

Chemically Post-Tensioned Ultrathin Joint Free Fibre Reinforced Concrete Slabs with Zero Shrinkage on Grade and on Piles

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Abstract:

Drying shrinkage contraction restraint is cause of severe cracking in most slabs while free contraction movements are main cause of slab edge curling and joint induced cracks. A novel technique has been developed and is in use also in Africa, in order to eliminate virtually all slab cracking and drying shrinkage induced movements in joints as they remain closed or open very little. Ultra wide bays up to 7000 m² area joint free have been built successfully.

The new concrete floor slab type enjoys the benefit of a permanent high amplitude chemical post-tensioning together with the advantages of smart steel fibre reinforcement.

When compared to state-of-the-art traditional slabs, its thickness is reduced to up to fifty percent, *i.e.* typically only a 100 mm thickness of the slab-on-ground will be required in order to support 120 kN loading intensity of back-to-back racking legs.

Corresponding piled structural slabs without any rebar or wire mesh reinforcement have also been built successfully, and a number of full scale loading tests of such suspended slabs have been organized to confirm the design.

The apparent benefits of the presented slab system are a much longer full service life expectancy, no maintenance costs, direct cost savings at the installation and a significantly reduced carbon footprint thanks to the reduction of concrete and cement consumption.

The new patented slab system developed by Primekss' has been in use since 2007 and is considered by owners and tenants as the ultimate generation of concrete flooring slabs.

Keywords: joint free floor, slab-on-ground, slab-on-piles, CO₂ emissions, zero shrinkage, steel fibres.

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1. Introduction

Concrete floors (slabs-on-ground and slabs-on-piles) are the most critical part of nearly all industrial buildings as a suitable floor is the key to effective operation of the whole facility. Once laid and in use, it is very difficult to repair a faulty floor [1]. While there are common design methods to account for the possible failure modes of the floor resulting from different loading cases, it is known from the practice that drying shrinkage of the concrete is the central mechanism behind nearly all the real issues with the industrial floors, such as uncontrolled cracking, curling at the edges, large joint openings and deterioration of the joint edges (Figure 1). A new development within the last decade to improve the performance and reliability of the known concrete flooring types has been the PrimeComposite concrete slab system [2], which seeks to reduce the required concrete slab thickness, and corresponding CO₂ emissions, while improving performance and durability compared to traditional slab systems. Thickness reductions are provided using a two-pronged approach: 1) replacement of all steel reinforcing bars with steel fibres for required tensile and flexural load capacities, and 2) elimination of concrete shrinkage with special proprietary admixtures. Performance and durability improvements are provided by eliminating the need for saw-cut joints and reducing the number of construction (day) joints.



Figure 1: Typical issues with industrial concrete floors resulting from the drying shrinkage of concrete.

2. PrimeComposite slab system - materials

PrimeComposite improves upon ordinary concrete by enhancing the tensile and flexural behaviour and by cancelling hygral (autogenous and drying) shrinkage, allowing for jointless slabs with thickness reductions up to and exceeding one half the thicknesses of other common slab systems. Mechanical characteristic improvements are realized through the controlled addition of steel fibres, while shrinkage control is accomplished by both careful mixture design and the addition of proprietary concrete additives, PrimeDC and PrimeFlow. Steel fibres, PrimeDC, and PrimeFlow are added to a specially designed concrete mix, supplied by a regular ready-mix producer, using equipment on the jobsite (Figure 2).



Figure 2: Addition of the PrimeDC, PrimeFlow additives and steel fibres to a specially designed concrete mix on site for the Prolecon Project in Johannesburg, South Africa.

2.1 Steel Fibre Reinforced Concrete (SFRC)

Based on experience using SFRC, typically a continuous field size of up to 1500 m² are obtainable with construction (day) joints at a maximum spacing of 40 meters [3]. Concrete for this application typically consists of a C30/37 (30 MPa cylinder strength) strength class with water-to-cement ratio (w/c) below 0.55. Reinforcement is provided by a moderate dosage rate, typically ≥ 30 kg/m³, of type I (cold-drawn) steel fibres [4].

