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CHEMICALLY POST-TENSIONED STEEL-FIBRE-REINFORCED INDUSTRIAL FLOORING SLABS

Chemically post-tensioned steel-fibre-reinforced slab technology is a novel construction approach for industrial ground- and pile-supported slabs. It allows for the same structural benefits as traditional post-tensioning approach with strand, while at the same time is more economical, faster to implement and allows for considerable embodied carbon savings. This technology was recently brought also to the UK by Primekss after almost 20 years of development and field experience in the Northern Europe. **Rolands Cepurītis** and **Krišjānis Grinšpons** of **Primekss Group** and **David A Martin** from **Primekss UK** report.

BELOW: Figures 1 and 2 – PrīmX SSSFRC slab on piles during curing period and during operation at Dogger Bank windfarm.

Winning both the Net Zero and Sustainability categories at the Construction Excellence Awards for Bowmer + Kirkland, the O&M facility for the Dogger Bank windfarm at Port of Tyne represents a pile-supported slab solution (see Figures 1 and 2). The project required the design and installation of a ground-level slab for warehouse, maintenance and office areas at various levels. The piling grid ranged from 3 × 3m to 4 × 6m with no enlarged heads.

Primekss was able to demonstrate through the extensive testing of local materials (part of the Prime Quality QA process) to ACREO and Fairhurst that the adoption of an efficient PrīmX self-stressing steel-fibre-reinforced concrete (PrīmX SSSFRC in short) solution would reduce the consumption of both concrete and reinforcement to achieve a net embodied carbon saving of 55%. This was demonstrated by comparing the traditional plain reinforced proposal of 260mm concrete with 180kg/m^3 reinforcing bar to the 190mm chemically post-tensioned solution with 50kg/m^3 steel-fibre reinforcement. In addition, the project delivered jointless panels with no dominant joints and a lifetimes flatness guarantee – no risk of drying shrinkage induced curling at the day-joints.

The PrīmX chemically post-tensioned slabs produced are designed strictly following the requirements of Eurocode 1(1) and Eurocode 2(2). When it comes to the industry recommendations, the compliance to Concrete Society TR34(3) is achieved by following the recommendations in Section 11.1.7, where it states that, "Post-tensioning can be used to construct jointless floors and is one method for overcoming some or all of the tensile stress that normally occurs. Panel sizes can be up to 100m × 100m and there is a low risk of cracks opening as tendons cast within the slab keep the concrete in compression.

"The design of post-tensioned floors is not covered in this publication. Suppliers of post-tensioning systems should be consulted. Consideration should also be given to the use of proprietary joint systems that can cope with potentially wide joint openings".

In this instance, Primekss is the supplier of the post-tensioned system; a post-tensioned system that can be designed in accordance (general expression) with TR34. For this system, the reinforcement is placed at the same time as the concrete. The concrete matrix phase begins to hydrate, reduce in volume and gain strength. This acts as 'shrinkage wrapping' for all constituent materials. Following the initial set and gain of strength, the concrete matrix begins to expand placing the steel-fibre reinforcement into tension. Here we provide a technical insight in the principles of this post-tensioning system, how the chemical post-tensioning can be verified, quantified and consequently applied for slab design purposes.

