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Guide for Structural Lightweight-Aggregate Concrete

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

This guide includes a definition of lightweight-aggregate concrete for structural purposes and discusses, in a condensed fashion, the production methods for and inherent properties of structural lightweight aggregates. Current practices for proportioning, mixing, transporting, and placing; properties of hardened concrete; and the design of structural concrete with reference to ACI 318 are all discussed.

Keywords: abrasion resistance; aggregate; bond; contact zone; durability; fire resistance; internal curing; lightweight aggregate; lightweight concrete; mixture proportion; shear; shrinkage; specified density concrete; strength; thermal conductivity.

CONTENTS

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The objectives of this guide are to provide information and guidelines for designing and using lightweight concrete. By using such guidelines and construction practices, the structures can be designed and performance predicted with the same confidence and reliability as normalweight concrete and other building materials.

This guide covers the unique characteristics and performance of structural lightweight-aggregate (LWA) concrete. General historical information is provided along with detailed information on LWA and proportioning, mixing, and placing of concrete containing these aggregates. The physical properties of the structural LWA, along with design information and applications, are also included.

Structural lightweight concrete has many and varied applications, including multistory building frames and floors, curtain walls, shell roofs, folded plates, bridge decks and girders, prestressed or precast elements of all types, and marine structures. In many cases, the architectural expression of form, combined with functional design, is achieved more readily with structural lightweight concrete than with any other medium. Many architects, engineers, and contractors recognize the inherent economies and advantages offered by this material, as evidenced by the many impressive lightweight concrete structures found throughout the world.

Because much of the properties and performance of lightweight concrete are dependent on the type of LWA used, the ready mix supplier, LWA producer, or both, might be an important source of specific information for attaining the project objectives.

1.2—Scope

1.2.1 *Historical background*—The first known use of lightweight concrete dates back over 2000 years. There are several lightweight concrete structures in the Mediterranean region, but the three most notable structures were built during the early Roman Empire and include the Port of Cosa, the Pantheon Dome, and the Coliseum.

Built in approximately 273 BC, the Port of Cosa used lightweight concrete made from natural volcanic materials. These early builders learned that expanded aggregates were better suited for marine facilities than the locally available beach sand and gravel. They traveled 25 mi. (40 km) to the northeast to quarry volcanic aggregates at the Volcine complex for use in the harbor at Cosa (Bremner et al. 1994). This harbor on the west coast of Italy consists of a series of four piers (~13 ft [4 m] cubes) extending into the sea. For two millennia the piers have withstood the forces of nature with only surface abrasion. They became obsolete only because of siltation of the harbor.

Built circa 126 AD, the Pantheon incorporates concrete varying in density from bottom to top of the dome. Roman engineers had sufficient confidence in lightweight concrete to build a dome with a diameter of 142 ft (43 m), which was not exceeded for almost two millennia. The structure is in excellent condition and is still being used today for spiritual purposes (Bremner et al. 1994).

The dome contains intricate recesses formed with wooden formwork to reduce the dead load and the imprint of the grain of the wood can still be seen. The excellent cast surfaces that are visible to the observer clearly show that these early builders had successfully mastered the art of casting concrete made with LWA. The Roman writer, architect, and engineer, Vitruvius, who took special interest in building construction, commented on several unusual features of the Pantheon. The fact that he did not single-out lightweight concrete for comment could imply that these early builders were fully familiar with this material (Morgan 1960).

Built in 75 to 80 AD, the Coliseum is a gigantic amphitheater with a seating capacity of 50,000 spectators. The foundations were cast with lightweight concrete using crushed volcanic lava. The walls were made using porous, crushed-brick aggregate. Vaults and spaces between the walls were constructed using porous-tufa cut stone.

1.2.2 *Development of manufacturing process*—After the fall of the Roman Empire, lightweight concrete use was limited until the 20th century when a new type of manufactured expanded shale LWA became available for commercial use.

