FRC in Switzerland: research, applications and perspectives

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ABSTRACT: This paper presents some applications of FRC in Switzerland and recent developments resulting from research activities carried out at Swiss university laboratories. The national recommendation SIA162/6 "Steel Fiber Reinforced Concrete" is also briefly presented in relation to the practical use of this material in terms of quality control and design. Finally, some perspectives of the use of FRC in the Swiss market are given.

Keywords: SFRC, UHPFRC, recommendation, durability, quality insurance, practical application, tunnel segments, tunneling, self compacting concrete.

1 INTRODUCTION

Until recently FRC has been used almost exclusively for industrial pavements and, as sprayed material, for excavation supports.

Thanks to its toughness and post-cracking behaviour new scenarios are now opening in the construction industry with new applications in tunneling, in pre-casting, in structural rehabilitation and in defense. Conception of innovative structures is also motivated by the market needs and encouraged by the increasing amount of standards, whose contents derive from the experimental and theoretical results of the research activities carried out worldwide by private and public institutions. This paper presents a brief overview of some experiences in connection with FRC recently made in Switzerland.

The wide experiences made with the shotcrete and with SFRC, a wider knowledge about the technology and properties of this material and the existing potential of development for research and practice, for example using SFRC in combination with reinforced concrete and/or with prestressed reinforced concrete, has been leaded Swiss Association of Engineers and Architects (SIA) to write a recommendation on this subject. This recommendation is briefly presented in next section.

2 THE RECOMMENDATION SIA 162/6

The recommendation SIA 162/6 "Steel Fiber Reinforced Concrete" is a short and concise document that explains the main design rules and a guide for the application of the steel fibers reinforced concrete in terms of choice of materials and execution. This norm belongs to the group of the structural norms issued in the ninety years.

The recommendation SIA 162/6 is directly connected with the SIA 162 norm "Concrete structures" issued from 1989 to 1993. In 2003, on the basis of the Eurocodes a new generation of structural SIA norms "Swisscodes" were developed, than, from the design point of view, it is necessary now to proceed with the revision of a certain number of definitions for the compatibility of the recommendation SIA 162/6 to the Swisscodes (SIA 260/261/262).

The structure of the recommendation SIA 162/6 (1999) is the following: the general chapters (preface, field of application), the technical part (terminology, principles, design, materials, execution) that consists in two parts, administrative and annexes respectively.

In order to determine the mechanical characteristics useful for the design of the SFRC structures the recommendation provide two type of tests that have to be carried out before the executive design.

Because of the importance of these values, the tests are explained in detail in the chapter of the annexes and they are here briefly described.
To determine the tensile strength the SIA 162/6 proposes two type of bending test: four points bending test on prismatic samples (see Figure 1) and the punching test on square or circular slab (see Figure 2).

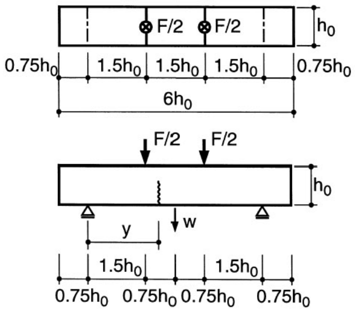

Fig. 1. Testing set-up for prism (SIA 162/6).

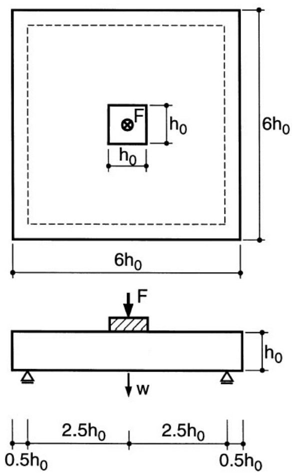

Fig. 2. Testing set-up for square slab (SIA 162/6).

A preference is given to the punching tests because huge theoretical and applied studies (Marti et al. 1999) had demonstrated better result reliability than bending tests on prismatic beams.
By the four point bending tests on square section prism the flexural tensile strength (f_{ctf}) is determined while the fracture energy (G_f) is determined by punching tests on square or circular slab as shown in table 1. The testing set-up for the two tests is indicated respectively in Figure 1 and Figure 2.
The determination of W_1 and W_2 is done according to the Figure 3. The final values are the average values determined in general respectively on the basis of 15 tests for four points bending tests and from at least three tests on a square or circular slab.

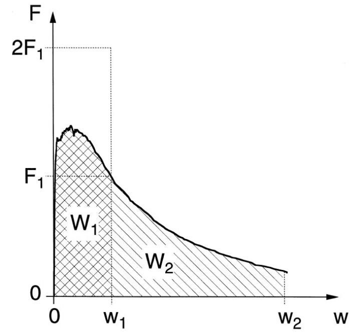

Fig. 3. Load vs. displacement diagram for FRC specimen (SIA 162/6).

