Pile-Supported Slabs for Sites with Poor Geotechnical Conditions

Shrinkage-compensating steel fiber-reinforced concrete provides a cost-effective solution

by Rolands Cepurītis, Brad J. Pease, Jānis Kamars, and Jānis Ošlejs

After centuries of land development, particularly in urban areas, optimal locations for new construction are limited. This increasingly forces owners to consider building warehouses and similar structures on sites with less-than-optimal geotechnical conditions.

A concrete slab placed on a poor and/or inconsistent subgrade might become susceptible to excessive cracking and reduced load capacity. While a poor subgrade can be improved through compaction, addition of base/subbase courses, and/or chemical stabilization,[1] elevated ground slabs (EGS) are an increasingly common alternative. As discussed in ACI 544.6R-15,[2] EGS systems are constructed on closely supported pile caps, with typical span-depth ratios between 8 and 30. Depending on project-specific details, an EGS comprising steel fiber-reinforced concrete (SFRC) may provide the optimal solution with regard to economics, sustainability, and overall slab performance.

This article presents results from a full-scale test of an EGS constructed using shrinkage-compensating SFRC.[3] The 220 mm (9 in.) thick slab was supported by a 4.0 x 4.7 m (13.1 x 15.4 ft) pile grid; the span-depth ratio was therefore near the middle of the range indicated in ACI 544.6R. The floor system was designed to carry 40 kN/m^2 (835 lb/ft^2) uniformly distributed load. Additional information on such systems, including the historic development and advantages, is provided in References 2 and 4.

Basic Process and Load Testing

Based on a patented shrinkage-compensating SFRC system,[3] the flooring contractor Primekss has developed and installed over a total of 2,000,000 m^2 (21,500,000 ft^2) of shrinkage-compensating EGS floors, marketed as PrīmXComposite slabs-on-piles. The slabs are designed to carry flexural and shear loads associated with a pile-supported ground-level slab. The main reinforcement is typically provided by steel fibers supplemented with traditional reinforcing bars at corners, columns, and around loading docks for local load transfer, moment redistribution, and crack width control. Depending on loading and span length, traditional reinforcement may also be added to increase negative and positive moment capacity. The following sections introduce the basic slab-on-pile construction process and provide results from a full-scale load test conducted on such slab.

On-site incorporation of fibers and additives

Concrete for the slabs initially arrives at the project site as a ready mixed concrete without fibers and with a target slump range of 60 ± 25 mm (2.5 ± 1 in.). Proprietary shrinkage-compensation additives (SCAs), liquid admixtures, and steel fibers are incorporated on site using a fiber blower device equipped with a pump (shown in Fig. 1). The proprietary SCA, initially a powder, is prepared as a uniform slurry and subsequently pumped into the concrete truck. During the addition of fibers and additives, the mixing drum is rotated at full speed to achieve a uniform mixture. Liquid admixtures are initially added to increase slump in preparation for addition of steel fibers. The fiber blower, which breaks up fiber clumps in the hopper using a revolving sieve drum, blows fibers gradually onto the top surface of the continuously agitated concrete. Lastly, the SCA slurry is pumped into the mixture. The resulting SFRC has a 220 ± 25 mm (8.75 ± 1 in.) target slump and is typically placed using an auger-equipped concrete transporter, a concrete pump, or directly from the concrete truck's chute. The placed concrete is then leveled with a laser screed, and (as necessary per project-specific requirements) dry shake is applied to the top surface.

The fresh concrete is routinely checked to verify a uniform distribution of fibers is achieved throughout the contents of each truck and from truck to truck. Fiber content testing is conducted in accordance with Method B of EN 14721+A1.[5] Concrete samples, each 10 L (0.35 ft^3) in volume, are collected from the first, middle, and final third of the volume of a load. A collected sample is slowly introduced and washed through a hopper equipped with a strong magnet, as shown in Fig. 2. The fibers are held by the magnet as water is poured through the hopper. After the other constituents are washed away, the fibers are released from the magnet, dried, and weighed.

