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Chemically Post-tensioned Steel Fibre Reinforced Concrete Suspended Slabs from Design to Application

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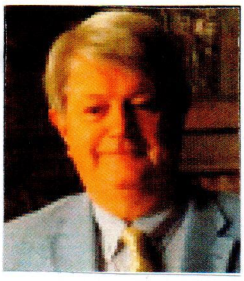

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Rolands Cepuritis is a civil and materials engineer with over ten years experience in concrete construction and the production of aggregate, cement and concrete. He is the author of many scientific publications and holds a PhD in concrete technology from the Norwegian University of Science and Technology, where he currently has a postdoctoral research position.

ABSTRACT: The post-tensioning effect in the concrete slabs described in this paper is achieved by an internally restrained expansion mechanism, which is the result of using an expansive additive in combination with steel fibre reinforcement. Due to this effect, the tensile stresses, caused by restrained contraction as well as flexure, are compensated and significantly reduced by up to 50 % while curling at the edges is eliminated. The modelling and design process are outlined, based on the experience of several million square metres of successfully completed slabs in the last decade. Multiple full-scale loading tests have been analysed by back-calculation and compared to laboratory test results of the constituent materials. The benefits of the presented slab system are an extended service life, significantly reduced maintenance requirements, direct cost savings at the installation stage and a reduced carbon footprint due to the reduction of concrete and cement consumption. The innovative slab system has been developed and patented by Primekss in Latvia. It has been in use since 2007 and is considered by owners and tenants as the new generation of concrete flooring technologies.

KEYWORDS: JOINT-FREE FLOOR, SUSPENDED SLAB-ON-PILES, CHEMICAL POST-TENSIONING, ZERO SHRINKAGE, STEEL FIBRES

Introduction

Concrete floor slabs (slabs-on-grade and slabs-on-piles) for large industrial, warehouse, retail and other applications, face a multitude of problems including cracking, curling of edges and joints, extensive opening of construction joints and chipping-out. Shrinkage is, however, the central mechanism behind nearly all these issues. In an attempt to localize and control the shrinkage cracking, saw-cut joints 5 to 7 m apart are installed once the slab surface has been finished.

These joints will open with time under the effect of the shrinkage contraction movement. Later the slab will, however, curl along the joints as a result of the differential shrinkage between the bottom and the top faces of the slab. Rocking of the opened joints under traffic induces severe cracking and spalling.

A great advance in concrete slab technology was the invention of joint-free slabs in road pavements around the year 1925 for highways, and around 1984 [1] with steel fibre reinforced concrete for industrial concrete floors.

Despite the advance obtained by the elimination of saw-cutting, thanks to steel fibre reinforcement, with the contribution of the needed armoured construction joints or day-joints up to 30 or 40 m

Figure 1: Typical 10 mm to 15 mm opening of armoured joints of steel fibre reinforced concrete joint-free floors compliant with The Concrete Society Technical Report N° 34

apart, shrinkage movements still develop openings of 10 – 15 mm. Opening and curling of the construction joints are not eliminated so that rocking and cracking still prevail.

Chemical post-tensioning

A further great advance would be to induce a permanent compression stress in the slab section in order to achieve an attempt to eliminate the detrimental cracking and the construction joint opening and rocking of joint-free steel fibre reinforced concrete slabs.

It is well known how to generate a chemical expansion during the hardening of concrete that is restrained in its movement by the friction of the slab over its base.

A possible way is to introduce a new hydraulic constituent in the regular cement clinker, the ye'elimite, known also as "Klein's Compound", with the formula $Ca_4(AlO_2)_6SO_4$, or using the abbreviations used in the cement chemistry C_4AS_6. The ye'elemite can be found naturally, but is also manufactured in a kiln where mainly limestone, bauxite and anhydrite are burnt together at a 1250 °C and then ground to a suitable particle size. During the hydration in the presence of calcium and sulfate ions, with the need of a large quantity of reaction water, it forms a swelling crystal, ettringite. Ettringite is a fibrous mineral also responsible for a fraction of the total strength in cementitious materials. The stoichiometric equation of the reaction is [2]:

$$3 \cdot CaO \cdot 3Al_2O_3 \cdot CaSO_4 + 8 \cdot CaSO_4 + 6 \cdot CaO + 96 \cdot H_2O \rightarrow 3 \cdot \{Ca_6[Al(OH)_6]_2 (SO_4)_3 \cdot 26 \cdot H_2O\} \quad \text{Eq. 1}$$

The expansion is caused by the quite high number of water molecules (indeed, 96) , as seen in (1), bound to form ettringite, the hydrated product of the reaction.