Table 1. Description of the tests value (SIA 162/6).

	Prism	Square slab
w_1	$\frac{l_f\ y}{16\ h_0}$	$(0.03n + 0.06)l_f$
W_1	$\frac{3\ h_0}{2\ y}\int_0^{w_1} F\ dw$	$\int_0^{w_1} F\ dw$
f_{ctf}	$\frac{12\ W_1}{h_0^2\ l_f}$	$(0.95 - 0.06n)\frac{W_1}{h_0^2\ l_f}$
w_2	-	$4w_1$
W_2	-	$\int_0^{w_2} F\ dw$
G_f	-	$(0.107 - 0.007n)\frac{W_2}{h_0^2}$

where: w_1 = displacement [mm] (see Figure 3); l_f = fiber length [mm]; h_0 = width of specimen [mm]; y = distance between the failure crack and the nearest support in the four points bending test [mm]; n = numbers of the cracks of rupture; W_1 = energy of rupture [J] (see Figure 3); f_{ctf} = tensile bending strength; w_2 = displacement [mm] (see Figure 3); W_2 = energy of rupture [J] (see Figure 3); G_f = Fracture energy [N/m]

To take into account the scattering of the results, the formulas indicated in table 1 for f_{ctf} contain a factor of reduction of 3/4.
The test have to be performed under displacement control in a rigid testing machine. The load must be increased uniformly so that displacement w_1 and w_2, according to the Figure 3, can be reached in about 250 and 1000 seconds respectively after the beginning of the test.
The diagrams load vs. displacement like indicated in the Figure 3 have to be recorded graphically until to reach w_1 and w_2. In the four point bending test, it is necessary to measure besides the distance

between the crack of rupture and the nearest support. For the tests of square or circular slab, it is necessary to count the n number of the similar cracks of rupture.

3 STRUCTURAL USE OF ULTRA-HIGH PERFORMANCE FIBER REINFORCED CONCRETE

A high performance concrete project currently under way at the Structural Concrete Laboratory (IS-BETON - EPFL) aims at examining new concepts and design approaches to design statically efficient and economically viable structures using ultra high performance concrete.
The scientific approach chosen is primarily to understand and characterize the behavior of UHPC by means of various laboratory experiences on material specimens and structural elements. On this basis, physical models will be subsequently developed to describe the observed behavior. Finally, design concepts will be examined, with a focus on potentially efficient structures.

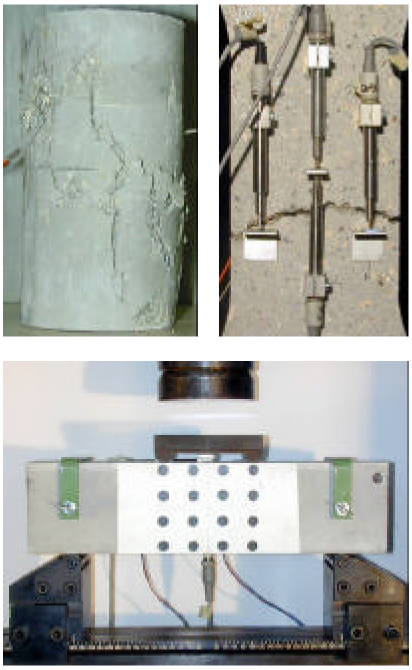

Figure 4. Material testing

Several studies have been made to establish a basis for developing design concepts:

The material characteristics were investigated by a wide experimental program studying the tensile, compressive and bending behaviors (Figure 4). In addition, tests for the bond behavior of UHPC with reinforcement bars and fibers were carried out (Jungwirth and Muttoni, 2004a).

Experimental results for bar reinforced structural members in compression and tension (Figure 5) have shown the particularities and advantages of UHPC compared to ordinary reinforced concrete (Jungwirth and Muttoni, 2004b).

