Reducing CO_2 emissions by design: the PrīmX system

While the CO_2 emission rates associated with concrete production and transport are far below other common building materials, it is possible to significantly reduce the carbon footprint of industrial flooring through the efficient and thoughtful use of Portland cement and reinforcement type. ***Xavier Destrée*** *of* ***ArcelorMittal, Brad J Pease*** *of* ***PrimeksssLabs*** *and* ***DA Martin*** *of* ***Primekss UK*** *report.*

One such development arising from a European research project at the start of the 21st Century is the Primekss system (PrīmX), which seeks to reduce the required section depth (and corresponding CO_2 emissions), while improving performance and durability when compared with traditional slab systems. The chemically prestressed system achieves this objective by adopting a two-pronged approach:

- replacement of all steel reinforcing bars with steel fibre for required tensile and flexural load capacities
- control of concrete shrinkage using proprietary admixtures.

Development

Concrete, when applied to large industrial spaces, faces a multitude of problems ranging from cracking and curling to opening of construction joints and damage at saw-cut joints, etc. The central mechanism to all these issues is shrinkage. Shrinkage induces cracking, necessitating the inclusion of joints in an attempt to localise and control cracking, and causes slab length reductions that lead to potentially significant openings of movement joints (see Figures 1a–1b).

The PrīmX system (see Figure 1c) improves upon ordinary concrete by enhancing its tensile and flexural behaviour and by controlling hygral (autogenous and drying) shrinkage. This permits jointless slabs in excess of 60m between construction joints, with section depths of around half that of other systems.

Improvements to mechanical properties are realised through the controlled addition of steel fibres, while shrinkage control is accomplished by careful concrete mix design and the addition of proprietary components – PrīmX DC and PrīmX Flow. These are added to the supplied concrete using specialised equipment on-site.

SFRC

Steel-fibre-reinforced concrete (SFRC) has been used for over 40 years to reinforce ground-supported concrete slabs and to limit the required amount of shrinkage. Concrete for this application typically consists of a C30-strength class with a water:cement ratio (w/c) below 0.50 and a maximised aggregate content to limit drying shrinkage. Reinforcement is provided by a moderate dosage rate of Type I (cold-drawn) steel fibres. Higher dosage rates can also be used depending on fibre shape and dimension, service loading, and subgrade bearing capacity.

For many years, full-scale testing has been carried out by ArcelorMittal and also by Primekss R&D. The tests simulated SFRC ground-supported slabs and exhibited a ductile flexural response with rotations concentrated along yield lines. Additional full-scale experiments indicated that yield line theory (ie, flexure) controls design of both pile-supported and elevated slabs. Under typical loading conditions, punching failure around column or pile heads does not occur due to limited flexural capacity of SFRC.

SFRC is traditionally cast on a slip membrane to minimise frictional restraint between the subgrade and the shrinking concrete. Steel fibre is very effective at controlling cracks and therefore these slabs typically exhibit minimal cracking. SFRC offers the reliable control of curling at movement joints and edges, although joint openings in the range of 10–20mm are common as can be seen in Figure 1a.

Control of shrinkage

Concrete shrinkage critically affects the performance of all slabs. Restrained shrinkage

Figure 1a: A typical construction joint opening in a ground-bearing concrete slab. The joint gap width is a function of concrete drying shrinkage.

Figure 1b: A typical saw-cut induced contraction joint. Saw-cut joints allow curling to take place and introduce a point of weakness where damage is localised requiring repair.

Figure 1c: A Primekss construction and column isolation joint at seven years of age.

results in random cracking of the slab, while unrestrained shrinkage causes substantial joint openings. Differential shrinkage causes curling at joints and edges after only 50 days with 'optimal' concrete for ground-bearing slab applications.

