Chemical prestressing of high-performance concrete reinforced with CFRP tendons

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Abstract

Chemical prestress (self-prestress) is a process, in which expansion of concrete with special additives can be used to generate tension in the reinforcement and prestress in the concrete. Until now, the prestress levels that could be reached with this technique were usually lower than with traditional (external) prestressing. With the new family of expansive high-performance concretes (HPC) developed by us, very high levels of residual expansion can be achieved without compromising the durability and still reaching very good mechanical properties of the concrete. In this paper, we combine the expansive HPC with tendons made of ultra-high modulus (>400 GPa) carbon fiber reinforced polymers (CFRP). Through the expansion of the concrete and its bond with the sand-coated tendons, we could introduce tensile stresses of more than 600 MPa in the tendons (for 1% reinforcement ratio), corresponding to more than 4 MPa compressive stress (prestress) in the concrete. 4-point bending tests show that the chemical prestress increased the cracking moment of slender concrete beams more than three times compared to the reference concrete. Our long-term tests of the strains of the tendons show that the losses of prestress due to shrinkage and compressive creep are very low.

Keywords: Chemical prestress; Self-prestress; CFRP; HPC; Prestress loss
1. Introduction

The idea of pretensioning (i.e. prestressing with direct bond) became technically feasible in the 1920s with the introduction of high strength steel tendons and wires together with efficient anchorage designs capable to tension the steel at high levels [1-3]. One main durability issue was guaranteeing the passivation of the prestressing steel over the planned service life [2]. In fact, for prestressed concrete exposed to the environment, depending on the exposure class, a concrete cover thickness of 50-65 mm needs to be guaranteed to protect the steel reinforcement from corrosion (see civil engineering standards like the European EN1992-1-1 or the American ACI 318R-05). With the advent of High Performance Concrete (HPC) having lower permeability than conventional concrete, e.g. [4, 5], and hence providing better corrosion protection [6, 7], the attempts at reducing the necessary concrete cover were made. However, as long as sound (uncracked) HPC provides better protection than ordinary concrete, the benefits become less significant once cracking of concrete occurs, exposing the reinforcement to the hazardous environment [8]. Still, lower corrosion rates, even in cracked concrete, are found for the thicker cover [8], which is one of the reasons why no significant reduction of sizes of prestressed concrete reinforced with steel could be achieved. In fact, according to EN1992-1-1, the minimum concrete cover can be reduced by only 5 mm in some cases, if concrete of high strength is used.

The introduction of alternative prestressing tendons of high strength and corrosion resistant Fiber Reinforced Polymers (FRP) [9-12] launched the research topic of thin, pre-fabricated, prestressed elements with FRP reinforcement [13]. FRP allow reducing the thickness of concrete cross-sections, since steel is absent and the concrete cover thickness can be reduced to a minimum, being defined only by the uptake of static forces and by the thermal compatibility of the FRP reinforcement with the HPC.

Prestressed HPC elements reinforced with tendons made of pultruded Carbon Fiber Reinforced Polymer (CFRP) have been studied at Empa since the 1990s [14]. With their low density (1.6 kg/m³) and very high strength (>1000 MPa) and relatively high modulus of elasticity (>150 GPa), CFRP tendons perform in many aspects better than traditional prestressing steel tendons [15, 16]. This regards especially their practically complete resistance to corrosion, whereas corrosion is the main drawback of traditional prestressing steel. Use of CFRP tendons allows reducing the thickness of the concrete cover to 15-25 mm and hence the dimensions and the weight of the whole element [15, 17] (the whole thickness of the element can be then reduced by even 100 mm, compared to only 10 mm reduction if HPC is used with steel reinforcement). The interfacial bond between the CFRP tendons and the HPC is achieved with an outer quartz-sand coating adhered on the CFRP tendon’s surface by an in-line spray coating after pultrusion [15, 16].
Notwithstanding the excellent properties of the constituent materials CFRP and HPC, the need for a prestressing step is one main drawback of the existing CFRP-HPC technology. Prestressing and anchoring, in particular with CFRP tendons, are time consuming, labor intensive, complex and delicate procedures [15]. The CFRP clamping anchorage presently used for the CFRP wires has a similar geometry and working principle to that of prestressing steel wires and allows for a pretensioning up to only 60% of the CFRP wire strength [18]. Moreover, some anchorage failures are unavoidable during prestressing, which can cause not only failure in the cast elements, but is also dangerous for the production staff, if long prestressing wires fail instantly with 100% elastic energy release.

