CONCRETE TECHNOLOGY

Structural Lightweight Aggregate Concrete

by Richard P. Bohan[†] and John Ries[‡]

Introduction

Lightweight concrete, sand lightweight concrete, specified density concrete, and structural lightweight aggregate concrete are all terms used to describe various types of lightweight concrete. Lightweight concrete is the generic term most commonly used to refer to structural lightweight aggregate concrete. ***Structural lightweight aggregate concrete*** is defined by the American Concrete Institute's (ACI) *Guide for Structural Lightweight-Aggregate Concrete (ACI 213R)* as concrete made with structural lightweight aggregate as defined in ASTM C330, *Standard Specification for Lightweight Aggregates for Structural Concrete*. The concrete has a minimum 28-day compressive strength of 17 MPa (2500 psi), an equilibrium density between 1120 and 1920 kg/m^3 (70 and 120 lb/ft^3), and consists entirely of lightweight aggregate or a combination of lightweight and normal weight aggregate.

A brief comparison between typical properties of lightweight and normal weight concrete appears in Table 1 (Holm 2000).

The primary advantage of lightweight concrete is the reduction of the dead load in a structure. Reduced dead load allows designers the opportunity to increase span lengths, decrease structural member depth, and reduce foundation loads. Additionally, lightweight concrete may require less reinforcing steel because of the reduced dead loads. Lower dead loads can also provide designers the opportunity to increase live loads and lower seismic design forces (ESCSI 2000). Precast lightweight concrete products are lighter so producers can potentially transport more product in each shipment. These opportunities provide designers a strong economic incentive to use lightweight concrete.

Table 1. Summary of Typical Properties of Lightweight and Normal Weight Concretes

Property	Lightweight Concrete	Normal Weight Concrete
Design density, kg/m^3 (lb/ft^3)	1850 (115)	2400 (150)
Compressive strength, MPa (psi)	20-50 (3000-7500)	20-70 (3000-10,000)
Tensile Strength, MPa (psi)	2.5 (360)	3.0 (435)
Modulus of elasticity, GPa (psi x 10^6)	17-28 (2.5-4.0)	20-40 (3-6)
Poisson's ratio	0.2	0.2
Shrinkage at 1 year, microstrain (strain x 10^{-6})	600	550
Specific creep, microstrain/MPa (microstrain/psi)	70-150 (0.5-1.0)	70-120 (0.5-0.8)
Specific heat, J/kg · K (B · in/hr · ft^2 °F)	960 (0.23)	920 (0.22)
Thermal conductivity, W/m · K (B · in/hr · ft^2 °F)	0.58-0.86 (4-6)	1.4-2.9 (10-20)
Thermal diffusivity, m^2/hr (ft^2/hr)	0.0015 (0.016)	0.0025-0.0079 (0.027-0.085)
Thermal expansion, microstrain/°C (microstrain/°F)	9± (5±)	11± (6±)

Note: Values shown are midrange numbers that vary depending on mixture constituents and strength levels: use for approximation purposes only (Holm 2000).

[†] Director, Construction and Manufacturing Technology, PCA
[‡] President, Expanded Shale, Clay and Slate Institute

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Figure 1. The Pantheon's dome consists of lightweight concrete that spans over 43 m (142 ft).

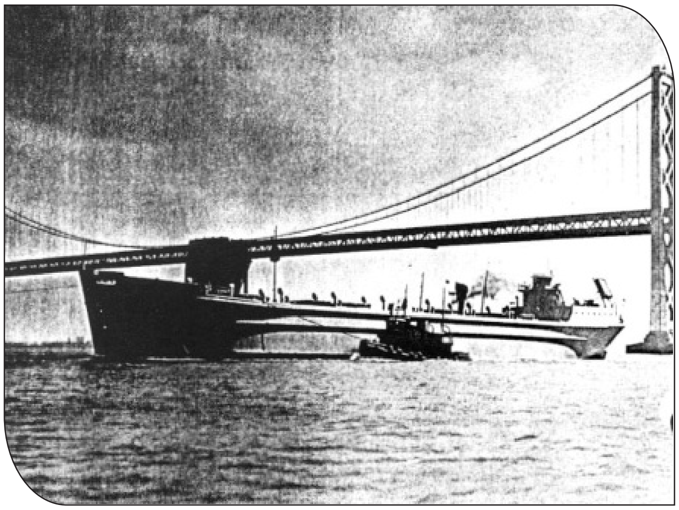

Figure 2. Concrete ship passing under San Francisco-Oakland Bay Bridge. Both ship and bridge made extensive use of lightweight concrete (ESCSI 1971).