The ye'elemite (indeed, the PrīmX DC by Primekss SIA) generated expansion develops during the first seven days of hardening while the E-modulus is still small so that the concrete does not burst. This is the opposite of when the ettringite is formed over a long term when the tri-calcite aluminate (C_3A) from the OPC meets external sulfate ions in the hardened Portland cement concrete.

The expansion can be measured on laboratory prismatic specimens as stipulated in ASTM C 157 [3], and typical values are shown in Figure 2, as functions of the age of concrete, starting from day 1, for different steel fibre reinforced concrete mixtures A to D with an increasing initial shrinkage from A to D. The abscissa in Figure 2, is given as the inverse of the square root of the number of days of age in order to be able to extrapolate to an infinite number of days at zero abscissa and so to obtain the permanent expansion.

It is well known [4] that the drying shrinkage value ofe plain concrete is a function of the following influences:

- excessive water content of concrete can be the cause of a 50-100% increase of shrinkage. The excess water also increases the porosity of concrete so that the vapour water loss is increased and accelerated;
- low aggregate content in the mix design leads to as much as a 100% increase in shrinkage. When the aggregate ratio is low, the sand and fine content of the mix becomes higher and this factor increases the water demand;
- aggregates with low stiffness increase the shrinkage as they contract easier than the higher stiffness aggregates. The increase of shrinkage can be as high as 30-50%;
- excessive dirt in aggregate is responsible for up to a 25% increase of shrinkage. This affects the aggregate-paste bond and load transfer between the two phases. Use of small aggregate size increases the shrinkage by up to 25%;
- the use of a high shrinkage cement results in a 30% increase in shrinkage;
- superplasticizers or high range water reducing admixtures, when used incorrectly, can increase significantly the drying shrinkage. The critical case is when the water content is not reduced despite the addition of an HRWRA (ACI 212 4R).

An interesting parameter to check on site is the unit weight of the fresh concrete, which is very much influenced by most of the items listed above.

When the density decreases to 2350 kg/m^3 or less, it could be attributed to a number of parameters discussed above that are out of control so that it adversely increases the shrinkage of the plain concrete. One should, of course, verify this parameter together with the unit weights of the aggregates used and the entrapped/entrained air content of the mix.

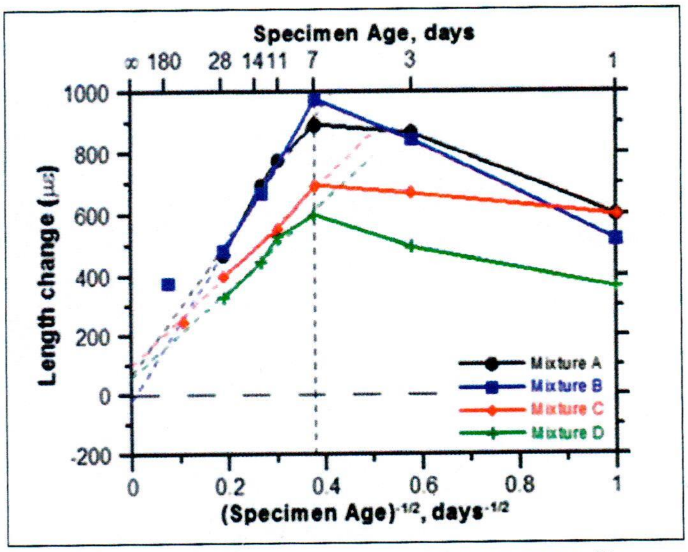

Figure 2: Expansion of the concrete v. concrete age expressed in 1/√days

To take advantage of the full capacity of the ye'elemite generated expansion, it is essential to mix it in a low shrinkage content plain concrete, thus mixtures A and B rather than C and D where the w/c ratio is less than 0.50.

In Figure 2, it is shown that the expansion culminates at a strain of 1000x10^{-6}, and that at its infinite age, 100x10^{-6} expansion still remains, a permanent expansion indeed. The slab becomes a zero-shrinkage concrete slab.

In order to generate a permanent compressive stress in the section, an expansion restraint is necessary, and this is provided by the friction of the slab on the subgrade. The service loading application onto the slab will contribute to restrain it from gliding freely on the base so that the slab and its base become an elastic bonded dual layer system where each layer resists the stresses depending on its modulus of elasticity. The higher the modulus of elasticity of the grade, the more external restraint the grade will provide to resist the slab movement.