As an alternative to the conventional pretensioning process, the chemical prestress (self‐prestress) technology has been proposed already in the 1960s [19‐21]. This approach is based on using highly expansive concrete that, while expanding during hardening, exerts tensile stress (pretension) on the tendons and compressive stress (prestress) in the concrete. Chemical prestress has been used with either steel reinforcement, e.g. [22‐25] or FRP, e.g. [26, 27] (including also external CFRP reinforcement [28]).

However, the tensile stress levels that could be obtained in the tendons due to expanding concrete were limited and could not achieve the levels obtained with conventional, externally pretensioned tendons. Concrete with expansion sufficient to introduce high tension in the tendons (i.e. in restrained conditions) can reach much higher expansion in the zones of an element where the expansion is unrestrained, e.g. between reinforcement, or at the free edges of the element, see e.g. [19, 29]. A negative effect of such excessive expansion is cracking or even disintegration of the concrete. The maximum expansion in restrained conditions recommended in [29] is 1000 µm/m (as assessed with uniaxial steel reinforcement at 0.95% reinforcement ratio, after 7 d of underwater curing according to the Japanese standard [30]). Further challenge in using chemically‐prestressed concrete is, similarly as in a conventionally prestressed concrete, loss of prestress due to shrinkage and (compressive) creep of concrete [3, 31].

In our recent study [32], we have shown that it is possible to obtain concrete with very high residual expansion, capable of providing high prestress levels, yet maintaining typical HPC features, i.e. high strength and stiffness and good durability. The restrained expansion at 0.9% reinforcement ratio reached over 1400 µm/m at 7 d (compare to 1000 µm/m allowed in [29]) and over 1800 µm/m at 28 d, and the long‐term expansion during underwater storage exceeded 5500 µm/m at 3 y. Despite these high expansion levels, the long‐term compressive strength of the concrete reached about 100 MPa after 3 years. The residual prestress recorded from 1 d (i.e. at demolding) reached about 2.5‐3.0 MPa after drying at 70 %RH. This value confirmed the prestressing potential, cannot be however used for any design of the
actual prestress in concrete elements. This is because the geometry and anchorage of the reinforcement is different
from real conditions and because the test does not measure prestressing occurring before demolding.
To this end, the goal of the study presented here was to test the self-prestressing ability of HPC with CFRP tendons. The
major motivation was to develop self-prestressed elements with CFRP tendons, therefore combine the advantages of
the non-ferrous pretensioned reinforcement, while avoiding the expensive, time- and labor-consuming pretensioning
process of the latter. This could open new applications for slender concrete with pretensioned CFRP reinforcement, e.g.
for structural façade elements, electricity poles, pavilions, or non-structural elements like fences, benches, etc.
We prepared different unidirectionally-reinforced elements (beams) made with expansive concrete and reinforced with
CFRP tendons. The elements were subject to different curing conditions (sealed or underwater) and exposed to different
drying conditions afterwards. Two types of tests were carried out to assess the feasibility of the chemical-prestress/CRFP
technology:
- 4-point bending tests of the chemically-prestressed beams were aimed at testing the effect of prestress on the
  cracking stress. This characteristic is relevant to structural applications designed under the Serviceability Limit
  State (SLS). The performance of the self-prestressed concrete was compared to a reference concrete (not
  expanding concrete). The reference concrete was adapted from a mix used in the precast industry to have
  similar mechanical properties as the expanding concrete (see Appendix). The beams made with the reference
  concrete were also reinforced (in this case passively) with the CFRP. Before (curing period) and during the
  bending tests, pretensioning of the tendons was measured by means of strain gauges glued on their surfaces.
- Long-term pretensioning/prestress tests. In these tests, the concrete prestress was assessed based on the
  strains of the pretensioned CFRP tendons measured after casting, during underwater curing and later during
  drying and periodic exposure to water. The tests lasted until 3 years of age and allowed assessing the long-
  term losses of prestress due to shrinkage, creep of concrete or possible damage (e.g. slip of tendons or
  excessive expansion of concrete resulting in cracking) under changing environmental conditions.
2. Materials and methods

2.1 Mix design

The raw materials used in this project were the same as in [32]. Ordinary Portland cement CEM I 52.5 R (Jura, Switzerland) had the following oxide composition (XRF, by mass): CaO 63.15%, SiO₂ 19.53%, Al₂O₃ 4.86%, Fe₂O₃ 3.49%, MgO 1.59%, K₂O 0.89%, Na₂O 0.14%, SO₃ 3.28%, loss on ignition 2.34%.