The use of lightweight concrete floor slabs supported on metal decking in steel frame buildings is a popular design option in mid- and high-rise construction. Lightweight concrete allows the use of a thinner slab than normal weight concrete for the same fire rating. The inherent fire resistance of lightweight concrete may often permit the avoidance of an unnecessary spray fireproofing on the decks.

Lightweight concrete also provides benefits in other areas, such as enhanced durability through reduced cracking and lower permeability compared to normal weight concrete of similar proportions.

History

There are several naturally occurring lightweight aggregate materials. These include pumice, scoria, or tuff. Natural lightweight aggregates were used in some of the earliest concrete structures including those built by the Romans. For example, the Roman Pantheon was built about 125 A.D. and is still in use today (Figure 1). It is impressive that many of these ancient structures exhibited strength and durability characteristics that rival today's structures.

The manufacture of lightweight aggregates and the design and construction of lightweight concrete structures began in the early 1900s in the United States. Stephen Hayde is credited as the discoverer of the manufacturing process.

Notable historical applications of modern lightweight concrete include the construction of ships built around 1920 and used during World War I and II (Figure 2). The use of lightweight concrete provided significant advantages to the load-carrying economy of a concrete ship. Translated into practical terms, a 16 kilogram reduction per cubic meter (1 pound reduction per cubic foot) in concrete density resulted in an added carrying capacity for the ship of 30,000 kg (32 tons). Therefore, a savings of 18 kg per m^3 (30 pounds per cubic yard), the difference between the density of lightweight and normal weight concrete, represented approximately one million kilograms (1,000 long tons) additional carrying capacity (Eberhardt 1995).

The hulls of some of these ships continue in service today as breakwaters. They provide a unique ongoing testing opportunity to evaluate the long-term performance of lightweight concrete (Sturm 1999). This long term proven performance with concrete ships enabled the widespread use of lightweight concrete in massive marine structures constructed in the 1980s and 1990s.

The earliest application of lightweight concrete for buildings in the U.S. was the vertical expansion of the Southwestern Bell office building in Kansas City, Missouri, in 1928. The use of lightweight concrete for the expansion allowed designers to add 14 stories to the building rather than the 8 stories originally designed. Other examples include the 18-story Statler Hilton Hotel in Dallas, Texas; the 42-story Prudential Life Building in Chicago, Illinois; and, at 217.7 m (714 ft.), the 50-story One Shell Plaza in Houston, Texas. One Shell Plaza was constructed using concrete throughout the structure including the decks and mat foundation with a density of 1840 kg/m^3 (115 lb/ft^3) and a 28-day compressive strength of 42 MPa (6100 psi) (Khan 1970).

Currently, lightweight concrete is used all across the United States in steel frame buildings (lightweight concrete on fire-rated steel deck assemblies), and in concrete frame buildings and parking decks. Lightweight concrete on steel decks was used in all of the elevated floor slabs of the

55-story Bank of America Plaza in Atlanta, Georgia, which at 311.8 m (1,023 ft.) is the tallest building in North America outside of Chicago and New York City. Concrete frame building construction includes lightweight concrete post-tensioned floor systems as well as lightweight concrete precast and prestressed elements. Parking structures have often been constructed with lightweight concrete precast double-tees, and recently the 48-story Wachovia Tower in Charlotte, North Carolina, utilized this type of construction.

