Self-Prestressed Carbon-Reinforced High Performance Concrete Elements

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ABSTRACT: Prestressed high performance concrete (HPC) elements using tendons made of pultruded carbon fiber reinforced polymer (CFRP) were developed by Empa in late 90ies. While the mechanical properties and the durability of the CFRP tendons are unique, their prestressing technology is similar to that used with conventional steel. This means that an external prestressing frame with massive steel beams anchored in the soil by means of concrete foundations is needed. Finally, hydraulic cylinders and dedicated anchorage elements of the tendons are also needed to prestress the CFRP tendons. The innovative idea developed in this Empa project consists of using concrete that expands after setting and therefore induces tension in the CFRP tendon and compressive prestress in HPC, thereby eliminating the need of an externally-imposed prestressing and simplifying substantially the production process of the prestressed elements. This process is referred to as chemical prestress or self-prestress and was applied until now only to achieve minor prestressing levels of steel reinforcement. In this project, concrete recipes with a combination of an expansive agent, an internal curing agent and a shrinkage-reducing admixture were developed. This expansive concretes allowed achieving levels of free and restrained expansion able to induce high and durable pretensioning in novel ultra-high modulus (E=464 GPa) CFRP tendons made of pitch-based carbon fibers. Thanks to the self-prestress of concrete, the cracking moment of CFRP-reinforced beam could be increased 3 times compared to a beam made with a reference concrete.

1 INTRODUCTION

Prestressing of concrete by means of pretensioned steel tendons or wires is a commonly applied technology that allows to improve the performance of concrete regarding its serviceability (e.g. reduced deflections and cracking), ultimate resistance, aesthetics and economics (more slender elements) (Billington 1976). One important limitation of the prestressing technology stems from the need for corrosion protection of the pretensioned reinforcement. This is normally obtained by providing sufficiently thick concrete cover (e.g. >50 mm according to Swiss code SIA 262), which imposes serious limitation on the minimum size of concrete elements. An important progress could be achieved with the introduction of alternative, non-metallic reinforcement for prestressing purposes. One example of such reinforcement are tendons made of Carbon Fiber Reinforced Polymers (CFRP). The application of CFRP for prestressing of concrete (both internally for pretensioning and externally for retrofitting) has been studied at Empa, and consequently introduced into Swiss precast industry since 1990s, see e.g. (Motavalli et al. 2011, Terrasi 2013). Thanks to the excellent corrosion resistance and durability of the CFRP tendons, the concrete cover could be reduced and slender prestressed elements could be obtained (Terrasi 2013). Other benefits compared to traditional pretensioning steel are low mass, high strength, low fatigue and negligible creep and relaxation, e.g. (Stoll et al. 2000). The prestressing technology could become especially effective with the new ultra-high modulus CFRP tendons studied in this and other Empa projects (E moduli of 464 or 509 GPa). At the same time, efforts have been made at Empa to improve the economic feasibility of the CFRP-prestressing technology. The conventional pretensioning technique of CFRP tendons requires, similarly as for steel tendons, massive prestressing beds, which incur high costs and hence limit the applicability of the CFRP-prestressing. Further, technical challenge emerges related to the anchorage of the CFRP tendons. Due to their low strength in the transversal direction, conventional clamping is not possible and labor-intensive ad-hoc solutions are necessary (Terrasi et al. 2010). Thus, avoiding the external prestressing process could offer an immediate benefit and open new market possibilities for the CFRP-prestressed concrete.

The objective of the study reported in this paper was to replace the traditional, external pretensioning process with the so-called chemical prestressing (self-prestressing), where the tendons are pretensioned solely by the expansion of special concrete that pulls the tendons along (Lin and Alexander 1963). This process requires that concrete be made with special expansive cements (alone or in combination with ordinary cement), mainly calcium-sulfoaluminate cements (CSA) that lead to expansion of concrete due to formation of ettringite crystals in the hydration process (Nagataki and Gomi 1998). Expansion of concrete was used in the past to produce prestress in both internal, e.g. (Tur et al. 2018) and external FRP reinforcement, e.g. (Cömert et al. 2009).