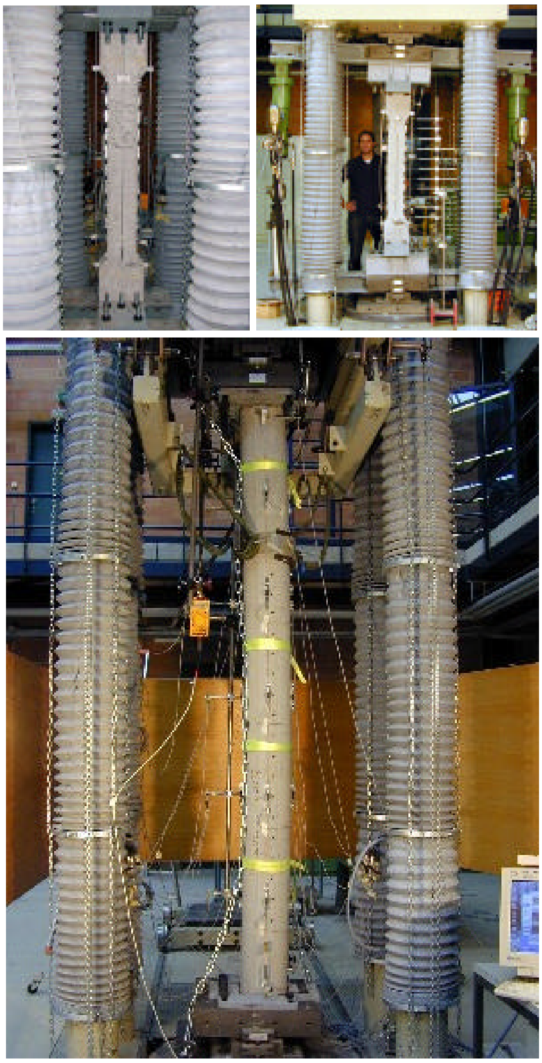

Figure 5. Testing on reinforced structural members in tension and compression

In a detailed study, the tensile behavior of bar reinforced and non reinforced structural members has been investigated (Jungwirth, 2004). To take into consideration the local effects of the crack opening, the tensile behavior of the material was characterized through two different series of tests. Unnotched specimens are used to study the uniformly distributed behavior until the crack opening occurs. The local effects of the crack opening are investigated on notched specimens (Figure 6).

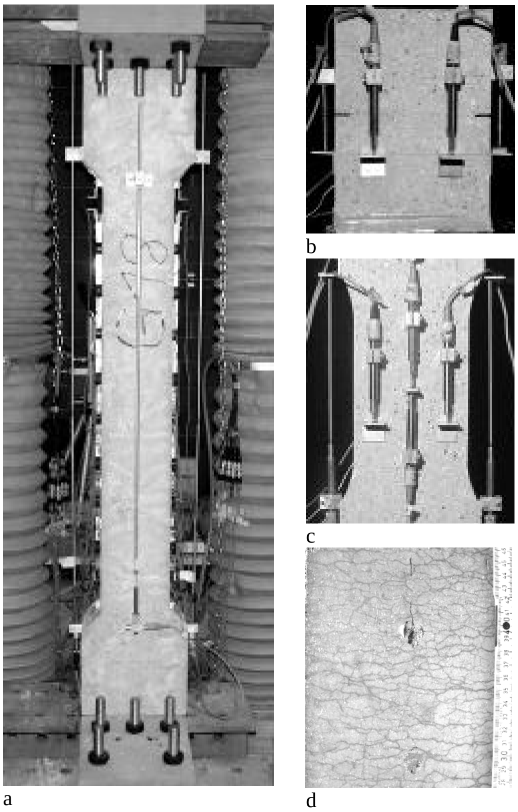

Figure 6. Material test on unnotched and notched specimens, reinforced tension member and crack pattern

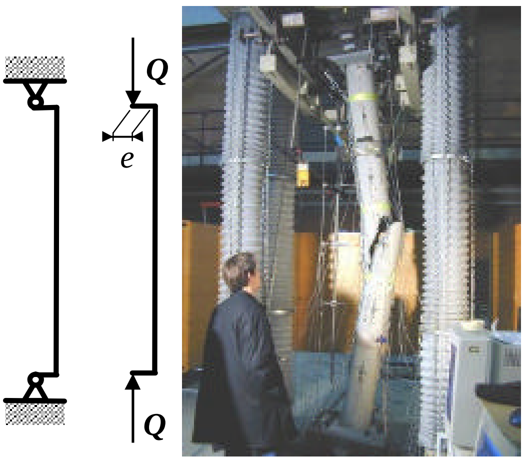

Figure 7: Testing of columns in UHPC

The experimental work has shown that the strength of reinforced UHPC members is composed by the strength of the reinforcement bars and a contribution from the UHPC. The contribution of the UHPC to the stiffness of the element (tension stiffening) is very high. The crack pattern shows a small crack spacing and only very little crack opening.

In a recent project, conducted in cooperation with an industrial partner, full scale columns were tested (Figure 7). The possibilities of application of UHPC in buildings were investigated and basic theoretical considerations about the structural behavior have been carried out (Stirnimann et al., 2004).