A commercially-available additive based on calcium-sulfoaluminate (CSA) (CSA#20 by Denka) was used in the amounts of 16 and 25% (by mass of Portland cement). The CSA additive had the following composition (Rietveld analysis, by mass): anhydrite 48%, ye’elimite 22%, lime 19%, portlandite 9%, pericline 1%, calcite 1%. The two amounts of CSA were aimed at reaching sufficient expansion in underwater and sealed conditions, respectively.

Additionally, one non-expanding concrete was prepared to serve as a reference for the 25%CSA mix in the four-point bending tests. In the reference mix, fly ash was used (Hydrolent by Holcim) in an amount of 25% by mass of cement.

The fly ash had the following oxide composition (XRF, by mass): CaO 9.09%, SiO₂ 50.83%, Al₂O₃ 19.65%, Fe₂O₃ 8.36%, MgO 2.13%, K₂O 2.61%, Na₂O 0.72%, SO₃ 0.87%, loss on ignition 3.35%. The reference mix was based on a concrete mix used in the Swiss precast industry, see [33, 34], with composition adjusted so that it had similar strength to the expanding concrete.

Limestone powder with >99% CaCO₃ content (by mass), density of 2.7 g/cm³ and a median particle size d₅₀= 4.5 μm was used in the expanding concrete as filler in an amount of 5% by mass of Portland cement.

The aggregate was alluvial sand from Switzerland with well-rounded particles of 0-4 mm size, density of 2.65 g/cm³ and very low water absorption (<0.6% according to EN1097-6).

A polycarboxylate-based superplasticizer (Viscocrete-1 S by SIKA) was used to control the workability (note that no vibration was necessary during casting thanks to the high flowability of the mixes, see Table 1). The shrinkage reducing admixture was a liquid commercial product (Control 60 by SIKA). Superabsorbent polymer (SAP) was a solution-polymerized hydrogel based on covalently cross-linked modified polyacrylamides with particle sizes (in the dry state) in the range 63-125 μm. The pore fluid absorption was assumed as equal to 17 g/g based on our previous study, where it was assessed based on micrographs of polished sections of cement paste [35]. The SAP was used to provide internal water curing and hence reduce the autogenous shrinkage [35, 36] and enhance the initial expansion of the concrete, for details see [32]. The mix compositions are summarized in Table 1.
Mixing took place in a rotating-pan concrete mixer (Eirich) with 80-l capacity. All dry constituents were initially mixed in the mixer. Special care was taken to uniformly distribute the small amount of SAP powder in the last dry mixing step.

Next, water with incorporated liquid additives (SRA and superplasticizer) was added and wet mixing took about 2 min.

Immediately after mixing, the fresh properties (air content, density and spread) were measured and the beams were cast without vibration. The molds were made of either stainless steel with polyethylene base (for 1200-mm beams) or plastic-coated plywood (for 500-mm beams).

Mixing took place at 21±1.0 °C, while sample storage and all the tests took place at 20±0.3 °C.

<table>
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<tr>
<th>Mix name/Material</th>
<th>Reference</th>
<th>25%CSA</th>
<th>10%CSA</th>
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<tr>
<td>Cement CEM I 52.5R</td>
<td>402</td>
<td>469</td>
<td>499</td>
</tr>
<tr>
<td>CSA-based expansive agent</td>
<td>-</td>
<td>117</td>
<td>79.9</td>
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<td>Fly ash</td>
<td>101</td>
<td>-</td>
<td>-</td>
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<td>25.0</td>
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<td>213</td>
<td>211</td>
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<td>Superplasticizer</td>
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<td>17.1</td>
<td>10.9</td>
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<tr>
<td>SRA</td>
<td>-</td>
<td>15.2</td>
<td>15.1</td>
</tr>
<tr>
<td>SAP</td>
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<td>1.78</td>
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<td>1431</td>
<td>1403</td>
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<tr>
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<td>0.35</td>
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</tr>
<tr>
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<td>790 mm</td>
<td>530 mm</td>
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<tr>
<td>Air content</td>
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<td>1.6%</td>
<td>3.7%</td>
</tr>
<tr>
<td>Fresh density</td>
<td>2261 kg/m³</td>
<td>2271 kg/m³</td>
<td>2239 kg/m³</td>
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</table>

