ESCSI TECHNICAL INFORMATION SHEET
EXPANDED SHALE, CLAY AND SLATE INSTITUTE / Rotary Kiln Structural lightweight Aggregate

Revised August 2024

Determining Service Life of Structural Lightweight Concrete Using Transport Properties

A Two-Millennia Service Life

The history of concrete-like materials in various regions of the world dates to the 4th century BCE. However, today, the most notable surviving concrete structures are Roman structures that utilized lightweight aggregate concrete between 300 BCE and 476 CE. The Pantheon Dome (113-125 CE), the largest unreinforced concrete dome in the world with a diameter of 43.3 m (142 ft), and the Colosseum (70-80 CE), the largest standing amphitheater in the world, seating 50,000 spectators, are classic examples of lightweight aggregate concrete applications that revolutionized the architecture of the time.


Pantheon, Rome (113-125)


Colosseum, Rome (70-80)

Images Courtesy of F M Tehrani (2019)

The improved bond between the pyroclastic — also known as volcanic aggregate — the binding ash, and the reduced mass of structure that enabled it to survive earthquakes, contributed to the durability and resilience of Roman structures. The Pantheon utilized concrete with decreasing density from 1600 kg/m^3 (100 lb/ft^3) at the bottom to 1350 kg/m3 (84 lb/ft^3) at the dome's top for the desired performance.

The application of volcanic materials and porous tufa provided the same performance for the Colosseum. Vitruvius (c. 80-70 BCE – c. 15 BCE) in de Architectura (30-22 BCE) describes the characteristics of lightweight aggregate in concrete and mortar products for marine concrete and other structures; their applications were further highlighted by Gaius Plinius Secundus, also known as Pliny the Elder (23/24-79 CE). The volcanic ash-lime mortar and pozzolanic concrete containing fine lightweight aggregates have been identified in many other structures, like the Markets of Trajan in Rome

(110 CE) and harbors, like the Port of Cosa in Orbetello (273 BCE). Piers in this port, with nearly square dimensions of about 4 m (13 ft), have been exposed to the sea but are still surviving. They are another example of a structure exposed to severe environmental conditions built using durable concrete containing lightweight aggregate and volcanic ash, in this case, imported from Pozzuoli, the ancient city of Puteoli. The source of quarried materials was the Volcine complex, 40 km (25 miles) northeast of the Cosa.

A Century of Contemporary Development

Marine Structures

Early applications of expanded shale, clay, and slate aggregates included concrete ships, such as the USS Selma (1919), ten ships in the Powell River (1920s-1940s), and many more during World War II (1940-1947). The lightweight concrete in these ships had densities between 1700 and 2080 kg/m^3 (106 and 130 lb/ft^3) and compressive strengths between 35 and 60 MPa (5000 to 8700 psi). Earlier ships used lighter densities and lower strengths, but their strength was still more than twice the strength of commercial normalweight concrete at the time.

USS Selma, Mobile, AL (1919)

Hibernia Offshore Platform, Canada (1998)

San Francisco-Oakland Bay Bridge, CA (1936)

Images Courtesy of ESCSI (1971); Holm and Bremner (2000)

Investigations of the materials in the hull and parts of these ships have indicated the durability of ESCS structural lightweight aggregate concrete in severe marine environments. For example, studies in 1953 on the USS Selma confirmed no cracking in the 125-mm (5-in.) thick hull and no corrosion in the steel reinforcement protected by the thin 16-mm (5/8-in.) concrete cover. Investigators recognized the integrity of the contact zone between the lightweight aggregate and cementitious matrix as a significant contributing factor to the durability of the ships.

The same concept applies to many other marine structures like the Heidrun floating concrete offshore platform (1995), Hibernia offshore platform (1998), and Braddock gated dam (2002). The Heidrun platform used lightweight concrete with a density of 2000 kg/m^3 (125 lb/ft^3), compressive strength of 60 MPa (8700 psi), and modulus of elasticity of 22 GPa (3190 ksi). The application of ESCS structural lightweight concrete in floating structures was also vital for the satisfaction of constructability, transportability, and floatability requirements for these projects.