Based on the presented studies, the following conclusions were drawn:

- Due to the fibers and their contribution to the behavior in tension, UHPC shows a different tensile behavior than ordinary concrete.
- Major tensile stresses should be carried by reinforcement bars or pre-stressed steel to guarantee a reliable and efficient tension bearing.
- The strain hardening effect caused by the fibers leads to a well distributed multi cracking. This eliminates the need of minimal reinforcement for crack distribution.
- A good bond between the reinforcement and the matrix leads to a short development length. This should make connection of precast elements very easy.
- Shear reinforcement and reinforcement for the punching zones are not needed for minor shear stresses because of the high tensile strength and the high shear strength, respectively.

This means that structures can be designed only with UHPC and pre-stressing cables or passive reinforcement carrying the major tensile stresses. No other reinforcement is needed.

One possible application of UHPC in tension is its utilization as a tendon in underspanned girders (Muttoni, 2003). Due to the high compressive strength of the UHPC, a high pre-stress ratio with a high pre-stress force can be used. This tendon has a very high cracking limit and will remain very stiff after cracking due to the fiber reinforcement. The small crack spacing and the small crack opening should also make this tendon very durable.

Figure 8. Tensile members for underspanned structures, possible replacement of a metallic tie by a UHPC pre-stressed member (Muttoni, 2003)

4 RESEARCH AND APPLICATION AT HES-SO: TUNNEL

The University of Applied Sciences of Western Switzerland in Fribourg (EIA-FR) was asked to investigate the behaviour of tunnel segments subject to a combined action of a bending moment and a normal force. A comparative study has been realized to verify the possibility to replace partially or totally the usual steel reinforcing bars by steel fibres (Suter, 2004).

Tested elements (Suter et al. , 2001) came from the precasting site for the Oenzberg tunnel (CFF, Rail 2000, Berne – Zurich). They are 5.42 m long, have a width of 0.85 m and their thickness is 0.30 m. The ray with the axis is worth 5.87 m for an average weight of 3.5 tons. The different segments are made of :

- S-frc : steel fibres reinforced concrete
- S-brc : steel bars reinforced concrete (usual)
- S-mrc : steel mixed reinforced concrete (fibres and bars)
- S-scfc : self-compacting concrete reinforced with steel fibres

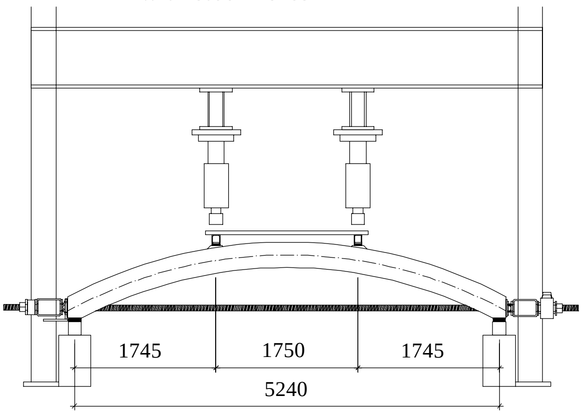

Figure 9. Testing installation

The segments are placed horizontally under a two hydraulic jacks testing installation at the EIA-FR structure laboratory. The two hydraulic jacks introduce the vertical sollicitations whereas the normal forces are produced by two metal pull-rods simulating an arch-effect (figure 9). The tests are conducted on three different pull-rods with diameters: 32, 40 and 63 mm.

4.1 *Experimental results*

Vertical deflection
Vertical deflection is related to the system's stiffness, which depends on the rod's diameter. The type of reinforced concrete composing the element has almost no impact on vertical deflections.

Size and distribution of cracks
The behaviour of the different segments can only be compared when service load is exceeded. With usual and mixed reinforced concrete, the relative elongation of the tensed side is mainly concentrated on two localised cracks under each points of loading. With steel fibres reinforced concrete the whole relative elongations concentrates in one crack where the damage takes place.
Pull-rods with small diameter cause larger horizontal displacement. Global elongation of the lower side of the elements is then higher.

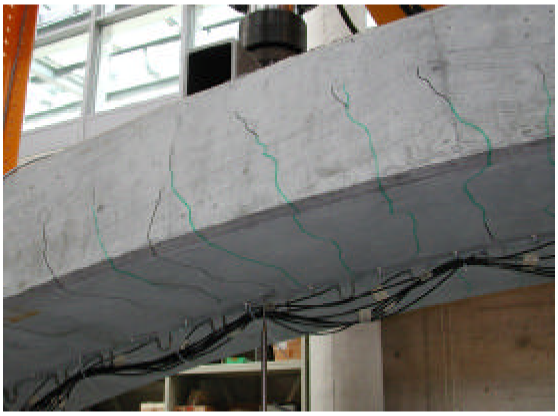

Figure 10. Distribution of cracks in a steel fibres reinforced segment.

