Competitive and Sustainable Growth (GROWTH) Programme

SAMARIS

Sustainable and Advanced MAterials for Road InfraStructure

WP 14: HPFRCC (High Performance Fibre Reinforced Cementitious Composites) for rehabilitation

Deliverable D13

Report on preliminary studies for the use of HPFRCC for the rehabilitation of road infrastructure components

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1 FOREWORD AND ACKNOWLEDGEMENTS

This report is the first of a series covering all aspects necessary to the implementation of UHPFRC (Ultra High Performance Fibre Reinforced Concretes) for the rehabilitation of reinforced concrete structures, within the framework of work package (WP) 14 "HPFRCC for rehabilitation" of project SAMARIS. The other reports are:

- D18 - Report on tests of UHPFRC in the laboratory
- D22 - Report on tests of UHPFRC in the field
- D26 - Modelling of UHPFRC in composite structures
- D25 - Specifications for the use of corrosion inhibitors and UHPFRC for rehabilitation of highway structures
- D31 - Guidelines on selection of innovative materials for the rehabilitation of highway structures.

Contributors to WP 14 are: MCS-EPFL (contractor and WP leader), LCPC – Dr. P. Rossi (contractor), and TRL – Dr. R. Woodward (contractor).

This report only presents a condensed view of all works realized in the context of the preliminary study of WP 14. More details and results can be found in [Habel04a and b] and [Charron04].

The original concept of application of UHPFRC for the rehabilitation of reinforced concrete structures was proposed at MCS, by Prof. Dr. E. Brühwiler, in 1999.

The researchers who contributed to these works at MCS-EPFL under the lead of Dr. E. Denarié (WP 14 leader) and Prof. Dr. E. Brühwiler (Director of MCS-EPFL) are:

- Dr. Katrin Habel (formerly doctoral student at MCS-EPFL, and postdoctoral student at MCS-EPFL from august 2004 on).
- Dr. Jean-Philipe Charron (formerly postdoctoral student at MCS-EPFL, professor at the Polytechnical school of Montréal, Canada from august 2004 on).
- John Wuest (civil Engineer EPFL, doctoral student at MCS-EPFL).
- Aicha Kamen (civil engineer, doctoral student at MCS-EPFL).

Sections 3.3 and 3.4 of the state of the art report on HPFRCC were taken from the doctoral thesis of Katrin Habel, [Habel04b].

Contributions by university of Cardiff (Prof. B. Barr, Dr. B. Lark, Dr. M.K. Lee) under guidance of TRL (R. Woodward) to the state of the art report on the use of HPFRCC (review of works and § 3.1 and 3.2 of the report), are gratefully acknowledged.

A major part of the experimental works described in § 4 was performed by John Wuest and Aicha Kamen.

Finally, Dr. Pierre Rossi of LCPC-France, inventor of $\text{CEMTEC}_{\text{multiscale}}^{®}$ and worldwide known expert of Fibre Reinforced Concretes, proposed the original UHPFRC recipes used in this study and the concepts for their tailoring to the specific applications of rehabilitation.

Lausanne, 31 august 2004 Dr. Emmanuel Denarié

2 INTRODUCTION

To address the problems of rapidly deteriorating civil infrastructures, new high performance construction materials have been developed. Popular methods of repair and strengthening include the use of steel plates and fibre reinforced polymers (FRP). The use of fibre reinforced cementitious (FRC) materials is also increasing. More recently, however, due to the advancements in material science, an exciting alternative has appeared in the form of high performance fibre reinforced cementitious composites (HPFRCC), such as Slurry infiltrated materials (SIFOC, SIMCON), Engineered cementitious Composites (ECC) or Ultra High Performance Fibre Reinforced Concretes (UHPFRC). All these materials exhibit a significant tensile strain hardening behaviour and as a consequence an extremely high deformability. Among those, however, only UHPFRC with an ultra compact matrix have at the same time an extremely low permeability, a strain hardening behaviour in tension and in some cases are self compacting at fresh state.

Currently, more attention has been placed upon the strength and deformability related performance parameters of HPFRCC. The durability characteristics of these materials have not been investigated as thoroughly so far and will be one of the major topics of the recently created RILEM TC "HFC" High Performance Fibre Concretes (Chair Prof. V. Li). This issue needs to be addressed to fulfil the full potential of the material in terms of its protective and load carrying function, in applications for the rehabilitation of reinforced concrete structures.

The *extremely low permeability* of UHPFRC associated to their *outstanding mechanical properties* make them especially suitable to locally "harden" reinforced concrete structures in *critical zones* subjected to an aggressive environment and to significant mechanical stresses. Composite UHPFRC-concrete structures promise a *long-term durability* which helps *avoid multiple interventions* on structures during their service life. UHPFRC materials can be applied on new structures, or on existing ones for rehabilitation, as thin *watertight overlays* in replacement of waterproofing membranes, as *repair layers*, as reinforcement layers combined with reinforcement bars, or as *prefabricated elements* such as curbs, as shown on Figure 2-1. However, the cost of these materials imposes to use them where they are worth it and to take the maximum benefit of their outstanding mechanical properties with an optimum level of loading at service state.

Project SAMARIS dedicates a major effort to demonstrate the applicability of UHPFRC for the rehabilitation and improvement of structures. In this context an extensive research and development program is conducted to: (1) study the relevant fundamental properties of UHPFRC, (2) make a first step towards the optimization of these materials for various applications of rehabilitation in composite structures, (3) provide guidelines for their use and their further optimization (conceptual design, numerical simulation tools, test methods, limit state criteria for design, compliance criteria), and (4) demonstrate their applicability by means of full-scale pilot tests of application on sites.

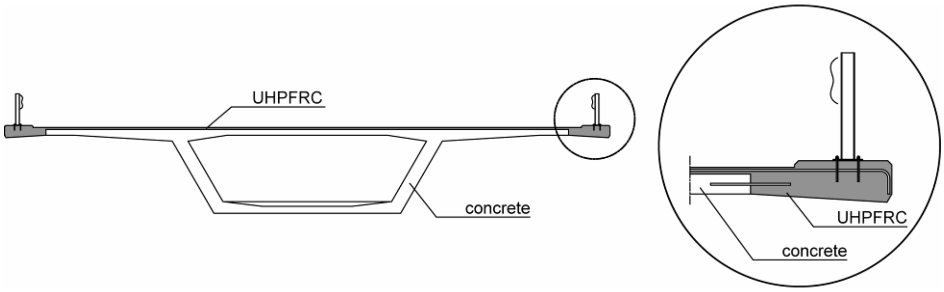


Figure 2-1: Conceptual approach for the application of ultra compact HPFRCC (UHPFRC) for the rehabilitation of reinforced concrete structures, [Brühwiler04b]

The aims of the preliminary study reported in this document were twofold. Firstly, within the context of the application of UHPFRC for the rehabilitation of reinforced concrete structures, to identify the phenomena that require further study with respect to the risk of delamination, transverse cracking and overall performance of the new layer and of the composite structural elements with UHPFRC. Secondly, on the basis of a state of the art, of experimental tests and numerical simulations, to select the UHPFRC materials that will be used in the main test series on the basis of their performance with respect to the processing (mixing, casting) as well as in the hardened state, for protection or reinforcement.

3 STATE OF THE ART REPORT ON USE OF HPFRCC

3.1 Introduction

It is important to differentiate between the terms repair, strengthening and retrofit, which are often used interchangeably, within the context of rehabilitation. Repairing a structure means to overcome a structural deficiency in order to restore it to its original performance level. On the other hand, the strengthening of structures actually enhances the existing design performance level. The term retrofit, however, is specifically used for the seismic upgrade of structures.

Considering the mechanical properties of fibre reinforced cementitious composites, these composites may be categorised into two classes: quasi-brittle and pseudo strain-hardening. Conventional FRC fall into the first category whereas HPFRCC fall into the latter. The development of HPFRCC has been made possible due to various factors [Guerrini2000] such as:

- The introduction of new reinforcement systems
- Advances in the study of fibre-matrix interfacial properties
- Development of high performance cementitious matrices with significantly improved microstructural properties in terms of strength and durability. The manufacture of HPFRCC mixes invariably involves the use of superplasticisers and micro-fillers such as silica fume.
- Innovation in processing techniques which allows the manufacture of materials with high toughness and low porosity.