Bridges

The weight reduction has justified the application of ESCS in numerous bridges, from early projects like the San Francisco-Oakland Bay Bridge, California (1936), to recent projects like Long Beach Gerald Desmond Bridge, California (2020). These bridge applications include the deck, girders, and piers, and typically utilize high-strength and high-performance lightweight concrete that is often exposed to corrosive and chemical agents on the superstructure and also severe marine environments at the substructure.

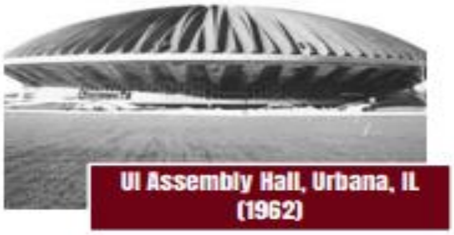
Due to the critical nature of bridge infrastructure as transportation lifelines, there have been numerous observations and studies on the long-term service life of lightweight concrete applications in bridges. These studies have highlighted the benefits of lightweight concrete to reduce early-age cracking, protect reinforcing steel against carbonation and corrosion, and enhance wearing characteristics.

Buildings

The high performance and light density of ESCS structural concrete has contributed to the design and construction of several architecturally exposed structures like the TWA Terminal at John F. Kennedy Airport, New York (1960); Dodger Stadium, Los Angeles (1961); the University of Illinois Assembly Hall, Urbana (1962); Marina Towers, Chicago (1962); and Wellington Stadium, New Zealand (1999).

The excellent performance of these structures is witness to the durability of ESCS structural lightweight concrete in various climate zones, maintaining undamaged surfaces through freeze-and-thaw cycles and intense storms. The durability of ESCS concrete is also evident in conventional


Southwestern Bell, Kansas City, MO (1929)


UI Assembly Hall, Urbana, IL (1962)


Marina Towers, Chicago, IL (1962)


One Shell Plaza, Houston, TX (1971)

Images Courtesy of ESCSI (1971); Wikipedia (2008, CC BY-SA 3.0) buildings, where the primary justification for ESCS application is the reduction of self-weight for new or retrofitted buildings. The Southwestern Bell building in Kansas City (1929) is an early example of such an application where the use of ESCS allowed the designer to add 14 more stories to the existing 14-story building, as opposed to the originally envisioned 8-floor addition using normalweight concrete.

The fireproofing and thermal insulation properties of ESCS have also contributed to the extended service life of numerous commercial and residential buildings throughout the century, including Chase-Park Plaza Hotel, St. Louis (1929), Bank of Georgia Building, Atlanta (1961), 1000 Lake Shore Plaza, Chicago (1964), Park Regis, Sydney (1967), Lake Point Tower, Chicago (1968), Nations Bank, Charlotte (1996), One Shell Plaza, Houston(1971) and others. The latter, which benefited from lightweight concrete in the frame, floors, and mat foundation, was designed by Fazlur Khan using a tube-in-tube system. This building was the tallest reinforced concrete building in the world at the time and still is the tallest lightweight concrete building in the world.

The Integrity of Contact Zone

Expanded shale, clay, and slate aggregates contribute to the integrity of concrete composites by enhancing contact zone characteristics. These contributions involve substantial improvements in the bond between the aggregate and the cementitious matrix due to the combination of the pozzolanic alumina-silicate surface of fired ceramic aggregates with the calcium hydroxide from the hydration of the Portland cement. Further, the porosity of lightweight aggregates facilitates the internal curing of cementitious materials and addresses the entrapped bleed-water lenses typically found in the contact zone around normalweight aggregates.

