CO_2 REDUCTIONS UTILISING SELF-STRESSING STEEL FIBRE REINFORCED CONCRETE

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Abstract. A novel system utilising steel-fibre reinforced concrete (SFRSSC) has been developed and implemented in projects in the recent years for structures such as ground-based slabs, ground-level elevated slabs on piles among others. Being that the system is chemically pre-stressing the concrete this compressive self-stress can be used to significantly decrease the thickness of the structures while maintaining their load bearing capacity yet decreasing the materials used and lowering the emissions caused by making the said structures. Recently a comparative full-scale testing has been conducted to compare the impact of the chemical self-stress on the load bearing capacity of a supposed ground-level slab on piles when looked in a comparison with a more traditional steel fibre reinforced concrete slab in a practically identical situation. This document shall shed light on the possibilities of reducing the CO_2 emissions via usage of SFRSSC when compared to other existing more traditional construction systems. The full-scale tests revealed that the SFRSSC slab could bear ~30% higher loading while maintaining 30% lower deflections and exhibiting lower number of cracking. This, in turn, allows for making SFRSSC slabs significantly thinner thus reducing the emissions caused by the extraction of raw materials, transportation of the said materials, production of the concrete as well as production of the structure itself.

Keywords: Steel fibre reinforced concrete, self -tressing steel fibre reinforced concrete, full-scale testing, CO_2 reduction.

1 Introduction

The introduction of various standards and guidelines aimed at the design of steel fibre reinforced concrete (SFRC) structures has made the implementation of SFRC structures more widespread. For a multitude of years, SS812310 [1], an SFRC standard has been used and now with the introduction of the new generation of Eurocode 2, which includes the informative Annex L [2] on fibre reinforced concrete design, the application of SFRC in structures should grow even more. Although SFRC as a material is not new *per se*, the design methods, safety of the structures [3, 4] among other topics are still disputed and researched to achieve safe yet economically and environmentally viable solutions. One of structures that are used extensively would be also ground-level slab supported on piles, discussed in detail in ACI544.6R-15 [5].

A novelty in the field of SFRC structures is the so-called steel fibre reinforced self-stressing concrete (SFRSSC), which is gaining popularity in the European, North American and other markets. The introduction of self-stressing agent in the randomly distributed fibre concrete matrix allows mimicking the traditional post-tensioned systems that would otherwise utilise steel cables yet the self-stress would be achieved chemically. The system proves to be feasible for ground level elevated slabs on piles [6, 7] and for other structures [8]. The chemical self-stressing of the structure acts similarly to traditional tensioned structures, giving the structure enhanced stiffness, reducing deflections, reducing cracking while also reducing the amount of necessary deformation joints. Previously, such a system has been looked at for slabs on ground where it proved to be a viable method of reducing CO_2 emissions [8] that can deliver tangible benefits already today which exceed those of introduction of GGBS or other supplementary materials to reduce the cement content in the concrete matrix.

The current publication is aimed to inform the community of the system being tested in full-scale for ground level elevated slabs on piles, once more proving the systems capability of reducing the CO_2 emissions by providing a stiffer, stronger slab when compared to conventional methods. The study shows the possible thickness reductions and subsequent CO_2 emission reductions as well as the differences in the behaviour of the SFRSSC in direct comparison to SFRC under the same conditions. The approbation of the system in said uses follows Eurocode 0 Section 5 Structural Analysis and Design Assisted by Testing.

2 Experimental Programme

The conducted full-scale experiments have been introduced to the public recently [9]. Nevertheless, the most crucial data will also be presented here for better context.

The full-scale test was conducted on two slabs, one of SFRC, one of SFRSSC. The tested slabs were directly placed on a grid of columns, mimicking piles, spaced at a grid of 3000 mm by 3000 mm, diameter of the columns being 300 mm. To imitate the internal span behaviour without influence from close edges, additional spans of various distances were introduced as shown in Fig. 1. The slabs were constructed as flat slabs, without drop panels or pile heads, freely supported and unconnected to the columns. The thickness of both slabs was 150 mm, with a span-to-depth ratio being 20 which is in the common range of industrial elevated ground slabs.