By equating the deformation following the Westergaard model of a slab on top of an elastic liquid base, to the fully solid elastic Boussinesq model deformation, a relation between *k* (Westergaard) and *E* (Young) is found. It is then possible to find a relationship between the *k*-value and a friction factor μ_s[4]:

$$\mu_s = 4.60 + ln\left(\frac{k}{u}\right), \qquad \text{Eq. 2}$$

where *u* is the unit of *k* so that we use a dimensionless argument of the Neperian logarithmic function.

From $k = 0.03$ N/mm³ to $k = 0.08$ N/mm³, the friction factor doubles as shown in Figure 3.

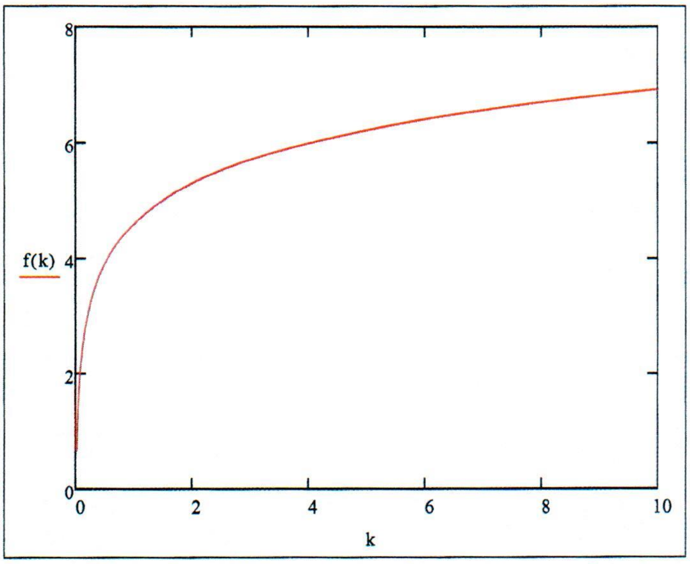

Figure 3: Friction factor (f(k)) = μs) on and from the base as a function of k-value of Westergaard

We can understand that in order to take advantage of the restrained expansion, a rather high *k*-value is desirable.

The other source of restraint is internal and attributable to the steel fibre reinforcing phase of the cementitious composite. Indeed, the internal friction with closely spaced steel fibres, about 15 mm to 20 mm distance between adjacent fibres, is identifiable by a simple laboratory expansion test (ASTM C 157 [3]) when a plain concrete is compared to a steel fibre reinforced concrete.

The internal loss of expansion attributable to the steel fibres amounts to about 50% of the total free expansion, as shown in Figure 4, from 800 down to 400 microstrains.

Steel fibres are a much better cause of restraint than traditional reinforcement steel bars (mesh), which is obvious, due to the considerably higher specific surface area of steel per m³ of concrete.

One can estimate the permanent compressive stress σ_p on the slab section as follows:

$$\sigma_p = \varepsilon_p \cdot E_{LT} = 100 \cdot 10^{-6} \cdot 20 \cdot 10^3 = 2 \text{ N/mm}^2, \qquad \text{Eq. 3}$$

where E_{LT} is the long term modulus of elasticity of the concrete and ε_p is the permanent expansion strain, as shown in Figure 4. As σ_p is a favourable effect, we'll use only $0.8 \cdot \sigma_p$ at the design stage.

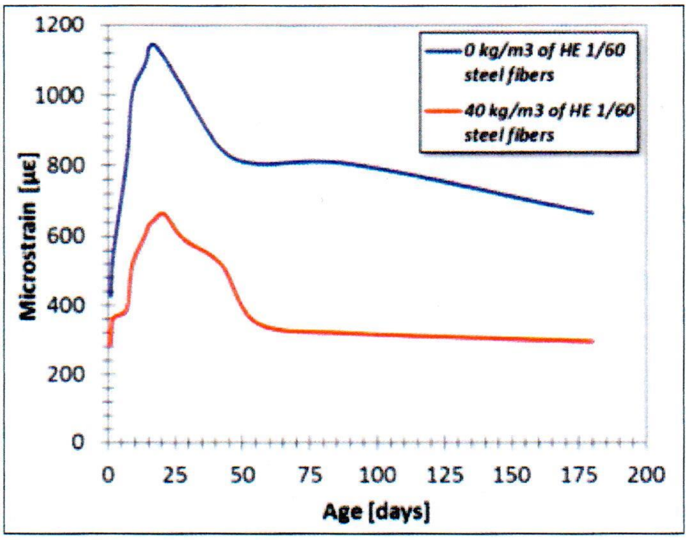

Figure 4: Effect of the steel fibre reinforcement as a restraint of the expansion

We have now to summarize the consequences of σ_p on the design of the slab (see the section on Design). The innovative slab system has been developed and patented by Primekss in Latvia. It has now been in use since 2007 and enjoys more than 10 million square metres of completed reference in Europe and North America. It is considered by owners and tenants as the ultimate generation of concrete flooring technologies regarding performance, design, materials used and installation.