As discussed in greater detail in Section 3.1 below, full-scale tests on SFRC ground- and pile-supported slabs exhibit a ductile flexural response with rotations concentrated along yield lines. Under the typical loading conditions, punching failure around column or pile heads does not occur before ultimate loading in flexion is attained. Steel fibres offer a reliable control of curling at construction joints and edges are kept at an affordable level. However, as shown in Figure 1c and Figure 1d, due to the drying shrinkage of the concrete joint openings in excess of 1 cm and excessive curling still are very common. Therefore, PrimeComposite includes proprietary additives to eliminate the hygral shrinkage and cancel joint opening and curling.

2.2 Zero-Shrinkage

The addition of PrimeDC, a cementitious expansive additive, and PrimeFlow, a liquid admixture, to SFRC controls a lifetime of concrete shrinkage, as shown in Figure 3a.

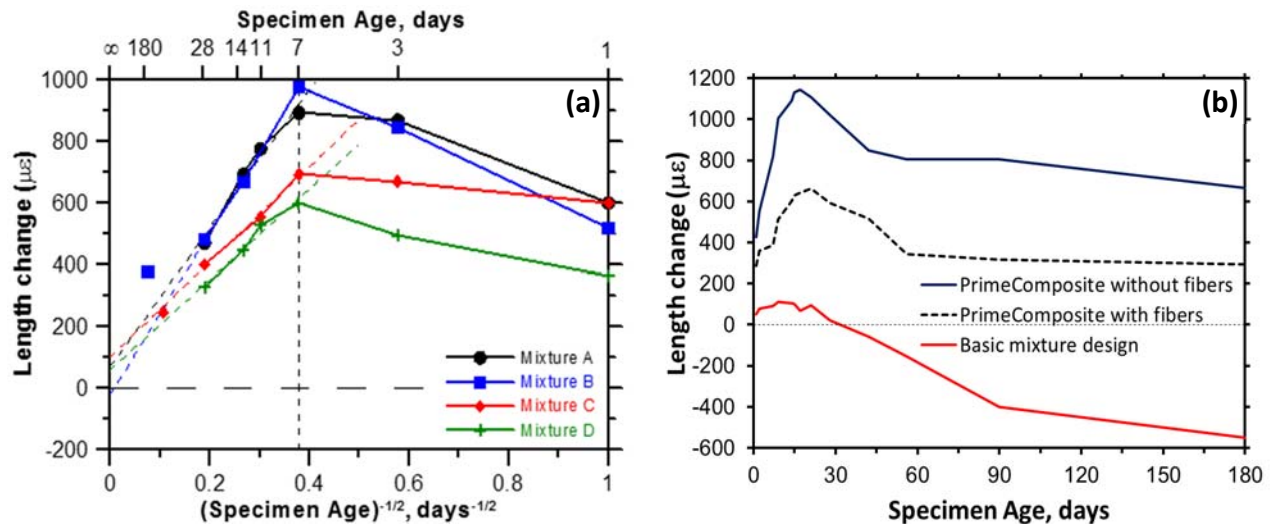


Figure 3: (a) zero shrinkage concrete deformations as function of age in days to infinite time; (b) controlled concrete post-tensioning process with PrimeComposite technology through restraining concrete expansion with steel fibres.

The main advantage of the zero-shrinkage concept is that slabs free from detrimental cracks and of very limited or almost none day-joint openings become feasible. This means that under temperature controlled conditions a virtually unlimited bay-size of the slab becomes possible and the only practical restraint being the volume of concrete that can be delivered during one shift. Ultra wide bays up to 7000 m² area joint free have been built successfully. Thanks to the steel fibre reinforcing, the tensile strength of the slab concrete becomes a viable property that the designer can rely on. Also the cancellation of the curling along the edges makes the slab in full and permanent contact to the grade so that negative moment cracking along the joints and edges is no longer a critical loading case to consider anymore so that forklift trucks enjoy completely smooth ride without bumps at each joint.

A permanent post-tensioning compressive stress takes place in the slab section when the expanding concrete slab is subjected to a movement restraint by the friction from the granular base and internal restraint by the dense random distribution of the steel fibres. The degree of restraint provided by the friction against the base is difficult to accurately estimate and control, while the effect from the steel fibres can be precisely quantified and provided. Example results from such an experiment from an actual PrimeComposite project are provided in Figure 3b. The difference between the results for the two PrimeComposite compositions shown in Figure 3b is the presence of 40 kg/m³ steel fibres in one of the compositions. This allows achieving a typical post-tensioning compressive stress in the range of 2.0 MPa, but the actual magnitude of this PrimeComposite concrete material parameter can be varied depending on the actual slab design.