The major challenge of this project was to provide high expansion of concrete that could introduce sufficient pretensioning in the tendons (and, per equilibrium, prestress in the concrete), without compromising the mechanical and durability performance of the concrete. It is generally agreed that the uncontrolled expansion of concrete can lead to its cracking and even disintegration (Nagataki and Tsuji 1994). This is why the chemical prestressing applications have been limited until now to only low or moderate levels of prestress, up to about 2.5 MPa (Tur et al. 2018). We could exceed this limit by using special expanding, high-performance mix composition developed specifically for this project at Empa (Wyrzykowski et al. 2018).

This paper reports on the most important results of a study on self-prestressed CFRP-reinforced high performance concrete (HPC). More details can be found in (Terrasi et al. 2016, Wyrzykowski et al. 2018, Wyrzykowski et al. 2019). In this study, we developed a novel concrete composition, where high levels of residual (i.e. after drying and creep takes place) expansion capable of generating prestress levels in excess of 4 MPa, yet maintaining the features of HPC, i.e. very high mechanical properties and good durability. This was possible thanks to combining CSA expansive cement, shrinkage reducing admixture (SRA) and internal curing by means of superabsorbent polymers (SAP), see also (Wyrzykowski et al. 2018). With this concrete, it was possible to generate high pretensioning in the CFRP tendons and obtain self-prestressed elements with significantly improved cracking resistance as evidenced with 4-point bending tests.

2 MATERIALS AND METHODS

2.1 Mix design

Concrete mixtures were prepared by blending an ordinary Portland cement CEM I 52.5 R with a CSA-based cement (CSA#20 by Denka) at different ratios. Here, the results are presented for concretes made with either 20% or 25% of CSA addition (by mass of cement). The chemical composition and physical properties of the cements can be found in (Wyrzykowski et al. 2018). In a reference mix (non-expanding concrete), fly ash was used instead of the CSA. The expansive concrete mixes also contained limestone filler (5% by cement mass). The shrinkage-reducing admixture was a commercial product SIKA Control 60. A solution-polymerized SAP with dry particle sizes in the range 63-125 µm was used as internal-curing agent; it had pore-solution absorption estimated as equal to 17 g/g (Justs et al. 2015). The workability was controlled with a liquid polycarboxylate-based superplasticizer. The aggregates were alluvial sand with particle sizes of 0-4 mm. The mix compositions are summarized in Table 1. The concretes were mixed in a rotating pan Eirich mixer with 80-l capacity for the big-scale elements (beams for 4-point bending tests) and in a 10-l Hobart mixer for small prisms (measurements of expansion). The concretes had workability that allowed casting without any vibrations (i.e. self-compacting mixtures).

Table 1. Mix compositions and mechanical properties of the concretes.

Material	**Mass [kg/m^3]**		
Mix name/Material	20%CSA+SRA+SAP	Reference	25%CSA+SRA+SAP
Cement CEM I 52.5R	500	402	469
CSA	100	-	117
Fly ash	-	101	-
Limestone powder	25	-	23.5
Water	219	216	213
Superplasticizer	14.4	6.03	17.1
SRA	15.6	-	15.2
SAP	1.84	-	1.79
Aggregates	1458	1568	1431
w/b	0.35	0.43	0.35
Compressive strength	-	69.3±3.0	64.9±0.4
Flexural strength at 28 d [MPa]	-	9.7±1.8	9.9±0.6

The beams used in 4-point bending tests were reinforced with CFRP tendons. The tendons were acting either as passive reinforcement (with reference concrete) or as pretensioned reinforcement (with expanding concrete). The tendons contained Mitsubishi DIALEAD™ fibers K63A12. The novel CFRP prestressing tendons have a diameter of 5.3 mm (±0.1 mm) and were produced batch wise by a tape-laying method. The tendons are quartz sand coated on their surface in order to produce a good bond to the HPC. These tendons behave linear elastically until tensile failure, have an average tensile strength of 1029 MPa and an average elastic modulus in tension in longitudinal direction of 464 GPa.