The addition of PrīmX DC (a cementitious additive) and PrīmX Flow (a liquid admixture) to SFRC results in a high-performance isotropic concrete that makes use of a controlled expansive chemical reaction to compensate for drying shrinkage and thus minimises cracks arising from internal stresses. Expansive mineral crystals form during the hardening process, causing the concrete to increase in volume after setting. This induces tension in the reinforcement and compression in the concrete. This mechanism controls concrete drying shrinkage and results in an irreversibly prestressed material, as shown in Figure 2.

This controlled expansion has to be consistent over time and from site to site, independent of the ambient temperature. The laboratory-assisted QA system developed by Primekss controls all admixtures and proprietary site techniques in order to regulate the setting time, hardening and consistence of the final concrete.

Figure 2 shows that at infinite time, the concrete sample remains in compression. It should be borne in mind that this is a five-faced drying prismatic specimen in a 50% relative humidity atmosphere. This is much more demanding than a single-faced drying slab on the ground. The drying shrinkage of the slab is eliminated and we have a zero-shrinkage concrete. In ambient conditions, this means that movement joints placed 60m apart remain closed for the life of the slab.

A significant advantage of the zero-shrinkage concept is to protect the slab from random cracking, curling and delamination. The elimination of curling at the edges maintains the slab in full contact with the ground support. This means that negative moment cracking along the joints and edges is no longer a critical loading case. Movement joints can now be tied and all sawn joints eliminated without any adverse effects, such as random cracking. The user sees the floor as being uninterrupted so that mechanical handling equipment enjoys a completely smooth ride, without bumps at any joint location.

The effect of the shrinkage compensating additives is a typical permanent compression stress of up to 2MPa. This takes place in the slab section when the slab is subjected to a movement restraint by the friction from the granular base. In Figure 2 it is shown that a permanent 50–100 μΣ in compression is being reached at infinite age so that the permanent compression stress εμ × E = 100.10^-6 × 20,000N/mm^2 = 2MPa, where E is the long-term modulus of elasticity of the concrete unaffected by shrinkage-induced micro-cracking damage.

Full-scale testing carried out at the University of Vaasa in Finland in 2011 indicates the type of research typically carried out by Primekss. This measured the deformation of a PrīmX chemically prestressed FRC slab of 100mm depth cast on a 100mm depth of EPS 200 insulation of 10MPa E and 0.09MPa long-term compressive strength (see Figure 3). The concrete compressive strength was of 32MPa

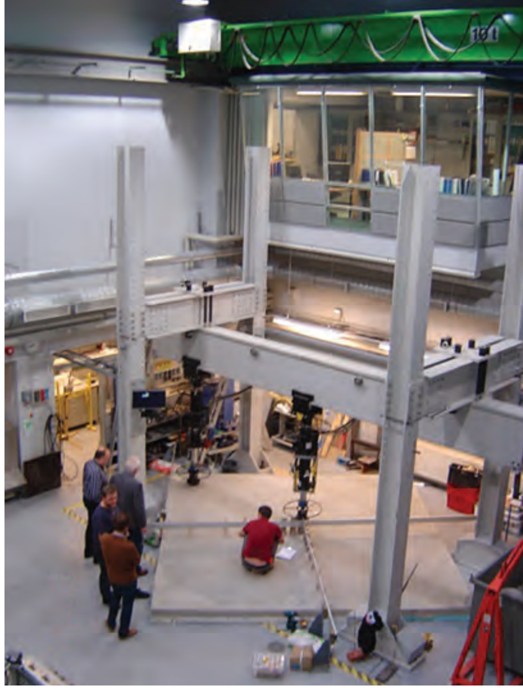

Figure 3: Primekss R&D: University of Vaasa 2011.

and the reinforcement of the slab was with 35kg/m^3 of randomly distributed hooked-end steel fibre of 0.75mm diameter, 50mm length, and 1100MPa tensile strength. The concrete shrinkage behaviour was controlled by 40kg/m^3 PrīmX DC and 4kg/m^3 PrīmX Flow.