Quasi-brittle materials, such as plain concrete and conventional FRC, usually fail due to the formation of a single macro-crack whereas pseudo strain-hardening cementitious materials such as HPFRCC undergo multiple cracking [Kabele97]. For conventional FRC, the typical upper limit for fibre volume fraction is 3%. For such a relatively low fibre content, the fibres mainly enhance the crack arresting ability, post cracking ductility, fatigue and impact resistance. The stress at first crack, maximum stress and the corresponding strain are not significantly improved compared to plain concrete [Krstulovic-Opara95].

On the other hand, HPFRCC display a large improvement in both strength and toughness compared with the plain matrix [Shah99]. The main feature of these materials is the optimum combination of strength and toughness which approaches the structural properties of steel. HPFRCC have been shown to provide not only markedly improved mechanical properties in comparison to plain concretes and conventional FRC, but also substantially higher durability [Krstulovic-Opara95].

HPFRCC is a generic term encompassing many different materials ranging from those that employ ultra-compact matrices and those that do not. However, the common point of all HPFRCC materials is their Hardening Tensile behaviour that helps control cracking to a much better extent than usual FRC (Fibre Reinforced Concretes). A clear distinction can be made between on one hand *ECC (Engineered Cementitious Composites)* and *Slurry infiltrated materials (SIFCON, SIMCON)* with a more permeable matrix, and on another hand *UHPFRC (Ultra High Performance Fibre Reinforced Composites)* which exhibit at the same time a significant tensile hardening behaviour and an extremely low permeability and which present the most interesting properties for the applications foreseen in WP 14.

Although the theoretical background, mix proportions and method of fabrication of various HPFRCC can be found in the literature, it has to be appreciated that material characteristics vary across different parts of the world. *With this in mind, methods of obtaining matrices and composites of certain characteristics with locally available components are needed. This, combined with knowledge in the mechanical behaviour of UHPFRC will enable the researcher or engineer to come up with a preliminary mix design using locally available materials, which is especially relevant for Central European Countries.*

3.2 Potential advantages of HPFRCC in repair systems

Previous studies on composite members such as concrete overlaid beams have revealed two major causes for the delamination of the overlay. The first is the cycling of traffic loads, which potentially causes fatigue failure and the cycling of temperature, which causes cyclic thermal stresses arising from the difference in coefficients of thermal expansion between the overlay material and substrate concrete [Wheat93]. It has been shown, by using FRC as an overlay material on concrete beams that overlaid beams can survive up to 100000 cycles (maximum load at 45% of ultimate static strength) without any delamination and without significant loss in stiffness [Ong97]. This finding bodes well for fibre reinforced cementitious composites, as it shows that the material may enhance the mechanical performance of the concrete substrate without any detrimental effects due to delamination.

Lim and Li [Lim98] demonstrated that the interface between substrate and repair material had the most important role in the system for durable repair. They surmised that interface fracture toughness is capable of predicting repair system performance associated with interface crack extension. Experimental measurements of the interface fracture toughness were carried out on three potential repair materials – plain concrete, steel fibre reinforced concrete and ECC. Furthermore, they introduced the concept of interface crack trapping mechanism the concrete/ECC system whereby the presence of this trapping mechanism was confirmed in experimental investigations. It was concluded that, the overlay system with trapping mechanism could prevent the most common failures in rehabilitated infrastructures such as spalling and delamination of the repair, and impart them with superior energy dissipation capacity.

The use of UHPFRC in any repair work would be expected to enhance the durability of the concrete substrate due to its extremely low permeability. The dense microstructure especially of UHPFRC employing ultra compact matrices discourages the ingress of deleterious substances. Furthermore, the presence of fibres capable of knitting cracks can limit the crack width thus further improving the protective function of the material. UHPFRC also has enhanced performance in terms of fatigue resistance and resistance to freeze-thaw cycles. Matsumoto and Mihashi summarised in [Matsumoto00] and [Mihashi03] the advantages and application concepts of HPFRCC in terms of crack geometry and material response.

3.3 Ultra-High Performance Fibre-Reinforced Concretes (UHPFRC)

This section deals with UHPFRC. It concentrates on the principles and on the material properties of UHPFRC. Typical constituents of UHPFRC and a short historical overview are also discussed.

3.3.1 General

Definition. UHPFRC are advanced cementitious materials (ACM) with specifically tailored properties. They are characterized by an ultra-compact matrix with *very low permeability* and by *tensile strain-hardening*. They are part of the group of HPFRCC as described in Figure 3-1.

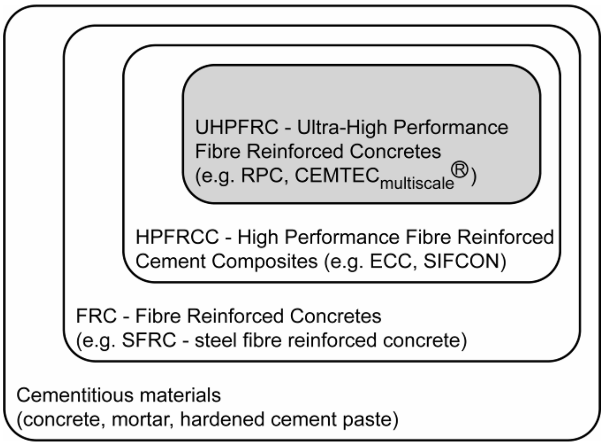


Figure 3-1: Classification of UHPFRC and HPFRCC among other cementitious materials

Historical overview. UHPFRC development found its origin in the studies of Odler, Brunauer and Yudenfreund in the beginning of the 1970s [Yudenfreund72,72a,72b, Odler72,72a, Brunauer73,73a]. They investigated high strength pastes with low w/c-ratios (w/c = 0.2 to 0.3) whose main characteristic was the low porosity leading to high compressive strengths (up to 200 MPa) and to low dimensional changes. Strength enhancement by hot pressing techniques was first applied by Roy [Roy72, 73] and resulted in very high strength cement pastes with compressive strengths up to 680 MPa.

With the development of superplasticizers and pozzolanic admixtures such as silica fume, two kinds of materials emerged in the 1980s: Birchall et al. developed polymer modified cementitious materials called Macro-Defect-Free (MDF) cements. The pores are filled by polymerization leading to a compact matrix. However, these concretes are susceptible to water and have high creep [Kendall83, Alford85]. Bache developed the DSP (Densified Small Particles) which use the interaction of superplasticizers and silica fume to decrease the porosity of the material and to increase the strengths. That way, he prepared the ground for modern UHPFRC development [Bache87]. The compacity of the matrix of these mixes was theoretically investigated and optimized e.g. by de Larrard and Sedran [DeLarrard94, Sedran94].

However, theses high strength cement pastes and mortars are very brittle. Consequently, the addition of fibres is necessary to enhance ductility (increase of G_F). Three tendencies are distinguished by Rossi [Rossi02]:

- DSP with an addition of 5 to 10% short steel fibres (l_f = 6 mm), commercialized under the name CRC [Bache87, Aarup04],
- the so-called Reactive Powder Concrete (RPC) with 2.5% of short slender steel fibres (l_f =13mm), developed by Bouygues, Lafarge and Rhodia and commercialized under the name Ductal® [Richard95, Orange00],
- and the Multi-Scale Cement Composite (MSCC) using a mixture of short and long steel fibres. MSCC are developed at the LCPC in France and are known under the name $\text{CEMTEC}_{\text{multiscale}}^{®}$ [Rossi97, Rossi02].

The development of UHPFRC and the tailoring of their specifically properties is still not entirely known and presents a research topic at several universities.

3.3.2 Principles of UHPFRC

The main principles for UHPFRC design are [Richard95]:

- *Homogeneity enhancement*: The homogeneity of the material is improved by eliminating coarse aggregates,
- *Compacity enhancement*: The density of the matrix is increased by optimizing the packing density. The different particle size classes are silica fume (mean size: 0.1 to 0.2 µm), cement (mean size: 15 µm) and fine sand (mean size: 0.2 mm). The optimum packing density can be determined with granular packing models by calculating the optimum ratio of the different aggregate classes [Sedran94, DeLarrard99, Jones02].
- *Ductility by fibres*: As the matrix of DSP is very brittle, steel or organic (e.g. carbon or glass) fibres have to be added to obtain strain-hardening behaviour in tension.

UHPFRC may be subjected to heat and / or pressure treatment. Pressure treatment of the fresh material increases the density by reducing the entrapped air, by removing excess water and by accelerating chemical shrinkage. Post-set heat treatment of 90 °C accelerates the pozzolanic reaction and modifies the microstructure of the hydrates.

