Building Blocks

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Is Lightweight Concrete All Wet?

The Advantages and Disadvantages of Lightweight Concrete in Building Construction

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Recently, lightweight concrete has been implicated as the primary culprit in moisture-related failures of adhered flooring systems. Although fast-track construction techniques and government-mandated changes in flooring adhesives also have contributed to these problems, some critics suggest that the consequences of a finish floor failure outweigh the benefits that lightweight concrete can bring to a project. In light of this controversy, it is worth evaluating the advantages and disadvantages of lightweight concrete, considering not only its interactions with flooring systems but also how it affects building aspects such as steel tonnage, foundations, and slab fire ratings. Despite the moisture-related challenges that lightweight concrete poses, properly designed and constructed lightweight concrete floor slabs offer a number of efficiencies over normal-weight concrete slabs that project teams should consider.

What is Lightweight Concrete?

Lightweight concrete is nothing new. It has been around in various forms for centuries. There are many types of lightweight concretes. For the purposes of this article, we are considering only structural lightweight concrete: a mixture of portland cement, water, fine (sand) aggregates, and expanded clay, shale, or slate coarse aggregates. While normal-weight concrete mixes typically weigh 145 to 155 pcf, lightweight concrete typically weighs 110 to 115 pcf. Structural lightweight concrete commonly has 28-day compression strengths comparable to normal-weight concretes.

The primary difference between normal-weight concretes and lightweight concretes for structural applications is the coarse-aggregate material. Normal-weight aggregates are typically natural crushed stone, whereas lightweight aggregates are produced by heating clay, shale, or slate in a rotary kiln at temperatures on the order of 2,000°F. At these temperatures, the aggregates expand and develop a network of interconnected internal pores (*Figure 1*) ranging in size from 5 to 300 microns (Chua, 2009). This internal pore network yields a lighter density than natural aggregates. Although concrete compressive strength generally is related to the compressive strength of the coarse aggregate, American Concrete Institute (ACI) 213R-03 reports that for typical building-slab compressive strengths – up to about 5,000 psi – "there is no reliable correlation between aggregate strength and concrete strength."

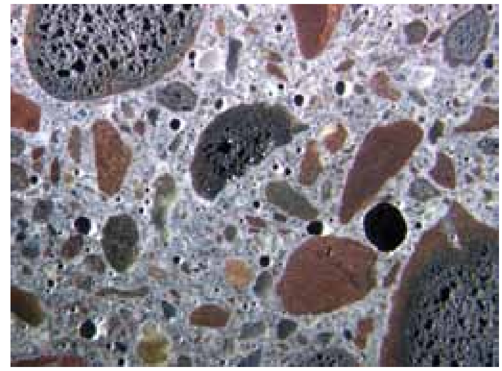

Figure 1: Micrograph of lightweight concrete with expanded shale aggregate and natural sand aggregate. Note the porosity of the expanded shale aggregate.

Water in Lightweight-Concrete Mixtures

Lightweight concrete is often implicated in moisture-related flooring failures because it often has a significantly higher water content than normal-weight concrete. Unlike natural aggregates, which tend to become saturated with water only on their surfaces, lightweight aggregate pore networks absorb and store water within the aggregate particles, releasing it gradually over time.

To understand how water content affects concrete, we need to consider how the water reacts in the mix. ACI 304.2, *Placing Concrete by Pumping Methods*, considers two types of water in lightweight concrete: free water and absorbed water. Free water influences the volume of the mix, the slump and workability of the mix, and the amount of water available for cement hydration reaction. Absorbed water is held in the pores of the lightweight aggregate. During mixing, some free water is converted to absorbed water, reducing the slump and the amount of water available for hydration. In addition, the pumping pressure drives additional free water into the porous lightweight aggregate, further reducing slump between the pump hopper and the point of discharge. To reduce the amount of mixing water absorbed by the lightweight aggregate, concrete suppliers pre-saturate the lightweight aggregates to fill the pore spaces prior to mixing. Concrete suppliers frequently use water-reducing admixtures to help reduce the total amount of mix water and, consequently, the amount of water that will potentially leave the slab over time.