2.1 SFRC and SFRSSC composite composition

The material composition of the SFRC and SFRSSC is given int Table 1.

The mix designs show the only difference between the two slabs being a self-stressing agent with a brand name PrīmX DC. The reinforcement of the slabs is fibre only, 0.9 mm in diameter, 60 mm in length, hooked-end steel fibres with 1500 MPa tensile strength. The concrete met the requirements of C30/37 concrete class with a S4 slump.

Table 1. Material composition for SFRC and SFRSSC.

Material	Amount, kg/m^3	
	SFRC	SFRSSC
CEM II/A-LL 52.5N	360	360
Water	162	162
w/c ratio	0.45	0.45
0-8 mm sand	952	952
5-16 mm crushed dolomite	914	914
PrīmX Flow HRWRA	3.6	3.6
Hooked end steel fibres (L=60 mm, d=0,9 mm)	50	50
PrīmX DC	–	40

To reduce the necessary water amount and maintain workability, PrīmX Flow high-range water reducing admixture (HRWRA) was introduced for both mix designs.

2.2 Loading

The full-scale slabs were tested by placing loads on the slab in SLS levels and up to collapse, thus the test was load-governed. The assumed SLS level for the comparison was set to be ~25kN/m^2 but the actual SLS levels for the slabs given the criteria of deflections and cracking for such slabs was observed after the test based on measurements of the behaviour of the slabs. The loading layout was chosen following a similar test done for a similar structure [10].

The loading pattern allows achieving the maximum possible positive and negative bending moments as well as the largest possible deflections, see Fig. 1.

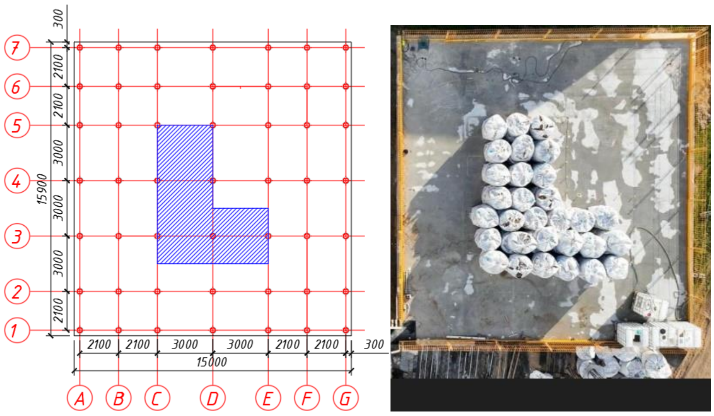

Fig. 1. Load layout: left - scheme, right – actual.

The slab was loaded by placing sandbags in layers, where each layer is regarded as a load level (LL). Seven distinctive points in the loading programme can be detailed, called loading situations (LS), see Fig. 2.

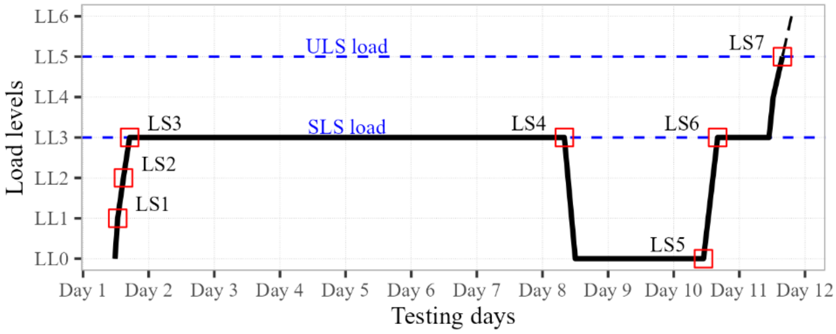

Fig. 2. Loading sequence with characteristic points denoted as loading situations (LS).

The loading material chosen was dry, sieved sand, weighed and secured in big-bags of 1000kg or 10kN per bag. This allows for the loading steps to be of uniform value as well as the weight of the bags did not change due to rain and water puddling on the slabs. The usage of sand in big-bags allowed to alleviate any possible interlock between the bags thus eliminating any arching effect which would otherwise be present in stiff materials, *p.e.* bricks, pavement bricks *etc*. The assumed SLS load level, LL3 is set to be 25kN/m^2.