These two treatments are difficult to apply in case of composite “UHPFRC-concrete” elements and in-situ applications and would present major drawbacks. UHPFRC without heat and pressure treatment are proposed and used in the present study.

3.3.3 Constituents of UHPFRC

UHPFRC consists of cement, silica fume, sand, fibres, water and superplasticizer. Typical water/ cement-ratios are 0.15 to 0.20 with 20 to 30% of silica fume.

Cement. The cement content (≥ 700 kg/m^3) is more than two times higher than for normal strength concrete. There is general agreement that the cement should have a low alkali content, low to medium fineness and a low C_3A-content, thus, reducing water need, ettringite formation and heat of hydration. In most cases, CEM I 52.5 is used, however, there are also promising tentatives with other cement types such as CEM III/B. [Richard95, Siebel03]

Silica fume. Silica fume fulfils three functions in UHPFRC: it fills voids between cement grains, it enhances the rheological characteristics and it forms hydration products by pozzolanic activity. Thus, the mechanical strengths are increased and microstructure and compacity of the UHPFRC are enhanced. Best results are reported for silica fume from the zirconium industry, having few impurities and a Blaine fineness of 14 m^2/g. The optimum filling performance of silica fume in cement is reached for silica fume-contents of 25% of cement content. [Richard95, Parant03].

Sand. UHPFRC aggregates are sand. Quartz sand is proposed, since it has a high hardness and provides good paste-aggregate interfaces. The mean particle size is often smaller than 1 mm, but also UHPFRC with maximum particle sizes of 8 to 16 mm are produced. [Holschemacher03, Richard95] It must be noted that the grain size distributions of cement, silica fume and sand have to be optimized in order to achieve high compacity and thus, a dense matrix with very low permeability.

Superplasticizer. Superplasticizers are essential for the processing (workability) of UHPFRC due to the low water-content. In general, superplasticizers of the 3rd generation - polycarboxylates and polycarboxylatethers - are used, as they are highly efficient and have no efficiency threshold for low w/c-ratios [Holschemacher03].

Fibres. Steel and organic fibres are used in UHPFRC. Naaman defined the demands on fibres as "short, stiff and strong" [Naaman02]. Thus, steel fibres seem to be the most adapted. Steel fibres are generally pulled out; therefore, fibre ductility is less important than their strength. Naaman developed limit curves for hardening under bending and uniaxial tension as a function of the fibre properties [Naaman02]. Rossi developed UHPFRC on the basis of the multiscale concept with several kinds of steel fibres - going from steel wool (lf ≈ 1 mm) to small steel fibres (5 to 15 mm) to long ones (> 15 mm). The different fibres work on the material scale to increase the tensile strength and on the structural scale to increase resistance and deformation capacity. [Rossi87, Rossi02] Typically, UHPFRC have fibre contents of more than 2 Vol.-%. The maximum fibre content in function of the aspect ratio of the fibres is limited by processing factors such as workability.

3.3.4 Material properties

3.3.4.1 Hydration

The low water-content of UHPFRC hinders full hydration, e.g. an UHPFRC with a w/c-ratio of 0.18 and with 26% of SF has a final degree of hydration of approximately 31%. The hydration rate of UHPFRC at early age is shown in Figure 3-2. It is characterized by a long dormant period (typically 24 hours or longer) which can be explained by the high amount of superplasticizer in the material, delaying setting of the material [Morin01]. Then, a strong hydration reaction starts which can be observed on heat release and the material starts to harden. The degree of hydration shows a high rate between 30 and 57 hours for the UHPFRC used by Morin et al., attaining a degree of hydration of 18% at 70 hours [Morin02].

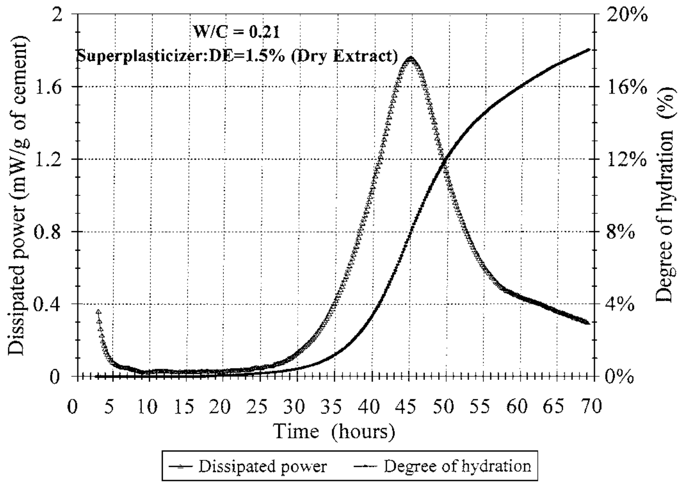


Figure 3-2: Heat release due to hydration and evolution of the degree of hydration of RPC [Morin02]

3.3.4.2 Mechanical properties

Compression. UHPFRC are characterized by high compressive strengths - typical values are 150 to 250 MPa at 28 days for UHPFRC without heat treatment. The secant modulus is also increased, but not to the same extent as the compressive strengths: E = 45 to 65 GPa at 28 days. The Poisson's ratio for RPC was determined to be 0.22 to 0.24 [Dugat96] and for $\text{CEMTEC}_{\text{multiscale}}^{®}$ to be 0.21 [Parant03] at 28 days.

Tension. One of the two main characteristics of UHPFRC is tensile strain-hardening. The comparison between strain hardening HPFRCC such as UHPFRC and conventional fibre reinforced concrete (FRC) is shown in Figure 3-3.

- D*omain I*: In the first part of the curves until point A, the stress rise is *quasi linear-elastic* until the cracking strength σ_{cc}.
- *Domain II*: It is followed by *strain-hardening* until point B with a post-cracking strength σ_{pc} for UHPFRC. The post-cracking strength of UHPFRC is higher than the cracking strength. Multiple cracks form during the strain-hardening, however, the macroscopic deformation is still uniform[1] and can be expressed by the strain ε.[2]
- *Domain III*: At point B, *crack localization* occurs and softening behaviour is observed (domain III), expressed by a σ-w-curve.

Domain II barely exists for conventional FRC. Typical maximum strengths of UHPFRC are 6 to 20 MPa with fracture energies of G_F = 10 to 40 kJ/m^2, mainly dependent on the compacity of the matrix and fibre composition [Dugat96, Parant03]. Real cracks form (i.e. the stress becomes zero) for a crack width of approximately half the fibre length (½ l_f).

[1] Macroscopic with respect to structural elements

[2] The extent of the tensile hardening domain will be often referred in what follows as "magnitude of hardening"

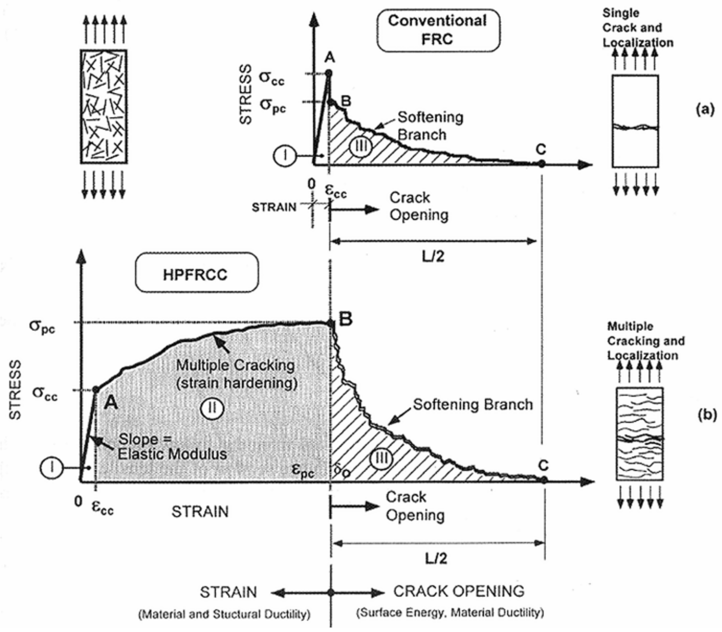


Figure 3-3: Comparison of typical stress-strain response of HPFRCC and FRC, adapted after [Naaman02]

Determination of tensile properties. Uniaxial tensile test for UHPFRC demand a stiff test set-up in order to avoid bending effects and an appropriate testing machine. An uniaxial tensile test was developed by Boulay [Boulay03]. The execution of uniaxial tensile tests is time intensive. So, the tensile behaviour of UHPFRC is often determined by bending tests (see e.g. [Parant03]). However, bending test results have to be carefully interpreted: the bending strength is often expressed by the modulus of rupture (MOR), which is the flexural strength calculated for a linear-elastic stress distribution. UHPFRC do not have linear-elastic stress distribution under bending beyond point A in Figure 3-3.