Evolution of compression strength
Figure 11 shows the relation between load applied by the hydraulic jacks and traction sollicitation in the rods. Theoretical values, computed with a finite elements analysis program, are shown in grey.

Computed values underestimate traction loads in the rods. The reason is that this value takes into account the inertia of an homogeneous section.
In fact, cracks in concrete highly decrease the segments inertia and cause a different distribution of sollicitations in that hyperstatic system.

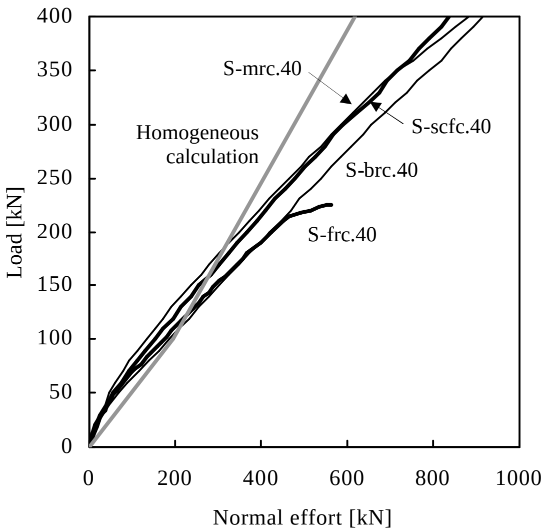

Figure 11. Evolution of the normal efforts for the tunnel segments having ties of 40 mm

Self compacting concrete
Two precast segments were made of self compactive concrete reinforced with metal fibres. This is a really promising combination of two young technologies with a clear practical interest.
Demands on field tests for fresh concrete and on laboratory tests for mechanical strengths were reached. However, that kind of concrete requires a good knowledge of concrete technology. These segments behaved in a completely satisfactory way with a slightly decreased cracking.

4.2 *Conclusions*

This experimental study on precast tunnel segments shows a good behaviour of steel fibres reinforced concrete under combined actions.
This study highlighted the major impact of the compression sollicitations in the bent section. Therefore, fibres reinforced concrete appears particularly well adapted for precast tunnel segments subjected to high compression loads.

Figure 12. Testing installation general view.

4.3 *Other research studies*

A first experimental study has been made to analyse connections between segments (Suter et al., 2003). The goal was to verify the behaviour of fibres reinforced concrete under highly concentrated forces (figure 14). Two other experimental studies, on six prestressed slabs and on six full scale tunnel segments were carried out. Obtained results confirm the conclusions discussed previously.
EIA-FR has also special interest in high performance concrete (BHP) combined with specially adapted steel fibres. Promising applications can be found in light composite structures, specially for old steel bridges rehabilitation (figure 13).

Figure 13. Punching test on BHP slabs, 70 mm thickness.

Figure 14. Study on the joints of tunnel segments (compression and punching of transverse and longitudinal joints).

5 ULTRA-HIGH PERFORMANCE FIBER REINFORCED CONCRETE

The properties of Ultra-High Performance Fiber Reinforced Concretes (UHPFRC) are out-standing in terms of strength and permeability when compared to ordinary concrete (Charron et al. 2004, Rossi 2000). UHPFRC materials may be used to improve strength and durability of structural elements. In composite structural elements formed of existing ordinary reinforced concrete and new concrete, these UHPFRC offer a high potential in view of the protective and load carrying function of the new layer. The basic conceptual idea for the improvement of existing reinforced concrete structures consists in applying the high performance cementitious materials in zones of severe mechanical and environmental exposure (Figure 15).

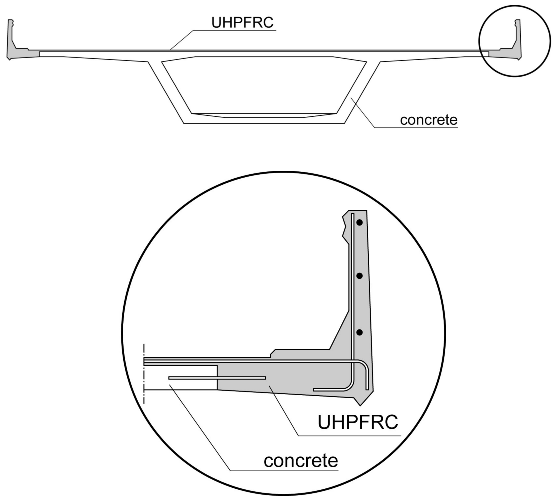

Figure 15. Conceptual idea for the improvement of deck slabs of existing concrete bridges

UHPFRC improves significantly the protection function of the cover concrete; ingress of water and chloride ions into UHPFRC is extremely low due to its low permeability (Charron et al 2004). In the case of bridges, zones of severe environmental exposure include the top surface of the deck slab and the curbs when the bridge is exposed to deicing salts.