2.2 Methods

Expansion of the concrete mixes was tested on prismatic samples 40×40×160 mm^3. The samples were cast in steel molds (commonly used for preparing mortar samples for tests of mechanical properties). At the age of 1 d, the samples were demolded and placed under water (underwater curing) or sealed with several layers of plastic food wrap (sealed curing). The samples were stored in climate-controlled rooms at 70±3 %RH and 20±0.3 °C. At chosen ages, some samples were exposed to drying, while part of the samples stayed underwater to study the long-term expansion and its effects on mechanical properties. The deformations were always referred to the age at demolding (1 d) and were measured using a horizontal measuring frame equipped with digital deformation transducer with resolution corresponding to 7 µm/m strain.

Restrained expansion tests of the prismatic samples was tested with a method adapted after the Japanese standard (JSA 1997). The prisms were restrained with threaded stainless steel (E=200 GPa) bars M5 and M8, resulting in reinforcement ratios of 0.9% and 2.3%, respectively.

The mechanical properties were measured in addition on the prismatic samples: flexural and compressive strength and elastic Young's modulus in compression (static).

4-point bending tests were performed on prismatic beams with the following cross-section: 45×150×1200 mm3. The scheme of the slabs and the 4-point bending test is presented in Fig. 1.

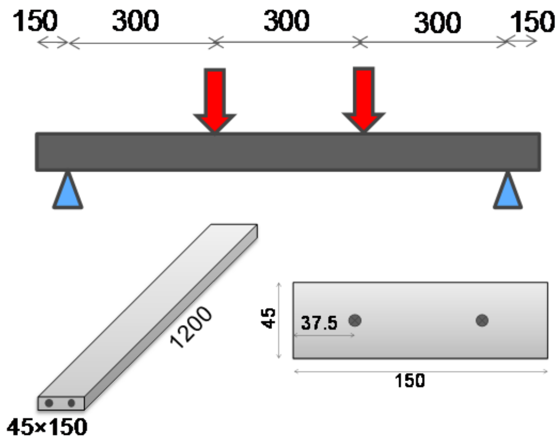

Figure 1. Scheme of the 4-point bending test and dimensions of the tested beams reinforced with CFRP tendons.

The beams made with either Reference or 25%CSA+SRA+SAP (see Table 1) concretes were cast in stainless steel molds with plastic base and demolded at the age of 1 d. At this point, the beams were wrapped in several layers of plastic foil and kept sealed until the age of 7 d, when they were opened to drying at 70±3 %RH and 20±0.3 °C until the age of 28 d, where the 4-point bending tests were carried out. The tests were run in a hydraulic machine with displacement control. The mid-span deflection was measured underneath the beams with a deflectometer. The results until first cracking are evaluated in this paper.

3 RESULTS AND DISCUSSION

3.1 *Expansive concrete*

As already mentioned, an important part of the project was providing concrete with sufficiently high and stable expansion. This was possible by carefully designing the mix composition containing three key components: CSA expansive cement, SRA and SAP. In Fig. 2 the effect of this combination on free expansion in sealed conditions and after drying is presented. The concretes tested were based on the 20%CSA+SRA+SAP concrete (see Table 1) after removing different components (SRA, SAP) individually or together. Concrete made with only 20%CSA addition can expand in sealed conditions until 7 d due to the formation of ettringite crystals (Nagataki and Gomi 1998); large part (more than 30%) of the initial expansion is however later lost due to drying shrinkage of concrete. When SAP is added (concrete 20%CSA+SAP), initial expansion is promoted. This is thanks to the so-called internal curing process, where SAP (added initially dry to the mix) absorb part of the mixing water and later release it to compensate for the water emptied by chemical shrinkage in the hydration process of cement, providing curing from the inside, hence *internal curing* (Jensen and Hansen 2001). This process has two positive effects in the expanding concrete: 1) it reduces autogenous shrinkage in the concrete with low water-to-binder ratio (w/b), that would otherwise compete with the expansion, and 2) moist curing most likely also promotes formation and crystallization pressure of the ettringite (Nagataki and Gomi 1998). The higher expansion can be still maintained even after drying shrinkage takes place. The addition of the SRA has a two-fold positive effect: it promotes the initial expansion, and also reduces drying shrinkage afterwards. The enhanced initial expansion is due to promoted formation and different morphology of ettringite (more elongated needles) (Monosi et al. 2011) and additionally due to reduction of autogenous shrinkage thanks to the reduced surface tension of pore fluid (Bentz et al. 2001). The SRA is also known to reduce drying shrinkage due to easier evaporation and hence lower average pore pressure acting on the skeleton during drying shrinkage (Weiss et al. 2008).