### 2.2 Geometry and reinforcement of the beams

Two different geometries of the beams were made for 4-point bending tests: 45×100×1200 mm³ and 45×150×1200 mm³, see Fig. 1. The two geometries were chosen in order to test the effect of two different reinforcement ratios (net ratios of 0.99% and 0.66%, respectively) that may be employed in practical applications. These beams were made of the 25%CSA and the Reference concretes (see Table 1). Duplicate beams were cast for the 25%CSA concrete.

For the long-term prestress tests, one geometry was studied: 45×200×500 mm³ (net reinforcement ratio of 0.49%). These beams were made of the 16%CSA concrete.
All beams were cast lying flat, as presented in Fig. 2.

Fig. 1 Schematic representation of the cross-sections of the tested beams and a photograph of a 45×200×500 mm³ beam. Dimensions in millimeters.

Each of the beams had two CFRP tendons placed at mid thickness at a horizontal distance corresponding to a uniform spacing in a virtually infinite slab, see Fig. 1. The CFRP tendons were manufactured batchwise by a commercial company (Carbolink AG) in a tape-laying method with ultra-high modulus pitch-based Mitsubishi DIALED™ carbon fibres. The resin-coated surfaces of the tendons were immersed in quartz sand that ensures good bond with the concrete [15, 16]. The tendons had a nominal diameter of 5.3 mm without coating and 7 mm with coating. Two types of tendons, based on two types of carbon fibers were used, type K63A12 for the 4-point bending tests and type K13916 for the long-term
prestress tests. The two types of tendons had elastic Young’s moduli in tension in the longitudinal direction equal to 464
GPa and 509 GPa, respectively [16]. The tensile strengths were equal to 1029 MPa and 1562 MPa, respectively.

Fig. 2. Casting of a 45×150×1200 mm³ beam. The strain gauges glued in the center of the tendons are visible.

2.3. Curing and storage

The free cast surfaces were covered with >4 layers of plastic foil (food wrap) directly after casting to avoid evaporation.

At the age of 17 ± 0.5 h, the ends of the molds were loosened in order not to hinder the expansion of the beams in the longitudinal direction. At the age of 24 ± 0.5h, the beams were removed carefully from the molds.

After demolding the beams for 4-point bending tests (concretes 25%CSA and Reference) were wrapped in >4 layers of food wrap. At 7 days from casting, the beams were opened to drying at 70±3 %RH and 20±0.3 °C. During storage, the beams were left in horizontal position.

The beams for long-term tests of prestress were stored under water after demolding. At the age of 28 d, the beams were removed from the water bath and exposed to drying at 56±3 %RH and 20±0.3 °C until an age of about 3 y, with a second 7-d period under water at 2 y. This short period under water was aimed at testing whether repeated water exposure would lead to uncontrolled expansion or whether repeated drying would lead to excessive prestress losses.
2.4. Measurements of strains of the tendons

Strains of the prestressing CFRP tendons were measured with strain gauges glued on the surfaces of the tendons in their central part. One or two strain gauges (on the opposite sides) per tendon were used. The strain gauges 1-LY41-3/120 by HBM with 3-mm-long measuring grid on an 8-mm-long carrier, configured in a quarter bridge circuit, were used. First, sand coating was removed from the surfaces of the tendons in their central part. The strain gauges were glued according to the manufacturer’s specification and covered with a water resistant resin or putty to protect them from the aggressive concrete environment (high-pH pore solution) and mechanical damage. The wires of the strain gauges were attached to the tendons to protect them from being pulled during casting. During casting the wires were lifted so that they projected out of the beam elements perpendicular to their surfaces, see Fig. 2.

The measurements were recorded with an MGCplus logger by HBM. For the tests on long-term prestress measurements, the strains were recorded at 10-min intervals during the first 7 days after casting, then at 7-d intervals until 28 d, and finally at 1-3-months intervals. In the slabs used for 4-point bending, strains were recorded at 3-min intervals during 28 d from casting (i.e. until bending tests) and at 1-s intervals during the bending tests, see Fig. 4.