The resistance of composite cross sections may be improved thanks to the enhanced mechanical properties of UHPFRC, in particular when it is combined with tensile reinforcement. The deck slab of bridges may also be subjected to higher mechanical loading when traffic loads are

increased, and the load carrying capacity has to be increased accordingly and possibly without increasing the dead weight of the structure in order not to trigger reinforcement interventions on other structural elements and the foundation.
In the case of bridge deck slabs, three different cross sections follow from the above conceptual idea (Figure 16):

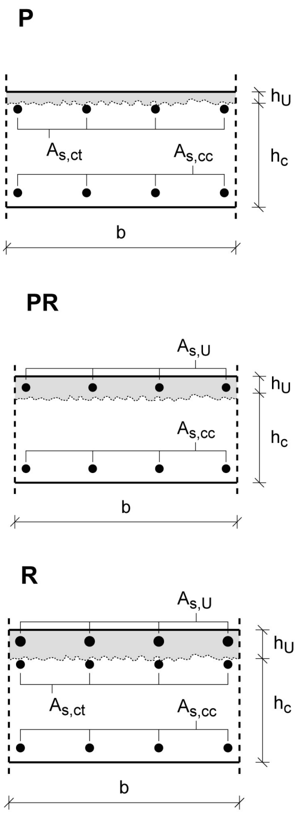

Figure 16. Three types of cross sections for improved composite bridge deck slab

(1) Cross section (P) with a thin UHPFRC layer is designed for protection purposes. The tensile reinforcement in the existing concrete is situated near the interface between the two concretes. Such cross-sections are obtained when the tensile reinforcement of the existing RC structure ($A_{s,ct}$) is not or only slightly deteriorated and the load carrying capacity is sufficient.
(2) Cross section (PR) represents the case when additional tensile reinforcement is placed into the UHPFRC layer to replace and/or to complement the existing strongly deteriorated rebars. This configuration provides both an improved protection function and an increase in load carrying capacity.
(3) Cross section (R) is designed primarily to increase significantly the load carrying resistance of the structural element. The cross-section consists of the original reinforced concrete section which is complemented by the reinforced UHPFRC layer which can be seen as an externally bonded additional reinforcement. Also, the UHPFRC provides the protection function for the structural element which is beneficial to durability of the element.
The structural behaviour of such composite elements consisting of UHPFRC and ordinary concrete has been investigated experimentally and analytically with respect to early age and long term behaviour as well as at ultimate limit state (Habel 2004).
As a result of the ongoing research at the Laboratory of Maintenance and Safety (MCS) at the Swiss Federal Institute of Technology (EPFL), the following major conclusions can be drawn (Brühwiler et al. 2004):
(1) UHPFRC offer high potential and new possibilities for the design of original composite structural elements with improved performance in terms of stiffness, resistance and durability.
(2) The suggested analytical model allows predicting the moment – curvature relationship of cross sections of composite UHPFRC – concrete elements. This model may be used to investigate the structural response of combinations of materials for different cross sectional geometries with the objective to find cross sections that reply best to given requirements.
(3) UHPFRC with a significant hardening behaviour improves the deformational properties of composite sections.
(4) Placing of reinforcing bars in the UHPFRC is an efficient way to improve the structural response of composite UHPFRC – concrete elements.
This concept is currently applied within a pilot project of a small reinforced concrete bridge in Switzerland that will undergo rehabilitation and deck widening this autumn.

6 DURABILITY OF FRC AND QUALITY CONTROL

6.1 *Durability*

At the University of Applied Sciences of Southern Switzerland, in collaboration with academic and industrial partners, an experimental campaign has been recently carried out to determine the concrete properties that affect durability (Teruzzi et al., 2004). In particular has been analysed: chloride diffusion coefficient (Figure 17), oxygen permeability, total and air-void porosity. Furthermore, concrete performance with regard to the degradation agents during artificial weathering cycles was studied; in particular, freezing-thawing tests with and without de-icing salts as well as carbonation tests were performed.