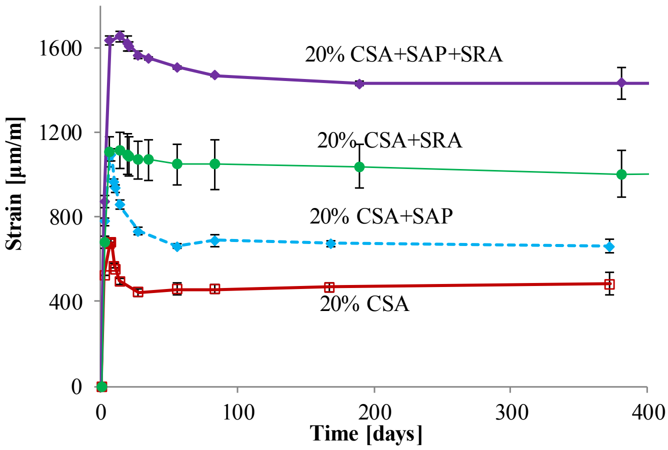

Figure 2. Effect of combination of different additives (CSA, SAP and SRA) expansion of concretes in sealed conditions (during initial 7d) and during drying at 70%RH and 20 °C. Adapted from (Wyrzykowski et al. 2018).

Finally, when the three key ingredients are combined in the 20%CSA+SRA+SAP concrete a very high initial expansion is reached that is only little reduced by drying shrinkage afterwards.

When the 20%CSA+SRA+SAP concrete is cured under water after demolding, considerably higher expansion could be reached that was only little compromised by drying shrinkage after exposing the samples to drying at 70 %RH, see Fig. 3. The concrete stored continuously under water, despite reaching very high free expansion (about 6000 µm/m), still had very high mechanical properties. The compressive strength after 3 y underwater storage was equal to 99.2±2.9 MPa, and for samples drying from 28 d it was 96.8±1.7 MPa. The elastic Young's moduli were equal to 37.1±0.2 GPa and 36.3±0.5 GPa, respectively.

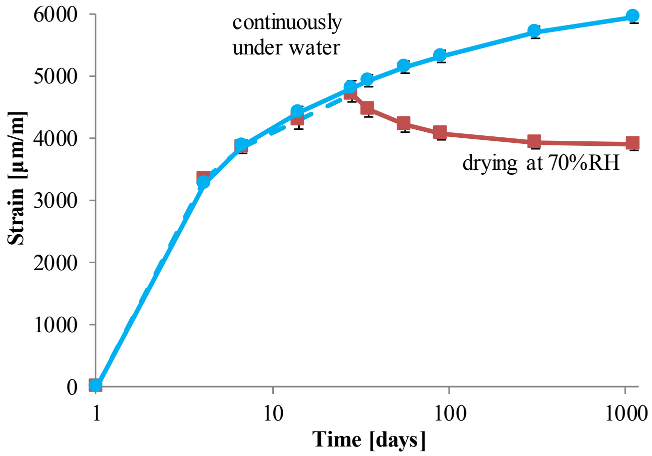

Figure 3. Free expansion of 20%CSA+SRA+SAP concrete stored continuously under water, or exposed to drying at 70%RH and 20 °C at the age of 28 d. Even though expansion reached about 6000 µm/m, the concrete could still reach almost 100 MPa compressive strength. Adapted from (Wyrzykowski et al. 2018).