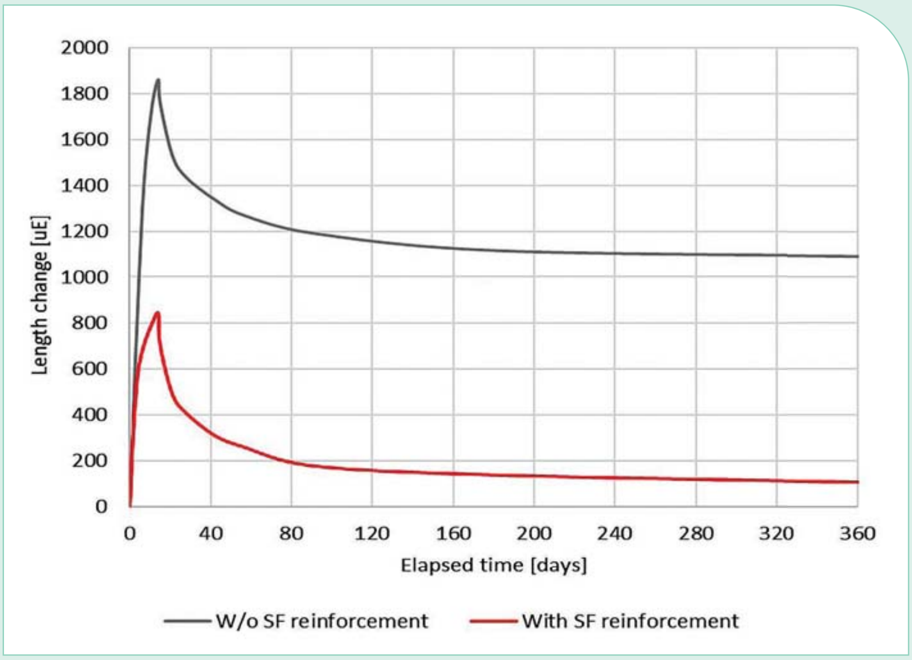
PRINCIPLES

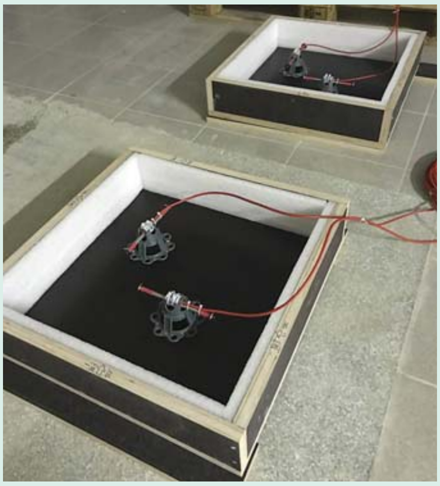
One of the back-bones of the PrīmX technology is use of an engineered

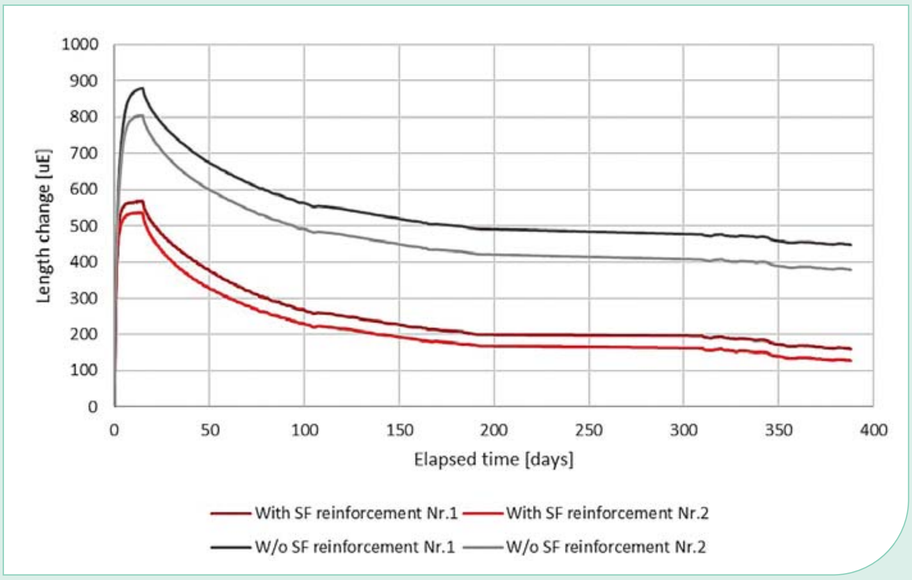
RIGHT:
Figure 3 – length change of PrīmX concrete prisms with and without steel-fibre reinforcement during curing period.

BELOW:
Figure 4 – monitoring laboratory-scale slab samples using vibrating wire strain gauges (VWSG).

BELOW RIGHT:
Figure 5 – length change of PrīmX concrete slabs with and without steel-fibre reinforcement during curing period.





