A Top-Down Approach

Raising the roof and enhancing the floor slab adds volume and utility to existing warehouses

by Edward B. Finkel

To meet the demands of the revolutionary merchandising phenomenon known as Internet retailing, online sales, or e-commerce, new distribution centers are being planned and constructed in strategic locations throughout the United States and Canada. Unlike existing structures lacking the necessary clear heights, these modern facilities feature uncommonly high storage racking systems and often employ wire-guided, swivel-reach materials-handling equipment. Accordingly, landlords holding expiring leases on vintage low-rise buildings are exploring the feasibility, and implementing the strategy, of raising the roofs of these buildings to clear heights upwards of 45 ft (13.5 m). This means an increased storage volume of 50% or more. But this maneuver is only part of the strategy. What logically follows is an imperative to evaluate the strength and serviceability characteristics of an existing conventional interior concrete slab-on-ground installed in the facility several decades prior to the advent of the laser screed and state-of-the-art construction practices used in floating and finishing operations, reliably reckoned flatness/levelness, slab thickness and subbase tolerances, and high-performance prescriptive low-shrinkage concrete mixtures.

Many modern "big box" distribution facilities now feature towering storage racking units separated by narrow pathways known as defined traffic aisles, traveled repetitiously around the clock by wire-guided, three-wheeled turret forklift trucks with tall masts having extraordinary reach. Needless to say, the floors carrying these vehicles must be exceptionally smooth to manage multidirectional travel while maintaining operational efficiency of the materials handling equipment. Thus, the emergence of F-min numbers prescribed by manufacturers matching the productivity standards established for their forklift equipment. The F-min is not to be confused with superflat, a term associated with random traffic floors traditionally measured with the F-Meter or other suitable handheld device. Defined traffic aisle tolerances are recorded by a profilograph replicating a three-wheel configuration and the F-min number is reconciled by computer analyses of this data. Meeting these goals requires special placing and finishing techniques by the flatwork contractor followed by local surface grinding, particularly at construction joints.

Meeting the demands associated with increased storage rack post loads and finely tuned flatness/levelness (F-min) values to cope with sophisticated operational strategies, however, begins with research and analyses leading to practical and economic considerations relative to the following options:

1. Bonded concrete topping;
2. Bonded epoxy mortar overlay;
3. Unbonded concrete overlay; and
4. Removal and replacement of the existing floor slab.

Design and construction of bonded and unbonded overlays and high-performance slab-on-ground are covered in ACI 302.1R-04[1] and ACI 360R-10.[2] Bonded and unbonded toppings were also discussed in the August 2013 *Concrete International* Concrete Q&A feature.[3]

For decades, existing, predominantly flexible, highway and roadway pavements have been rehabilitated with concrete overlays commonly known as whitetopping. These measures are classified as conventional, thin, and ultrathin, with thicknesses of more than 8 in. (200 mm), 4 to 8 in. (100 to 200 mm), and 2 to 4 in. (50 to 100 mm), respectively. The ultrathin version, 4 in. (100 mm) thickness preferred, is popular because it is designed to bond compositely with the original pavement. Regarding behavioral characteristics and life-cycle predictions, caution is advised in drawing comparisons between roadway paving and industrial floor rehabilitation protocols, given the disparities in load distribution (large, tandem pneumatic tires versus small, hard polyurethane wheels), serviceability requirements, and construction methodology.

Comparative Features of the Four Options

Before the most suitable choice is selected in connection with conversion of an existing facility to Internet-era function, the original floor slab-on-ground installation must be thoroughly investigated. Studies pertinent to forming judgments about the bonded, unbonded, and replacement options include:

- Flatness/levelness and impulse radar (slab thickness) measurements;
- Petrographic and environmental studies;
- Moisture emission tests; and
- Compressive and flexural strength evaluations of in-place concrete test specimens.