(a)


(b)

Figure 17. Chloride penetration depth in plain concrete (a) and in fibre reinforced concrete (b)

These experiments were addressed to analyse the behaviour and the durability of SFRC for three types of applications, in which such material is widely used or in which it might have further developments. Two mixtures have been selected for the construction of industrial floors (internal and for an external environment) while the third mixture has been selected for the construction of precast elements for industrial halls. For the sake of comparison, three equivalent mixes have been prepared without fibre-reinforcement.
Results from mechanical tests show that fibres slightly reduce compressive strength of normal concrete while they increase the compressive strength of high strength concrete. The splitting tensile strength and the elastic modulus as well as the shrinkage coefficient (after 90 days) are non influenced by the presence of 40-60 kg/m^3 of steel fibres. Fracture tests on notched beam specimens evidenced the enhanced toughness of steel fibre reinforced concrete and the better efficiency of fibres in high strength concrete (Cadoni et al, 2005).
The results concerning durability clearly show that the addition of steel fibres does not induce any significant change in the concrete performance. This fact demonstrates that fibres or, more precisely, the concrete boundary zone around the fibres, does not act as a preferential path for the penetration of the degradation (promoting) agents and does not represent any weaker zone with respect to frost resistance.

6.2 *Quality control*

As an example of a possible approach to quality control of FRC, a case study relative to the construction of the Gotthard base tunnel is briefly presented in the following.

The Gotthard base tunnel through the Swiss Alps is at present undoubtedly one of the greatest construction sites in Europe and represents, for its overall complexity and for the number of issues designers are faced to, the most challenging geological and technical engineering project currently going on.
The tunnel, which will be operating in 2011, is going to be the key element of the new transalpine network of railways through the Swiss Alps. It will consist of two 57 km long tubes drilled under 2000 meters of rock, through which high speed passenger trains and heavy goods trains are going to run with an estimated pace of 220 trains a day.

Many efforts are being made within this project to guarantee high quality levels for the concretes used for the structures outside and inside the tunnel in order to achieve a service life of over 100 years. The University of Applied Sciences of Southern Switzerland (Laboratorio Tecnico Sperimentale) was in charge of the quality controls of the mortars and concretes used for the preliminary rock stabilisation, the excavation support and the cast-in-place base at the southern portal in Bodio.

The excavation support (see figure 18), which prevent the falling of rock before the final roof is placed, is subject to considerable pressure and effect of groundwater. For its realization metallic fibre reinforced sprayed concrete (FRSC) was used.

Figure 18. Picture of the metallic fibre reinforced sprayed concrete excavation support at the southern portal of the Gotthard base tunnel

The tests considered in the control plan for the FRSC covered the usual properties of the fresh mix (density, water/binder ratio, air-porosity, flow and steel fibre content) and compressive strength, bonding strength, energy of rupture and water impermeability of the hardened shotcrete. The test frequencies were once a working week for the fresh concrete properties, every 200 m^3 of placed shotcrete for the compressive strength and once a working month for the energy of rupture.
The energy of rupture was determined on square slabs according to the puncture-flexure test proposed by the recommendation of the Association Française des Travaux en Souterrain (AFTES) relative to fibre-reinforced sprayed concrete technology and practice (Legrand, 1999).

Figure 19 FRSC-slab after the puncture-flexure test.

According to this recommendation the rupture energy is defined as the work done by the load applying punch when failure of the slab occurs or when a punch displacement of 30 mm is reached. This corresponds to the area under the stress-displacement curve between 0 and 30 mm displacement (see figure 20).

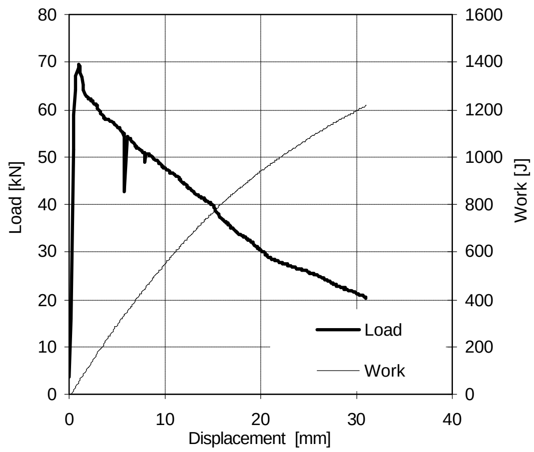

Figure 20. Load-displacement curve and work diagram relative to a puncture-flexure test on a square FRSC-slab.

The required energy of rupture was 800 J. As shown by the data displayed in the graph of figure 21 this requirement was always largely satisfied by the tested slabs.