3. PrimeComposite slab system – development of structural design methods

3.1 Full-Scale Structural Testing

A full-scale test of a zero shrinkage PrimeComposite slab subjected to a point loading has been organized at the University of Vaasa in Finland, as shown in Figure 4. It can be seen in Figure 4 that a square slab of 4.5 m x 4.5 m size and of 100 mm thickness has been installed on top of a base of 100 mm thick EPS 200 polystyrene with $E = 10$ MPa and 0.09 MPa long term compressive strength at 1 % deformation. The insulation layer was installed on top of a concrete base and the resulting K_w bearing coefficient of Westergaard was also measured with the 760 mm round plate diameter: $K_w = 30$ MPa/m = 0.03 N/mm³.

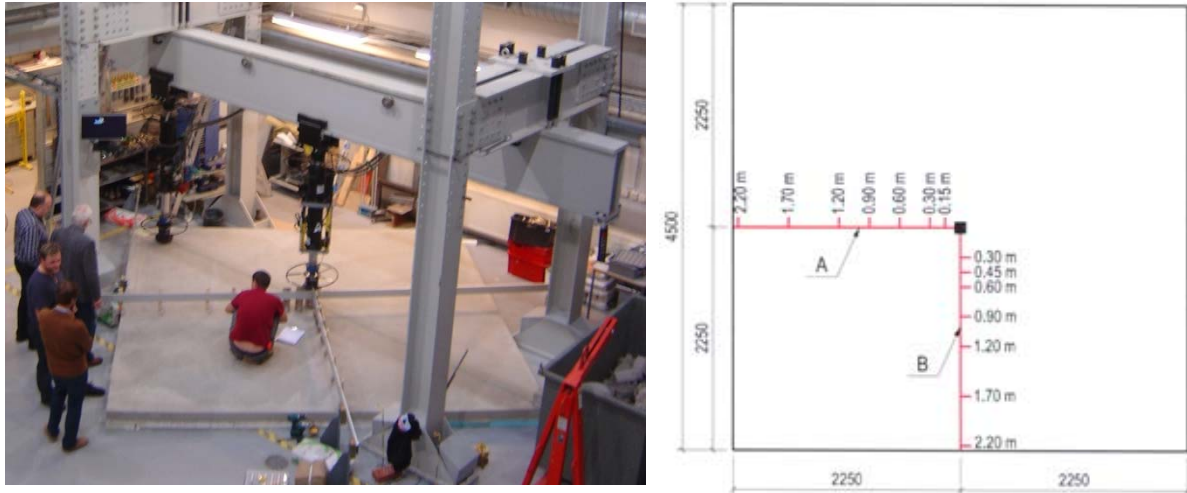


Figure 4: Test set-up of the centre point loading case of the full-scale scale test slab. The deflections of the slab were recorded along x and y axis at 0.15 m, 0.30 m, 0.45 m, 0.60 m, 0.90 m and 2.20 m distance from the centre point.

The ultimate loading intensity at collapse of the portal frame shown in Figure 4 was recorded at 270 kN point loading intensity, while the slab although cracked in the bottom, could still resist more loading. Figure 5 shows the recorded deflections along the length of the slab as the centre point loading increased from 10 kN to 213 kN.

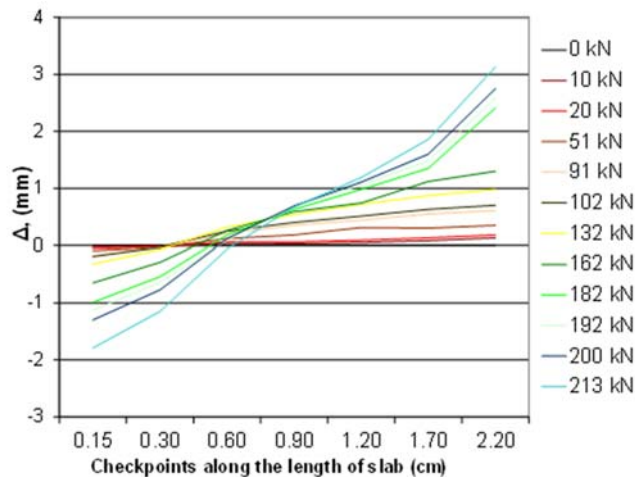


Figure 5: Deflections recorded from 0.3 m distance to 2.20 m distance.