The radius of rigidity for the slab was calculated at 537mm according to the theory of Westergaard. This was confirmed by testing and the ultimate load to failure recorded at 270kN.

The design of a centre point loading case assumes a plastic slab with yield lines forming a fan pattern of the positive moment together with a circular yield line. The external moment equilibrium considers the point-loading intensity and the elastic reaction of the EPS200.

The typical theory and equation of the equilibrium of the moments have been developed and written by F Van

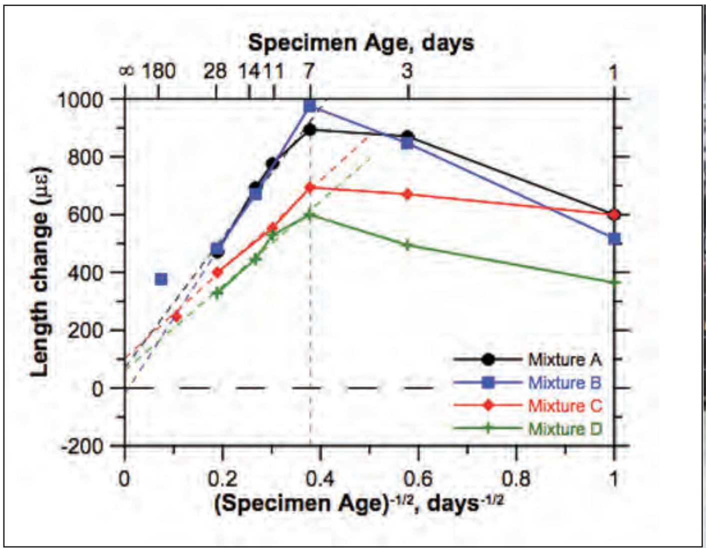

Figure 2: Zero-shrinkage concrete deformations in function of age in days to infinite time.

Figure 4: PrīmX system installed by Nationwide Concreting.

Table 1 – Primekss reference projects

Project	Area and loading	PrīmX solution	Traditional solution	CO_2 reduction (concrete only)
Post Office DC (Norway)/Bing, Installed in 2008	42,000m^2 70kN b-t-b racking	110mm	160mm SFRC	14kg/m^2 601t overall
John Deere, Marsta (Sweden)	15,000m^2 50kN racking	100mm	170mm mesh	17kg/m^2 258t overall
Inex high bay storage (Finland)	200,000m^2 75–240kN racking	120–250mm	200 to 350mm SFRC	28kg/m^2 5764t overall
Unil Logistic Centre (Norway),	42,000m^2 70kN racking	120mm	175mm mesh	16kg/m^2 665t overall
DSV DC (South Africa) (Figure 5)	110,000m^2 123kN racking	150mm	220mm SFRC	20kg/m^2 2213t overall

Cauwelaert[1]. The equation in this case gives an ultimate loading intensity of P_{ult} = 172kNn and a maximum service point loading intensity of 77kN.

The test verified the average pressure underneath the slab under the centre point loading as $77{,}000n/\pi L_r 2 = 0.085$MPa, which is almost the limit pressure of 0.09MPa under long-term service conditions. We can conclude therefore that the plastic design of the slab bearing on an elastic base leads to a quite realistic and safe estimate of the maximum permissible centre point loading intensity in service. Indeed, at 77kN point-loading intensity, the global safety to rupture is 270/77 = 3.50.

CO_2 emissions reductions

Since the development of the PrīmX system, approximately 20,000,000m^2 of chemically prestressed zero-shrinkage SFRC slabs have been successfully completed to the full satisfaction of the customer and the end-user.

For a normal shrinkage concrete, a minimum thickness of 150mm is suggested for ground-bearing slabs. However, when using a zero-shrinkage concrete, this is no longer the case. 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 cases of point loading do not exist anymore. Against the perimeter wall, there is indeed no traffic and the shelves are only loaded on one side and thus at the half of the full intensity.

