Cite as: Terrasi G, Maluk C, Bisby L, Hugi E and Kanik B. 2012. Fire Experiments of Thin-Walled CFRP Pretensioned High Strength Concrete Slabs Under Service Load. Proceedings of the 6th International Conference on FRP Composites in Civil Engineering (CICE 2012), 13-15 June, 2012, Rome, Italy.

FIRE EXPERIMENTS OF THIN-WALLED CFRP PRETENSIONED HIGH STRENGTH CONCRETE SLABS UNDER SERVICE LOAD

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Abstract

Sustainable precast concrete elements are emerging utilizing high-performance, self-consolidating, fibre-reinforced concrete (HPSCC) reinforced with high-strength, lightweight, and non-corroding prestressed carbon fibre reinforced plastic tendons. One example of this is a new type of precast carbon FRP pretensioned HPSCC panel intended as load-bearing panels for glass concrete building facades. It is known that the bond strength between both steel and FRP reinforcing tendons and concrete deteriorates at elevated temperature and that high strength concrete tends to an explosive spalling failure mode when subjected to a fire. The bond strength reductions in fire, their impacts on the load-bearing capacity of prestressed concrete structures, and the spalling behaviour of high-strength concrete remain poorly understood. This paper gives insight in the fire behaviour of filigree CFRP prestressed HPSCC slabs and presents selected results and analysis of an experimental fire test series on 45 mm and 60 mm thin-walled slabs. The main findings are that the fire resistance of the slabs is determined by spalling of the HPSCC or – if spalling can be avoided by the use of 5 kg/m^3 PP microfibers in the concrete – by the thermal splitting-crack induced bond failure of the CFRP tendons in their prestress transfer zone.

Keywords: Carbon fiber reinforced polymer, Fire resistance, Full-scale fire tests, High-strength concrete, Precast prestressed concrete,

1. Introduction and Materials

The structural elements in the current study were CFRP prestressed concrete planks. 5.4 mm diameter, round, pultruded, quartz sand-coated CFRP prestressing tendons were used. The carbon fiber volume fraction was 62% and the tendons had an epoxy polymer resin matrix with a glass transition temperature, T_g, of 121 °C. The tendons' nominal tensile strength was 2000 MPa with an elastic modulus of 150 GPa and an ultimate strain of 1.33%. The low density, excellent stress-corrosion resistance, and low creep and relaxation [1] of CFRP are well known. The above properties make unidirectional CFRP tendons particularly suitable as prestressing reinforcements for concrete elements [2].

The current study used a high performance, self-consolidating concrete (HPSCC) of strength class C90 (minimum 150mm cube strength after 28 days of 90 MPa); this material is becoming popular for producing slender precast, prestressed elements in Switzerland. The HPSCC is characterized by a precise grain size distribution of selected 0-8 mm limestone aggregates, with a cement content of 450 kg/m^3. Silica fume, fly ash, and high performance superplasticizers play a key role in the mix. This particular HPSCC mix design allowed for optimum self-compacting properties at water/(cement+silica fume+fly ash) ratios in the range of 0.39-0.40. 20 mm long (37 x 200 μm cross-section) polypropylene (PP) fibres with a melting temperature of 160-170°C were included in the some of the concrete mixes (mixture 042, without fibres) at 2 kg/m^3 (mixture 142) and at 5 kg/m^3 (mixture 242), with the objective of preventing shrinkage cracking and fire induced explosive spalling. For mixture 242, self-compacting behaviour could not be achieved because the PP fibre content was too high and the water/binder ratio too low (0.324). After casting the elements were kept under a polyethylene sheet for 5 days and then left to cure under ambient conditions.

The combination of CFRP and HPSCC, along with an appropriate interface between them (sand-coating of the CFRP), make it possible to minimise the weight of prestressed bending elements by reducing concrete cover and wall thickness while providing excellent serviceability (no susceptibility to corrosion, high bending stiffness, and high fatigue strength). However, the performance of these elements during fire is not well unknown.