Literally hundreds of lightweight concrete bridges have been built in virtually every climatic environment. Most of these are located in North America. Lightweight concrete is used for bridge decks as well as for the entire structure. Notable examples of lightweight concrete bridge construction include: the upper deck of the San Francisco Oakland Suspension Bridge (1936), which is still in service, the Chesapeake Bay Bridges (first crossing 1952, second parallel crossing in 1975), and the new Benecia-Martinez Bridge (2007) (Murugesh 2008). The precast concrete segmental box girders for the new San Francisco Oakland Bridge use 50 MPa (7250 psi) lightweight concrete for the sloping panels that support the edge of the cantilever slab.

One of the most impressive uses of lightweight concrete in bridge construction is the Stolma Bridge in Norway. Using 1600 m^3 (2100 cy) of lightweight concrete with 28-day compressive cube strength of 70.4 MPa (10,200 psi) for the center portion of the main span, designers were able to achieve the world record for free-cantilever concrete construction with a main span of 301 m (990 ft).

Lightweight concrete with a design compressive strength of 70 MPa (10,000 psi) and a maximum equilibrium density of 1920 kg/m^3 (120 lb/ft^3) has been specified for a demonstration bridge project in Coweta County, Georgia (Castrodale 2007). This project follows research performed at Georgia Tech that demonstrated the feasibility of using lightweight concrete to extend prestressed concrete bridge girder spans to 46 m (150 ft) without exceeding certain load limits.

Aggregate Characteristics

Lightweight concrete aggregates specified by ASTM C330, *Standard Specification for Lightweight Aggregates for Structural Concrete,* include rotary kiln expanded shales, clays and slates, pelletized or extruded fly ash, and expanded slags along with natural materials like pumice, scoria, and tuff. The manufacturing process using shale, clay or slate heats these raw materials so they expand to about twice their original volume. This expansion is the result of gas formation in the raw material. As the material cools, the gas bubbles form a relatively uniform network of pores that range in size from approximately 5 to 300 µm. The relative density changes from about 2.65 prior to heating to less than 1.55 after cooling (Holm 2000). The heating process also converts the raw material into a durable vitreous ceramic material.

Engineering Properties

The engineering properties of lightweight concrete are compiled in a variety of sources and include information on density, equilibrium density, compressive strength, shear and tensile strength, modulus of elasticity, Poisson's ratio, maximum strain capacity, permeability, freeze-thaw resistance, carbonation, abrasion resistance, shrinkage, creep, bond strength and development length, thermal expansion, specific heat, thermal diffusivity, thermal conductivity, fire resistance, seawater absorption, ductility, and fatigue. This information sheet will briefly review density, equilibrium density, compressive strength, and fire resistance. For more detailed information on remaining engineering properties consult the *State-of-the-Art Report on High-Strength, High-Durability, Structural Low-Density Concrete for Applications in Severe Marine Environments* (Holm 2000).

Density

The most obvious characteristic of lightweight concrete is its lower density. This is a direct result of the relatively porous nature of the aggregates used. Most lightweight concrete has an equilibrium density from about 1600 to 1840 kg/m^3 (100 to 115 lb/ft^3). In comparison, normal weight concrete has a density (unit weight) ranging from 2080 to 2480 kg/m^3 (130 to 155 lb/ft^3). Lightweight concrete is achieved by replacing normal weight concrete aggregates with lightweight concrete aggregates. The approximate bulk density of aggregate commonly used in normal weight concrete ranges from about 1200 to 1750 kg/m^3 (75 to 110 lb/ft^3) while lightweight concrete aggregates range from 560 to 1120 kg/m^3 (35 to 70 lb/ft^3) (Kosmatka 2002).

The lowest density lightweight concrete uses lightweight aggregate for both fine and coarse aggregate fractions. However, most lightweight concrete mixtures contain normal weight sand and lightweight coarse aggregate, which is referred to as sand lightweight concrete. Other mixtures contain a blend of lightweight and normal weight coarse aggregates to produce specified density concrete.

The density of structural lightweight concrete can be determined using ASTM C567, *Standard Test Method for Determining Density of Structural Lightweight Concrete*. ASTM C567 provides procedures for both the measurement and the calculation of the oven-dry density of lightweight concrete.