An example of CO_2 savings resulting from the adoption of a PrīmX solution can be seen with the installation of the system at the 17,000m^2 Shinfield Research Centre near Reading (Figure 4) by Nationwide Concreting in 2020:

1. Original design: C32/40 at 250mm depth c/w two layers A252 fabric
   a) Ground conditions – very poor, 3% CBR values
   b) Loading intensity – 20kN/m^2 generally but with 10-tonne point loads and artefacts of up to 20 tonnes.
2. PrīmX solution: C30/37 at 130mm depth c/w 35kg/m^3 75/50 steel fibre, 40kg/m^3 PrīmX DC and 4kg/m^3.
3. CO_2 savings (materials only):
   a) Concrete – 48% saving by volume, equating to 26.83kg CO_2/m^2
   b) Steel – 41% saving by mass, equating to 6.27kg CO_2/m^2
   c) Overall CO_2 saving of 563 tonnes for 17,000m^2 building footprint.

Other typical reference projects provide an indication of CO_2 savings when compared with traditional systems (Table 1).

With respect to Table 1, we recently visited the Post Office/Bing slab completed in 2008, poured in a 4000m^2 bay size with up to 65m construction joint distance. The construction joints remain closed today and with zero curling. The slab shows a few hairline cracks (of less than 0.5mm opening) of limited length although it undergoes heavy robotised small-wheeled forklift truck traffic. The slab, after more than 11 years of heavy-duty service, doesn't show any traces of ageing. This is also an important aspect of the CO_2 reduction, since the Post Office slab won't have to be replaced or remediated before the building becomes obsolete.

Clearly, the savings indicated are focused on the quantities of cement used, but reductions of secondary sources of CO_2 emissions in terms of steel and transport are also likely to be considerable.

Concluding remarks

Given the sheer volume of floors produced with the PrīmX system worldwide over the past 20 years, it is clearly the case that zero-shrinkage concrete systems work and perform well. The savings in CO_2 emissions, regardless of cement type, are such that the system cannot be ignored. We can draw the following conclusions from this article:

- The proprietary additives PrīmX DC and PrīmX Flow control the shrinkage of concrete, permitting jointless slab sections exhibiting zero shrinkage cracking, curling or significant joint opening.
- Full-scale testing of PrīmX systems indicates that a 100mm-thick slab, with sufficient quality subgrade, will support point loads of 75kN with a safety factor of 3.5.
- CO_2 emissions for concrete alone can be reduced by circa 40% by replacing traditional concrete slabs with the PrīmX zero-shrinkage system.
- CO_2 emissions for steel, aggregate production, transportation etc are also significantly reduced by adopting a PrīmX solution. ■

Reference:

1. VAN CAUWELAERT, F. Evolution dans le dimensionnement rationnel des revêtements eb béton et des sols industriels. *Bouwkroniek*, October 1996, pp.24–34.

Authors' note:

This article results from the updating in 2021 of a paper presented at the International Conference on Concrete Sustainability (a joint conference ACI-FIB) in 2013 in Tokyo. To ease the reading, the mathematical and mechanical analysis has been skipped and the CO_2 reduction aspect has been completed by adding some case studies.

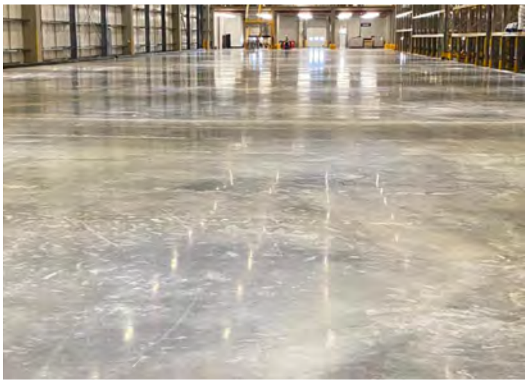

Figure 5: DSV Distribution Centre, South Africa.