The subbase materials also need to be examined for evidence of latent adverse chemical activity and, perhaps, prior leakage of stored toxic liquids or intrusion of contaminated floor cleaning solutions. This information is essential to evolving structural section properties, finishing and detailing characteristics, moisture mitigation techniques, construction practices, and comparative costs commensurate with anticipated usage criteria and serviceability standards. Historically, the thickness of an industrial concrete floor slab has been derived manually from empirical data embodied in design charts published by the Portland Cement Association (PCA) in several editions dating back to 1967. The essentials of this method, also appearing in the appendixes of ACI 360R-10,[2] are rooted in the pioneering work of H.M. Westergaard[4] and others early in the twentieth century. In theory, the floor slab is assumed to behave as a flexible mat, relying on such criteria as modulus of subgrade reaction, in lieu of bearing capacity applicable to rigid foundations, and modulus of rupture (flexural strength) assigned to the subbase soil and plain concrete slab, respectively. Early on, the determinations were bloated with rather sizeable safety factors. It is also notable that the allowable unit stress for flexural tension, for example, stipulated in the ACI 318-56 Building Code,[5] hovered around 100 psi (700 kPa). Estimates of flexural strength can be determined conservatively from the popular compressive strength test on cylinders commonly cast at construction sites. Actually, flexural beam specimens drawn from modern concrete floor slabs made up of uniformly graded and well-proportioned concrete mixtures have yielded upwards of 10 times the flexural capacity of plain concrete contemplated generations ago. Nowadays, safety factors are being streamlined and slab thickness analyses are relegated to the computer in a futile search for greater accuracy, despite the fact that software programs also ask for modulus of subgrade reaction input. No matter how you figure it, the concrete floor slab-on-ground is demonstrably stronger than it looks on paper.

Nonetheless, judicious estimates need to be made about loading expectations consistent with enlarged storage volume. The building adaptation may be undertaken on a speculative basis or with particular new tenant occupancy in mind. Manufacturer's rated rack post load data are not normally available until the equipment is ordered, so the product should be "weighed" or the loading otherwise rationally determined statistically.

Option 1: Bonded concrete topping

Structural capacity of an existing industrial floor slab can, theoretically, be substantially enhanced by a relatively thin, reliably bonded overlay minimally 2 in. (50 mm) thick, but this option requires invasive preparation involving rehabilitation of intrusive random drying shrinkage cracks and curled joint edges as well as sealant replacement. Surface contaminants, dirt, and debris are removed by blast-tracking (a minimally intrusive dust-free process in which a hand-operated apparatus spews a metal abrasive by means of a rotating blast wheel) to render a uniformly bondable texture. This is followed by grinding at repair locations, using equipment fitted with high-efficiency air filters to protect workers and others from accumulated dust. It is critically important to install this topping immediately after application of a proper, uniformly distributed bonding agent. To facilitate placement and finishing of a thin topping, the concrete mixture must uniquely incorporate a single coarse aggregate with a nominal maximum top size of 3/8 in. (9.5 mm), commonly referred to as pea gravel. Such a mixture, tending to be highly shrinkage-prone, requires especially judicious proportioning of the mixture ingredients and rigorous water control management. The finished topping slab is to be moist cured and provided with full-depth early entry saw cuts at precisely matched, existing, closely spaced contraction joints.

Option 2: Bonded epoxy mortar overlay

Contrasted with the other options, an oversized epoxy mortar/fine aggregate blended material, 1/2 to 3/4 in. (13 to 19 mm) thick, provides a dependable bonded topping capable of increasing the geometric section properties of a nominal 6 in. (152 mm) existing industrial concrete floor as much as 20 to 30%—sufficient to sustain correspondingly elevated rack post loads. The finished surface is notably strong, with superior abrasion and impact resistance, and may preclude dock leveler adjustments. This method entails a multistep epoxy installation entrusted to an experienced coating contractor with demonstrated expertise in this particular specialty.[6]

Option 3: Unbonded concrete overlay

The minimum thickness of this plain concrete installation must be 4 in. (102 mm). Considerably thicker than a bonded topping, it is much less invasive. Surface preparation comprises only power-washing the existing slab and placement of a puncture-resistant plastic membrane spread evenly over the entire floor area (to mask existing slab abnormalities such as cracks, curled joint edges, and repairs) and lapped upward to form a flashing continuously at the perimeter. Slab anchorages, embedments, and steel reinforcing bars tending to restrain or otherwise inhibit slab movement are to be scrupulously avoided. Obtrusive cracking and slab edge curling are directly related to restrained drying shrinkage. The smooth membrane acting as a slip sheet directly beneath the overlay dramatically reduces subgrade drag, thereby permitting the new slab to shrink freely.