In both normal-weight concrete and lightweight concrete, water that is not consumed in the hydration of the cement particles slowly evaporates through the exposed surfaces of the concrete which, as is later discussed, can create problems with floor finishes. Almost all concrete mixes contain more water than necessary for the cement hydration reaction, but the excess water facilitates placement and finishing. After the cement paste has hardened, the hydration reaction continues, albeit at a slower pace, throughout the life of the concrete as the excess water evaporates. In lightweight aggregate, some absorbed pore water will be drawn out and contribute to more complete hydration of the cement in a layer around the aggregates, but there will still be significant amounts of absorbed water remaining in the pores which, will escape over time.

With the increasingly fast pace of construction, reducing the drying time – the time between the end of curing and when floor finishes can be installed – is often critical to the schedule. Elevated slabs on metal decks are susceptible to longer drying times because the water can only escape through the top surface of the slab (*Figure 2*). With the exception of some techniques that we discussed later in this article, relatively little can be done to the mixture to reduce drying time other than reducing the water in the mix. ACI 302.2R-96 reports that "there is no reason to include or exclude any concrete materials with the exception of the addition of silica fume [in place of some portland cement] in an attempt to reduce the needed drying time for a given water-to-cement ratio." The report notes that replacing 5% to 10% of the portland cement with silica fume can decrease concrete drying time by several weeks. However, this is often not enough time savings for fast-track construction.

Figure 2: Placing lightweight concrete on composite metal floor deck. The metal floor deck allows the concrete to dry only through its top surface.

Table 1: Slab thickness and fire rating.

Restrained Assembly Fire Rating	Minimum Slab Thickness on 2 or 3 in. Steel Floor or Form Deck without Spray-Applied Fireproofing	
	Lightweight Concrete (107-113 pcf)	**Normal-weight Concrete (147-153 pcf)**
1 hour	2⅝ in.	3½ in.
2 hours	3¼ in.	4½ in.
3 hours	4³⁄₁₆ in.	5¼ in.

Design with Lightweight Concrete

Despite the moisture issues, lightweight concrete provides a number of benefits. Lightweight concrete composite slabs are inherently more efficient than normal-weight composite slabs with nearly identical structural characteristics and design strengths.

Concrete slab-on-metal deck thicknesses are typically controlled by fire-rating requirements as opposed to strength requirements. Lightweight concrete is more fire resistant than normal-weight concrete due to its lower thermal conductivity and lower coefficient of thermal expansion. In accordance with ASTM E119, *Standard Methods of Fire Tests of Building Construction and Materials*, the American National Standards Institute (ANSI) and Underwriters Laboratories (UL) list minimum concrete thicknesses required for various fire ratings. *Table 1* is summarized from ANSI/UL 263 Design No. J718.

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Table 2: Material quantities.

Material	System A (Normal-Weight Concrete)	System B (Lightweight Concrete)
Structural Steel Framing	6.2 psf	4.77 psf
Concrete Volume	0.458 ft^3/sq ft	0.354 ft^3/sq ft
4,000 psi Composite Slab (including deck weight)	68 psf	43 psf
Headed Stud Shear Connectors	0.09 studs/sq ft	0.12 studs/sq ft

Table 3: Cost (based on approximate unit costs).

Material (and Unit Cost)	System A (Normal-Weight Concrete)	System B (Lightweight Concrete)	Cost Ratio (A/B)
Structural Steel Framing (assume $4,000/ton)	$12.40/sq ft	$9.53/sq ft	1.30
4,000 psi Composite Slab (assume $105/CY NWC and $135/CY LWC)	$1.78/sq ft	$1.77/sq ft	1.01
Headed Stud Shear Connectors (assume $2/stud)	$0.17/sq ft	$0.23/sq ft	0.74
Total	$14.35/sq ft	$11.53/sq ft	1.24

For a two-hour fire-rated slab, the use of lightweight concrete results in approximately 38% concrete material savings over normal-weight concrete. Lighter slabs reduce the overall building mass, effective seismic loads, and foundation design loads, and may also reduce the required steel framing depth if deflection and vibration criteria are satisfied.

The thinner slab is not without drawbacks, but these factors rarely govern design in a typical commercial building. The thinner lightweight concrete slab has a reduced flexural capacity, but the capacity is still sufficient to support most commercial occupancy floor loads. ACI 318-08 requires a 0.75 reduction factor for lightweight concrete shear capacity. However, in composite slabs, the design is most often governed by the flexural strength. For most buildings, the diaphragm shear capacity reduction is offset by the many other benefits of the overall system.

