Designing with Lightweight Concrete

By William H. Wolfe

Each year, in the United States alone, several hundred steel frame commercial office buildings are constructed utilizing lightweight concrete and steel composite decking. This type of construction represents the majority of mid-rise construction today. During the design process, many factors such as initial costs, life cycle costs, past product performance, and availability are considered when choosing appropriate building materials. Once all these factors have been evaluated, Structural Lightweight Concrete is often the material of choice.

Figure 1: Lightweight aggregate particle showing ceramic matrix and void structure.

What is Structural Lightweight Concrete?

The American Concrete Institute (ACI) defines Structural Lightweight Concrete (SLC) as concrete with a minimum compressive strength of 2,500 psi (17 MPa) and an equilibrium density of between 70 and 120 pounds per cubic foot (1,120-1,920 kg/m3). It consists of entirely lightweight aggregate, or a combination of lightweight and normal-density aggregates. Each structure is design specific, with the majority of the concrete specified for suspended slabs having an equilibrium density between 105 and 120 pounds per cubic foot (1,620 – 1,920 kg/m3) and a compressive strength of at least 3,500 psi (20.7 MPa). Other structures, such as bridges and precast elements, are often designed utilizing SLC with strengths above 5,000 psi (34.5 MPa).

Early Beginnings

Lightweight concrete has been utilized in construction projects for over 2,000 years. Some of the early structures from the Roman Empire that still survive today have elements that were constructed with lightweight concrete. A great example is the Pantheon, which was completed in 27 BC. The roman builders utilized natural lightweight volcanic materials found in the region to modify the density of the concrete used in the roof of the structure. The 142-foot (43.3-meter) diameter domed roof has concrete that varied in density based on changes in the amount of lightweight aggregate placed in the concrete. The structure is in excellent shape and is still being utilized today.

Lightweight concrete got its start in the North America in the early 1900s. Steven J. Hayde, a brickmaker from Kansas City, MO, discovered that bricks bloated after they came up to temperature too quickly in kilns. These bricks were distorted and out of the dimensional tolerances needed for construction. From this initial observation and many years of process refinement, Hayde developed the rotary kiln method for expanding clays, shales and slates. The aggregate that was manufactured with Hayde's process had a ceramic matrix surrounding air voids contained within the aggregate particle (*Figure 1*). Early development of lightweight concrete was accelerated when it was discovered that lightweight concrete could be used as a replacement for sheet steel, which was in great demand during World War I and World War II. Over one hundred ships were constructed from lightweight concrete during this time period.

Today's Buildings

A great deal of the three story and higher commercial structures that dominate the suburban and inner-city landscape are constructed with structural lightweight concrete slabs on steel deck (*Figure 2*). Annually, these suspended slabs account for over 200 million square feet of flooring. One of the major advantages of lowering the density of concrete on projects is the reduction of dead loads. Typical normal weight concrete weighs approximately 145 pounds per cubic foot as compared to a typically specified lightweight concrete density of 115 pounds per cubic foot. This reduction of density allows a concrete weight savings of over 20 percent.

Figure 2: Most of the structural lightweight concrete that is placed in commercial structures is pumped.

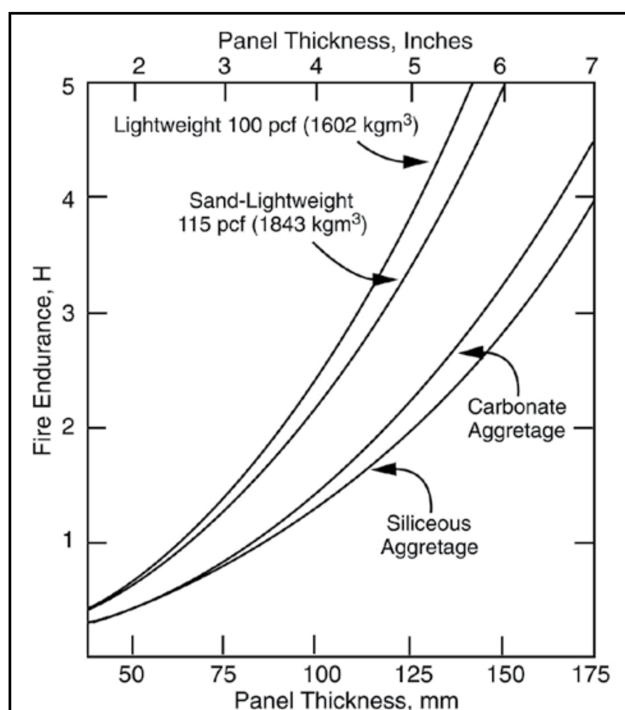

Figure 3: Fire endurance of concrete slabs as a function of thickness for naturally dried specimens.

Additionally, thinner slab sections are allowed for lightweight concrete to achieve the same fire ratings of similar normal weight decks. A reduction in slab thickness from 4½ inches for normal weight concrete to a slab thickness of 3¼ inches for lightweight concrete, when combined with the concrete density savings, will reduce the total slab weight by 38 percent. The load reduction often reduces the size of columns, beams, and girders, as well as foundations and reinforcing steel. An example of weight savings for a 2 hour fire rated deck is shown in *Table 1*. Seismic performance is also improved because the lateral and horizontal forces acting on a structure during an earthquake are directly proportional to the inertia or the mass of a structure. The reduced slab weight also allows for greater spans, thereby improving the overall structural efficiency of the building.