Zero-shrinkage

The main advantage of the zero-shrinkage concept is that slabs are free from detrimental cracks and a very limited or almost no day-joint openings become feasible. This means that under temperature controlled conditions a virtually unlimited bay size of the slab becomes possible; the only practical restraint being the volume of concrete that can be delivered during one shift. Ultra-wide bays up to 7000 m² in area and 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 joint opening, and hence curling along the edges and across the joints, make the slab in full and permanent contact with the grade so that negative moment cracking along the joints and edges is no longer a critical loading case to consider. Forklift trucks enjoy a completely smooth ride without any bump at each joint.

Design

Both ground bearing slabs and piled slabs are not expected or supposed to crack under the most onerous flexion moment, but they can however crack from shrinkage or plastic settlement of their supports just like any traditional slab.

As the section undergoes a permanent compression stress resulting from the restrained expansion from the friction onto the grade and/or on pile heads and the internal friction from the steel fibres, the resisting moment gain is indeed significant as it is increased by a factor α:

$$\alpha = (f_L + 0.8 \cdot \sigma_p)/f_L, \quad \text{Eq. 4}$$

where f_L is the flexion cracking strength.

Using a C 30/37 mix of $f_L = 4.5$ N/mm², we calculate $\alpha = (4.5 + 0.8 \cdot 2)/4.5 = 1.36$, which means that the cracking moment is increased by 36% under the influence only of the restrained expansion.

Thus, a plain concrete slab of 200 mm shall be replaced by a 200 mm $/\sqrt{1.36} = 170$ mm thickness one, thanks to the restrained expansion as in Figure 4, and this is for the same loading capacity, resulting from the much better practical stiffness of the slab, attributable to the absence of cracking.

The governing issues in these ye'elemite modified steel fibre reinforced concrete slabs are the ultimate verification and the maximum flexion stress under service conditions instead of the traditional shrinkage-induced crack opening. The stiffness of the section is then significantly enhanced so that the deflections are very small in the range of the span/1000 to 3000.

The expression (J.2) of ACI 544 6R15 [6] is suitable to calculate the deflection:

$$\delta/L = (0.185 \cdot (q+w))/(E \cdot (L/h)^{1/2}). \quad \text{Eq. 5}$$

so that here in the example: $\delta/L = 1200$, where $E = 20\,000$ N/mm².
A more detailed design method is presented in references 5 and 6.

The presented philosophy of design has been implemented at the Tingstad project in Sweden. The slab of 220 mm thickness in a ye'elemite-modified OPC concrete was laid on a 4 m x 4.70 m grid of piles, provided with 45 kg/m³ of ArcelorMittal HE+1/60 steel fibres and designed to offer a 40 kN/m² load bearing capacity in service. Two years later after the installation of the 220 mm thick slab, the CBI (Swedish Cement and Concrete Institute) tested the slab in full scale. The maximum service load requirement was of 40 kN/m². The full-scale test procedure, as shown in Figure 5, provided a distributed load of 45 kN/m² over the loaded area of the slab. The load was held constant for 8 days. There was a 21 mm gap underneath the slab, and thus it was under fully suspended elevated conditions.

During the loading, the deflection of the slab was very limited and there were no signs of any significant deformations or yield lines (no noticeable or permanent deflections, no cracking, no 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, thus a span to deflection ratio of 1700 and so, far better than 500, the code limit.

The expression (25) shows here a calculated value of $\delta/L = 1321$, thus significantly smaller than the experimental 8 days experimental recording.

These results proved that the combination of HE+1/60 fibre reinforced concrete and the ye'elemite addition technology have created a slab that enjoys a very high stiffness, able to carry high loads although the span to depth ratio of 19is quite slender for a pile supported slab.