According to EN 206+A1,[6] fiber-reinforced concrete is deemed to come from a conforming population if both of the following criteria are met:

- Every sample contains at least 80% of the specified minimum fiber content; and
- The average of three samples from a load contains at least 85% of the specified minimum fiber content.

Figure 3 shows typical fiber content measurements from seven concrete batches, normalized by a target fiber dosage. The lowest normalized fiber content measurements observed (0.95 and 0.90 in the first- and middle-third samples, respectively, for batch No. 2) complied with the aforementioned criteria. Overall results demonstrate that the conformity criteria are obtained and that a highly uniform distribution of fibers is achievable using an on-site fiber blowing machine.

In a separate study,[7] the effects of placement and leveling of the concrete (by laser screed with associated vibration) were studied. Concrete samples were taken from the upper and lower halves of the slabs after leveling (Fig. 4). Numerous measurements were performed at projects with slab thicknesses ranging from 140 to 330 mm (5.5 to 13 in.). In all cases, the fiber content in the upper half of the slab was within 3.5 kg/m^3 (5.9 lb/yd^3) of the fiber content of the lower half of the slab.

The results show that the process used for on-site incorporation of steel fibers can achieve a highly uniform distribution of fibers within an individual load and between concrete loads. Further, the placement, leveling, and consolidation of the SFRC does not

Fig. 1: Fiber blower in action at a Gresser Companies, Inc. building site in Minneapolis, MN (left) and chute with loaded fibers (right)

Fig. 2: Equipment for collecting and weighing steel fibers from sample of fresh concrete

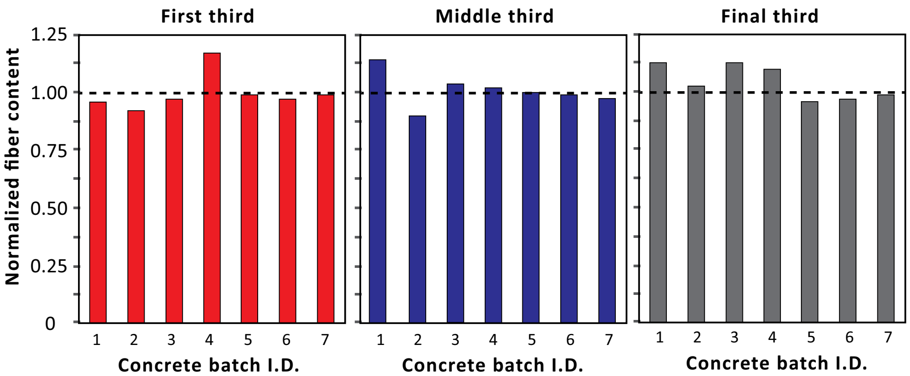

Fig. 3: Typical fiber distribution for first, middle, and final third of individual truck loads with steel fibers incorporated by fiber blower

Fig. 4: Sampling from top half of slab

Table 1:
Comparison of expansion measurements based on ASTM C878/C878M

Set – Description	Average expansion, microstrain	
	1 day	7 days
1 – Unrestrained	520	715
2 – Restrained by rod	320	375
3 – Restrained by fibers	350	450

significantly influence the distribution of steel fibers through the slab thickness.

As described in ACI 223R-10,[8] the initial expansion of shrinkage-compensated slabs should be restrained and appropriate details (for example, compressible foam placed around columns) implemented. Deformed bars or welded wire reinforcement are suggested to provide internal restraint. To evaluate the restraint of expansion provided by steel fibers, a series of experiments based on ASTM C878/C878M, "Standard Test Method for Restrained Expansion of Shrinkage-Compensating Concrete," was performed. The mixture used for the tests consisted of 270 kg/m³ (455 lb/yd³) of a CEM I cement per EN 197-1[9] and included a proprietary expansive additive dosage of 10% by weight of cementitious materials. Three sample sets were produced (Table 1). To evaluate unrestrained expansion of the mixture, Set 1 comprised three samples produced without fibers. To evaluate restraint by conventional reinforcing, Set 2 comprised three samples constructed with an internal restraining rod. To evaluate restraint by steel fibers, Set 3 comprised three samples cast with steel fiber content of 40 kg/m³ (67.4 lb/yd³). The steel fibers had hooked ends and the same dimensions and properties as described in the following section. Table 1 presents the average expansion strains measured after 1 and 7 days. Although the fibers provided less restraint than the rod, a comparison with the data for Set 1 shows that they provided substantial restraint. It should be noted that the restraint level can be adjusted by changing fiber type and dosage.