Tensile properties depend significantly on the fibre distribution. This distribution is influenced by the way of casting and the specimen geometry as for FRC. Furthermore, fibre segregation may occur leading to an inhomogeneous distribution of the tensile properties over the depth of the element.

3.3.4.3 Time-dependent deformations

Influence of stress rate. The effect of the stress rate on the resistance of UHPFRC specimens in bending was investigated by Parant for rates from 0.1 MPa/s to 100 GPa/s (Figure 3-4). Two domains are distinguished: domain I for quasi-static loading, where the increase of resistance (expressed by the MOR) is small, and domain II for dynamic loading where the stress rate increases significantly the resistance. The increase of resistance is reported to be more important for UHPFRC than for conventional FRC which is attributed to the high fibre content of UHPFRC [Parant03].

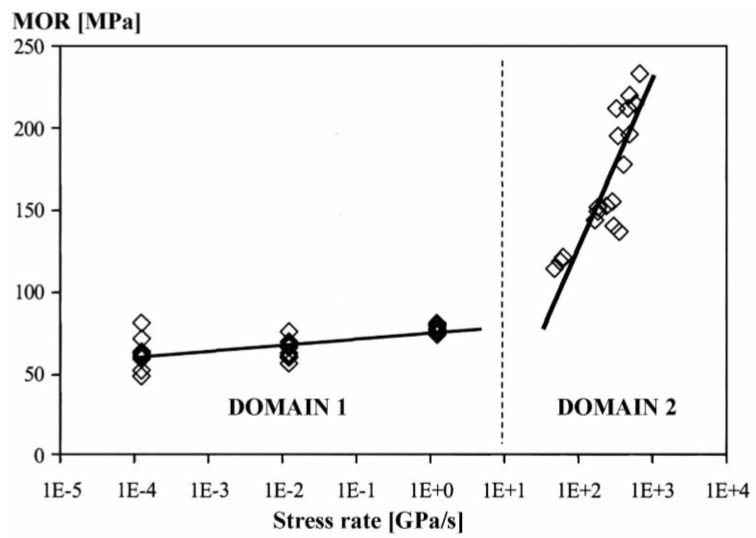


Figure 3-4: Influence of stress rate on the apparent MOR for the UHPFRC CEMTEC $_{multiscale}$®, adapted from [Parant03]

Shrinkage. Shrinkage on UHPFRC was measured for CRC, RPC and CEMTEC$_{multiscale}$®. The measurements started after setting of the material, i.e. the early age deformations were not considered. The shrinkage of heat-treated UHPFRC is zero after the application of the treatment, as all the shrinkage occurs during the heat treatment.

Autogenous and drying shrinkage was measured for CRC and RPC on cylindrical specimens (∅ 9 cm, l = 60 cm), starting 24 hours after water addition. The autogenous shrinkage after 160 days was approximately 450 µm/m after 8 days. The evolution of autogenous shrinkage is shown for RPC in Figure 3-5. The high autogenous shrinkage is mainly explained by the high self-desiccation of UHPFRC. Drying shrinkage evolution was strong during the first 10 days and stabilized at a value of 180 µm/m at higher ages. Furthermore, the results showed that autogenous and drying shrinkage decreased for decreasing w/b-ratio for RPC having w/b-ratio between 0.09 and 0.20, which is explained by the low hydration rate of UHPFRC. Additional weight loss measurements showed that microcracking occurred in the RPC during the first 10 days. The addition of steel fibres reduced shrinkage deformations by 10 to 20% [Loukili96, Cheyrezy01]. Acker explained that the major part of shrinkage is due to viscous response of CSH to hygral stresses provoked by capillary tension in the pores and disjoining pressure, since CSH is the only viscous component in UHPFRC. He determined the saturated pore size to be 3 nm at a relative humidity of 75% [Acker01].

Schachinger et al. conducted linear autogenous shrinkage measurements on ultra-high performance concretes without fibres. The measurements started before setting of the UHPFRC. He confirmed that the major part of autogenous shrinkage occurs during 5 to 10 hours after setting. Then, the evolution slows down, but, it does not stabilize until the end of measurements at 56 days [Schachinger03].

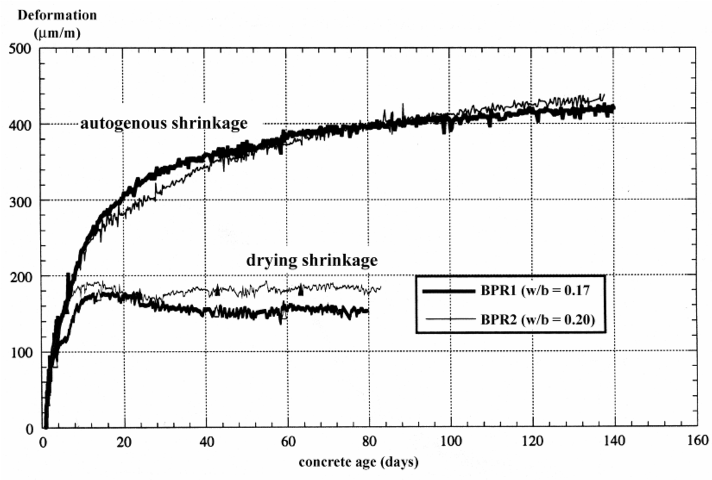


Figure 3-5: Autogenous and drying shrinkage of RPC (adapted from [Loukili96])

Autogenous shrinkage was also measured for $CEMTEC_{multiscale}^{®}$ at the LCPC. The tests started 3 days after casting. The autogenous shrinkage was 500 µm/m after 325 days. [Parant03]

The results of shrinkage measurements show that the critical phase for these material is during the first 10 days after water addition. Therefore, good curing is essential during early age to prevent micro-cracking on the surface. Autogenous shrinkage deformations are high at very early age. Consequently, it is necessary to quantify the deformations from the setting point on.

Creep. Compressive creep of RPC at several loading ages is shown in Figure 2.15. The creep coefficient ($\varepsilon_{creep} = \varepsilon_{el} \cdot K_{cr}$) decreases from $K_{cr} = 2.5$ to 0.6 with increasing age and stabilizes after 100 to 150 days (load level of 20%). RPC shows fast creep kinetics: 35% of the deformation occurs during the first 24 hours. The creep coefficient is smaller for lower w/b-ratios. Steel fibres reduce the creep compliance by 20 to 25%. [Cheyrezy01 Loukili96] The creep deformations are mainly attributed to visco-plastic CSH behaviour. The small creep compliance is explained by the fact that internal creep is high at early age due to the hygral stresses in the microstructure which arise with ongoing self-desiccation. Thus, the major part of creep is already finished when the UHPFRC is externally loaded. [Acker01]

The creep compliance was determined for $CEMTEC_{multiscale}^{®}$ at the LCPC. The specimens were loaded at 28 days to 45% of their compressive strength. The creep coefficient was $K_{cr} = 1.0$, and the creep compliance 45 µm/m/MPa, considering the elastic deformation. [Parant03]

No studies have been conducted for tensile creep of UHPFRC yet. Thus, it is difficult to estimate if tensile creep is of the same magnitude as compressive creep. It is known that tensile creep of normal strength concrete increases with decreasing cement content. i.e. with increasing interfaces between aggregates and cement. UHPFRC have only small aggregates, however, the steel fibres may have the same effect as aggregates, and a major part of tensile creep may have its origin at the interfaces between fibres and matrix.