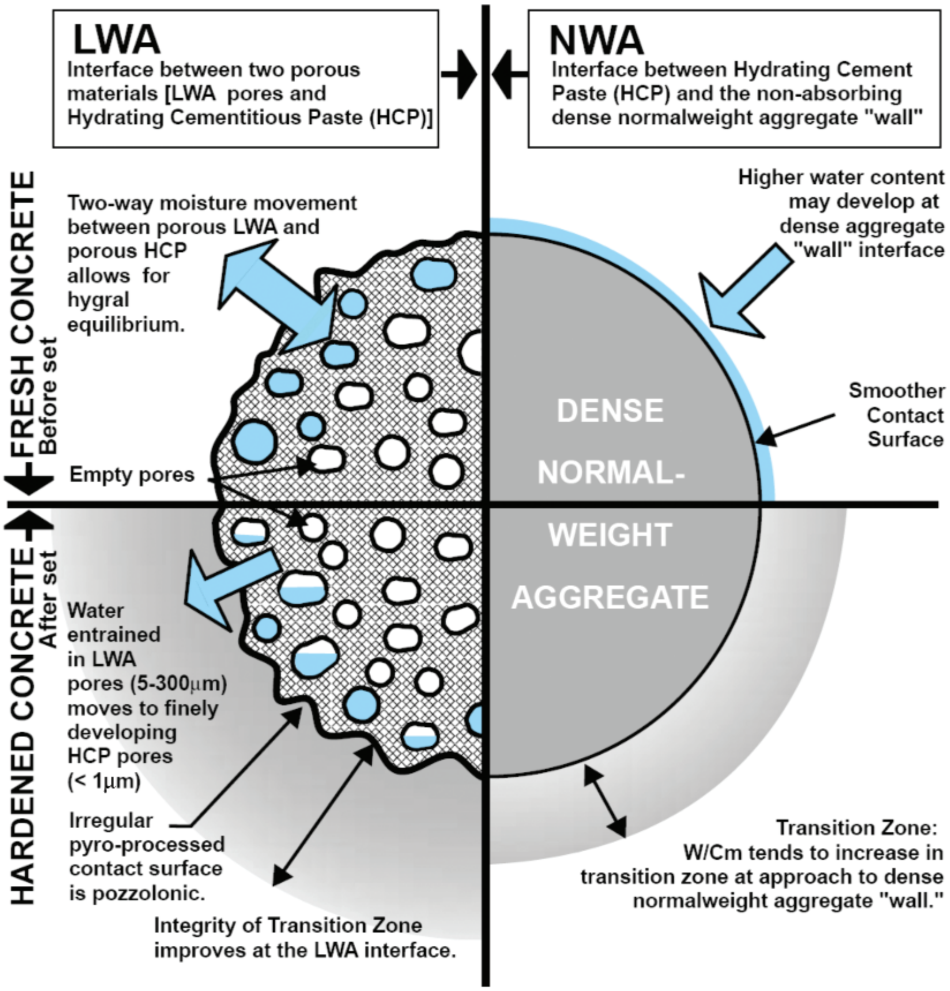

Figure 3. Internal curing at the contact zone (ESCI 2007).

The equilibrium density is calculated using either the measured or calculated oven-dry density. Equilibrium density is achieved once a concrete sample reaches a constant mass under controlled temperature and moisture conditions. Based on extensive testing, the equilibrium density will be approximately 50 kg/m^3 (3 lb/ft^3) more than the oven-dry density. It is generally accepted that the equilibrium density is reached at 90 days for most lightweight concretes and at 180 days for high-strength lightweight concretes (ASTM C567 2005). Consequently, the fresh lightweight concrete density measured at the time of placement will be significantly higher than the hardened in-place lightweight concrete equilibrium density.

Compressive Strength

Lightweight concretes that achieve 28-day design strengths of 20 to 35 MPa (2900 to 5000 psi) are widely available. Higher strength lightweight concretes with compressive strengths on the order of 70 MPa (10,000 psi) are also available.