Figure 5: Full scale loading test of the Tingstad project (Gothenburg, Sweden, 2014) of a ye'elemite modified steel fibre reinforced concrete slab-on-piles

The above design case has also been checked in full scale, on a slab in Lithuania as shown in Figure 6.

Figure 6: Full scale loading test of the Klaipeda project (Klaipeda, Lithuania) of a ye'elemite modified steel fibre reinforced concrete slab-on-piles

The Klaipeda (Lithuania) slab was also of a 220 mm thickness with 50 kg/m³ 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 in service. The full-scale load test (Figure 6) 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 1.5 mm, although the ground underneath had settled to lose any contact to the ye'elemite modified steel fibre reinforced concrete suspended slab. This confirms the quite high stiffness obtained of L/ 2600; L/500 is the EC 2 code limit.

The very small deflections in the order of span/2000 recorded at the Tingstad and Klaipeda, show that the 30 - 45 kN/m² UDL imposed is still quite far under the slab capacity limit that is probably 3 or 4 times higher.

Again the expression (5) shows here a calculated value $\delta/L = 2120$, thus significantly more deflection than the experimental recording.

The expression (5) has been proven in many more full-scale loaded test slabs, in order to become a very reliable, simple easy to use expression of the span to deflection ratio.

These suspended slabs made out of steel fibre reinforced ye'elemite modified concrete have been in use from the year 2007 in a constantly growing number over 2 continents, and enjoy a completely flawless 10 million square metres list of references by the Primekss SIA company.

As a result of the experience, their thickness can then be given by the following experimental formula:

$$H = 0.58 \cdot (R_p/(f_{R3} + 0.8 \cdot \sigma_{cp}))^{1/2}, \qquad \text{Eq. 6}$$

where R_p is the total unfactored pile reaction, f_{R3} the flexural strength of the SFRC according to EN 14651 and σ_{cp} the permanent chemical post-tensioning compression stress. When pile heads are not used, the thickness should be increased by 20 mm.

Then for the above described Tingstad project full-scale testing case: $f_{R3} = 5$ N/mm^2, a typical dosage of 50 kg/m^3 of HE+1/60 steel fibres in a C 30/37 concrete matrix, $\sigma_{cp} = 1.5$ N/mm^2 with $R_p = 4.0$ m x 4.70 m x (40 + 5.04) kN/m^2 = 880.84 kN, so that H, the designed thickness, is:

$$H = 0.58 \cdot (8467572\ (5 + 1.2\ ))^{1/2} = 214 \text{ mm}. \qquad \text{Eq. 7}$$

Thus, the solution here is the slab thickness H = 220 mm with pile heads in order to carry the specified 40 kN/m^2 uniformly distributed load over a 4 m x 4.70 m grid of piles.

When following the Technical Report 34 4th edition provisions, a 40 % thicker steel fibre reinforced slab is needed. The chemical post tensioning with steel fibre reinforcing is thus very economical, offers a more stable slab with less deflection, no shrinkage movement and no detrimental cracking.

CO_2 saving

The example of the Tingstad slab teaches us that when compared to the initial traditional reinforced concrete solution of 300 mm with 120 kg/m^3 rebar reinforcing, we can, calculate the saving on the CO_2 by cement and steel reinforcing as follows:

Cement: (320 kg/m^3 x (0.30 – 0.22) m = 25 kg, or 1/40 of 1 tonne of cement responsible for 800 kg CO_2, thus here (1/40 t) gives a 20 kg/m^2 CO_2 saving.

Steel reinforcing: (0.30 m x 120 kg/m^3 - 0.22 m x 50 kg/m^3) = 25 kg/m^2 saving of steel thus also 1/40 of 1 t of steel, responsible for 1500 kg CO_2, thus here a saving of 1500/40 = 37 kg/m^2 of CO_2.

In total (20 + 37) kg/m^2 = 57 kg/m^2 CO_2 savings are attributable to the Primekss proprietary new technology here. The whole Tingstad slab area of the example was of 14 000 m^2, thus saving 798 tonness of CO_2.

Conclusions

It has been explained here how a ye'elemite modified steel fibre reinforced concrete induces a permanent compressive stress in the section that, together with the steel fibre reinforcing, is suitable to minimize and reduce to zero the need for any joints in the described slabs, on grade or piled, and balso provides a significantly increased stiffness so that the slab thickness is reduced by up to 50 %.

A simple design method is described, as well as a service limit, in terms of a maximum deflection translated into a span to deflection ratio. A rapid reliable formula is also given here to calculate the deflection.

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