The overlay concrete is to be proportioned for the lowest shrinkage characteristics attainable with locally available materials. This formulation typically embodies at least two coarse aggregates, beginning with a reasonably well-graded No. 57 ASTM C33/C33M blend, 1 in. (25.0 mm) top size, and an added No. 8, a 3/8 in. (9.5 mm) intermediate size. It is also strongly recommended that the mixture includes monofilament synthetic fibers for control of plastic shrinkage cracking and properly configured ASTM A820/820M Type II steel fibers, 1 in. (25 mm) long and continuously deformed, at dosage rates prescribed by the manufacturer and consistent with contractor experience, proportioned according to slab thickness, and meeting targeted widely spaced contraction jointing. Needless to say, minimization of contraction joints in a finely tuned floor slab, with embedded wire guidance and meeting critical surface tolerances, is a high priority. Achieving crucial F-min readings at construction joints may require special localized grinding, particularly at those that are armored. Expectations of extending joint spacing boundaries to column lines and beyond, enclosing two full bays in each direction, are not unreasonable in a floor slab constructed by an experienced and enlightened flatwork contractor.

ACI 302.1R-04[1] has traditionally advocated limiting joint spacing in feet as a function of 2 to 3 times slab thickness (expressed in inches). This, of course, is a capitulation to the inevitability of excessive drying shrinkage in generic floor slabs made up of unworthy concrete mixtures. Chapter 6 of this guide delves thoroughly into the fundamentals of prescriptive, low-shrinkage concrete mixture proportioning which, when combined with judgment and experience, will dramatically reduce drying shrinkage. Yet, inexplicably, a recent trend favors limiting this outmoded ratio to 2 to 2.5 times the slab thickness. After all, a sawn joint is also a crack, albeit aesthetically more pleasing than a random drying shrinkage crack but more likely to curl.

Option 4: Removal and replacement of existing slab

This option virtually precludes investigative study of the existing slab. Only the subbase will require rehabilitation. Industrial floors and the subbase strata below them, constructed before 1990, in general, are known to vary considerably in thickness and are not notably flat or leveled. Demolished recyclable crushed concrete retrieved from the existing slab can be used to improve subbase properties and, through re-grading adjustments, restore a level profile and allow space within the original subbase to accommodate increased slab thickness. Recycling trucks are designed to selectively root out reinforcing steel and other unwanted embedments and equipped to minimize dispersion of dust, while reducing the concrete to a suitably well-graded and compactible subbase material. The new floor slab can then be designed to meet anticipated forklift truck wheel and rack post loading criteria and usage and serviceability requirements. The concrete mixture, with an added ASTM C33/C33M No. 4, 1-1/2 in. (37.5 mm) top size coarse aggregate, will fundamentally mirror Option 3, focusing on a low-shrinkage mixture with optimized aggregate grading, minimal mixing water and paste contents, and steel fibers; likewise affording the opportunity for extended contraction joint spacing boundaries.[7] Under special circumstances, depending upon contractor skill and experience in managing paste content, placement of a membrane slip-sheet between bottom of slab and the subbase will drastically reduce subgrade drag.[8] Naturally, Option 4 has additional benefits that accrue from beginning anew.

Discussion

The surge in Internet commerce underlying the discussion of floor Options 3 and 4 lends a sense of urgency to challenges facing a concrete industry overwhelmingly reluctant to change course with respect to the traditional strength-driven performance mixture design strategy. These formulations are usually gap graded and offer little prospect for shrinkage curtailment, which is vital to modern industrial floors. Surely, the substantial expenditure involved in reaching historic heights in new and adapted buildings outfitted with sophisticated materials handling equipment is not to be squandered due to neglect of the important role played by slab-on-ground under these circumstances. Unfortunately, it often is.

Understandably, the idea of prescriptive lowest shrinkage concrete mixtures is not about to become universal overnight but personal experience, during the past two decades with hundreds of floors, has proven that the prescriptive mixture is easy to do and quality control managers in ready mixed concrete plants throughout the country are eager for the opportunity. Meanwhile, added to the usual list of suspects enlisted in the battle against excessive random cracking and joint edge curling in the generically formulated concrete floor is the notion that a chemical additive will magically lower the shrinkage threshold to a prescribed limit confirmed by standardized test. It should be noted that a 4 x 4 x 11 in. (102 x 102 x 279 mm) specimen, tested in a controlled laboratory environment per ASTM C157/C157M, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," does not replicate acres of