The limiting factor for compressive strength of lightweight concrete is the strength of the aggregate particle. This limiting factor, often referred to as the "strength ceiling," is reached when increasing the quantity of cementitious materials or decreasing the water-to-cementitious materials ratio (w/cm) will not produce a corresponding increase in compressive strength. However, this limitation can be mitigated through the use of smaller sizes of lightweight aggregates (ACI 213 2003). While normal weight concrete generally fractures through the paste matrix around aggregate particles, lightweight concrete tends to fracture through the lightweight aggregate particles since the stiffness of the aggregate and paste are similar (Holm 2000).

Fire Resistance

The fire resistance of lightweight concrete is generally greater than normal weight concrete for the same thickness. The basis for this behavior is the reduced thermal conductivity and thermal expansion provided by lightweight aggregates. Also, the pyroprocessing required to manufacture lightweight aggregates provides an inherent stability of an aggregate already heated to over 1100°C (2000°F) (Holm 2000).

Durability

In general, the durability of lightweight concrete is equal to or better than normal weight concrete. Evaluation of the earliest concrete ships provides an insight into the long-term durability of lightweight concrete performance when exposed to severe marine environments. The environmental conditions to which these ships have been exposed are generally much more severe than environments for most building and bridge applications using lightweight concrete. Distress observed on these ships was primarily due to corrosion-induced spalling resulting from inadequate cover over steel reinforcement and also due to structural cracking. Microscopic observations revealed a dense cement matrix microstructure indicative of a low permeability concrete (Sturm 1999). Additional long-term durability studies of lightweight concrete have been conducted at the Treat Island, Maine, marine exposure facility operated by the U.S. Army Corps of Engineers. This particular facility allows exposure of test samples to more than 100 freeze-thaw cycles annually. Specific results are reported by Malhotra and Bremner (1996), and are also compiled by Holm and Bremner (2000). Analysis of these data indicates at least equal performance of lightweight concrete with normal weight concrete when compared at similar ages and similar binders (Holm 2000).

Interfacial Transition Zone

Lightweight concrete is comprised of two basic components: a mortar matrix and aggregate. The interface between the aggregate and paste in a concrete mixture is a critical component to the long term durability of concrete. Researchers have noticed a more dense interfacial transition zone (ITZ) in lightweight concrete than in ordinary concrete as illustrated schematically in Figure 3. This means that porous lightweight concrete aggregate particles tend to provide a more intimate bond at the paste aggregate interface (Lam 2005 and Bentz 1999).

Mixture Proportioning

ACI 211.2, *Standard Practice for Selecting Proportions for Structural Lightweight Concrete,* provides two distinct mixture proportioning methods for lightweight concrete.

Absolute Volume Method (specific gravity pycnometer)

Proportioning using the absolute volume method can be performed on the basis of an approximate water-to-cementitious materials content (w/cm) since the sum of the weights per unit volume of each mixture component is equal to the total weight of the same mixture. The determination of the relative density factor provides the link between weight and volume. The procedures for determining the relative density factors and structural coarse aggregate absorption are specified within the appendices of ACI 211.2. Determining the correct coarse aggregate absorbed moisture content (absorption is defined by ASTM C127, *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate*, and C128, *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate*) becomes critical for these calculations.

The steps involved in the absolute volume method of proportioning include: choice of slump, choice of nominal maximum size of lightweight aggregate, estimation of mixing water and air content, selection of approximate w/cm, calculation of cement content, estimation of lightweight coarse aggregate content, and estimation of fine aggregate content. Adjustments to the first trial mixture are then made based upon the observed results. The w/cm ratio may be calculated in a manner similar to proportioning normal weight concrete.

Volumetric Method (damp loose volume)

The volumetric method (damp loose volume) relies upon trial mixture proportions that are based on damp loose material volumes converted to batch weights. This method estimates required batch weights, including cement contents, based upon the required compressive strength. This method requires accurate first estimates of cement and aggregate contents required for specified equilibrium density and compressive strength. Without close approximations on the first estimates (typically provided by the lightweight aggregate producer), it may be necessary to produce a range of trial mixtures.