Fire Resistance

The fire resistivity of a structure is directly related to the properties of the building materials that make up that structure. These materials must be able to withstand high temperatures and still maintain their structural stability. Lightweight concrete is more fire resistant than normal weight concrete due to its lower thermal conductivity and its lower coefficient of thermal expansion. The expanded aggregates used in lightweight concrete have already been heated to temperatures in excess of 2000°F (1093°C). These characteristics allow lightweight concrete to have thinner slab sections than comparable normal weight slabs that have identical fire ratings. Building materials are tested for fire resistivity in accordance with ASTM E 119, *Fire Tests of Building Construction and Materials*. These ASTM E 119 tests have shown that slabs constructed with lightweight concrete have demonstrated greater fire endurance periods than slabs constructed with normal weight concrete of an equivalent thickness (*Figure 3*).

Proportioning and Pumping

Like normal weight concrete, lightweight concrete should be designed in accordance with ACI 318. The proportioning of lightweight concrete mixtures can be done by volumetric or specific gravity methods. The ready-mix supplier and the lightweight aggregate manufacturer should be consulted when the concrete mixture is designed. The design should have a cementitious content sufficient to accommodate a 4- to 6-inch slump at the point of placement, typically a minimum of 611 pounds per cubic year (363 kg/m3). Water reducing admixtures that aid pumping

Table 1: Deck Comparison - UL Design No. D916 - 2 hour fire rating in 2 inch deck.

Concrete Type	Fire Rating (hours)	Pan Depth (inches)	Slab Depth (inches)	Total Slab Depth (inches)	Concrete Density (lb/cu ft)	Theoretical Concrete Volume		Concrete Slab Weight (lb/sq ft)	Weight Reduction (%)
						(cu ft/sq ft)	(cu yd/100 sq ft)		
Normal Weight	2	2	4.5	6.5	150 +/- 3	0.461	1.71	69.15	-
Lightweight	2	2	3.25	5.25	110 +/- 3	0.357	1.32	39.27	43%

Figure 4: The concrete pump should have access for two ready mix trucks to prevent delays in pumping.

should be used, as well as an air entraining agent that improves pumpability, finishability and durability of the concrete. A well graded combination of coarse and fine aggregates will aid in the quality of the mix as well improve pumpability. The fine aggregate should be a well-graded natural sand with a good particle shape and a fineness modulus between 2.2 and 2.7. The concrete utilized in today's unique projects should be adequately tested to verify the specifications are met.

Figure 5: Lightweight concrete being placed on metal decking.

Pumping structural lightweight concrete (*Figure 4*) is quite common and easily achieved, as long as a few guidelines are followed. The lightweight aggregate should be prewetted to a moisture level that the aggregate's manufacturer recommends. This will help prevent excessive slump loss during pumping. The pressures developed during pumping may force the mixing water into the pores of undersaturated aggregate. Adequate aggregate saturation is easily obtained through the use of a sprinkler, or by being vacuum saturated at the lightweight aggregate manufacturing facility.

The pump system should be designed to ensure a smooth job. A typical concrete pumping system can be made up of the pump, a steel pumping line, piping reducers used to go from a large diameter line to a smaller diameter line, elbows placed at bends in the line, and a rubber hose to allow movement at the end of the line. Use the largest line available with a minimum diameter of 5 inches (127 mm). Increasing from a 4 inch (102mm) to a 5 inch (127mm) diameter line increases the volume carried by the line by over 50 percent. Keep the diameter of the pumping line the same from the pump discharge to the point of placement by eliminating piping reducers. Also keep the amount of rubber hose to the minimum length, one that still allows easy placement of the concrete (*Figure 5*). These are areas where the consistent flow of concrete through the line can be hampered by more resistance. Design the system to have the minimum amount of bends possible and brace all bends. The line should be "buttered" with grout prior to pumping concrete.

Figure 6: Finisher making first pass over lightweight concrete with walk behind power trowel.

A pre-pump meeting, as well as a field trial, should be conducted prior to concrete placement. These meetings should be attended by the contractor, the design engineer, the ready-mix supplier, the lightweight aggregate supplier, the admix supplier, the pumping contractor, and the testing laboratory.

Concrete Finishing

For foot traffic in office, commercial, multi-unit residential and institutional buildings, lightweight suspended floors are typically finished with floor coverings. The American Concrete Institute's Committee 302 (ACI 302) calls this type of floor a Class 2 Floor, which has a flat and level slab suitable for applied coverings, and a "light" steel-troweled finish (*Figure 6*). The floor flatness/levelness tolerances for this floor are F_F25/F_L20. On some occasions, flatness/levelness tolerances are higher to meet specific design requirements. This "light" steel-troweled finish is not the same as a "normal" or a "hard" steel-troweled finish that is recommended by ACI 302 for commercial or industrial floors subject to vehicular traffic. There is really no need to over-finish a floor that will be taking these types of floor coverings. The concrete needs to be able to reach a moisture equilibrium as the water within the concrete evaporates or is utilized for internal curing.

Sustainability

The sustainability of a structure and its effect on the environment are moving to the forefront of building design and construction. The use of lightweight concrete in a structure can save on materials utilized in the construction of that project. Material and cost savings include: less labor, lower dead loads, better fire resistance resulting in reduced concrete thickness, less reinforcing and concrete required in foundations, and reduced structural members such as columns, beams, girders, and piers. Transportation costs are less for building components that are manufactured with lightweight concrete. A ready-mix concrete truck requires less fuel to carry lightweight concrete due to its lighter weight. This saves precious natural resources and helps to reduce air pollution.

Conclusion

Over the past eighty years, over 500,000 floors have been constructed with lightweight concrete. The design considerations for structures that contain these floors have been thoroughly studied and evaluated. Utilizing a building material that is typically 25% to 35% lighter in weight, and that has a lower thermal conductivity than normal weight concrete, allows design flexibility as well as numerous material and cost savings. It offers improved fire safety for building occupants and improved sustainability of projects. From its ancient beginnings to today's high strength, low density concretes, lightweight concrete has a record of proven performance and has resolved numerous design challenges.▪

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