3.2 Design Procedure

When the K_w value of Westergaard used in the full-scale loading experiment is increased from 0.03 N/mm^3 to 0.08 N/mm^3 and all other parameter are kept constant, the moment and the maximum permissible point loading intensity are increased by almost 50 %. Hence a zero-shrinkage fibre reinforced concrete PrimeComposite slab of 100 mm thickness on top of a base showing $K_w = 0.08 \text{ N/mm}^3$ becomes suitable in case of point loading intensities of up to 120 kN. When compared to the traditional slabs, 60 mm to 80 mm thickness of concrete are thus saved. As shown in Figure 6, a diagram summarizes the thickness needed as the function of the static point loading intensity in case of a steel fibre reinforced zero-shrinkage concrete slab. The diagram has been calculated for $K_w = 0.08 \text{ N/mm}^3$ and includes the load intensity of a single leg of the back-to-back case typically used for design of the industrial flooring slabs.

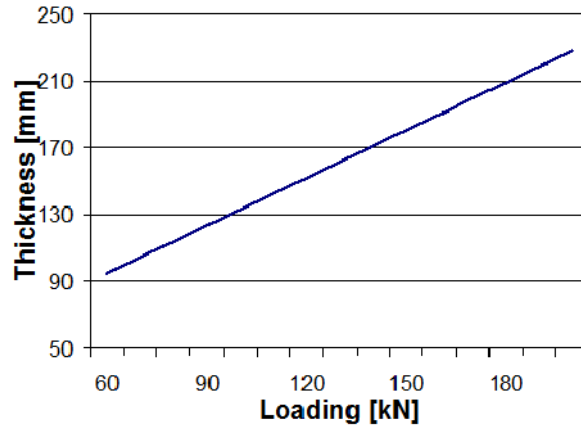


Figure 6: Design diagram showing the necessary slab thickness vs. single point loading intensity of a single leg of the back-to-back case when $K_w = 80 \text{ MPa/m} = 0.08 \text{ N/mm}^3$.

3.3 Practical design

The diagram shown in Figure 6 results from the following equation to obtain the PrimeComposite slab thickness H (mm) as a linear function of Q (kN), which is the single leg load intensity of the back-to-back case, when the $K_w = 80 \text{ MPa/m} = 0.08 \text{ N/mm}^3$:

$$H(80) = 0.45 \cdot P + 48, \quad (1)$$

where $P = 2 \cdot Q$ (kN).

When K_w is no longer 80 MPa/m , but is of a K_2 value, the thickness is given by the following expression:

$$H(K_2) = H(80) \cdot (80/K_2)^{1/4}.$$

For example, for the total back-to-back loading intensity of $P = 120 \text{ kN}$ and a K_w value of 80 MPa/m , it is required to have $H(80) = 0.45 \times 120 + 46 = 100 \text{ mm}$ of PrimeComposite thickness. When the K_w value drops to 30 MPa/m , the PrimeComposite slab needs to become thicker: $H(30) = 100 \text{ mm} \cdot (80/30)^{1/4} = 100 \times 1.28 = 128 \text{ mm}$.

When using a zero-shrinkage slab, as full continuity is obtained across the construction joints the only loading case to verify is that of the centre point loading. The edge and corner of point loading do not need to be considered anymore.

Since the year 2007, approximately 5 million m^2 of SFRC PrimeComposite zero-shrinkage slabs have been successfully installed globally based upon the design, as outlined above. Not a single failure has been registered for any of the installed slabs and full functionality has been maintained for the period of observations allowing for a full satisfaction of the customer and the end-users.

4. Reductions in CO₂ emissions

Considering the reduced volumetric demand for cement/concrete and steel of the PrimeComposite slabs it is then possible to estimate that the corresponding CO₂ emissions are reduced by about 22.5 kg CO₂ or 40 % per square meter of a slab.

5. Structural PrimeComposite on piles

Two full-scale tests have been carried out on PrimeComposite slab-on-piles concrete floors: in Klaipeda (Lithuania, 2011) and Gothenburg (Sweden, 2014) for the Tingstad project.