Fig. 3. Strain gauge glued on the surface of a CFRP tendon (after removal of the sand coating), covered with water-resistant resin for measurements of strains during pretensioning.
2.5. 4-point bending tests

At the age of 28 days, the slabs were tested according to a 4-point bending scheme, see Fig. 4. A hydraulic machine (Walter&Bai) was used working in a displacement-controlled mode, with loading speed corresponding to displacement of the loading piston of 0.2-0.5 mm/min (depending on the test). The mid-span deflection of the beams was measured by the deflectometer placed underneath the beams, see Fig. 4.

Fig. 4. a) Scheme of the test setup (dimensions in mm) and b) a photograph of a self-prestressed beam during testing.

Before testing, about 2-3 mm were cut from the ends of each beam and ground with sand paper in order to provide a flat surface and enable observing a possible draw-in (loss of bond due to slip) of the tendons in the beam during bending. Side and bottom faces of some slabs were painted with white emulsion paint in order to facilitate the observation of cracks.
3. Results

3.1. Chemical prestress prior to loading

Before testing the performance of self-prestressed beams under load, the development of pretensioning force in the tendons during curing until 28 d was studied. The pretensioning force in the tendons was determined based on the strains recorded by the glued strain gauges and considering the elastic Young's modulus of the tendons equal to 464 MPa. The results are presented in Fig. 5a. The stress curves calculated based on strains of the tendons were obtained as average from two strain gauges per tendon (on opposite sides of the tendon and in the center of its length) and from two tendons per beam (i.e. 4 strain gauges per beam). Each curve thus represents the average stress in a separate beam.

Only one strain gauge (out of a total of 16 gauges in all tests) failed and was not included in the data evaluation. The difference in measured strains between the two tendons in each beam corresponded to a difference in the estimated stress of 80 MPa at most, and typically below 40 MPa (about 6% of maximum stress). Note that the pairs of the same geometries come from separate concrete batches. In general, the strains/stresses obtained from different beams of the same geometries mixed and cast independently showed very good agreement, see Fig 5a.

Further, knowing the pretensioning force in the tendons, we could estimate the development of the average prestress in the concrete net cross-section (i.e. after excluding the area of the tendons) assuming the force equilibrium in the cross-section, Fig. 5b.

The beams with a wider cross-section (45×150 mm²) could exert higher pretensioning stress on the tendons, see Fig. 5a. This could be expected, considering the higher ratio between the areas of concrete and tendons in these beams, and hence the lower degree of restraint. Interestingly, with different pretensioning strains and stresses in the tendons, the pretensioning force divided by the concrete net cross-section, i.e. the actual average prestress in concrete, was practically equal in both tested geometries, see Fig. 5b. The maximum prestress level (compression) of around 4.5 MPa (and residual of around 4.1 MPa) obtained here with chemical prestress is comparable to the externally applied prestress reported in literature. E.g. 5.6 MPa was applied in beams with pretensioned steel wires in [37]. Prestress levels in high-performance concrete obtained with externally-prestressed CFRP tendons reported in [15] were: about 2.9 MPa in load-bearing façade beams (U-shape cross-section), 6.5-14 MPa in concrete electricity pylons (the difference is due to the variable cross-section of the pylon), 6-7 MPa in window and balcony sills and load-bearing façade beams (L-shape cross-section) and 4.9-7.4 MPa in façade columns. It should be mentioned that in the case of external CFRP prestressing, the maximum prestress level was limited by the anchorage of the tendons (the anchorage reported in [18] allowed
pretensioning the tendons to only 60% of their strength). On the contrary, no such limitation exists in the case of self-prestress, as no external anchorage is necessary.

The prestress obtained here is also considerably higher than what obtained previously with chemical prestress, e.g. 2.0 MPa could be obtained with low-modulus FRP tendons and 2.4 MPa with steel tendons in [38].

Fig. 5. a) Evolution of stress in the CFRP tendons (tension) due to expansion of the 25%CSA concrete. Each curve represents the average stress from two tendons in a single beam. Stresses in tendons were calculated from strains, with Young’s modulus of the CFRP tendons equal to 464 GPa; b) estimated evolution of average compressive stress (prestress)
in concrete net cross-sections for each beam. The beams were kept sealed during the first 7 d and then opened to drying at 70 %RH until 28 d.