2.3 Instrumentation on site

To measure the structural response of the slabs, a multitude of measuring systems was introduced in the experiment, *p.e.* fibre optic sensors for strain measuring, digital image correlation, LVDTs for deflection, piezoelectric strain gauges, vibrating wire strain gauges (VWSG) among others. The instrumentation is described in more detail in the following publication [9] and will not be further discussed in this publication.

2.4 Lab tests

A multitude of samples were prepared during the pouring of the slabs to assess the various properties of the used concrete, *p.e.* concrete compressive strength, residual flexural strength, plastic tensile strength among others. The samples created ranged from cubes of 100x100x100 mm^3 according to EN12390-2, 150x150x600 mm^3 beams according to EN14651 and EN12390-5, slabs d=800 mm h=100 mm according to ACI544.6R-15, slabs d=1500 mm h=180 mm according to ACI544.6R-15, up to samples of beams, cores, cylinders and slabs cut out and drilled from the tested structure itself.

The post cracking residual strength and plastic tensile strength of the concrete was evaluated for a comparison of a similar testing methodology for a similar composition of SFRSSC continuing a previously done experiment [12, 13] where a comparison between different testing methods and their results was done to evaluate the impact of chosen testing methodology on the necessary thickness of the structure.

3 Equivalent design

The results of the two slabs revealed that the SFRC slab exhibited larger deflections, larger crack openings, longer cracks lengths under the same loading conditions as SFRSSC, see Fig. 3.

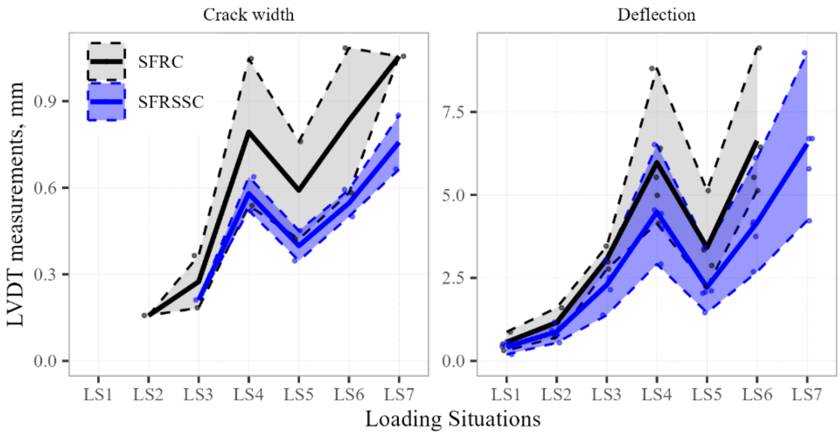

Fig. 3. Comparison of crack width and deflections measured by LVDTs for SFRC and SFRSSC slabs at different loading situations.

The final failure load of the two slabs were also significantly different where the SFRC collapsed at 45.7 kN/m^2 and the SFRSSC collapsed at 60.5 kN/m^2, thus a 32.3 %

increase over the performance of the SFRC. At the same loading levels the SFRSSC exhibited 33 % lower deflections at the assumed SLS load, LL3. 6 mm for the SFRSSC and 9 mm for the SFRC. Additionally, the top surface cracking of the SFRSSC was limited to a single crack of 0.04 mm width, while the SFRC exhibited a noticeable cracking fan pattern on the top surface after LL3 loading, see Fig. 4.

Fig. 4. Comparison of crack patterns in place of maximums negative bending moment after LL3, left – SFRC, right – SFRSSC.

Taking the results into account, it can be concluded, that the actual values of SLS loading that meets the SLS criteria for the two slabs is 19 kN/m^2 and 28 kN/m^2 for SFRC and SFRSSC respectively, thus a 47 % increase in the loading intensity. To achieve the same load bearing capacity, the slab of SFRC with the same material properties should therefore be designed with a thickness of 180 mm versus the 150 mm SFRSSC slab, a 16.6 % decrease in thickness.