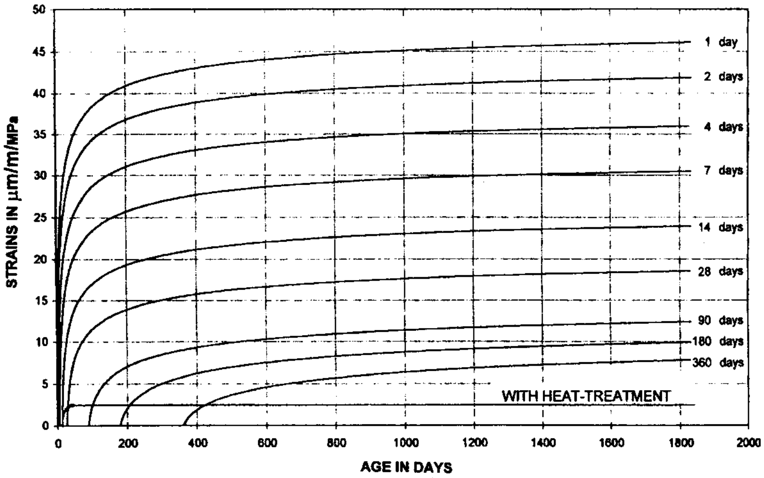


Figure 3-6: Creep deformation of RPC at different loading ages [Cheyrezy01]

3.3.4.4 Other physical properties

Porosity. The cumulative porosity of UHPFRC was measured with mercury intrusion porosimetry (MIP) by Roux et al. for RPC subjected to different curing treatments (Figure 3-7). Pores with sizes from 6 nm to 100 µm can be measured with this test method. The cumulative porosity of RPC was less than 9% for RPC without heat treatment and pressing and less than 0.5% for RPC subjected to different curing methods. In comparison, normal strength concrete has a cumulative porosity between 10 and 15%. A threshold value was observed, below which the porosity increased rapidly. This porosity is called microporosity. Capillary porosity is very small or even absent in UHPFRC [Cheyrezy95, Roux96].

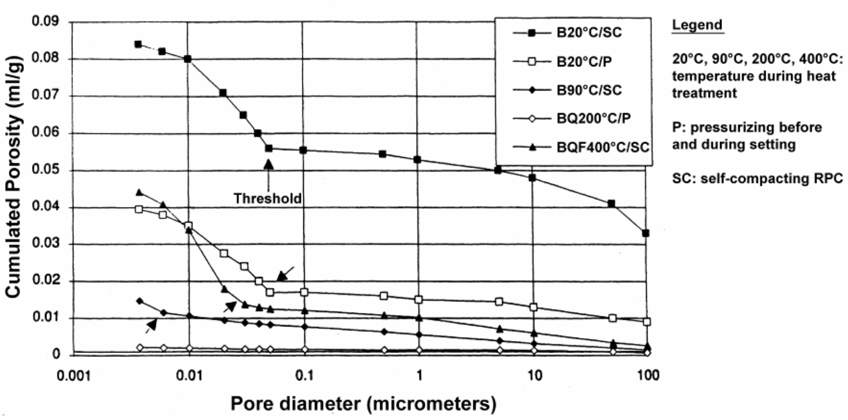


Figure 3-7: Cumulative porosity of UHPFRC, from [Cheyrezy95]

Permeability. Roux et al. also measured the air permeability on heat-treated sound RPC specimens. The permeability coefficient $k = 2.5 \cdot 10^{-18}$ m^2 was 50 to 500 times lower than the one of normal strength concrete. The measured values were near the sensitivity threshold of the used test method.

Permeability measurements were conducted at the MCS on damaged and undamaged UHPFRC specimens [Charron04]. The investigated UHPFRC, $CEMTEC_{multiscale}^{®}$, was identical to the one used in the experimental campaign of the present study. The damage, expressed by cumulated crack openings, was induced with the uniaxial tensile test described in [Habel04a]. The displacement Δl refers to the deformation over 10 cm that was reached during the uniaxial tensile test just before unloading (Figure 3-8a), i.e. the reversible part of the deformation during unloading is included in the given values.

a) b)

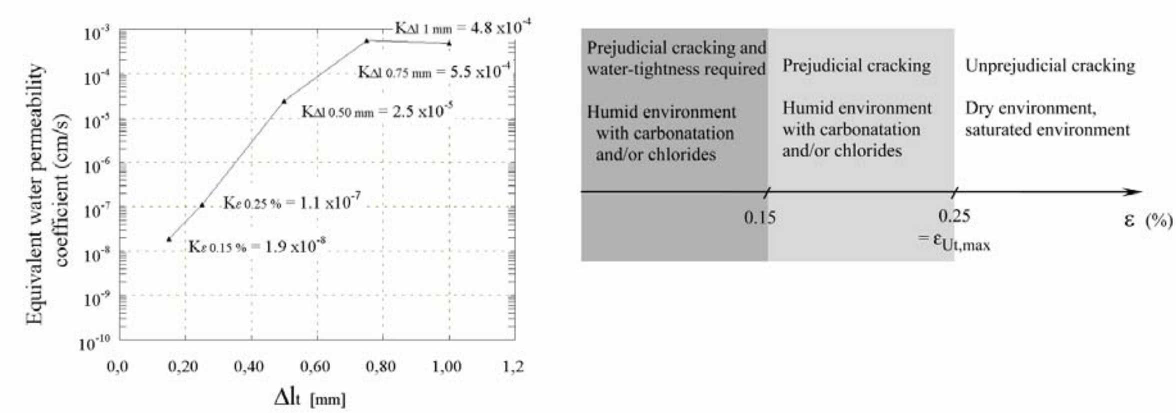


Figure 3-8: Permeability of $CEMTEC_{multiscale}^{®}$: a) water permeability coefficients, b) proposed classes for structural application, after [Charron04]

The evolution of the water permeability for increasing tensile deformation Δl is shown in Figure 3-8a. In the hardening domain of the UHPFRC (see Figure 3-3), multiple cracking with small widths occurs, and the permeability remains small. Here, the permeability coefficient K_{ε} refers to the deformation in the specimen ε. When the UHPFRC is in the softening domain, a strong increase in crack width in a localized crack and consequently in the permeability coefficient were observed. The permeability coefficient $K_{\Delta l}$ is referred to the deformation Δl measured during the uniaxial tensile test.

On the basis of the test results, durability and serviceability criteria for structural applications were defined by Charron (Figure 3-8b). If severe conditions such as water tightness are required, the deformation ε is limited to 0.15%, a value that lies approximately in the middle of the hardening domain of the UHPFRC (see Section 3.2.4). In case of high requirements on permeability, e.g. structural elements in humid environment with carbonation and/or chlorides, the deformation is limited to the deformation at the end of the hardening domain $\varepsilon_{Ut,max}$, corresponding to 0.25% for the tested material. If the protection function of UHPFRC is of secondary importance, higher crack widths may be admitted.

Water adsorption. The water adsorption of RPC was measured by Roux et al. It was more than 15 times smaller with 0.2 kg/m^2 than for normal strength concrete after 20 days. This can be explained by the small porosity and the absence of capillary pores [Roux96].

Chloride ions diffusion and migration, corrosion. The chloride ingress into heat-treated, pressed RPC was measured with a steady-state chloride flow through potential differences. It was very low with an effective diffusion coefficient $D_{eff} = 0.02 \cdot 10^{-12}$ m^2/s, which was more than 30 times lower than for normal strength concrete [Roux96]. Roux measured also the corrosion rate of RPC. RPC has a very high ohmic resistance in comparison to normal strength concrete, which reduces the electrical current and the corrosion rate. The corrosion rate was not exactly determined, since the measurements attained the sensitivity threshold of the test method [Roux96].

The deterioration of damaged UHPFRC ($CEMTEC_{multiscale}^{®}$) was investigated by Parant. Microcracks were created in plates under bending that were exposed to wetting-drying cycles (in NaCl-solution) in their loaded stage. The results showed that the effect of self-healing was more important than the effect of chloride ingress. The cracks were closed by new hydrates that could form due the water supply of the NaCl solution. No significant corrosion was observed on the steel fibres in the UHPFRC. [Parant03]

Carbonation. Roux et al. determined the resistance of RPC to the penetration of carbon dioxide by one natural and two accelerated carbonation tests. The carbonation was monitored by a phenolphthalein colour indicator. No carbonation was detected for the RPC, compared to a carbonation coefficient of 50 $mm/year^{0.5}$ for normal strength concrete in the accelerated test [Roux96].

Freeze-thaw cycles. Bonneau et al. investigated the resistance of RPC to freeze-thaw cycles according to ASTM C 666 [Bonneau97]. The durability was evaluated after 300 freezing and thawing cycles in form of the ratio of the moduli before and after the cycles. No reduction of the moduli was observed.

The measurements of permeability and transport properties showed that the ingress of substances in the UHPFRC is significantly reduced when compared to normal strength concrete. Consequently, UHPFRC seem to be appropriate materials in case of high requirements on protection.