Internally cured composites mitigate early-age cracking and autogenous shrinkage. Furthermore, a similar modulus of elasticity of the aggregate

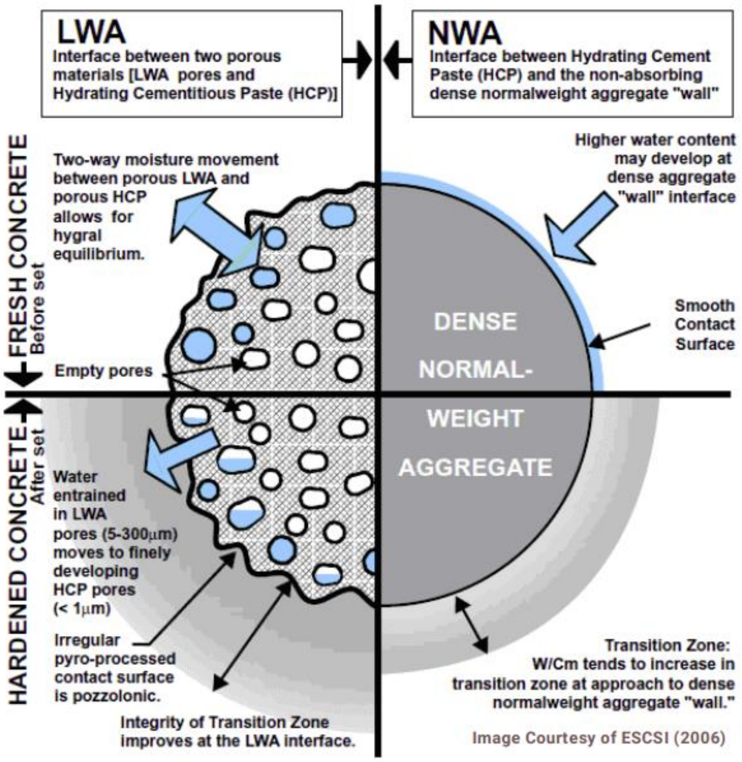


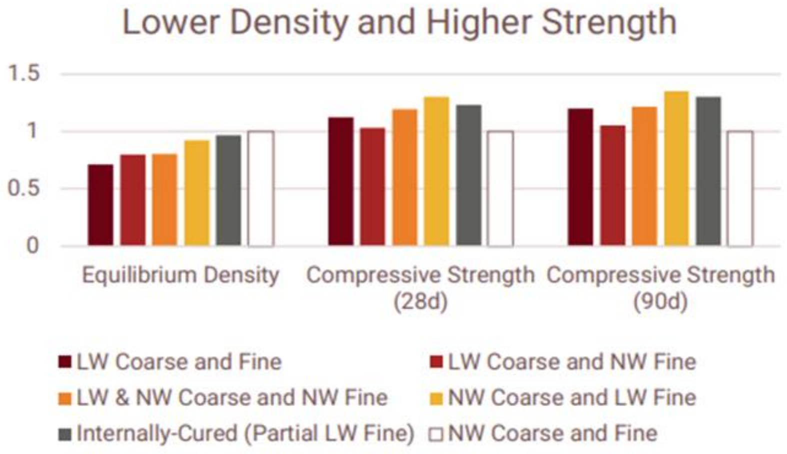
Image Courtesy of ESCSI (2006)

and cementitious matrix contributes to the reduction of microcracking in the interfacial zone. Mitigation of cracking provides long-term benefits by extending the service life of the concrete. In addition, the improved contact zone provides higher resistance against brittle failures like tensile, shear, and bond fractures governed by the weakest-link failure mechanism. The limitation of tensile cracks due to thermal and structural loads deters the penetration of corrosive agents in the long term and improves concrete members' durability.