4 CO_2 emission calculations

Based on the equivalent designs discussed in Section 3, a comparison of CO_2 emissions for multiple solutions, i.e. SFRSSC, SFRC and welded wire mesh reinforced concrete- (WWMRC) can be done, see Table 2.

Table 2. Comparison of CO_2 emissions for different components of concrete.

Material	Specific emissions	CO_2 emissions, kg/m^2		
		SFRSSC	SFRC	WWMRC
Concrete C30/37 [14]	273 kg CO_2eq/m^3	40.95	49.14	49.14

Green concrete C30/37 [14]	230 kg CO_2eq/m^3	32.25	38.70	38.70
Reinforcement [15]	1.14 kg CO_2eq/kg	-	-	36.94
Green reinforcement [16]	0.30 kg CO_2eq/kg	-	-	9.72
Steel fibres [17]	1.24 kg CO_2eq/kg	9.26	11.12	-
XCarb steel fibres [17]	0.37 kg CO_2eq/kg	2.74	3.29	-
HRWRA [18]	0.30 kg CO_2eq/kg	0.16	0.2	0.2
PrīmX DC [19]	0.65 kg CO_2eq/kg	3.9	-	-

To develop an envelope of CO_2 emissions for the solutions ranging from the worst case to the best, a combination of the materials was used using either the greenest or the least green options. The outcomes and their comparisons are shown in Table 3. The greenest options are denoted with a letter "G". The solutions are ranked from 1 to 6 with 1 being the greenest and 6 the least green solution.

Table 3. Comparison of CO_2 emissions for different systems.

System	CO_2 emissions, kg/m^2	Rank
SFRSSC	54.28 kg CO_2eq/m^2	4
SFRSSC G	39.05 kg CO_2eq/m^2	1
SFRC	60.45 kg CO_2eq/m^2	5
SFRC G	42.18 kg CO_2eq/m^2	2
WWMRC	86.27 kg CO_2eq/m^2	6
WWMRC G	48.62 kg CO_2eq/m^2	3

From Table 3 it can be clearly seen that at the same circumstances the SFRSSC solution emits the least amount of CO_2, while the WWMRC emits the most. This is true for both the greenest solutions and the less green solutions. Depending on the solutions to be compared, the SFRSSC solutions provide from 11 to 59 % reduction while SFRSSC G solutions provide from 8 to 24 % reduction when comparing similarly green solutions.

The presented calculation covers only the materials part and does not include other areas of productions, *p.e.* transportation of materials to site *etc.* Following that there is less material to be transported and poured in-situ, the actual CO_2 savings are even higher than the values presented here, yet it is not feasible to cover this topic in this publication due to the transportation costs being highly linked with the location of the project and may highly vary.

5 Results and Discussion

The full-scale tests showed that the SFRSSC slab exhibited smaller deflections, less crack widths, less overall cracking at the same load levels as explained previously. The actual SLS load for SFRC was of 19 kN/m^2 while the SFRSSC reached SLS state at 28 kN/m^2, thus for the same loading conditions the SFRSSC slab can be thinner when compared to the SFRC slab due to the self-stressing effect of PrīmX DC.

From the premise that the SFRSSC slab can be thinner than the SFRC slab for the same loading conditions it is possible to estimate the CO_2 footprint of the systems, which shows significant benefit in reduction of the CO_2 gas emissions by up to 59 %. The calculations of the CO_2 emissions also show that at the worst case the SFRSSC solution has less emissions than at any of the best cases of the comparative solutions. In case, green concrete, green fibres can be used, the greenhouse gas savings are increased significantly by up to 24 %.

6 Conclusions

The full-scale tests of SFRC and SFRSSC along with appropriate calculations shown in this publication reveals the following conclusions:

- At failure the SFRSSC slab held 33 % higher load- than SFRC;
- At the same loading conditions SFRSSC exhibited ~33 % lower deflections;
- At same loading conditions SFRC exhibited almost no cracking on the top surface;
- For same loading conditions the SFRC would render a slab of 180 mm thickness versus 150 mm for SFRSSC;
- The usage of SFRSSC system lowers carbon emissions by 8 - 55 % when compared to regular SFRC and by 10 - 51 % when compared to WWMRC.

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