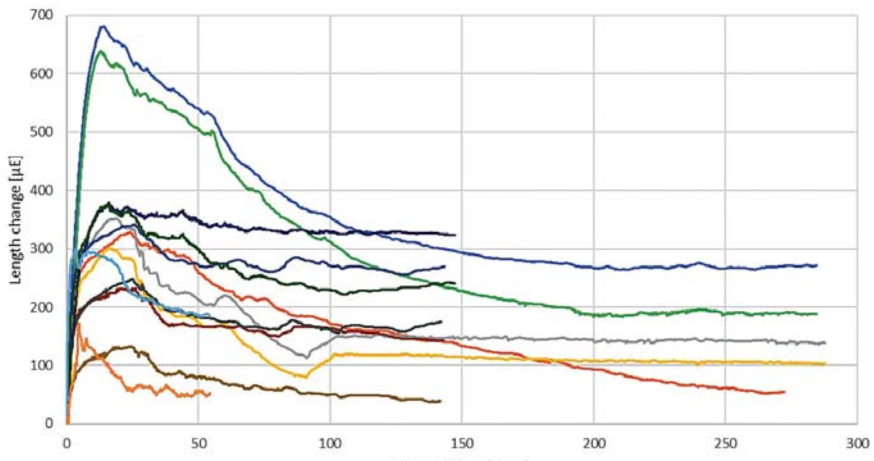


chemical post-tensioning mechanism. This mechanism includes use of proprietary expansive cement, PrīmX DC, that generates an expansive deformation in the cement matrix of concrete, which, in turn, is restrained by high amount of steel fibres and friction against the sub-base. This effect puts the PrīmX concrete in a permanent pre-compression, while the steel fibres are tensioned. The timing and the rate of the expansion of concrete is vitally important, because expanding concrete during the fresh plastic phase is useless, not only because the material does not have any stiffness, but also because no bond with the restraining fibres has developed. Managing both essential characteristics of PrīmX DC has been the focus of extensive study in the development of the additive. The proprietary cement is engineered to create expansion already from quite early age, when concrete begins to gain stiffness and to continue in a controlled manner for approximately 14 days. Also due to considerably higher specific surface in m^2 per m^3 of concrete, steel fibres are a much better restraint than traditional reinforcement steel bars (fabric).

> “The timing and the rate of the expansion of concrete is vitally important, because expanding concrete during the fresh plastic phase is useless, not only because the material does not have any stiffness, but also because no bond with the restraining fibres has developed.”

PrīmX system takes advantage of the fact that there is always a horizontal restraint due to friction between floor and foundation. This is evident because otherwise concrete floors would not crack due to the negative drying shrinkage strains. Restraint conditions at the foundation–floor interface can still be quite variable depending on the actual properties of the base layer. For example, whether the floor is cast on a layer of crushed rock, natural sand, crushed sand etc, which can be materials with very different grain shapes, angularity and grading. This is one of the reasons why Primekss, while still accounting that this form of additional restraint exists, does not rely on this horizontal restraint when modelling the compressive prestress in the PrīmX.

LEFT:
Figure 6 – installation of VWSG sensors at Primekss jobsite.



BELOW:
Figure 7 – in-situ measurements of PrīmX concrete length changes in various jobsites.

LABORATORY AND IN-SITU TESTING

PrīmX R&D Concrete Research centre uses several testing methods to verify the design assumptions before the project execution. One of the used methods in laboratory conditions, is casting of concrete prisms according to a modified ASTM C157(4) test procedure. The experimental measurements include casting of three concrete prisms in 75 × 75 × 250mm standard steel forms. Once demoulded, concrete prisms are cured and completely submerged in lime-saturated water for 14 days. At day 15, prisms are taken out of water and stored in the climate chamber, where constant temperature and humidity is maintained. During this curing period and at the drying stage at the set number of days, length-change measurements using a comparator in accordance with ASTM C157 are taken. These tests are used not only for assessing how PrīmX DC works together with a particular cement type in question but also to identify the steel- fibre restraint amount generated using the designed amount and type of fibres intended for the project. In that case, two sets of concrete prisms are cast – with and without the presence of steel fibres (see Figure 3 for typical prism results).