Durability and Transport Properties

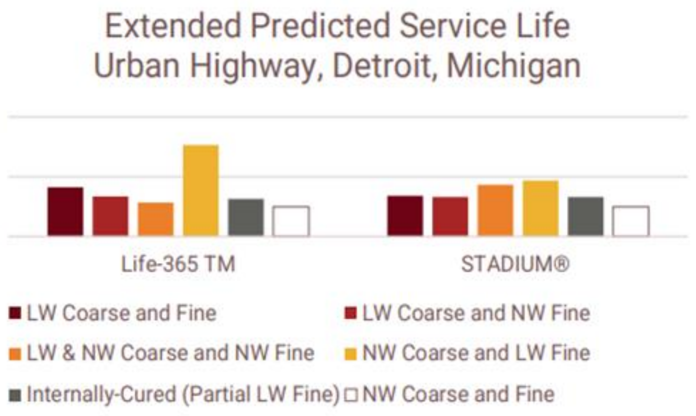
Primary mechanisms of degradation of concrete and corrosion of steel reinforcement involve the transportation of aggressive ions from the concrete surface to the surface of reinforcing bars. Hence, transport properties are vital modeling parameters for predicting the service life of the concrete. The use of lightweight (LW) aggregate enhances these properties in structural lightweight concrete due to improvements in the contact zone and other factors. In addition, internal curing using fine lightweight aggregate enhances the durability of normalweight (NW) concrete through improvements in transport properties. The same enhancement is evident in other classes of lightweight aggregate concrete with various combinations of coarse and fine lightweight aggregates.

Experimental studies on concrete containing expanded shale, clay, and slate aggregate indicate reduced ionic diffusion and moisture transport coefficients and increased chloride threshold for internally cured normalweight concrete and all classes of lightweight concrete. Investigated concrete had a lower equilibrium density and higher compressive strength than normalweight concrete. All concrete containing expanded shale, clay, and slate aggregates had higher rates of increase in the compressive strength from 28- to 90-day age.

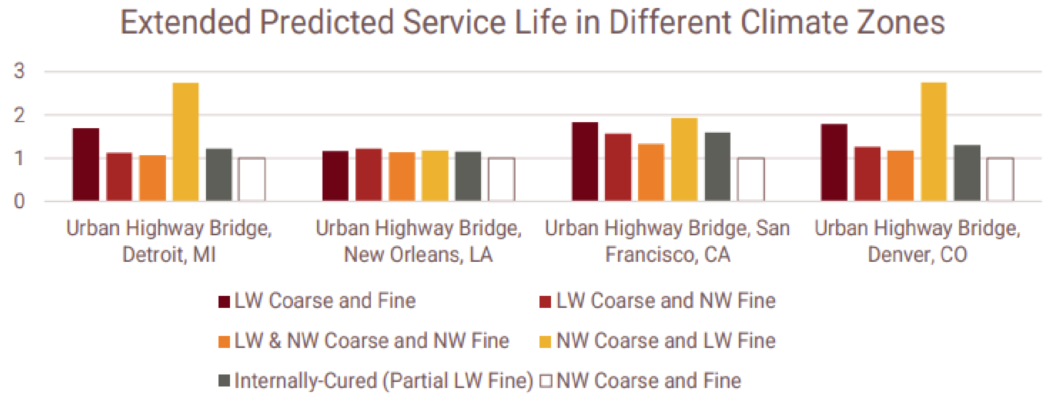


Improving Predicted Service Life with Internal Curing

Prediction models utilizing transport properties per fib Bulletin 34, including Life 365TM and STADIUM®, indicate that using expanded shale, clay, and slate aggregates provide a significant beneficial influence on the service life of concrete systems. This observation remains valid, disregarding the employed software, as the difference in the predicted service life of the witness sample with normalweight coarse and fine aggregate using Life365TM and STADIUM® is only 3%.



For a simulated bridge deck in the Detroit area, the STADIUM® results show that the time to corrosion will be increased by approximately 22% for lightweight concrete mixtures compared to the control mixture with normalweight aggregates. The replacement of normalweight sand with lightweight fines results in approximately a 34% to 88% increase in the time to corrosion. The Life 365™ analysis also shows performance improvement in lightweight coarse aggregate mixtures compared to the control mixture. Lightweight fines show a three-time improvement when used to replace normalweight fines. Further, an internal curing mixture with a small quantity of lightweight fines extends the service life compared to the control concrete in both STADIUM® and Life 365™. Expanding the prediction model to various climate zones defined by FHWA (Federal Highway Administration) results in the same outcome for the effectiveness of LWA in all wet-dry and freeze-no-freeze zones.



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