The curing history is clearly reflected in the shapes of the stress curves in Fig. 5. The expansion started at about 0.7 d. Even though final set occurred already likely before 0.5 d (estimated based on a similar mix with 20%CSA tested in [32]), the relatively stiff steel molds restrained the initial expansion of the concrete. At about 0.7 d, the screws of the mold were loosened (and the mold was removed completely at about 1 d) and rapid expansion started, leading to very high pretensioning of the tendons. The beams were sealed from the time of demolding until 7 d. Next, the expansion was arrested due to drying shrinkage that started directly after removing the sealing foil and exposing the beams to drying at 70 %RH. Drying shrinkage and compressive creep of the (prestressed) concrete competing with still ongoing expansion (see [32]) led however only to negligible loss of prestressing force until 28 d of age.

3.2. Bending cracking resistance

The 4-point bending tests were carried out at an age of 28 d on 4 beams made with 25%CSA concrete (2 beams of 100-mm width and 2 beams of 150-mm width, chemical prestress reported in the previous section) and 1 pair of the beams made with the Reference concrete. The bending stress-deflection curves until the first crack are presented in Fig. 6. The bending stress was calculated as $6M/(bh^2)$, with $M$-bending moment in mid-span, $b$-width (100 mm or 150 mm), $h$-height (45 mm) of the cross-section, using in the calculations the whole section height also after cracking; this enables comparing beams of different cross-sections. The opening of the first crack was clearly visible on the curves for the reference concrete, where a clear drop of stress could be seen, see Fig. 6. Moreover, the first crack opened abruptly and was very clearly visible on the bottom and side surfaces of the beams. For the chemically-prestressed concrete, the first crack was first visually evident at stress levels above 12.5 MPa and deflection of about 2.5 mm. Unlike for the reference beams, no clear drop of the stress could be observed on the curves.
Fig. 6. Stress-deflection curves from 4-point bending stress of the beams made of the reference concrete and the chemically prestressed concrete (25%CSA, see Table 1), presented until first crack. Note that for the chemically-prestressed concrete 2 beams were tested for each width (100 mm and 150 mm), coming from independent mixings (4 curves in total). A more than threefold increase in cracking stress was obtained with chemical prestress.

However, the occurrence of the first crack can be assessed based on the strains of the tendons during the 4-point bending test, Fig. 7. This was carried out on one 45×100×1200 mm³ beam and one 45×150×1200 mm³ beam as continuation of the measurements of prestress development (see the results of the two beams in Fig. 5). The strain gauges were glued on the bottom and top surfaces of the tendons. As previously, the results from the strain gauges are transformed to stresses. Before cracking, the strain gauges at the top side of the tendons could measure a slight decrease of the length (resulting in a slight drop of the pretensioning stress) as the tendons were placed centrally in the height of the cross-sections and hence their top surfaces were above the neutral axis before cracking. On the other hand, a slight increase in the extension and hence increase of the pretensioning stress was measured by the strain gauges glued on the bottom of the tendons, i.e. below the neutral axis. The change from shortening to extension measured on the top surfaces of the tendons, and at the same time the clear change in slope of the extension at the bottom surface of the tendons, allow identifying the moment when the beam cracks (see Fig. 6). After first cracking of the chemically-prestressed beams, the contribution of the tendons to bearing the stress in the cross-section increases and the tendons extend considerably, with the bottom face extending more than the upper face. Even though the beams were loaded until failure, the behavior after cracking is beyond the scope of this study, which aims at improving the
cracking resistance under the SLS. It is only worth mentioning that the extension (and hence tension) in the tendons after cracking and until failure was approximately proportional to the bending stress in the cross-section of the beam, which proves a perfect bond between the sand-coated CFRP and the concrete. Also, no draw-in of the tendons could be observed on the beams after the failure.

**Fig. 7.** Stress (tension) in the mid-length of the CFRP tendons in chemically-prestressed beams (25%CSA concrete): a) 45×100×1200 mm³ and b) 45×150×1200 mm³, as a function of the mid-span deflection of the beam in 4-point bending test (primary ordinate axis). Stresses in the tendons were estimated based on strains.
measured with strain gauges glued on the two CFRP tendons reinforcing the beam, at the top and bottom surfaces of the tendons. The instant at which the first crack occurs is identified as the point at which shortening of the upper face of the tendon changes to extension. Additionally, the bending stress in the section is presented (secondary ordinate axis).