2. Experimental Specimens

Eleven thin walled (45-60 mm total thickness) slabs with rectangular cross-sections (200 mm wide) were produced by precaster SACAC AG in Lenzburg, Switzerland (Table 1). The CFRP tendons were stressed to an initial prestress of either 800 or 1200 MPa. Tendons were located at mid-plane of the slabs in order to obtain a central prestress. A maximum of nineteen type K thermocouples (TCs) were placed at several locations along the tendons' lower edge (midspan and anchorage zone), and at midspan, 10 mm or 13.5 mm from the fire-exposed surface (at the middle of the concrete cover).

All slabs were tested in large-scale furnace tests, with an exposed length of 3040 mm and 130, 160 and 280 mm of cold overhangs on each end. The slabs thus had a total length of 3300, 3360 or 3600 mm (Table 1). The tendons had a lateral cover of 22.5 mm and a tendon-to-tendon clear distance of 45 mm.

The slabs were stored for between 4 and 7.5 months in the SACAC production hall before being delivered to Empa's fire laboratories where they were stored outside under a covered storage area for maximally 2 months before testing. The moisture content of the slabs was determined by mass loss during dehydration of material taken from the core of an additional slab after 1 and 7.8 months from casting. Concrete 142 had a moisture content of 4.8% (1 month) and 4.4% (7.8 months), while for concrete 242 it was 4.1% after 7 months.

Table 1. Experimental programme and main fire test results.

SLAB	AGE [Months]	PRESTRESS [mm]	COVER [mm]	OVERHANG [mm]	CONCRETE TYPE	PP FIBRES IN SCC [kg/m^3]	FAILURE TIME [min]	FAILURE MODE*	FIRE TEST No., SLAB LOCATION
13	9.4	800	20	160	142	2	67	sp→c	3, C
19	9.4	800	20	160	042	0	17	sp→c	3, D
16	9.4	800	20	280	142	2	58	sp→c	3, E
4	9.3	1200	20	160	142	2	26	sp→c	1, C
7	8.8	1200	20	280	142	2	34	sp→c	2, A
45	6.9	1200	20	160	242	5	30	lb→c	5, C
46	6.9	1200	20	130	242	5	29	lb→c	5, D
47	6.9	1200	20	280	242	5	30	lb→c	5, E
20	9.0	800	27.5	160	042	0	22	sp→c	4. D
5	8.4	1200	27.5	160	142	2	47	sp→c	3, B
8	8.4	1200	27.5	280	142	2	24	sp→c	3, A

* lb→c = bond loss → crushing; sp→c = spalling → crushing; slab location in furnace (A, B, C, D or E) according to Figure 4.

3. Fire Test Setup

An ISO 834 fire [3] was considered to represent a credible worst-case scenario for façade elements; a typical application of the thin-walled CFRP prestressed HPSCC slabs being studied. This produces a furnace temperature, for example, of 850°C after 30 minutes. Figure 1 shows the average temperature development in fire test Nos. 1 through 5.

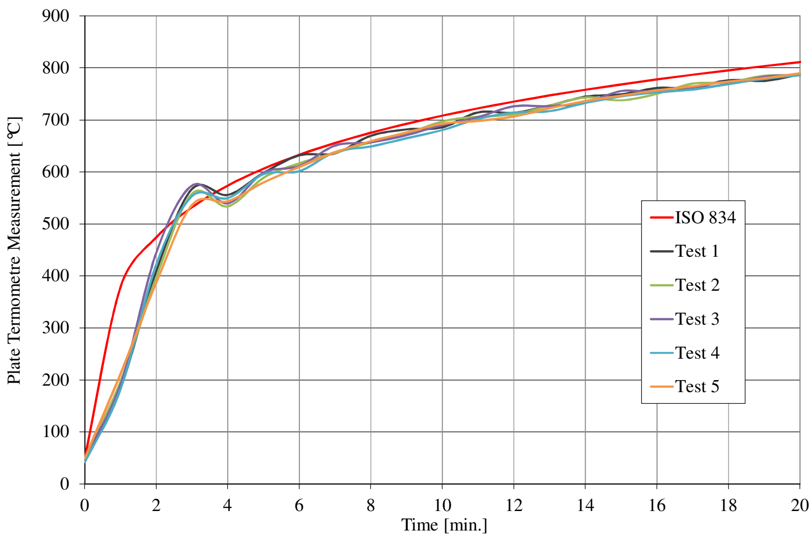

Figure 1. Mean furnace temperatures vs. time in the five fire tests.