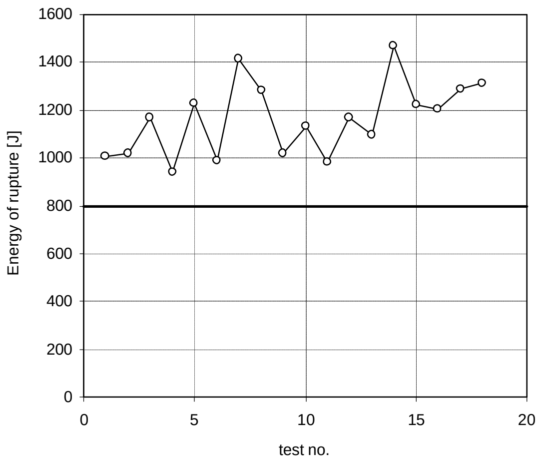

Figure 21. Evolution of the energy of rupture as a function of time.

7 CONCLUDING REMARKS

As demonstrated previously the FRC has a very good characteristics in terms of toughness, post-cracking behaviour and durability.
Further improvements might concern:

- tunneling
- rehabilitation
- precasting

In order to obtain a wider diffusion of FRC and to widen its application range some needs should be satisfied. For example the standard should be more exhaustive and cover all development needs so to facilitate and increase the designer engagement. More research activities is necessary for example for fatigue, impact, ……….
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8 REFERENCES

Buchs, P. 2004. Le béton à haute performance pour des structures plus exigeantes, Béton à fibres – Performances et perspectives, EIA-Fribourg

Brühwiler, E., Habel, K., Denarié, E. 2004. Advanced reinforced concrete for the improvement of bridges. Proceedings, 2nd International Conference on Bridge Maintenance, Safety and Management (IAB-MAS'04), Kyoto, Japan, October 2004.

Cadoni, E., Cangiano, S., Frigeri, G., Plizzari, G.A. Teruzzi, T., 2005, On durability of Steel Fibre Reinforced Concrete, to be published in proceedings of 6th international conference "Global Construction: Ultimate Concrete Opportunities", Dundee (UK) 5-7 july 2005.

Charron, J.P., Denarié, E. & Brühwiler, E. 2004. Permeability of UHPFRC under high stresses, Proceedings, RILEM Symposium, Advances in Concrete Through Science and Engineering, March 22-24, 12 p., Chicago, USA, 2004.

Habel, K. 2004. Structural behaviour of composite UHPFRC – concrete elements, Doctoral thesis, Swiss Federal Institute of Technology, Lausanne, Switzerland, to be published.

Jungwirth, J., Muttoni, A., 2004a, Versuche an Bauteilen aus ultrahochfesten Beton – Teil 1 Material, EPFL-IS-BETON, Lausanne.

Jungwirth, J., Muttoni, A., 2004b, Versuche an Bauteilen aus ultrahochfesten Beton – Teil 2 Bauteile, EPFL-IS-BETON, Lausanne.

Jungwirth, J., 2004, Structural Behavior of Tension Members in Ultra High Performance Concrete, International Symposium on UHPC 2004, Kassel.

Legrand, M. et al., 1999,AFTES-recommendation: Fibre-reinforced sprayed concrete technology and practice, Tunnels et ouvrages souterrains, October 1999, p. 56-65

Marti, P., Pfyl, Th., Sigris, V., Ulaga, T., 1999, Harmonized test procedures for steel fibre reinforced concrete, ACI Materials Journal, Vol. 96, No 6,.

Muttoni, A., 2003, Innovationen im Brückenbau am Beispiel der unterspannten Tragwerke, Internationales Brückensymposium, Darmstadt.

Rossi, P. 2000. Ultra-high performance fibre reinforced concretes (UHPFRC): an overview. BEFIB'2000, Proceedings of the Fifth International RILEM Symposium on Fibre-Reinforced Concretes, edited by P. Rossi and G. Chanvillard, Lyon, France : 87-100.

Stirnimann, D., Jungwirth, J., Muttoni, A., 2004, Bruchverhalten von Stützen aus ultra-hochfestem Beton, Projekt 00.02, Bericht 00.02.R5, EPFL-IS-BETON, Lausanne.

Suter, R. & Bütschi, P.Y. 2001. CFF-Rail 2000 – Tunnel du Oenzberg / Voussoirs en béton, avec ou sans fibres, mandat de recherché n° P.0209, EIA-Fribourg

Suter, R. 2004. La recherche appliquée dans le développement de structures – les voussoirs de tunnel, Béton à fibres – Performances et perspectives, EIA-Fribourg

Suter, R. & Baudin, G. 2003. Etude expérimentale sur des dalles minces en BHP, avec ou sans fibres, EIA-Fribourg

Teruzzi, T., Cadoni, E., Frigeri, G., Cangiano, S., Plizzari, G.A., 2004, Durability aspects of steel fibre reinforced concrete, Proceedings of the 6th Rilem Symp. on Fibre Reinforced Concrete -BEFIB 2004, 20-22 sept., Varenna (Italy)