The Klaipeda slab was of a 210 mm thickness with 50 kg/m³ of twincone steel fibres on a pile grid of 4 m x 4 m, with pile heads of 1 m x 1 m and designed to be subjected to 30 kN/m² loading. The full scale load test (Figure 7) consisted of a 30 kN/m² loading intensity imposed on a 100 m² area for a period of 3 months. After the three months, the maximum deflection recorded was of 1.5 mm although the ground underneath had settled to lose any contact to the PrimeComposite suspended slab.



Figure 7: Full scale loading test of the Klaipeda (Lithuania, 2011) PrimeComposite slab-on-piles.

The slab at the Tingstad project was with a design thickness of 220 mm and deepening to 250 mm over the pile heads. The piles of 300 mm diameter were with heads of 1 m diameter and were spaced in a 4.0 m by 4.7 m grid. The slab was reinforced with 55 kg/m³ of HE+ 1/60 steel fibres as the only structural reinforcement to meet the 40 kN/m² service requirement.



Figure 8: Full scale loading test of the Tingstad project (Gothenburg, Sweden, 2014) PrimeComposite slab-on-piles.

The full-scale testing at Tingstad project (Figure 8) was carried out by the Swedish Cement and Concrete Research Institute (CBI). The full scale test procedure was providing a distributed load of 44.8 kN/m² over the loaded area of the slab. Load was applied and held constant for 8 days. There was a 21 mm gap underneath the slab and thus it was under fully suspended elevated conditions.

During loading, deflection of the slab was very limited and there were no signs of distress or structural failure (e.g., no excessive and permanent deflections, significant cracking, development of yield lines, etc.). The average pile settlement was 0.95 mm after 8 days of

loading and the maximum differential mid-span deflection of the slab, calculated as the mid-span settlement minus the average pile settlement, was 2.3 mm.

These results proved that the combination of Primekss' concrete technology and HE+1/60 steel fibres at high dosage rate have created a PrimeComposite slab that enjoys a very high stiffness. The slab easily supported full-scale load testing, proving that the slab has the required load bearing capacity and that the design assumptions for the slab are correct.

The PrimeComposite structural slab thickness can then be given by the following experimental formula:

$$H = 0.65 \cdot (R_p / (f_{R,3} + \sigma_{cp}))^{1/2}, \quad (3)$$

where R_p is the total unfactored pile reaction, $f_{R,3}$ the flexural strength of the SFRC according to EN 14651 and σ_{cp} the permanent PrimeComposite post-tensioning compression stress. When pile heads are used H , as calculated above, is to be decreased by 20 mm thickness.

Then for the above described Tingstad project full-scale testing case: $f_{R,3} = 5 \text{ N/mm}^2$, $\sigma_{cp} = 1.2 \text{ N/mm}^2$, $R_p = 4.0 \text{ m} \cdot 4.70 \text{ m} \cdot (40 + 5.28) \text{ kN/m}^2 = 851254 \text{ N} = 851.54 \text{ kN}$.

Thus, here $H = 240 \text{ mm}$ without pile heads and 220 mm with pile heads in order to carry the specified 40 kN/m^2 uniformly distributed load.

6. Conclusions

- Shrinkage cracking, curling, and joint opening are significantly reduced or eliminated in the described patented [5] SFRC slab systems.
- CO₂ emissions are reduced by no less than 22.5 kg/m² of slab by replacing traditional concrete slab systems with the PrimeComposite slab system.
- Practical design formulae are provided in the paper to design the thickness of both ground bearing and suspended PrimeComposite slabs. These formulae are derived from a number of full scale tests and the 8 year long experience without any failure or loss of functionality. Total satisfaction of the customer has been achieved in all cases.

References

- [1] P. Mass, "Industrial Floors," 22 11 2007. [Online]. Available: http://www.archicom.nl/seminars/media/Maas_221107.pdf. [Accessed 23 09 2015].
- [2] X. Destrée and B. Pease, "Reducing CO₂ emissions of concrete slab construction with the PrimeComposite slab system," in *Proceedings of the First International Conference on Concrete Sustainability*, Tokyo, 2013.
- [3] J. Oslejs, "New frontiers of steel fiber-reinforced concrete," *Concrete International*, vol. 30, pp. 45-50, 2008.
- [4] American Society for Testing and Materials, "Standard Specification for Steel Fibers for Fiber-Reinforced Concrete," ASTM International, West Conshohocken, 2011.
- [5] J. Oslejs and K. Kravalis, "Composite Concrete for Floor Slabs and Rafts". European Patent EP2493834B1, 16 7 2014.