The fire tests consisted of exposing a series of five simply supported slabs to the ISO 834 fire while simultaneously loading the slabs in four-point bending (Fig. 2) to reach decompression at the tension fibre of the slabs in the constant moment region (i.e. $\sigma_{c,bottom}$ = 0 MPa). The primary objective was to determine the time to failure of the slabs in fire under service load.

This loading condition corresponds to a typical service load condition for CFRP prestressed façade elements [4]. When planning the fire tests, the overhang lenth, l_0, was felt likely to be a critical parameter (along with cover spalling) for fire survivability of the slabs. It was hypothesized that loss of tendon bond would be severe at temperatures in the range of the tendons' resin's T_g (121°C in this case). Note that the pultruded CFRP tendons' matrix (epoxy) was used to coat the tendons with a bond-enhancing quartz sand layer directly after pultrusion, and that this outer epoxy layer reached only a T_g of only 70°C because only partial curing was achieved with the in-line tendon coating facility. The decision was taken that (within the practical limits dictated by Empa's furnace dimensions) the overhang length would be a key parameter studied. An overhang length at least as long as the room temperature prestress development length was considered as a minimum requirement for the slabs' design; this prestress development length was assumed to be approximately 30 times the tendon diameter, or 160 mm, based on prior research. Therefore the minimum length of the overhang of the slabs was fixed to 160 mm (short overhang). For Slab 46, this length was reduced to 130 mm (Table 1), because one 60 mm long section of the slab was taken in order to measure the moisture content of type 242 concrete (see Section 2.). Bearing in mind that the overhang would experience some heating due to heat transfer along the slab, and that CFRP has a relatively high thermal conductivity in the fibre direction, it was decided to also consider a maximum possible overhang length of 280 mm (long overhang), which was limited by the furnace's width. This corresponds to 1.75 times the room temperature prestress development length at an initial prestress, σ_{p0} of 1200 MPa. Both overhang lengths are considered realistic for building façade applications for which these elements are envisioned [4]. The test parameters considered are given in Table 1.

One vertical LVDT with range 450 mm and accuracy of ± 0.5 mm was placed at midspan for every slab (Figure 2). Five slabs were tested in parallel per fire test.