From this, it can be concluded that the first crack (not yet visible, i.e. thinner than about 0.1 mm) started already earlier (about 2 min earlier than visually spotted), around the stress of about 11 MPa and deflection of about 1.7 mm for the 100-mm wide beam, Fig. 7a and around the stress of about 10.4 MPa and deflection of about 1.6 mm for the 150-mm wide beam, Fig. 7b. The changes in the slopes of the strains/stresses of the tendons correspond also to the points at which the slope of the bending stress-deflection curves of the chemically prestressed beams clearly drops, see Fig. 7.

It should be noted that the two different geometries of the chemically-prestressed beams had almost identical course of the curves, which is in line with similar levels of prestress in the two beams shown in Fig. 5b. Also, the very close results for all beams prove a very good reliability and replicability of the tests (mind that beams were cast in pairs in independent mixings).

The results in Fig. 6 clearly show that the cracking stress/resistance in chemically-prestressed beams is more than 3 times higher than in the reference concrete.

The clearly positive effect of chemical prestressing on the cracking resistance becomes even more obvious when one considers that the two concretes compared had very similar compressive and flexural strengths, and the Reference concrete had significantly higher elastic Young’s modulus than the 25%CSA concrete, see Fig. A1 in the Appendix. The latter difference is due to a relatively higher content of aggregates in the reference concrete compared to 25%CSA concrete, about 60% by volume compared to about 55%, respectively.

3.3. Long-term prestress

After proving the feasibility of the technology of chemical-prestressing of the HPC-CFRP elements for improving the cracking resistance reported in the previous chapter, the long-term performance of the chemical prestress was studied. For this purpose, two small-scale beams of sizes 45×200×500 mm³ were studied, see Figure 1. The length of the beam equal to only 500 mm was chosen to enable easy handling of the elements during the tests, yet providing sufficient
prestress transfer length for CFRP tendons. The latter was assumed to be equal to 160 mm for the sand-coated CFRP [39].

In the course of the project it was found that lower amount of expansive CSA additive combined with underwater curing is a more robust solution for providing durable prestressed concrete. As long as high prestress could be obtained with the 25%CSA addition cured in sealed conditions (see previous chapter), the risk of excessive expansion continuing at later ages exists in case the elements were exposed to water. For this reason, the amount of CSA was reduced to 16% and water curing was applied to enhance the hydration of the CSA cement and hence exhaust the expansion and prestressing potential already during the curing stage. As shown in [32], such procedure allows obtaining high-strength and durable concrete even for extended periods of underwater curing i.e. up to 3 y and high levels of free expansion.

In Fig. 8 the stresses calculated based on the measured strains of each tendon are presented (for elastic Young's modulus of the tendons equal to 509 GPa). The high scatter of the results is most likely due to the relatively low precision of the dimensions of the beams. As long as high-precision steel molds were used for the long beams presented in the previous chapter, resulting in a very small scatter of the results, see Fig. 5, the beams studied in this part of the project were cast in plywood molds, where the precision of the dimensions was about ±3 mm. This may lead to relatively large eccentricities of the tendons and hence large differences in their strains. Also, somehow strange results were obtained from two tendons. Strain gauge glued on the tendon 1 in beam 1 measured first shortening after the beam had been exposed to drying, but it was followed by a considerable expansion that started a couple of days later and continued until about 90 d. Later, shortening of the tendon was again measured. On the other hand, the strain gauge on tendon 2 in beam 2 experienced extension from about 180 d that continued until about 600 d. The reasons of such behaviors are not clear. Besides the aforementioned probable eccentricity of the tendons, it is also possible that the expanding concrete pressing on the strain gauges affected their performance, or that the strain gauges were exposed to water (despite the sealing) during underwater storage of the beams. In spite of these negative effects, it is still possible to assess the long-term performance of the chemical prestress.

Considerably higher levels of pretensioning stress in the tendons were reached compared to the beams tested for 4-point bending. This was primarily due to larger concrete cross-section (at the same area of reinforcement), and hence lower degree of restraint of the expanding concrete and due to underwater storage. However, after transforming the stresses in the tendons to the average prestress in net concrete cross-section, similar levels of prestress are found as in Fig. 5, i.e. the average prestress at the age of 2 y is equal to about 5.2 MPa. The loss of prestress due to drying or creep
of concrete were very low compared to the initial prestress reached at the end of the curing period and it stabilized around 1 y already. No long-term decrease of prestress was visible; such loss could occur e.g. due to damage of the concrete (cracking) or slip of the tendons.