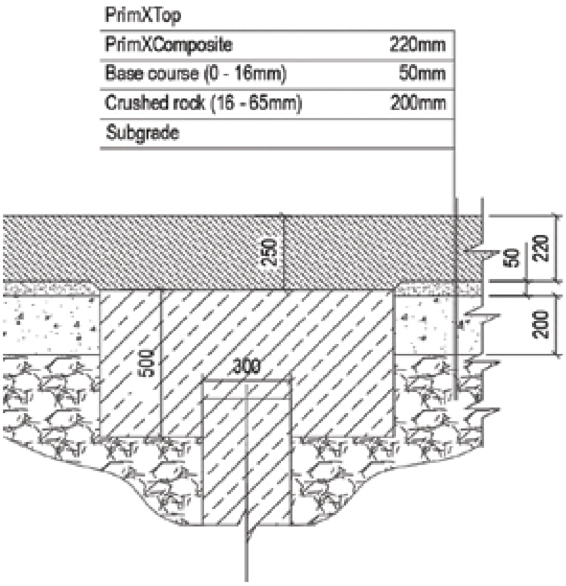

Fig. 5: Cross section of floor with pile and circular pile cap (Note: 1 mm = 0.04 in.)

Full-scale load testing

The full-scale load testing was conducted by CBI, Swedish Cement and Concrete Research Institute. A uniformly distributed load was applied to a portion of an EGS within an industrial warehouse that had been built in 2013. Constructed by Logistic Contractor in Gothenburg, Sweden,[10] the shrinkage-compensating SFRC slab was reinforced exclusively with 55 kg/m³ (93 lb/yd³) of 1 mm (0.04 in.) diameter and 60 mm (2.4 in.) long hooked-end steel fibers (HE+ 1/60). The tensile strength of the fiber wire was 1500 MPa (220 ksi). The 28-day design cylinder strength of the concrete was 35 MPa (5100 psi), and the mean in-place compressive strength from concrete cores extracted in April 2014 (concrete age between 8 to 10 months) was 56.5 MPa (8194 psi).

The slab was designed, as described in Reference 11, to carry a 40 kN/m² uniformly distributed load. It had a design thickness of 220 mm except directly over the pile caps, where the design thickness was 250 mm (10 in.) (Fig. 5). The foundation comprised individual, 300 mm (12 in.) diameter concrete piles capped with 500 mm (20 in.) deep, 1000 mm (40 in.) diameter pile caps. While larger spans can be accommodated, piles were spaced in a 4.0 x 4.7 m grid. The total area of the pile-supported slabs is approximately 28,010 m² (301,500 ft²), and the tested area consisted of a single 18.8 m² (201.7 ft²) area among the pile grid.

Prior to load application, cores were extracted near the loaded area and the ground settlements were measured to be an average of 21 mm (13/16 in.), meaning a 21 mm gap existed between the slab and the soil.

The slab was loaded by stacking concrete blocks over a limited area of the slab, as illustrated in Fig. 6(a). The loading arrangement was intended to maximize midspan deflection. A total of 576 blocks, weighing 40 kg (88.2 lb) each, were arranged in two strips 1.5 m (4.9 ft) wide and 3 m (9.8 ft) long, providing a distributed load of 43.9 kN/m^2 (917 lb/ft^2) on the loaded area. The blocks remained in place for 8 days, during which deflection measurements were captured by digital level at locations shown in Fig. 6(b).