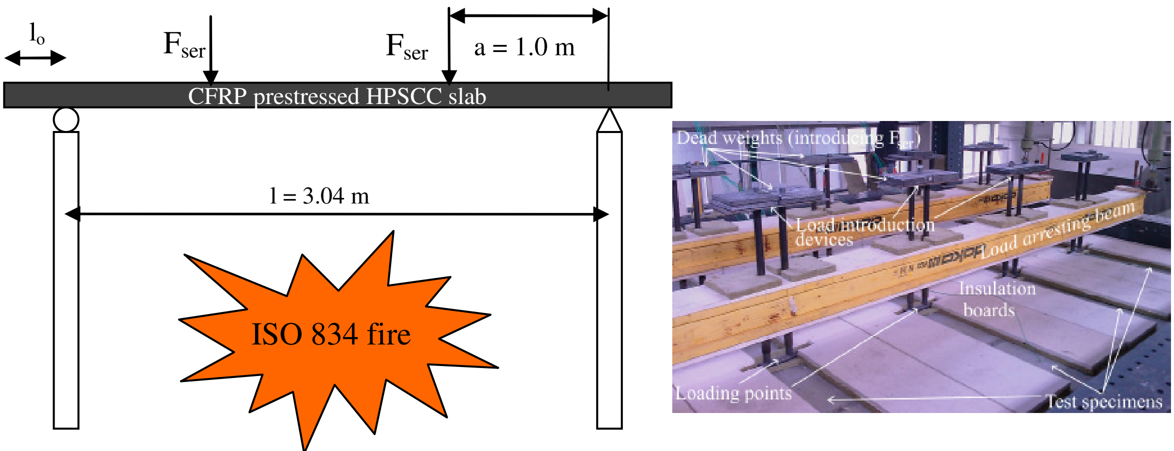

Figure 2. ISO 834 fire test setup for CFRP prestressed HPSCC slabs under service load (F_{ser}) and top view of furnace with load introduction devices used to apply sustained service loads during testing.

4. Results and Discussion

Failure times and failure mechanisms of the slabs are given in Table 1. For all slabs with PP fibre dosages of 0 and 2 kg/m^3 the failure mode was sudden collapse due to "accumulated" HSPCC spalling that reduced the cross-sectional depth, eventually producing bending failure due to crushing of the remaining concrete under the sustained service load. For Slab 13, tested in Test 3, the first spalling was identified 10 minutes from the start of the test. This slab was located at the centre of the furnace (Position C), for which the plate thermometer registered the highest temperatures during the first 10 minutes of Test 3. Figure 3 shows the measured temperature deviation for each plate thermometer from the ISO 834 time-temperature curve during Test 3. A higher temperature was recorded in the centre of the furnace (plate thermometers I.B, I.C and II.C in Fig. 3) which is the area in which Slab 13 was placed. This considerably higher thermal load to which Slab 13 was subjected (70°C above the ISO 834 curve after 3 minutes, with a more rapid temperature development between minutes 1 and 2 of the test), is suspected to have played a role in triggering the first spalling. It is noteworthy that in all cases the first spalling was localized near the slabs' supports, where the bending moment was low and the slabs' soffits were most highly pre-compressed [5]. It is well established that concrete spalling is exacerbated by compressive stress, hence the decompressed central span of the slabs was consistently less affected by spalling.

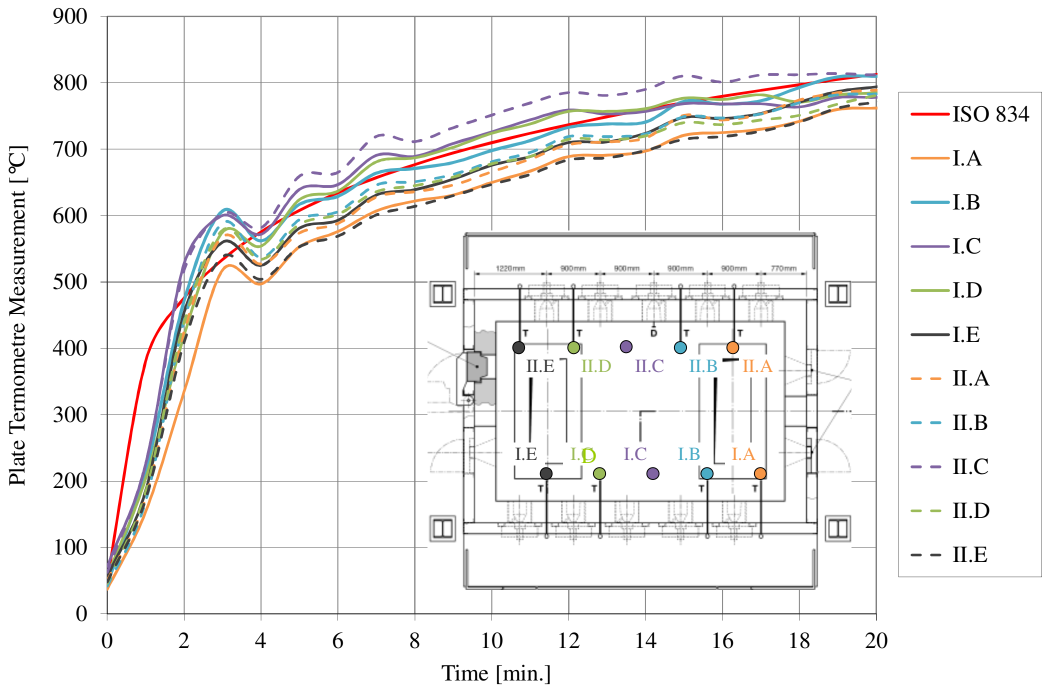

Figure 3. Gas temperature measurements (plate thermometers) for Test 3 compared with ISO 834 temperature curve.