Raising the Roof

The proprietary E-Z Riser process can be used to lift an existing roof to two or more times its original height. Interior columns are enclosed within steel sleeves that allow the original columns to rise as they lift the roof. The original columns remain attached to the roof structure, and the sleeves remain in place to provide new and stronger lower support. Perimeter columns are fitted with additional telescoping columns that remain as integral parts of the lifted, strengthened structure. The condition and pitch of the existing roof are maintained, and the existing foundation system continues to support the roof. While additional cladding is required and the floor slab may require modification, raising the roof is an economical and sustainable way to modernize a facility. Additional information can be found at **www.rooflift.com**.

An example of capturing unused air space to enlarge an industrial facility *(photo courtesy of John J. Bernauer, EZ Riser Roof Raising Services)*

slab-on-ground cast in the field under variable climatic conditions, moist at the bottom while drying out at the top. Larger-size test specimens have been suggested to overcome this disparity dating back, at least, to 1984, but there is little in the way of reported statistical data to support this alternative.

The concrete floor slab-on-ground, operational heart of an industrial facility is much less expensive than the roof that hovers above it. Consider the following fundamental truths about plain concrete: it is a nonhomogenous material that, unlike structural steel, is inconsistent in manufacture and behaviorally unpredictable, especially when formulated generically in accordance with mythical rules limited to a single quality marker, compressive strength, often accompanied by a targeted water-cement ratio (*w/c*) bearing no known relationship to it. Compressive strength is not normally influential in the design of concrete subjected to flexure, notably slabs-on-ground, and *w/c* is evolved at the jobsite to suit optimum paste content consistent with hard-trowel finishability. The historic fascination with vapor retarder positioning relative to the "blotter effect" of the subbase centers upon bleed water management, profoundly important in the "window of finishability" period during the floating and finishing processes. The debate persists because excessive initial slump has predominated slab-on-ground discourse since time immemorial. Judgment of the finisher regarding "set time" is guided by skill honed through prior experience. This skill can be successfully adapted to managing low slump in concrete mixtures cast directly upon a membrane slip-sheet.

In the strictest sense, concrete is not an elastic material. It is, nevertheless, blessed with an ill-defined modulus of elasticity (*E*) that varies with time and stress gradient. Concrete is an exceptional material, when treated with respect. Blended to its full potential, the results are uniformity of strength and shrinkage properties. No other remedies are necessary. A proper, well-blended formulation negotiated with the local ready mixed concrete supplier is as good as it gets and no one need bear the onus of a target shrinkage limit governed by an indeterminate standard of measurement. The concrete industry, languishing in a perpetual state of inertia, is burdened with an archaic method of formulating concrete mixtures, notably those dedicated to slab-on-ground usage. Most building materials are manufactured under strict quality control protocols aimed at product quality and consistency. An industrial floor constructed of a worthy plain concrete and treated to a superior hard trowel finish will surely suffice. The performance concept applied to concrete manufactured universally under the aegis of the concrete industry is a good idea. Why not merge it with the lowest attainable shrinkage characteristics of the prescriptive formula and make them one and the same? This is inevitable; simply a matter of time.

Summary

The slabs covered in Options 1 through 3 will reside upon an impervious, virtually inflexible, concrete substrate (rather than directly against a proper moisture absorbent granular subbase). All of the options provide aesthetic improvement and refined surface tolerances. Options 3 and 4 also offer substantially reduced subgrade drag, allowing the new slab increased shrinkage freedom, thereby dramatically reducing the incidence of random restrained drying shrinkage cracking and perceptible joint edge curling. Both options will necessitate rearrangement of embedded steel load dock leveler apparatus to meet the newly raised floor elevation.

While roof and floor adaptations may be implemented in footprint segments as small as 100,000 ft^2 (9290 m^2), it is likely that buildings selected for high-rise conversion will be considerably larger. Floor slab upgrades in a vacant space may begin at once, await arrival of a prospective tenant with specific usage requirements, or may not be done at all depending on investigative findings and economic considerations.