When the beams were exposed to water for 7 d (at the age of about 2 y), the expansion continued during the exposure. However, after exposing the beams to drying again, it could be seen that this cycle did not lead to any negative effects in terms of the prestress. It can be assumed that the occasional exposure to water and hence continuing expansion followed by re-drying does not negatively affect the durability.

The good long-term bond between the sand-coated CFRP tendons and concrete is in line with previous measurements, where bending creep in conventionally prestressed elements was studied [40].

![Graph showing stress in tendons over time](image)

*Fig. 8. Evolution of stress in the CFRP tendons (tension) due to expansion of the 16%CSA concrete. Stresses in tendons were calculated from strains, with Young’s modulus of the CFRP tendons equal to 509 GPa. The beams with cross-section of 45x200x500 mm³ reinforced with 2 CFRP tendons were kept underwater during the first 28 d and next opened to drying at 56 %RH. At the age of about 2 y the beams were placed underwater for 7 d, followed by drying.*

**Conclusions**

In this study we investigated the self-pressurizing potential of expansive HPC in elements reinforced with ultra-high modulus (>460 GPa) CFRP tendons. A special concrete mix, containing a combination of CSA-based expansive cement,
SRA and SAP developed at Empa [32] was used for this purpose. The expansion of concrete leads to a gradual extension of the tendons during hardening, thanks to the good bond between the concrete and the quartz-coated CFRP tendons. The extension of the tendons, measured with strain gauges glued on their surfaces, results in a tensile stress (pretension) from >400 to > 1000 MPa (depending on curing conditions and reinforcement ratio). As a consequence, an average compressive stress (prestress) of 4 to 5 MPa is induced in the concrete. This level of prestress is comparable to that applied currently in conventional (external) prestressing technology of concrete reinforced with CFRP [15]. At the same time, chemical prestressing considerably simplifies this technology (no prestressing bed nor elaborate anchorage systems for the tendons are necessary with self-prestress).

The high initial pretensioning/prestress levels can be maintained even after prolonged drying periods (e.g. drying at 56 %RH during 2 y). This shows that the prestress losses due to drying shrinkage and compressive creep of concrete are very low. At the same time, the creep and relaxation of the tendons can be assumed negligible. It also shows that the bond between the tendons and the concrete can be maintained for the long-term.

The self-prestressing action of the concrete in combination with the CFRP tendons was also assessed by means of 4-point bending tests. In these tests, cracking resistance (stress at cracking) of rectangular beams made with reference (non-expanding) and expanding concretes was determined. Both reference and self-prestressed beams were reinforced with CFRP tendons. The beams with chemical prestress had more than 3 times higher cracking stress than the reference beams. Also, perfect bond between the tendons and the concrete could be maintained until failure, as shown by the strain measurements on the tendons. These results show that chemical prestress (self-prestress) of HPC combined with CFRP reinforcement can be used as an alternative to conventional prestressing, in particular conventional prestressing with CFRP reinforcement.

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Conflict of interest

The authors declare that they are inventors in a patent application related to the self-prestressed HPC-CFRP technology presented in this paper, filed by the institution of the authors (Empa): Lura, Terrasi, Wyrzykowski: Self-prestressed reinforced concrete elements (2016) EP3106446A1.
Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time due to legal reasons (patent application).

References


Appendix

The mechanical properties of the Reference concrete and of the expanding concrete (25%CSA), see Table 1, used in 4-point bending tests are presented here. Flexural strength was first measured and next compressive strength was measured on the halves of the prisms according to the standard EN 196. Static Young’s modulus in compression was measured by loading the samples to 30% of their compressive strength, following the standard EN 12390-13:2013. The tests were carried out on prisms 25×25×100 mm$^3$ instead of 40×40×160 mm$^3$ prescribed in the standards. The smaller sample sizes were chosen considering that relatively small aggregates size (up to 4mm) were used. The prisms were cast in steel molds and stored at >95%RH and 20 °C. At the age of 1 d, the prisms were demolded and wrapped in several layers of food wrap (sealed curing) until the age of testing. Duplicate samples were used for the tests. The results are presented in Fig. A1.
Fig. A1. Mechanical properties of concretes used in 4-point bending tests: a) compressive strength, b) flexural strength, c) static elastic Young’s modulus in compression. The tests were carried out on prismatic samples (25×25×100 mm$^3$) cured in sealed conditions. Error bars represent standard deviation from duplicate samples.