Differing from this, slabs 45, 46 and 47 (with 5 kg/m^3 of PP fibres) failed due to tendon bond failure after 30±0.5 minutes, without showing any spalling. For these slabs a crack induced loss of bond caused slippage of single CFRP tendons (i.e. loss of prestress) in their anchorage zones, which eventually led to localised bending cracks over which local crushing of the concrete occurred and led to collapse (the slabs fell into the furnace, see Figure 4). HPSCC type 242 thus showed better spalling resistance than the HPSCC types 042 and 142 (Table 1), since pores opened at the fire exposed surface through melting of the polypropylene fibres, Figure 5).

The following remarks can be made from Table 1 and from the measurements of temperatures during the fire tests:

1. The slab overhang, l_0, of 160 or 280 mm did not appear to influence the fire resistance of

the slabs when failure was by spalling. An overhang of 160 mm was sufficient for anchoring the CFRP tendons, as long the concrete did not spall near the support. The temperature at the tendons in the overhangs remained at room temperature during the full duration of the tests.

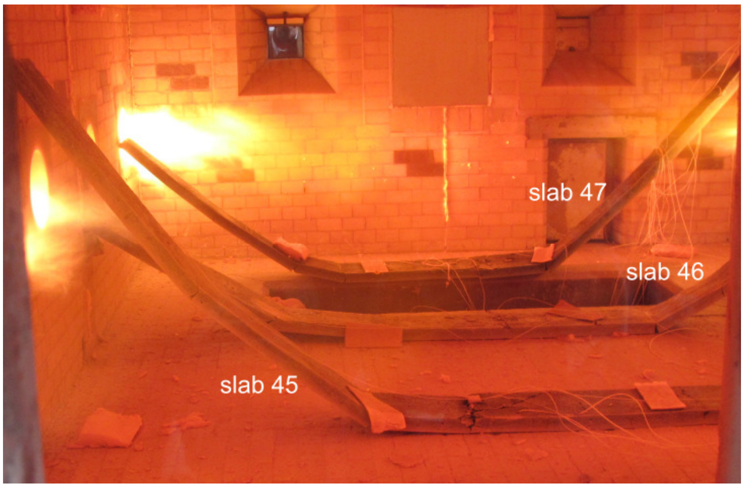

Figure 4. Sudden (bond induced) failure of Slabs 45, 46 and 47.

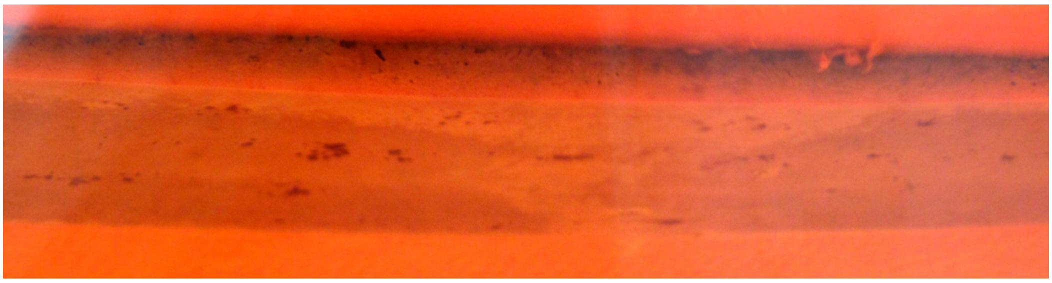

Figure 5. Pores opened at the fire exposed surface of Slab 46 through melting of the short polypropylene fibres (1 minute before failure).