The steps involved in the volumetric method of proportioning include: estimate 1 m^3 (yd^3) trial batch weights on an oven-dry basis, determine the approximate SSD weight, and convert oven-dry proportions to batch proportions. The batch proportions represent the actual in-situ moisture condition of the material at the time of batching.

Cementitious Materials Content

The porous nature of lightweight aggregates coupled with the amount and rate of water absorption means that lightweight concretes typically have higher cementitious material contents. In the case of high strength lightweight concrete the additional cementitious material may be slightly higher than would be used with normal weight concrete mixtures.

Water-to-Cementitious Materials Ratio

A maximum water-to-cementitious materials content is not typically specified for lightweight concrete unless it will be used for bridges or marine structures (NRMCA 2003).

The water-to-cementitious materials ratio can be determined for lightweight concrete and used in mix proportioning per the absolute volume method as described in ACI 211.2. When lightweight aggregates are 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 w/cm can be established with precision. Thus, lightweight concrete can meet w/cm specification requirements with the same accuracy as normal weight concrete. Water absorbed within the lightweight aggregate prior to mixing is not used for calculating the w/cm at the time of setting. However, this absorbed water is available for internal curing which continues cement hydration after the external curing period has ended.

Air entrainment

Current practice for lightweight concrete that will be exposed to freezing and thawing conditions is to entrain 4% to 8% air for a nominal maximum aggregate size of 19.0 mm (3/4 in.) and 5% to 9% for a nominal maximum aggregate size of 9.5 mm (3/8 in.). A well distributed air void system is just as necessary for proper performance with lightweight concrete as with normal weight concrete (Holm 2000).

Air content testing of lightweight concrete must be conducted using ASTM C173, *Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method*. The volumetric method is the only acceptable testing method for lightweight concrete. It is important to understand that this particular test method provides an indication of the total air content of the fresh concrete including purposely entrained air and entrapped air generated through mechanical action of the mixing process.

In an air-entrained lightweight concrete mixture, the mortar matrix contains numerous air voids for protection against freezing and thawing (Lam 2005). In a similar fashion the lightweight concrete aggregate particles contain numerous pores produced during the manufacturing process. This similarity means that the lightweight concrete aggregate particles are elastically compatible with the mortar matrix within concrete. The decrease in compressive strength typically associated with an increase in air content is not as significant with lightweight concretes due to this elastic compatibility.

Design and Construction Considerations

The porous nature of lightweight aggregates requires several important considerations. Lightweight aggregate particles are able to absorb and retain significantly greater amounts of water than typical non-porous normal weight aggregate particles. Typical 24-hour absorption of lightweight aggregate may range from 5% to more than 20% by weight of dry aggregate (NRMCA 2003).

If the lightweight aggregate particles are not fully prewetted, the mixing water can be absorbed by the lightweight aggregate particles during the mixing process, or it can be forced into the pores of the lightweight aggregate particles during concrete pumping.

Prewetting Lightweight Aggregates

Prewetting (or presoaking) is a simple but proven and effective precaution against absorption of mix water by lightweight aggregate that has not reached its full absorptive capacity. Prewetting is not intended to completely saturate lightweight aggregate particles. Rather, prewetting is intended to allow the lightweight aggregate particles an opportunity to absorb as large a portion of their total absorptive capacity as is practical. The 24-hour absorption test, specified by ASTM C127 and C128, provides an indication that can be used for comparison against the total absorptive capacity. Lightweight aggregate particles immersed for 24 hours will generally be not fully saturated although their rate of moisture absorption may be low enough that weight measurements will remain unchanged (Holm 2006).

Lightweight aggregates may tend to be pushed to the surface of a lightweight concrete slab as the heavier materials settle. This can be avoided by presoaking the lightweight aggregate and carefully monitoring mixture adjustments (NRMCA 2003).

The vacuum saturation process is used to soak lightweight aggregate that does not absorb water quickly enough under ambient wetting conditions to become properly wetted in a reasonable amount of time. With some lightweight aggregates, vacuum saturation can achieve a moisture content that would take weeks or even months of wetting under regular atmospheric pressure.