The freeze-thaw tests reported in (Wyrzykowski et al. 2018) also show that the 20%CSA+SRA+SAP concrete possesses good durability (exposure class XF4 after 28 freeze-thaw cycles -15°C to 15°C with 3% deicing salts, according to the standards SIA 262/1:2003 and SN EN 206-1/NE:2003).

Finally, the ability of the concrete to provide pretensioning of the reinforcement and hence self-prestress was confirmed by the restrained expansion tests. The results of these tests are presented in Fig. 4. These results were obtained after calculating the force in restraining bars based on their measured expansion and for the elastic modulus of 200 GPa, and next, calculating, per equilibrium, the average stress (prestress) in net concrete cross-section, for details see (Wyrzykowski et al. 2018). It should be stressed here that the peak expansion of restrained concretes reached about 1820 µm/m for the reinforcement ratio of 0.9% and 920 µm/m for 2.3%. These values considerably exceed the maximum expansion (700-1000 µm/m in restrained conditions) recommended in (Nagataki and Tsuji 1994), yet without compromising the mechanical properties and durability even in unrestrained conditions.

The levels of residual prestress measured after 1 d (demolding) of about 2.5-3 MPa (note much higher peak values at 28 d, around 4.5-6 MPa, later reduced due to shrinkage and compressive creep of concrete) prove the feasibility of the concrete with combined CSA, SRA and SAP for self-prestressing applications. Hence, the next section of this paper is devoted to the application of such material in combination with the CFRP reinforcement.

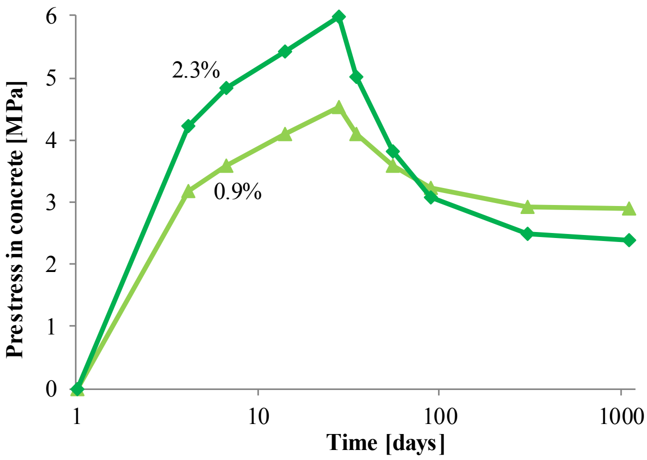

Figure 4. Prestress (self-prestress) in 20%CSA+SRA+SAP concrete restrained with stainless steel bars at two different reinforcement ratios: 0.9% and 2.3%. The samples were kept under water from demolding until 28 d and later drying at 70 %RH. Adapted from (Wyrzykowski et al. 2018).

3.2 Self-prestress of expansive concrete with CFRP – 4-point bending tests

The 4-point bending tests (see scheme in Fig. 1) were carried out in order to determine the influence of self-prestress with CFRP reinforcement on cracking moment, relevant in the serviceability limit state. The two concretes tested (non-expanding and expanding) chosen here had very similar strengths at the age of testing (see Table 1).

In Figure 5, the results of the tests are presented until the point of first cracking. The reference beam experienced significant drop of capacity at the point of cracking, which was due to the relatively high position of the CFRP reinforcement (in this case acting only passively). Note that in the beams with chemical prestress, the time instant of first cracking could not be easily recognized on the curve. The first visible crack could be first spotted around deflection of 2.5 mm and moment of 0.6 kNm. However, based on the change of slope of the curve already earlier the start of cracking can be estimated to have occurred earlier (at deflection of about 1.7 mm and moment of 0.53 kNm). It should be noted that in the second loading cycle (after first cracking, results not presented here), the slope of the moment-deflection curve for the reference beam was lower than in the beams with chemical prestress in the range of deflections considered here, with numerous drops of capacity resulting from further cracking.