2. The slab overhang, l_0, of 130, 160 or 280 mm slightly influenced the fire resistance of 45 mm thick slabs when failure was by bond failure. Through the use of HPSCC type 242 (with 5kg/m^3 of PP fibres) in slabs 45, 46 and 47, spalling was be avoided until these slabs failed because of tendon bond failure after 30 ± 0.5 minutes.

3. The five 45 mm thick CFRP prestressed concrete slabs with σ_{p0} = 1200 MPa made with HPSCC types 142 and 242 showed failure times between 26 (Slab 4) and 34 minutes (Slab 7).

4. A lower prestress level of σ_{p0} = 800 MPa had a positive effect on the fire resistance of slabs made of HPSCC type 142 (2 kg/m^3 PP fibres). The failure times of Slab 16 and Slab 13 were 58 and 67 minutes, respectively.

6. The use of the HPSCC without PP fibres (type 042) increases the spalling rate of slabs with lower CFRP prestress (σ_{p0} = 800 MPa) with wall thickness of 45 mm and 60 mm. The failure times of slabs 19 and 20 were modest, at 17 and 22 minutes, respectively.

7. The 60 mm thick CFRP prestressed concrete slabs with σ_{p0} = 1200 MPa made with type 142 concrete (with 2 kg/m^3 PP fibres) showed only a limited increase in fire resistance when compared to the thinner slabs 7 and 4 (45 mm thickness), with failure times of 24 mins (Slab 8) to 47 mins (Slab 5).

The deflection versus time behaviour of the slabs is shown in Figure 6. The slabs' deflection increased rapidly during the first 3-4 minutes of heating due to thermal bowing arising from the temperature gradient over the slab thickness (with furnace temperatures having reached 549°C-591°C), and then increased at a slower rate until a stabilisation was attained. Thereafter, localized concrete spalling caused small decreases of midspan deflection through cross-section reduction of the then eccentrically prestressed slab's region of spalling (see slabs 4 and 20 in Figure 6). Finally, collapse was often preceded by a second steady increase of midspan deflection caused by loss of bond of single CFRP-tendons which was experimentally assessed by measuring the end-slippage of tendons with laser gauges.

Figure 7 shows the non-exposed (top) surface temperature at midspan for all slabs (Table 1). The first obvious difference can be identified between the 45 and 60 mm thick slabs, for which thicker slabs showed a slower heating rate at the non-exposed surface. Additionally, the thermal response of the slabs made from Type 242 concrete (5 kg/m^3 of PP fibres) is clearly different from types 042 and 142 (0 and 2 kg/m^3 of PP fibres), in particular at the moment the non-exposed surface reached 100°C for slabs made of type 242 concrete due to moisture evaporation. It has been reported in the literature that increasing the PP fibre content in a concrete mixture increases its porosity [6]. In an attempt to understand the thermal behaviour seen in Figure 7, the authors propose an hypothesis based on the fact that a higher content of PP fibres increases the porosity of concrete, and when exposed to elevated temperatures this increases the moisture transport within the concrete (from hot areas to colder areas near the non-exposed surface). Due to the higher moisture transport, the accumulation of moisture near the non-exposed surface is higher when a higher dosage of PP fibres is used.