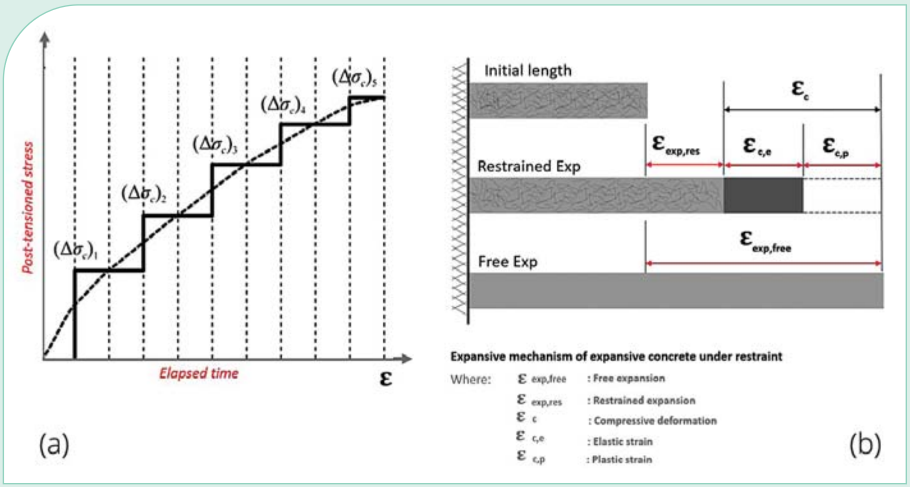
Although the data obtain from these laboratory tests are reliable and repeatable, it must be noted that due to the small scale of the samples it is hard to draw definite conclusions when thinking about the full-scale performance of the flooring slab. Also, effective curing from all the prism sides and deeper water penetration relative to thickness in concrete, allows for expansion far greater than in full-scale slabs to occur.

Accordingly, yet another testing method is used in laboratory conditions monitoring mock-up 500 × 500 × 100mm concrete slabs with the help of vibrating wire strain gauges (VWSG) (see Figure 4). Use of these sensors allows for real-time data collection from the moment of concrete placement. As in the case of the full-scale slabs, these laboratory-scale slabs are also cured only from the top side for a 14-day curing period and each day numerous data points of length change are gathered. An increase in sample size also allows for better understanding of fibre-restraint degree when it comes to full-scale slabs (see Figure 5).

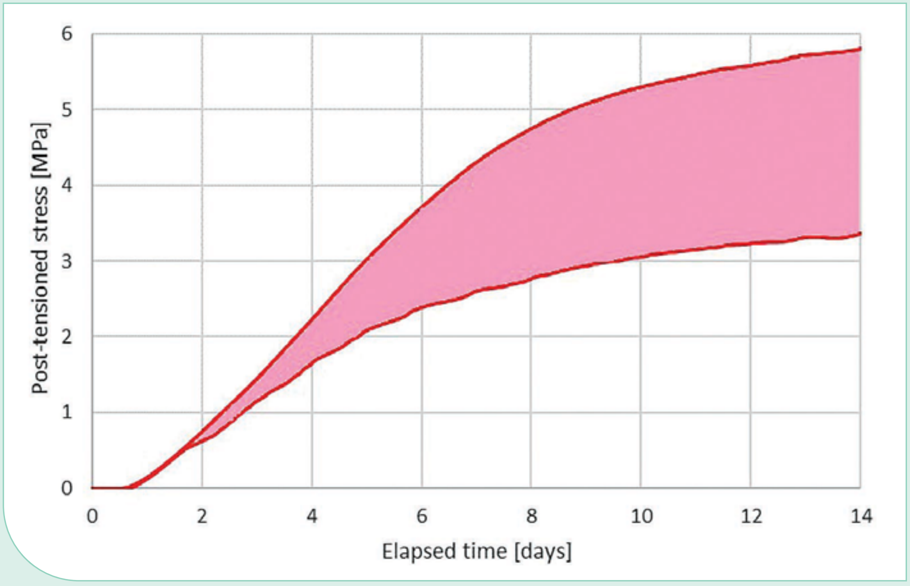
Primekss has also taken active steps to take the testing out of the laboratory to numerous building sites across the world (see Figure 6). VWSG, which is a very robust and reliable technology with a rich history of usage in actual jobsite conditions, allows us to complete the testing loop of concrete – from laboratory to actual concrete placement. Some of the length-change measurements obtained from various projects can be seen in Figure 7.

MODEL AND EXAMPLE CALCULATION

Over the past two decades, there have been proposed models(5–7) for the calculation of initial strains and stresses in self-stressing concrete based on consideration of free expansion strains of the concrete member, together with creep and Young's modulus development of the expansive concrete at early age, plus the corresponding restraint conditions. Some of these, have already been incorporated into the Codes for structural design purposes(8). Such a model can also be used to quantify the generated initial chemical post-tensioned stress in the PrīmX SSSFRC for further structural design purposes. A simple quantification (see Equation 1) would involve assuming



LEFT:
Figure 8 – (a) Incremental approach to numerically quantifying the generated post-tensioned stress; (b) PrīmX SSSFRC strain development under symmetric finite stiffness restrain conditions.