Cost Implications of Lightweight Concrete

Is lightweight concrete more expensive than normal weight? Yes and no. In order to accurately address this question, one must consider how concrete weight affects overall structural costs. The material unit cost of lightweight concrete is typically higher than that of normal-weight concrete, but the unit cost usually is more than offset by the overall reduction in concrete volume and steel tonnage for the structural system.

Consider, for example, a typical multi-use composite structural steel building in the Boston, Massachusetts, area. We assume a two-hour fire-rated floor assembly using 2-inch deep, 18-gauge composite metal deck with beams spaced to maximize allowable unshored "two-span condition" deck spans. Lighter wet-concrete loads on composite metal deck allow for longer deck spans between supports, and can effectively reduce the number of steel support beams and the steel framing tonnage. According to a Boston-area concrete supplier, there is typically no difference in cost for placement and finishing lightweight and normal-weight concrete, but the material unit cost of lightweight concrete ($135/cu yd for lightweight concrete vs. $105/cu yd for normal-weight concrete) is slightly higher due to aggregate processing and shipping costs from nonlocal sources. In this study, we considered both cambered and non-cambered steel framing, but found little difference in quantities and cost between the framing systems. Our general design assumptions included a superimposed dead load of 20 psf, a live load of 100 psf, and maximum total and live-load deflections of L/240 and L/360, respectively. *Tables 2* and *3* illustrate a comparison of material quantities and approximate costs for a typical bay (*Figure 3, page 26*).

While there is often a higher unit cost for lightweight concrete, there is significant structural steel tonnage and cost savings with using lightweight concrete slabs-on-metal deck. Compared with a normal-weight slab, lightweight slabs may also save inches of structural framing depth per story, which can result in a substantial savings in steel, foundations, and cladding costs for multistory buildings.

Flooring Interactions with Lightweight Concrete

Lightweight concrete aggregates absorb, retain, and release more moisture than normal-weight aggregates, so does that mean using normal-weight concrete in lieu of lightweight concrete will eliminate moisture-related flooring failures? No.

Moisture-mitigation will likely be required for moisture-sensitive flooring systems regardless of whether the concrete is normal weight or lightweight. In a study conducted in 2000, Suprenant and Malisch reported that under controlled air, temperature, and relative humidity conditions, lightweight concrete took 183 days to reach a moisture vapor emission (MVER) of 3.0 lbs/ 1,000 sq ft/24 hr. In a 1998 study performed under the same controlled conditions, Suprenant and Malisch reported that a normal-weight slab of the same thickness took 46 days to achieve the same MVER. In 2007-2008, the Expanded Shale, Clay and Slate Institute (ESCSI) conducted a study in non-controlled environments (similar to those found on construction sites) and found that while lightweight concrete slabs did take longer than normal-weight slabs to dry, the difference in drying times was smaller than Suprenant and Malisch reported. So what does this all mean? As reported by ESCSI, it is difficult for a concrete slab (normal weight or lightweight) to reach the moisture levels currently required by many flooring material manufacturers and industry standards without months of favorable interior drying conditions.

Several elements contribute to the failure of flooring systems, whether the slab is composed of lightweight or normal-weight concrete. Topping the list is the change in flooring adhesives composition due to the now-government-regulated use of hazardous materials and volatile organic compounds (VOCs). For example, the *National Volatile Organic Compound Emission Standards for Architectural Coatings* under Section 183 (e) of the Clean Air Act and the South Coast Air Quality Management District (SCAQMD) of California Rule 1168 require limitations on VOC content of floor coatings, concrete protective coatings, sealers, and stains. The most-common low- or no-VOC reformulation flooring adhesives are water-based acrylic emulsions, some of which are susceptible to re-emulsification when exposed to water and alkalinity in a concrete floor slab. Couple these moisture sensitive adhesives with construction schedule pressures to install the flooring as quickly as possible, and there is often not enough time to wait for the slab to adequately dry.