Measured deflections from various locations are shown in Fig. 7, including the midspan measurements. The deflections exclude the coinciding average measured pile settlement (that is, deflections measured at the centers of the pile caps). After 8 days of loading, the average pile settlement was 0.95 mm (0.037 in.) which recovered, on average, to preload levels upon unloading. The maximum additional deflection of the slab, measured from the midspan, was 2.3 mm (0.091 in.). This midspan deflection is within 0.90 mm (0.035 in.) of estimated elastic deformation. Upon unloading, the slab midspan deflection recovered to less than 0.43 mm (0.017 in.) of the initial level.

The test demonstrated the high stiffness of the shrinkage-compensated SFRC slab. Further, there were no signs of structural failure (that is, excessive and permanent deflections, significant cracking, or development of yield lines). Well-controlled cracks were observed over pile caps, with a maximum observed crack width of less than 0.20 mm (0.008 in.). These findings are similar to results from previous full-scale loading tests of suspended elevated structural SFRC slabs completed in the last 20 years.[2,4]

Other Benefits of Shrinkage-Compensating SFRC

Even ground-supported slabs can benefit from the use of shrinkage-compensating SFRC. For all cases, whether ground-supported slabs or EGS, benefits include a reduced number of joints, lowered curling potential, faster construction speed, and lowered CO_2 emissions.

Reduction in joints and curling

Traditional flooring slabs tend to suffer from two of the most commonly known shortcomings of concrete—shrinkage and low tensile strength—and these often result in cracking, curling, damage, and need for maintenance.[12,13] Typical methods used to control shrinkage-induced cracking include saw-cutting or installing various forms of armored joints.[14,15] Joints are, however, planes of weakness that may be damaged (or cause damage to equipment) relatively rapidly as the slab panels curl and become uneven with time. The tested slab had a joint spacing up to 55 m (180 ft), and therefore had a significantly lower number of weak planes and reduced potential for curling.

Construction speed

As traditional reinforcement is largely avoided in slabs constructed using shrinkage-compensating SFRC, the construction process is expedited. Time savings are realized by avoiding the need for placement of reinforcement. Time savings are also realized by more rapid concrete placement,

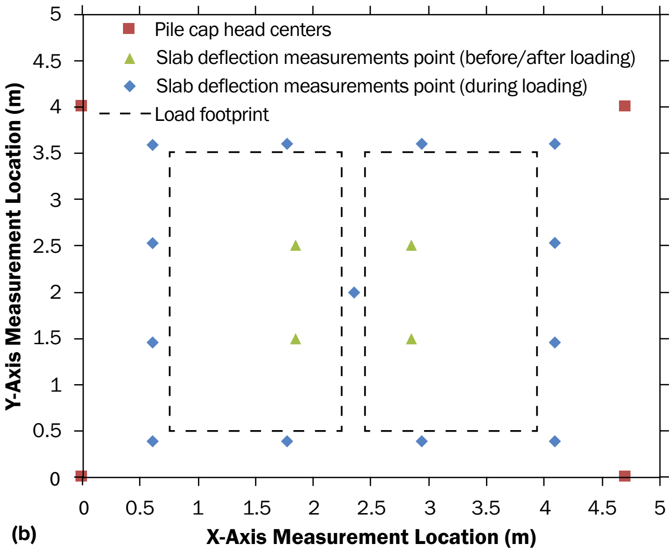

Fig. 6: Load test: (a) a uniformly distributed load was applied using stacked concrete blocks; and (b) map of the loaded area, showing locations where deflection measurements were taken before, during, and after loading (Note: 1 m = 3.3 ft)