The rotary kiln process was developed in 1918 and is used to produce expanded shale, clay, and slate. LWAs are manufactured by heating small particles of shale, clay, or slate in a rotary kiln. A particle size was discovered that, with limited crushing, produced an aggregate grading suitable for making lightweight concrete (Expanded Shale, Clay and Slate Institute 1971). When clay bricks are manufactured, it is important to heat the preformed clay slowly so that evolved gases have an opportunity to diffuse out of the clay. If they are heated too rapidly, a bloater is formed that does not meet the dimensional uniformity essential for a successfully fired brick. These rejected bricks were recognized by Hayde as an ideal material for making a special concrete. When reduced to appropriate aggregate size and grading, these bloated bricks could be used to produce a lightweight concrete with mechanical properties similar to regular concrete.

Commercial production of expanded slag (that is, expanded shale, clay, or slate) began in 1928, and in 1948, the first structural-quality sintered-shale LWA was produced using shale in eastern Pennsylvania.

One of the earliest uses of reinforced lightweight concrete was in the construction of ships and barges in the early 1900s. The U.S. Emergency Fleet Building Corporation found that for concrete to be effective in ship construction, the concrete would need a maximum density of about 110 lb/ft^3 (1760 kg/m^3) and a compressive strength of approximately 4000 psi (28 MPa) (Expanded Shale, Clay, and Slate Institute 1960). Concrete was obtained with a compressive strength of approximately 5000 psi (34 MPa) and a unit weight of 110 lb/ft^3 (1760 kg/m^3) or less using rotary-kiln-produced expanded shale and clay aggregate.

1.2.3 *Early modern uses*—Considerable impetus was given to the development of lightweight concrete in the late 1940s when a survey was conducted on the potential use of lightweight concrete for home construction. This led to an extensive study of concrete made with LWAs. Sponsored by the Housing and Home Finance Agency (1949), parallel studies were conducted simultaneously in the laboratories of the National Bureau of Standards (Kluge et al. 1949) and the U.S. Bureau of Reclamation (Price and Cordon 1949) to determine properties of concrete made with a broad range of LWA types. These studies and earlier works focused attention on the potential structural use of some LWA concrete and initiated a renewed interest in lightweight members for building frames, bridge decks, and precast products in the early 1950s. Following the collapse of the original Tacoma Narrows Bridge in Washington, the replacement suspension structure design used lightweight concrete in the deck to incorporate additional roadway lanes without the necessity of replacing the original piers.

During the 1950s, many multistory structures were designed with lightweight concrete from the foundations up, taking advantage of reduced dead weight. Examples include the 42-story Prudential Life Building in Chicago, which used lightweight concrete floors, and the 18-story Statler Hilton Hotel in Dallas, designed with a lightweight concrete frame and flat plate floors.

These structural applications stimulated more concentrated research into the properties of lightweight concrete. In energy-related floating structures, such as an oil drilling rig, great efficiencies are achieved when a lightweight material is used. A reduction of 25 percent in mass in reinforced normalweight concrete will result in a 50 percent reduction in load when submerged. Because of this, the oil and gas industry recognized that lightweight concrete could be used to good advantage in its floating structures and structures built in a graving dock, and then floated to the production site and bottom-founded. To provide the technical data necessary to construct huge offshore concrete structures, a consortium of oil companies and contractors was formed to evaluate which LWA candidates were suitable for making high-strength lightweight concrete that would meet their design requirements. The evaluations began in the early 1980s with results available in 1992. As a result of this research, design information became readily available and has enabled lightweight concrete to be used for new and novel applications where high strength and high durability are desirable (Hoff 1992).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A = fractional solid volume (without pores) of the vitreous material of an individual particle
B = subsequent fractional volume of pore (within the particle)
BD = bulk density, lb/ft^3 (kg/m^3)
C = fractional volume of particles
C_f = cement factor or the mass of cement per cubic foot (cubic meter)
CS = chemical shrinkage of the binder per unit mass of the binder at 100 percent reaction (typically 0.07 mL/g cement)
c = heat capacity, Btu/(lb · °F) (kJ/(kg · K))
D = fractional volume of interstitial voids (between particles)
E = calculated equilibrium density, lb/ft^3 (kg/m^3)
E_c = modulus of elasticity, ksi (GPa)
E_{cd} = dynamic modulus of elasticity of the particle, ksi (GPa)
f_c = concrete compressive strength, psi (MPa)
f_{ct} = average splitting tensile strength, ksi (MPa)
f_c' = compressive strength
k = thermal conductivity, Btu/(hr · ft · °F) (W/(m · K))
M_{LWA} = mass of the lightweight aggregate
p = dry mean particle density, lb/ft^3 (k/m^3)
R = thermal resistance
RD = relative density, lb/ft^3 (kg/m^3)
U = thermal transmittance, Btu/(hr · ft^2 · °F) (W/(m^2 · K))
S = saturation level of the LWA
V = volume of concrete produced, ft^3 (m^3)
W_c = oven-dry density of concrete, lb/ft^3 (kg/m^3)
W_{ct} = weight of cement in batch, lb (kg)
W_{dc} = weight of coarse aggregate in batch, lb (kg)
W_{df} = weight of dry fine aggregate in batch, lb (kg)
w_c = unit weight of normal concrete or equilibrium density of lightweight concrete, lb/ft^3 (kg/m^3)
w_m = densities in moist conditions, lb/ft^3 (k/m^3)
w_{od} = densities in oven-dry conditions, lb/ft^3 (k/m^3)
α_{max} = expected maximum degree of reaction for the binder ranging from 0 to 1
Φ_{LWA} = measured absorption capacity of the lightweight aggregate