3.3.5 Applications

UHPFRC were originally developed for the precast industry. The typical way to use UHPFRC is to produce precast elements that are assembled on the building site. The high strengths and the low permeability suggest an use of UHPFRC for zones subjected to detrimental substances or where high mechanical loads have to be introduced or transferred. UHPFRC have been applied for example for footbridges, beams in nuclear power plants, staircases and offshore structures [Cheyrezy97, Bekaert99, Behloul03, Aarup04]. They have not been cast in-situ yet. Moreover, the concept of UHPFRC was either to use them without additional reinforcement or in prestressed elements. To the author’s knowledge, they have not been used in combination with rebars yet.

UHPFRC material properties make them ideal materials for rehabilitation and in new composite “UHPFRC-concrete” elements. However, it has to be demonstrated that the outstanding properties of UHPFRC can be exploited in composite element with and without rebars in the UHPFRC layer.

Experimental campaigns have been conducted on some types of UHPFRC, however, there is still few knowledge of their material properties, in particular with regard to early age effects, viscoelasticity, tensile behaviour and the evolution of the material properties in time.

3.4 Composite structural elements of reinforced cementitious materials

The behaviour of composite elements consisting of reinforced cementitious materials is described in this section. First, the degree of restraint is discussed. Then, composite reinforced concrete (RC) elements are presented in brief with a focus on the aspects of time-dependent behaviour that are important for composite "UHPFRC-concrete" members and on failure modes. Finally, an overview of composite "ACM-concrete" elements is given concentrating on composite "UHPFRC-concrete" elements.

3.4.1 Degree of restraint

In composite elements, the stress state in the new layer due to shrinkage can be estimated by the degree of restraint μ. Shrinkage deformations of the new layer induce residual stresses in the structural element (Figure 3-9). The maximum tensile stresses build up in the new layer at the interface. They can be calculated by using the degree of restraint μ (EQ. 2.3).The degree of restraint for composite slabs, consisting of two rectangles with an identical width, is calculated by [Silfwerbrand97], it is extended to more general cross-sections by [Bernard00] as developed in the following.

$$\sigma_{new,2} = \mu \, E_{new} \, \varepsilon_{free} \qquad \textit{(EQ 2.3)}$$

with $\sigma_{new,2}$ [MPa]: tensile stress in the new layer at the interface, μ [-]: degree of restraint, E_{new} [MPa]: modulus of elasticity of the new layer, ε_{free} [-]: mean shrinkage strain in the new layer.

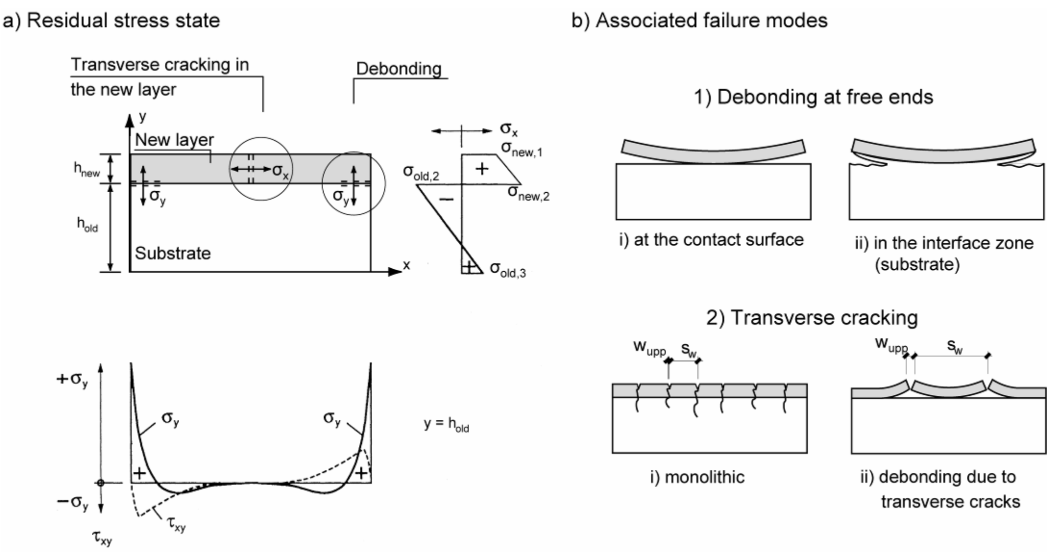


Figure 3-9: a) residual stress state in a composite element after [Haardt91] and b) associated failure modes (from [Bernard00])

The degree of restraint is calculated with EQ. 2.4 under the following hypotheses:

- linear-elastic material behaviour,
- Poisson's ratio ν =0,
- the cross-section of the new layer is a rectangle, the cross-section of the substrate can be of any shape,
- plane sections remain plain (hypothesis of Bernoulli) and
- perfect adherence between new layer and substrate.

$$\mu = \frac{\sigma_{new,2}}{\sigma_{rest}} = \frac{\sigma_{rest} + \sigma_N + \sigma_{M,2}}{\sigma_{rest}} = 1 + \mu_N + \mu_M \qquad (EQ\ 2.4)$$

The principle of the analysis consists in determining the tensile force N_t that is necessary to compensate the unrestrained shrinkage deformation ε_{free} in the new layer (Figure 3-10). The tensile force is balanced in the composite member by a compressive force N_c and a bending moment M_c acting in the centre of gravity (cg). The stress state in the composite element is determined by the superposition of N_t, and N_c and M_c.

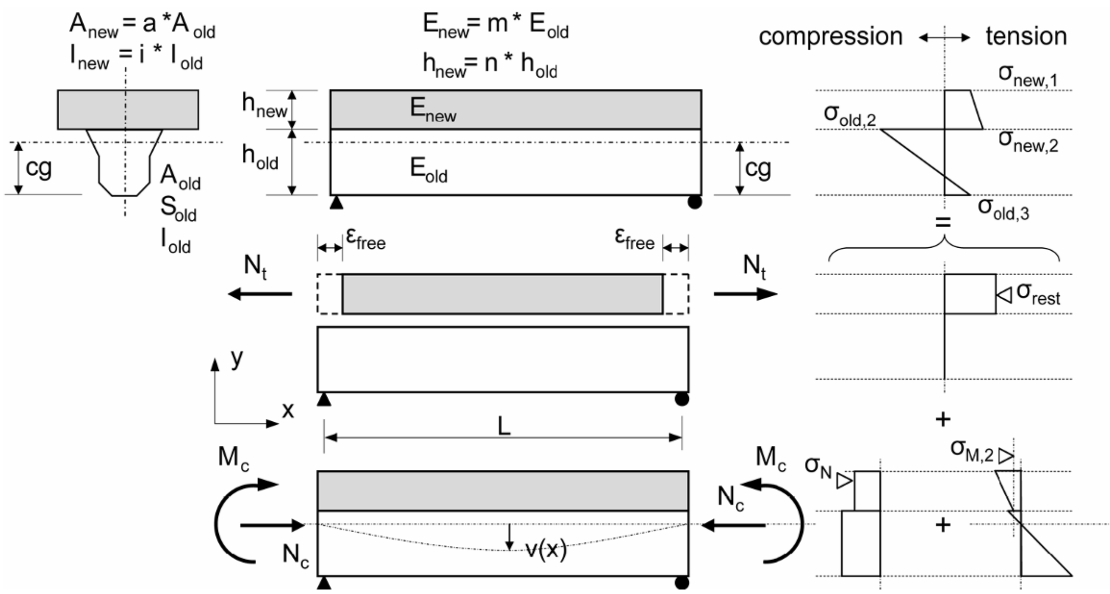


Figure 3-10: Axial stresses in a statically determinate composite beam (elastic stress-strain relation), after [Bernard00]

Statically determinate systems. The degree of restraint μ can be subdivided into the part of the axial force μ_N and the part of the bending moment μ_M. The equations for statically determinate beams (SD) are given in EQ. 2.5 and EQ. 2.6, the equation for the centre of gravity in EQ. 2.7. They apply to rectangular cross-sections of the new layer and cross-sections of any shape of the substrate.

$$\mu_{N,SD} = \frac{-m\ a}{1 + m\ a} \quad \textit{(EQ 2.5)}$$

$$\mu_{M,SD} = \frac{-m\ a\ A_{old}\left(h_{old}\left(1+\frac{n}{2}\right)-cg\right)(h_{old}-cg)}{I_{old}(1+m\ i)+A_{old}\left(cg-\frac{S_{old}}{A_{old}}\right)^2+m\ a\ A_{old}\left(h_{old}\left(1+\frac{n}{2}\right)-cg\right)^2} \quad \textit{(EQ 2.6)}$$

$$\text{with} \qquad cg = \frac{S_{old} + m\ a\ h_{old}\ A_{old}}{A_{old}(1 + m\ a)} \quad \textit{(EQ 2.7)}$$