There are a number of strategies that can reduce the likelihood of a moisture-related flooring failure. One such technique is moist-curing slabs in lieu of using liquid film-forming curing compounds. Curing compounds trap moisture in the concrete to enable the curing process, but until they are removed (typically just prior to flooring installation), they prevent concrete from drying. Limited use of retardants, slag, and fly-ash content can also help reduce drying times. Also, when the slab is exposed to rain and humidity, the slab cannot dry adequately. Enclosing the building and activating the HVAC system is when the real slab drying begins. Lowering the ambient relative humidity (RH) and increasing the ambient temperature generally decreases the drying time of the concrete slab.

A Look to the Future

Self-desiccating normal-weight concrete mixes are beginning to appear on the U.S. market. ACI defines self-desiccation as "the removal of free water by chemical reaction so as to leave insufficient water to cover the solid surfaces and cause a decrease in the relative humidity of the system; applied to an effect occurring in sealed concretes, mortars, and pastes." In other words, the cement hydration reaction uses all the available free water to such an extent that not enough water is left to cover the unhydrated particle surfaces or to maintain 100% relative humidity within the concrete. Fast-drying concrete mixes utilizing this concept of internal hydration have been used internationally for years, and even though they are gaining momentum in the U.S., there a few roadblocks including limited regional availability, lack of lightweight concrete mix options, relatively slow placement (up to approximately 85 cu yd/hr), and sticky trowel-finishing. Ready-mix suppliers are working on resolutions that could soon be available.

Waterproof flooring adhesives are becoming more prevalent. These adhesives offer limited surface preparation and resistance to moisture exposure and high pH levels. Priming is not typically required for waterproof adhesive application, but light surface grinding of the concrete slabs is necessary.

Conclusions

Although lightweight concrete has the potential to cause problems with adhered flooring systems, normal-weight concrete floors can also influence moisture-related problems. Regardless of the concrete's density, the project team needs to consider the risks of moisture-related failures and, if necessary, to evaluate potential mitigation strategies. The team needs to make realistic estimates for concrete drying time and assess the selected flooring system MVER requirements. Limiting the concrete's water-to-cement ratio, incorporating silica fume, and limiting moisture-retaining pozzolans such as fly ash, will reduce drying time. Enclosing the building early (to limit environmental moisture sources) and conditioning the interior space will help dry the slab. Incorporating admixtures into the concrete that lock free moisture into the slab through a crystalline material or that promote self-desiccation may speed the installation of flooring systems, often with a cost on the order of $1 per square foot. Topically applied sealers that indefinitely keep the free water from dissipating through the top surface of the concrete have a history of good performance, but these can cost as much as $5 per square foot. Each of these strategies can add cost to the project.

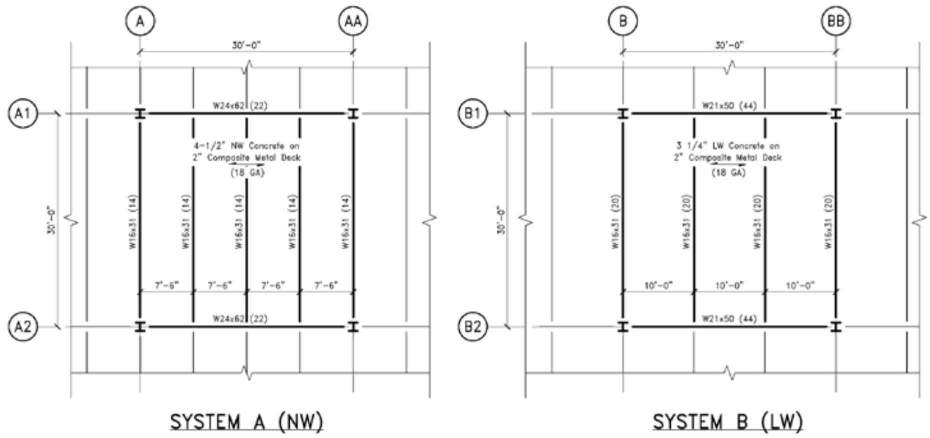

Figure 3: Example framing bays with normal-weight and lightweight concrete slabs on composite metal floor deck.

The costs of a well-conceived and properly implemented moisture control system can be offset by savings in structural steel, foundations, and fireproofing. Careful planning by the entire project team – the owners, architects, contractors, and engineers – early in the design process can help reduce or eliminate the risks of moisture-related flooring failures on both lightweight and normal-weight concrete slabs.▪

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