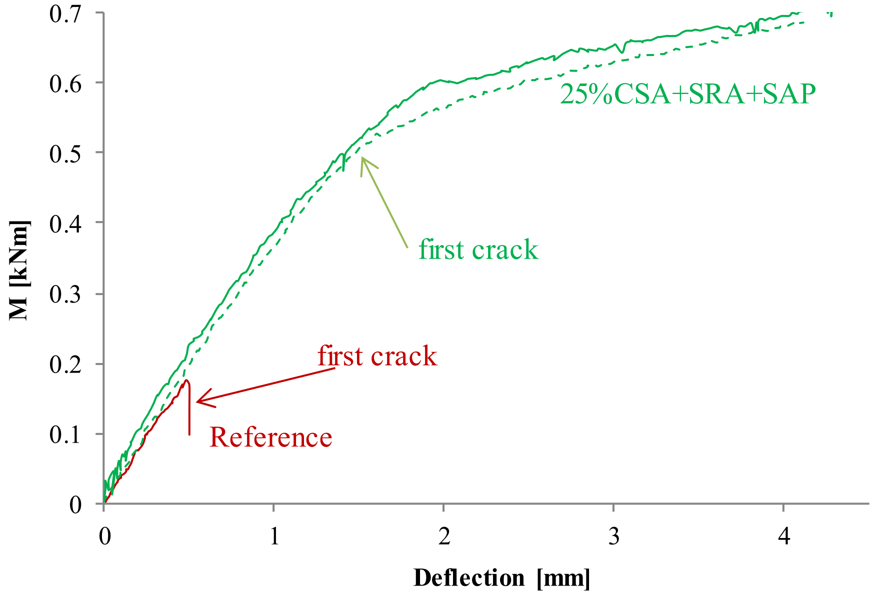

Figure 5. Bending moment vs. deflection curves from 4-point bending tests. The reference beam was made with non-expanding concrete and CFRP tendons (acting as passive reinforcement). The beams made with expanding concrete (25%CSA+SRA+SAP) and CFRP tendons (results for duplicate beams from two separate mixings are shown) could reach ~3 times higher cracking moment than the reference beam.

It can be seen in Fig. 5 that the self-prestress led to a significantly higher cracking resistance – the cracking moment was about 3 times higher compared to the reference beam. Additionally, the crack opening in the reference beam occurred much more abruptly compared to a slow crack opening in the self-prestressed beams.

4 CONCLUSIONS

Self-prestress (chemical prestress) of concrete reinforced with CFRP tendons can offer a series of advantages compared to the traditional prestressing technology, in particular rendering the technology economic and hence more available. However, the main limitation until now has been due to problems with reaching high enough expansion and prestressing potential of concrete without compromising its mechanical and durability properties. Further limitation was due to drying shrinkage and creep of concrete that lead to loss of self-prestress over time. In this work, we show that the highly expansive HPC can be obtained, capable of self-generating high and stable prestress. This is obtained by combining expansive cement (based on CSA), SRA and internal curing with SAP. Even though the concrete expands up to 6000 μm/m in underwater conditions, it can still reach very high compressive strength of almost 100 MPa and experience no visible cracking. The prestressing potential of this concrete, even after exposure to drying, is still very significant as confirmed by the restrained expansion tests, where prestress of about 2.5-3 MPa could be reached. The unique combination of expansion-promoting and shrinkage-reducing components was next used for pretensioning of the CFRP tendons. As shown by the 4-point bending tests, the self-prestressed beams with CFRP reinforcement had about 3 times higher cracking moment than the corresponding reference beam.

These results show that the self-prestress technology with CFRP reinforcement developed recently at Empa can be a viable alternative to the conventional prestressing process and provide slender concrete elements of very high mechanical and durability properties.

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