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," http://www.concrete.org/Tools/ConcreteTerminology.aspx. Definitions provided here compliment that resource.

all-lightweight concrete—concrete in which both the coarse- and fine-aggregate components are lightweight aggregates.

contact zone—transitional layer of material connecting aggregate particles with the enveloping continuous mortar matrix.

fresh density—mass-per-unit volume of concrete in fresh state, before setting.

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

insulating aggregate—nonstructural aggregate meeting the requirements of ASTM C332; includes Group I aggregate, perlite with a bulk density between 7.5 and 12 lb/ft^3 (120 and 192 kg/m^3), expanded vermiculite with a bulk density between 5.5 and 10 lb/ft^3 (88 and 160 kg/m^3), and Group II aggregate that meets the requirements of ASTM C330/C330M and ASTM C331/C331M.

internally stored water—water internally held by the lightweight aggregate that is not readily available at mixing and, therefore, does not affect water-cementitious material ratio (w/cm).

masonry-lightweight aggregate (MLWA)—aggregate meeting the requirements of ASTM C331/C331M with bulk density less than 70 lb/ft^3 (1120 kg/m^3) for fine aggregate and less than 55 lb/ft^3 (880 kg/m^3) for coarse aggregate.

net water—total water less amount of water absorbed by the aggregate.

oven-dry density—density reached by structural lightweight concrete after being placed in a drying oven at 230 ± 9°F (110 ± 5°C) for a period of time sufficient to reach constant density, as defined in ASTM C567/C567M.

specified density concrete—structural concrete having a specified equilibrium density between 50 to 140 lb/ft^3 (800 to 2240 kg/m^3) or greater than 155 lb/ft^3 (2480 kg/m^3).

structural lightweight aggregate—structural aggregate meeting the requirements of ASTM C330/C330M with bulk density less than 70 lb/ft^3 (1120 kg/m^3) for fine aggregate and less than 55 lb/ft^3 (880 kg/m^3) for coarse aggregate.

CHAPTER 3—STRUCTURAL LIGHTWEIGHT AGGREGATES

3.1—Internal structure of lightweight aggregates

Lightweight aggregates (LWAs) have a low-particle relative density because of the cellular pore system. The cellular structure within the particles is normally developed by heating certain raw materials to incipient fusion; at this temperature, gases evolve within the pyroplastic mass, causing expansion that is retained upon cooling. Strong, durable LWAs contain a uniformly distributed system of pores that have a size range of approximately 5 to 300 µm, developed in a continuous, relatively crack-free, high-strength vitreous phase. Pores close to the surface are readily permeable and fill with water within a few hours to days of exposure to moisture. Interior pores, however, fill extremely slowly, with many months of submersion required to approach saturation. A small fraction of interior pores are essentially noninterconnected and remain unfilled after years of immersion.

3.2—Production of lightweight aggregates

Lightweight aggregates (LWAs) are produced in several ways. Some are produced in manufacturing plants from raw materials, including suitable shales, clays, slates, fly ashes,