concrete Containing Aggregates with a High Degree of Saturation in the Freezing and Thawing Experiments***

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 µm) 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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