Options 1, 3, and 4 contemplate uniquely blended plain concrete mixtures with lowest attainable shrinkage characteristics, conventionally deposited and appropriately flowable for laser placement without benefit of excess mixing water; adding a first-generation high-range water-reducing admixture

(Super P) in the field to insure control of initial "water slump." It is not necessary or beneficial to perform shrinkage tests to quantify shrinkage limits in such concrete formulations. Shrinkage test prism specimens in the laboratory do not replicate the behavior of a slab-on-ground in the field, and adding a shrinkage-reducing admixture to an unworthy concrete is an unacceptable alternative.

Option 1 not only requires less concrete volume than Option 3, it adds theoretically reliable composite geometric section properties and increases flexural capacity of the floor. However, there is insufficient evidence to engender full confidence in the long-term survivability of a thin concrete topping bonded to a generic industrial floor that is destined, in the modern era under perennial 24/7 continuous operations, to endure hard-wheeled forklift traffic abuse. While the degree of risk associated with debonding may not be fully known, the consequences of operational interruption are all but unthinkable.

Option 2 combines reliably with an existing floor slab to effect composite structural enhancement at a threshold meeting the needs of many prospective tenants. Absent the specter of major adaptations, it lends an attractive, nonslip, durable finish to a worn and outmoded floor, significantly prolonging its serviceable life and limiting maintenance costs.

Favoring the low-shrinkage approach, Option 3 involves twice as much concrete volume as Option 1. Extensive rehabilitation of the existing floor slab is avoided and the opportunity to broaden joint spacing boundaries is available. Unlike Option 1, the independent overlay does not unite with the existing slab in creating composite geometric section characteristics essential to enhanced structural behavior. But, the thickened overlay does improve the surface profile as it introduces a stratum of broadened influence over which concentrated loads are distributed through the existing slab to the subbase.

Option 4 requires minimal study and will not usually involve extensive reworking of the subbase or membrane vapor emission protection (except in relatively small areas destined for office occupancy). It offers the best attributes of the other options, fulfilling modern usage requirements, serviceability standards, and minimal future maintenance expectations, while curtailing investigative efforts and rehabilitation protocols.

Nevertheless, it is prudent to compare and contrast the expectations and costs associated with all of the options on a project-specific tenant usage basis. Depending on building size, scope of façade work, and extent of utility, mechanical, and electrical adaptations, the expenditure for a floor slab upgrade is estimated to be somewhat less than the cost of the roof conversion. The roof transformation adds substantially to the property value and is also environmentally friendly; adding little new material to the building, it simply moves things around. But, the floor does not just lie there covering the earth. It deserves more than a sprucing up with a surface hardener or deep-penetrating chemical densifier to meet the demands of modern commerce. The total adaptation expenditure can be expected to reach many millions of dollars. The urgent need for higher space accommodating vastly expanded storage volume is often accompanied by the yearning for larger floor area. Major Internet-commerce companies are currently building facilities more than 1,000,000 ft^2 (92,900 m^2) in area throughout the Northern Hemisphere. Landlords holding smaller, low-rise buildings with expiring leases may opt to hold out for a tenant whose needs suit the space. Inevitably, contemplation of adapting a building trumps the thought of replacing it.

References

1. ACI Committee 302, "Guide for Concrete Floor and Slab Construction (ACI 302.1R-04)," American Concrete Institute, Farmington Hills, MI, 2004, 76 pp.
2. ACI Committee 360, "Guide to Design of Slabs-on-Ground (ACI 360R-10)," American Concrete Institute, Farmington Hills, MI, 2010, 72 pp.
3. Tarr, S., "Concrete Q&A: Concrete Toppings," *Concrete International*, V. 35, No. 8, Aug. 2013, pp. 83-84.
4. Westergaard, H.M., "On the Design of Slabs on Elastic Foundation with Special Reference to Stresses in Concrete Pavements," *Ingenioren*, V. 12, 1923, Copenhagen, Denmark. (in German)
5. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-56)," American Concrete Institute, Farmington Hills, MI, 1956, 74 pp.
6. Gardner, M., "Replace or Resurface?," *CoatingsPro*, NACE International, Houston, TX, Jan. 2006.
7. Finkel, E.B., "What's Up Down Under and Elsewhere?," *Concrete International*, American Concrete Institute, Farmington Hills, MI, V. 33, No. 7, July 2011, pp. 45-50.
8. Finkel, E., "The Inevitable Choice for Industrial Floor Slabs," *Concrete Construction*, Hanley Wood, Rosemont, IL, Sept. 2013.

Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

Selected for reader interest by the editors.

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