BELOW:
Figure 9 – development of the PrīmX SSSFRC initial chemical post-tensioned stress during the 14-day curing period of the slab.

a linear and uniform post-tensioned stress (σpt) distribution over the cross-section of the slab and considering expansion process on the elementary time intervals Δ_{ti} (see Figure 8) where the stress defining creep coefficient (φ), Young's modulus (E_c) and concrete member free ($\varepsilon_{exp,\,free}$) and restrained ($\varepsilon_{exp,\,res}$) expansion strains are time-dependent.

The calculation of the initial post-tensioned stress (at the end of the 14-day curing period) for the example introduced under 'Principles' (page 6) is then as follows:

$$\sigma_{cp} = \sum_1^i (\sigma_{cp})_i = \sum_1^i \frac{(\varepsilon_{exp,free,i} - \varepsilon_{exp,res,i}) \cdot E_{c,i}}{1+\varphi}$$

The Young's modulus for PrīmX SSSFRC at early age, $E_c(t)$ can be obtained from the relation based on the Eurocode 2 model:

$$E_c(t) = E_{cm,28} \cdot \exp\left[s \left(1 - \left(\frac{t_{m,28} - a}{t_i - a} \right)^{0.5} \right) \right]$$

The creep coefficient φ (t, t_0) for the PrīmX SSSFRC concrete at early ages can also be evaluated based on the Eurocode 2 model:

$$\Phi(t,t_0) = \Phi_0 \cdot \beta_c(t,t_0)$$

More details on these factors and their determination can be found in the relevant chapters of Eurocode 2.

When the described model principles are applied on the actual measurement results presented in 'Laboratory testing' (page 8), an initial (at the end of the curing period of 14 days) generated concrete post-tensioned stress in the order of 3–5MPa is calculated. The development of the concrete chemical post-tensioned stress over time in the PrīmX SSSFRC is also presented graphically in Figure 9.

CONCLUDING REMARKS

Data from laboratory, as well as from the in-situ measurements, is showing the PrīmX SFRSSC net positive length-change deformations after drying shrinkage processes have taken place. We can see that evenly distributed steel fibres indeed work as a very effective 3D reinforcement and in addition to slab sub-base and other adjacent structures (acting as sources of external restraint) can provide a high degree of overall expansion restraint. In-situ monitoring of concrete slabs has also allowed us to conclude that the extent of (drying) shrinkage in full-scale operational constructions is far less compared with small-scale prism and slab tests. The eventual permanent post-tensioned stress σpt achieved in concrete constructions (which is confirmed by net positive length change) can be considered when designing for industrial ground- and pile-supported slab construction.

References:

1. BRITISH STANDARDS INSTITUTION, BS EN 1991-1-1. *Eurocode 1. Actions on structures – General actions – Densities, self-weight, imposed loads for buildings*. BSI, London, 2002.
2. BRITISH STANDARDS INSTITUTION, BS EN 1992-1-1. *Eurocode 2: Design of concrete structures – General rules and rules for buildings*. BSI, London, 2004+A1:2014.
3. THE CONCRETE SOCIETY. *Concrete industrial ground floors. A guide to design and construction*. Technical Report 34, Fourth edition, Camberley, 2018.
4. AMERICAN SOCIETY FOR TESTING AND MATERIALS, ASTM C157/C157M. *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*. ASTM International, West Conshohocken, PA, USA, 2014.
5. ITO, H., MARUYAMA, I., TANIMURA, M. and SATO, R. Early age deformation and resultant induced stress in expansive high strength concrete. *Journal of Advanced Concrete Technology*, Vol.2, No.2, 2004, pp.155–174.
6. NGUYEN, D.T., SAHAMITMONGKOL, R., TRONG, L.N., TONGAROONSRI, S. and TANGTERMSIRIKUL, S. Prediction of shrinkage cracking age of concrete with and without expansive additive. *Songklanakarin Journal of Science and Technology*, Vol.32, No.5, 2010, pp.469–480.
7. LEI, X., CHENGKUI, H. and YI, L. Expansive performance of self-stressing and self-compacting concrete confined with steel tube. *Journal of Wuhan University of Technology. Material Science Edition*, Vol.22, 2007, pp.341–345.
8. SEMIANIUK, V., TUR, V., HERRADOR, M.F. and PAREDES G.M. Early age strains and self-stresses of expansive concrete members under uniaxial restrain conditions. *Construction and Building Materials*, Vol.131, No.30, January 2017, pp.9–49.