The procedure involves introducing dry lightweight aggregate into a steel tank, then running a vacuum pump to remove air from the tank. Once the full vacuum is achieved, water is introduced into the tank, flooding the aggregate while the vacuum is maintained by the vacuum pump. Once the material is flooded, the vacuum is released and the aggregate is discharged from the tank.

Pumping Considerations

Pumping lightweight concrete can force water into the pores of the lightweight aggregate particles. This can be mitigated by sufficient prewetting of the lightweight aggregate particles. Current practices for pumping lightweight concrete suggest a minimum slump of 75 mm (3 in.) be attained before any addition of water reducing admixtures. Additional practices suggest: the use of large pump lines (125 mm [5 in.]); the use of clean, unobstructed and properly lubricated pump lines; smooth transitions between fixed and flexible piping; and reduced operating pressures consistent with an efficient hydraulic system.

Designers should pay particular attention to specifying equilibrium density and the precautions that may be required for placement by pumping.

Internal Curing

Fully prewetted lightweight concrete aggregates provide a source of moisture for internal curing. Internal curing refers to the process by which hydration of cement and pozzolanic reactions can continue because of an internal water supply that is available in addition to the mixing water (ACI 213 2003 and Lam 2005). This internal curing process allows the concrete to gain additional strength and also results in a reduction of permeability due to a significant extension in the time of curing (Holm 2006). Internal curing can also help to avoid early age cracking of concrete with high cementitious materials content that is typical of many high strength concretes. Likewise, early shrinkage of concrete caused by rapid drying can also be avoided through internal curing.

Additionally, since lightweight aggregate particles have a higher water content from prewetting, a longer period of internal curing and a larger difference between fresh concrete density and equilibrium density will be observed (Holm 2000). In most cases, any excess moisture will eventually diffuse out of the concrete. The time it takes for the concrete to dry must be taken into consideration when a lightweight concrete is to be covered with a moisture-sensitive flooring system.

Design and Construction Communication

Production of a concrete structure requires that everyone involved has the same expectations. Pre-construction meetings allow all parties share concerns. The properties of the specific lightweight aggregate to be used should be considered when determining the best methods for construction.

Properties of potential lightweight aggregate should be considered when designing the structure and the concrete mixture. Having the involvement of lightweight aggregate producers, concrete producers, and concrete contractors in the design process allows these parties to input their concerns regarding material incompatibilities, construction scheduling, and construction methods.

Specifications

The first mention of lightweight concrete in the ACI 318 *Building Code Requirements for Structural Concrete* was in the 1963 edition (Holm 2000). The Expanded Shale, Clay & Slate Institute (ESCSI) publishes a guide specification that provides designers with appropriate guidance and commentary to develop a specification (ESCSI 2001). Guide specifications for structural low-density concrete are included as an appendix to the *State-of-the-Art Report on High-Strength, High-Durability Structural Low-Density Concrete for Applications in Severe Marine Environments* (Holm 2000). Although intended for marine applications, the guide specifications may be adapted for more conventional applications of lightweight concrete.

Summary

From ancient domes to modern elevated decks, the use of lightweight concrete continues to provide structural efficiency and economic advantages. With a 25% reduction in density, comparable compressive strengths, and enhanced thermal behavior, well documented performance over a period of decades has demonstrated that lightweight concrete can be used reliably in most concrete applications.

The characteristics of lightweight aggregates lead to an improved interaction with the mortar matrix compared to normal weight aggregates. This results in enhanced behavior of lightweight concrete. The porosity of lightweight aggregates provides a better bond with the mortar matrix and an inherent resistance to freeze-thaw cycles. The pyroprocessing of the aggregates provides thermal stability.

The use of lightweight concrete has an effect on the mix design, mixture proportioning, and construction methods that may be used when designing a concrete structure. The greatest applications of lightweight concrete are those that take advantage of the inherent performance benefits of lightweight concrete.

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PCA

Portland Cement Association
5420 Old Orchard Road
Skokie, Illinois 60077-1083
847.966.6200 Fax 847.966.9781

500 New Jersey Avenue NW, 7th Floor
Washington, DC 20001-2066
202.408.9494 Fax 202.408.0877
www.cement.org

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