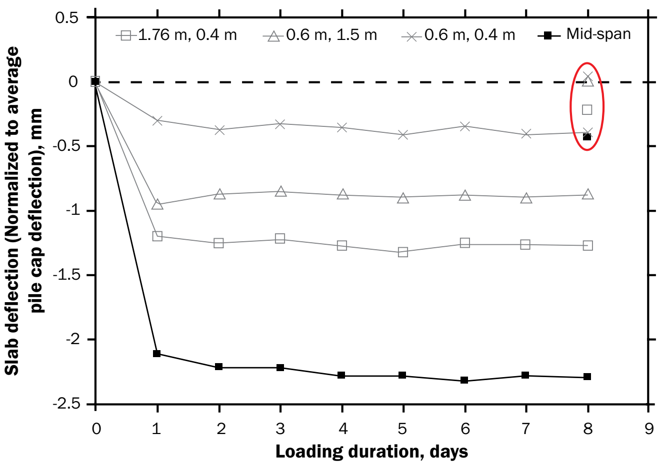

Fig. 7: Deflections measured at various locations on slab with pile settlement subtracted during loading and deflection recovery upon unloading (Note: 1 m = 3.3 ft; 1 mm = 0.04 in.)

either by direct discharge via concrete truck or by concrete transporters with augers.

Reduced CO_2 emissions

Concrete is the most widely used man-made building material, and CO_2 emissions associated with the production of cement and concrete are widely documented.[16-18] To be capable of supporting the loading described for the tested floor, an EGS floor constructed with traditional reinforcement would have required about a 300 mm thickness. For the 28,010 m^2 floor, the reduced slab thickness decreases the concrete volume by 2240 m^3 (2930 yd^3). Production of the cement needed for this additional concrete volume yields an estimated 548.7 tonnes (604.8 tons) of CO_2, assuming a weighted average of 0.83 tonnes (0.91 tons) of CO_2 emitted per 1 tonnes (1.1 tons) of cement produced[18] and a cement content of 295 kg/m^3 (497 lb/yd^3) in the concrete. Reinforcement for the traditional slab would typically consist of a top layer of welded 16 mm (0.6 in.) diameter wire reinforcement at 200 mm (8 in.) spacing and a bottom layer of 12 mm (0.6 in.) diameter wire reinforcement at 150 mm (6 in.) spacing, yielding about 31.7 kg/m^2 (6.5 lb/ft^2) of steel per floor. By contrast, a steel fiber dosage of 55 kg/m^3 results in 12.1 kg/m^2 (2.5 lb/ft^2) of steel per floor. Steel production typically emits more than 1 kg (2.2 lb) of CO_2 per 1 kg steel.[19] Therefore, the CO_2 emissions for the project were hypothetically reduced by a further 19.6 kg/m^2 (4 lb/ft^2) of slab. In total, the use of shrinkage-compensating SFRC in the EGS floor resulted in an estimated reduction of over 1000 tonnes (1200 tons) of CO_2.

References

1. ACI Committee 360, "Guide to Design of Slabs-on-Ground (ACI 360R-10)," American Concrete Institute, Farmington Hills, MI, 2010, 72 pp.

2. ACI Committee 544, "Report on Design and Construction of Steel Fiber-Reinforced Concrete Elevated Slabs (ACI 544.6R-15)," American Concrete Institute, Farmington Hills, MI, 2015, 38 pp.

3. Oslejs, J., and Kravalis, K., "Composite Concrete for Floor Slabs and Rafts," U.S. Patent No.: US 9,284,225 B2, Mar. 15, 2016.

4. Oslejs, J., "New Frontiers for Steel Fiber-Reinforced Concrete," *Concrete International*, V. 30, No. 5, May 2008, pp. 45-50.

5. EN 14721+A1: Test Method for Metallic Fibre Concrete – Measuring the Fibre Content in Fresh and Hardened Concrete, European Committee for Standardization, Brussels, Belgium, 2005.

6. EN 206+A1: Concrete – Specification, Performance, Production, and Conformity, European Committee for Standardization, Brussels, Belgium, 2016.