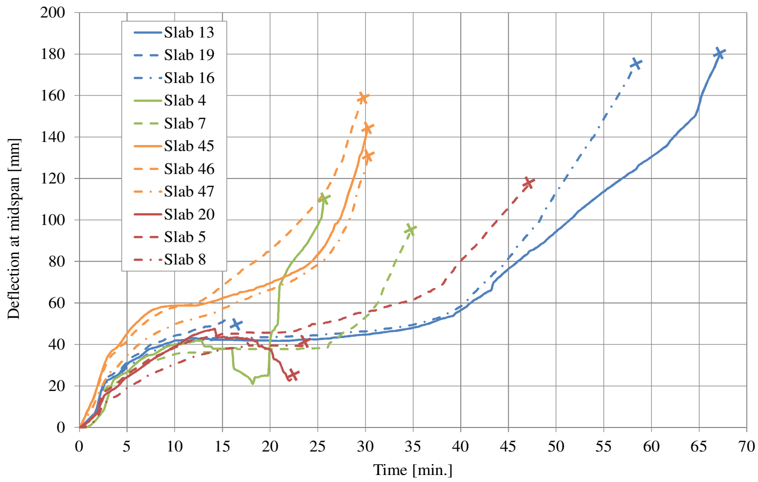

Figure 6. Midspan deflection vs. time curves.

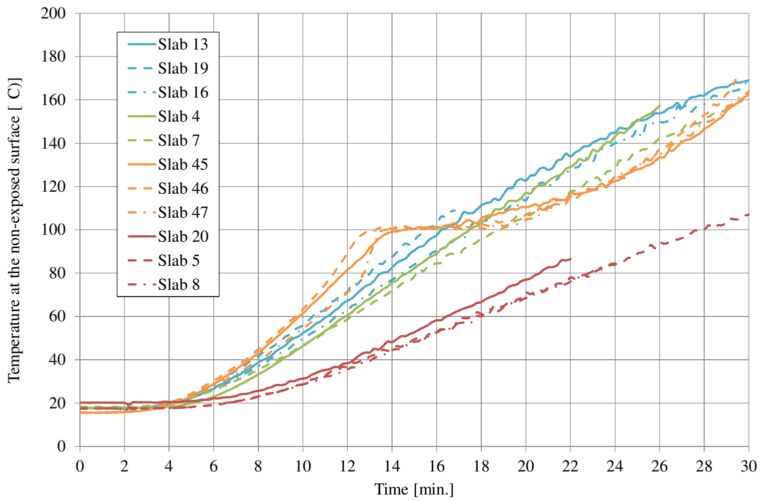

Figure 7. Non-exposed (top) surface temperature at midspan for all 45 mm and 60 mm thick slabs tested.

5. Conclusions

The following conclusions can be drawn on the basis of the testing briefly described in this paper:

- A fire resistance of R30 (which is an important prerequisite for the design of façades in Switzerland) was achieved with a significant overrun for CFRP prestressed HPSCC slabs with a concrete cover of 20 mm. This conclusion is valid for a lower tendon prestressing level (800 MPa) in conjunction with a HPSCC type 142 containing 2 kg/m^3 of short PP fibres. For such elements explosive concrete cover spalling was the failure mechanism.
- A fire resistance of R30 is possible for CFRP prestressed HPSCC slabs when a concrete cover of 20 mm and a cold overhang of at least 160 mm is used. This conclusion is valid for the higher tendon prestressing level (1200 MPa) in conjunction with a HPSCC type 242 containing 5 kg/m^3 of PP fibres. For such specimens bond failure becomes the determining failure mechanism and spalling of the HPSCC can be avoided for at least 30 minutes in an ISO 834 fire. However this highly PP fibre filled concrete loses its self compacting properties and has to be additionally vibrated during casting.
- The temperature measurements by standardized plate thermometers during all five fire tests showed that during the first ten minutes of the tests it is difficult to comply with the ISO 834 time-temperature curve. This is due to the mandatory and standardized controlling of the temperature increase (using oil burners) and to the thermal inertia when heating a 50 m^3 standard floor furnace. This non-homogeneity in temperatures, which is most severe during the first ten minutes of the fire exposure, presents no problems when testing for fire rating of structural elements, but it is not recommended by the authors if the aim is to study the spalling and failure mechanisms in fire of new, optimized, high strength concrete elements for civil engineering applications like the thin-walled CFRP prestressed HPSCC slabs studied herein. Studies of the explosive spalling of concrete should not be done in large-scale standard fire testing furnaces, since explosive spalling is so highly dependant on the thermal insult to the structural element during the very early stages of a fire [7].

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