The degree of restraint in a statically determinate system μ_{SD} is shown in Figure 3-11a for beams or slabs consisting of two rectangles with the same width in function of the ratio of the thicknesses n and the ratio of the moduli of elasticity m. The degree of restraint is the highest for low ratios m, i.e. when the modulus of elasticity of the new layer is small, corresponding to the early age of the composite element. For for composite "UHPFRC-concrete", the final ratio m members lies between m = 1.2 and 2.0 (for higher ages). The degree of restraint has the highest values for a ratio of the thicknesses n < 0.3 to 0.5 (depending on m). This indicates that tensile stresses and cracking risk are maximal for thin layers.

a) *b)*

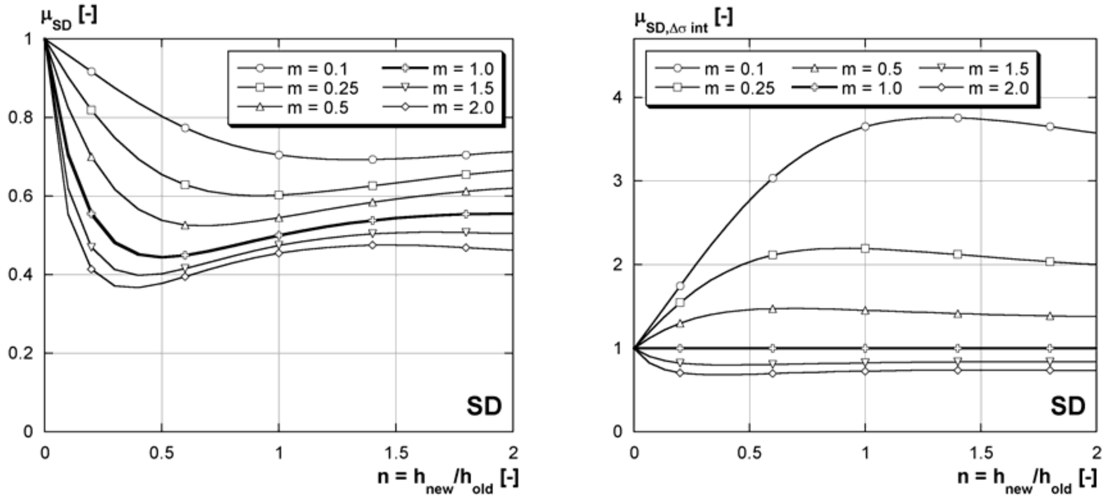


Figure 3-11: a) degree of restraint of a statically determinate beam, b) relative stress difference at the interface between new layer and substrate

Figure 3-11b indicates the relative stress difference between old and new layer for statically determinate systems according to EQ. 2.8. At free ends, this stress difference induces stresses perpendicular to the interface (σ_y) which are determinant for debonding due to shrinkage of the new layer (case 1 in Figure 1.5b). Consequently it can be used to determine the debonding risk. The latter is highest for low values of m, i.e. at early age of the composite member and decreases with increasing m and age respectively.

$$\sigma_{new,2} - \sigma_{old,2} = \mu_{SD,\Delta\sigma int} E_{new} \varepsilon_{free} \qquad \textit{(EQ 2.8)}$$

Statically indeterminate systems. In statically indeterminate systems, the internal stresses due to restrained shrinkage are partially redistributed. The degree of restrained shrinkage is significantly increased. Yuan determined an increase of 30% in an example [Yuan94]. The effect of statically indeterminate systems is considered by factors θ_N and θ_M for axial and bending restraint respectively (EQ. 2.9, EQ. 2.10). These factors are the ratio between the statically indeterminate part of the reaction (N_{SID}, M_{SID}) and the reaction in case of total restraint (N_c, M_c). They are 0 for statically determinate systems and 1 in completely restrained systems.

$$\mu_{SID} = 1 + (1-\theta_N)\mu_{N,det} + (1-\theta_M)\mu_{M,det} \qquad \textit{(EQ 2.9)}$$

$$\text{with} \quad \theta_N = \frac{N_{SID}}{N_c} \quad \text{and} \quad \theta_M = \frac{M_{SID}}{M_c} \qquad \textit{(EQ 2.10)}$$

The degree of restraint as it is presented here does not consider viscoelasticity and non-linear stress-strain distributions which would be the case in composite “UHPFRC-concrete” members. However, it is a simple tool for the estimation of the stress state in composite elements.

3.4.2 Composite RC elements

3.4.2.1 Processing

The durability of composite elements depends essentially on correct processing and has been extensively studied (e.g. by [Emmons00, Pigeon92, Schrader92]). The preparation of the contact surface is essential to guarantee monolithic behaviour under actions. Sandblasting and hydrojetting are the most adapted methods with regard to damage and roughness (e.g. [Courard99, Silfwerbrand90, Warner98, Zhu91]). The contact surface of the substrate should be humid, but not wet. In general, bonding agents and mechanical connectors are not necessary, if a surface preparation method is applied that creates sufficient roughness and if the design of the structural member is adapted in zones of force introduction [Bissonnette00, Bernard00]. A new concrete should be chosen whose properties are close to the substrate and good curing (minimum of 5 days) should be performed. A comprehensive overview of correct processing can be found in [Bernard00].

3.4.2.2 Time-dependent behaviour

The determinant time-dependent phenomena for composite RC members are deformations due to hydration effects, i.e. thermal deformations due to the heat release and autogenous shrinkage as shown by [Bernard00], and drying shrinkage in the long term.

Thermal effects due to heat of hydration. During hydration, heat is released in the new layer, first leading to a temperature rise and when the hydration reaction slows down to cooling of the element. The temperature increase is high in the new layer and relatively low in the substrate leading to a temperature gradient in the element. The evolution of maximum and minimum temperature in a composite element is schematically shown in Figure 3-12a. Due to the restraint, temperature rise induces compressive stresses in the new layer until time t_{peak} (Figure 3-12b). During cooling, tensile stresses build up in the new layer and may lead to cracking. The determinant parameter for residual thermal stresses is the *maximum temperature difference between old and new layer* $\Delta T_{o\text{-}n,peak}$ [Bernard00]. Bernard proposed a simplified approach to estimate the cracking risk due to early age thermal deformations and found a threshold value of $\Delta T_{o\text{-}n,peak} \leq 12$ °C to avoid cracking for average properties of normal strength concrete [Bernard00]. The temperature difference in composite elements becomes important for massive members such as curbs [Brühwiler00].

a) *b)*

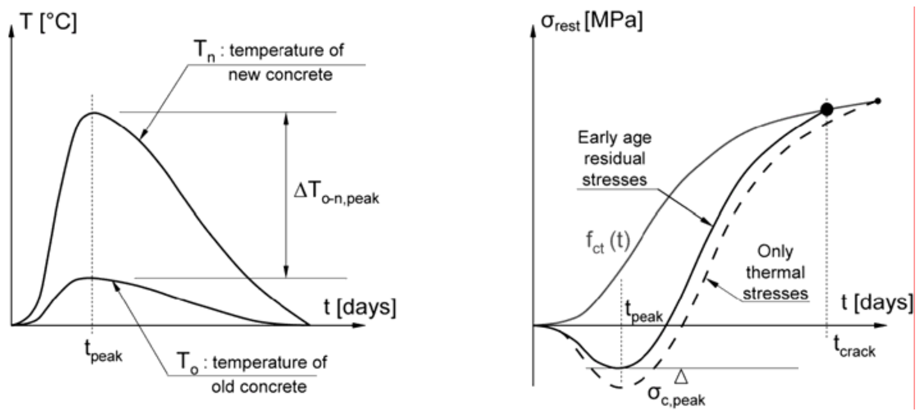


Figure 3-12: Early-age behaviour of composite elements : a) temperature evolution, b) stress evolution in the new layer, considering only thermal stresses, autogenous shrinkage and viscoelasticity (adapted from [Bernard00])

The *cracking risk* is small for slender composite beams with a thickness ratio of new to old layer between $h_{new}/h_{old} = 0.45$ and 1.1 under constant ambient temperature of 20 °C [Bernard02]. However, ambient temperature and its variation may significantly increase the stresses due to thermal effects [Brühwiler00]. The cracking risk due to thermal stresses can be limited by adapting the temperature of the fresh concrete, by using an adapted low-heat concrete mix design, by heating the existing structural element during heat rise and by adapted curing. Further details about adequate methods can be found in [Bernard00, Bernard01, Brühwiler00].