7. Khudhair, A., "Fiber Distribution of Steel Fibers in Industrial Floors – Field Measurements," MS thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2016. (in Swedish)

8. ACI Committee 223, "Guide for the Use of Shrinkage-Compensating Concrete (223R-10)," American Concrete Institute, Farmington Hills, MI, 2010, 16 pp.

9. EN 197-1: Cement. Composition, Specifications and Conformity Criteria for Common Cements, European Committee for Standardization, Brussels, Belgium, 2011.

10. Nyman, B., and Melander, R., "Load Testing of Industrial Floor for Tingstad Papper," CBI Uppdragsrapport 4P00214, Swedish Cement and Concrete Research Institute, Stockholm, Sweden, 2014. (in Swedish)

11. Destrée, X., and Cepuritis, R., "Chemically Post-Tensioned Ultrathin Joint Free Fibre Reinforced Concrete Slabs with Zero Shrinkage on Grade and on Piles," *Proceedings of the 2nd International Conference – Advances in Cement and Concrete Technology in Africa*, W. Schmidt and S. Msinjii, eds., Dar es Saalam, Tanzania, 2016, pp. 227-234.

12. Walker, W.W., and Holland, J.A., "The First Commandment for Floor Slabs: Thou Shalt Not Curl Nor Crack ... (Hopefully)," *Concrete International*, V. 21, No. 1, Jan. 1999, pp. 47-53.

13. Silfwerbrand, J.L., and Farhang, A.A., "Reducing Crack Risk in Industrial Concrete Floors," *ACI Materials Journal*, V. 111, No. 6, Nov.-Dec. 2014, pp. 681-690.

14. "Concrete Industrial Ground Floors: A Guide to Design and Construction," Technical Report 34, 4th edition, The Concrete Society, Surrey, UK, 2014, 91 pp.

15. "Industrigolv—Rekommendationer för projektering, materialval, produktion, drift och underhåll (Industrial Floors—Recommendations for Design, Material Selection, Production, Operation and Maintenance)," Concrete Report No. 13, first edition, Swedish Concrete Association, Stockholm, Sweden, 2008, 296 pp. (in Swedish)

16. "Building the Cost Curves for CO_2 Storage, Part 1: Sources of CO_2," Report No. PH4/9, International Energy Agency (IEA), Paris, France, 2002, 48 pp.

17. "Carbon Dioxide Capture and Storage," B. Metz, O. Davidson, H. de Coninck, M. Loos, and Meyer, L., eds., Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 2005, 431 pp.

18. "Tracking Industrial Energy Efficiency and CO_2 Emissions," International Energy Agency (IEA), Paris, France, 2007, 321 pp.

19. Price, L.; Worrell, E.; and Phylipsen, D., "Energy Use and Carbon Dioxide Emissions in Energy-Intensive Industries in Key Developing Countries," *Proceedings of the 1999 Earth Technologies Forum*, Washington, DC, Sept. 27-29, 1999.

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

Received and reviewed under Institute publication policies.

Rolands Cepurītis is a Civil and Concrete Materials Engineer with over 10 years of experience in concrete construction and aggregate, cement, and concrete production. He authored many scientific publications and received his PhD in concrete technology from the Norwegian University of Science and Technology, Trondheim, Norway, where he is a Postdoctoral Researcher.

Jānis Kamars is a Civil Engineer specialized in the design of steel fiber-reinforced concrete structures. He has more than 15 years of experience in structural design and building site management. He received his MS in civil engineering from the Riga Technical University, Riga, Latvia.

Brad J. Pease is a Consultant at COWI A/S, Lyngby, Denmark. He received his PhD in the areas of concrete durability and technology from the Technical University of Denmark, Lyngby, Denmark.

Jānis Ošlejs is CEO of Primekss Group, headquartered in Riga, that serves customers through self-performing contracting service in Scandinavia and the Baltics, and a network of licensees in Europe, Asia, Africa, and the Americas. Ošlejs received his BA from the University of Latvia, Riga, Latvia, and his MBA from the Stockholm School of Economics, Riga, Latvia.