Autogenous Shrinkage. Autogenous shrinkage is an important phenomenon that induces curvature and tensile stress at early age, even for normal strength concrete with w/c = 0.5. It is mainly important during the first two days after casting of the new layer. Autogenous shrinkage reduces the compressive strength $\sigma_{c,peak}$ and increases the tensile stresses in the new layer, i.e. the curve of stress evolution due to thermal effects is shifted towards tension (e.g. upwards in Figure 2.23b). The tensile stresses may lead to transverse crack formation in the composite element [Bernard02].

Viscoelasticity. The stresses in the composite element are partially relaxed by concrete viscoelasticity. Viscoelasticity is significant for early age concrete and decreases gradually. Ducret measured residual stresses in composite “reinforced concrete - steel” beams even at a concrete age of 28 days [Ducret97].

Viscoelasticity is higher in the new concrete layer and leads mainly to stress relaxation in the new layer of 50 to 70% after one year. [Bernard00] The importance of viscoelasticity on the reduction of the cracking risk in new layers is demonstrated by Silfwerbrand, Bissonnette and Bernard [Silfwerbrand87, Bissonnette00]. In consequence, Bissonnette proposes the concept of global deformation to evaluate stress state and cracking in composite elements.

Drying Shrinkage. Drying shrinkage is the most important phenomenon in composite members consisting of two layers of normal strength concrete. Various studies show its importance for thin repair layers and thicker structural layers (e.g. [Bernard00, Granju01, Martinola01, Sadouki97, Silfwerbrand97]). Drying shrinkage induces a moisture gradient in the new layer, leading to increased tensile stresses at the surface. Bernard determined the conditions under which transverse cracks are induced. Structural parameters such as geometry and static system and material parameters decide upon the cracking risk due to drying shrinkage. A comprehensive overview of drying and its influence on composite concrete elements can be found in [Bernard00].

Since drying shrinkage does not seem to play a major role in composite "UHPFRC-concrete" members, it is not discussed any further in this section and reference is made to the extensive literature. However, thermal effects and self-desiccation shrinkage are important in UHPFRC and may govern the behaviour of composite "UHPFRC-concrete" elements.

Role of reinforcement. Rebars in the new layer induce additional local restraint thus increasing the cracking risk. In parallel, the deformations of the composite elements are reduced. This is demonstrated for drying shrinkage by Bernard [Bernard03].

Steel fibres in the new layer reduce crack widths and spacing and debonding. For thin SFRC overlays, Chausson identified as most important factor the ratio post-cracking strength to tensile strength, since this ratio is determinant for the control of cracking. [Chausson97] The effect of materials with strain-hardening is discussed in Section 2.6.3.1.

Modelling. The time-dependent behaviour of composite concrete elements is either evaluated by analytical models or by FE-programs.

The analytical models are mainly developed to determine the residual stresses in the new layer and at the interface. In general, they consider uniform shrinkage and in some cases also creep [Silfwerbrand97, Yuan94].

FE-programs give the possibility to take into account thermal, hygral, chemical effects and the resulting deformations and crack formation either by the fictitious crack model or the crack band model. The options of the programs and their degree of couplings between the phenomena vary from program to program. Such models were developed and extended for example by [Bernard00, Emborg89, Femmasse04, Martinola01, Kranz99]. A detailed description of the models can be found in [Bernard00].

3.4.2.3 Failure modes

Composite elements consisting of normal strength reinforced concrete are designed in the same way as reinforced concrete structures, if monolithic behaviour is guaranteed. Residual stresses do not play a role in design, since they are small in the substrate in compression and tensile stresses of concrete are neglected at the ultimate limit state (ULS). This is demonstrated in [Silfwerbrand97]. Thus, nearly all investigations of the fracture behaviour of composite members focus on the evaluation of debonding.

Debonding. The properties of the interface zone depend on the design and processing. The influence of material parameters and surface preparation methods, partially in combination with connectors, on the debonding resistance has been extensively studied (e.g. by [Courard99, Randl00, Silfwerbrand90, Trausch01, Vaysburd01, Warner98]). By using adequate surface preparation methods (i.e. hydrojetting or sandblasting), the tensile strength in the interface zone amounts to approximately 60 to 70% of the concrete strength of the substrate or the new concrete [Bernard00a, Warner98]. Moreover, the modulus of elasticity of the new layer should be close to the one of the old layer (E = ±10 GPa) in order to minimize the debonding risk [Emberson96].

Brenni conducted structural beam tests in order to determine the interface resistance by using different surface preparation methods and type of connectors. He concluded that best results are obtained by combining a high interface roughness with connectors. He proposed to design the composite members by exclusively considering the connectors and by neglecting the adherence between the two layers [Brenni95].

This approach is rather conservatory, since it has been shown that composite concrete elements may behave in a monolithic way without connectors [Bernard00, Silfwerbrand87]. Bernard showed that structural (geometry, static system) and material parameters influence the debonding risk and defined limit conditions to avoid debonding. His debonding criterion is conservatory - debonding already occurs when an interface crack starts to form. However, small interface cracks do not alter the structural response of the composite member. A design method is proposed for the determination of the thickness of and the reinforcement ratio in the new layer by respecting the design moment and by preventing debonding [Bernard00, Habel00].

3.4.3 Composite “ACM-concrete” elements

3.4.3.1 Composite “HPFRCC-concrete” beams

Composite “ACM-concrete” elements have been investigated using the HPFRCC ECC and SIFCON/SIMCON. The HPFRCC are used as thin overlays with thicknesses from 1 to 5 cm for deteriorated structures such as cracked pavements or bridge decks. Their tensile strain-hardening improves deformation and energy adsorption capacity.

Thus, they are able to bridge cracks in the existing concrete substrate. The cracks in HPFRCC remain small (between 30 and 50 μm) and are densely distributed [Krstulovic96].

Promising results have been obtained in field studies with SIFCON. No damage and no debonding were observed in an thin pavement overlay (thickness: 2.5 cm) after 9 years of service life [Schneider92].

It is argued that the small crack widths diminish considerably the penetration of detrimental substances and thus, the deterioration of reinforcement in the composite element. [Li00, Krstulovic97, Krstulovic96].

Studies on chloride penetration into SIFCON showed that the corrosion rate is reduced compared to SFRC, but, corrosion also occurs in non-damaged SIFCON elements [Kosa91]. This can be attributed to the porosity of the non-optimized SIFCON matrix and on possible shrinkage cracking at early age [Lemberg96]. The diffusion coefficient of sound ECC is similar to the one of concrete (with w/c = 0.35) for RH < 65%; for RH > 65%, the diffusion coefficient of ECC is higher than for concrete [Weimann03] and attempts are made to modify the ECC composition with internal water repellent agents in order to guarantee durability [Martinola02]. Consequently, HPFRCC are subjected to deterioration processes in time and should not significantly improve the durability of a structural element in the long term when compared to normal strength concrete.

Existing research results show that tensile strain-hardening of HPFRCC is beneficial in composite elements with regard to crack widths. However, the relatively high permeability of ECC and SIFCON may reduce the protection function of the HPFRCC layer in the long term.

3.4.3.2 Composite “UHPFRC-concrete” beams

Composite “UHPFRC-concrete” beams were tested at the MCS in 3-point-bending in order to investigate the structural response and cracking (Figure 2.24) [Denarie01, Denarie03]. The used UHPFRC was a type of DUCTAL® with short steel fibres (l_f = 13 mm) [Orange00]. No rebars were placed in the UHPFRC layer. Reference beams in RC with a reinforcement ratio ρ = 0.8% were also tested.

The results show that the maximum force of the beams was comparable for the RC beams and the composite beams (Figure 3-13).The stiffness of the composite beams was increased until the maximum force was reached. This is explained by the improved tensile properties of UHPFRC, in particular by the high tensile strength and by strain hardening increasing the deformation capacity of the UHPFRC before the formation of a localized macrocrack. However, the force decreased strongly after its maximum for the composite beams, while the RC beams showed hardening behaviour. Moreover, the measured crack openings increased less quickly for the beams than for the composite beams.

This was due to the relatively small length of the steel fibres in the UHPFRC that were pulled out and could not transfer force through cracks with large widths.

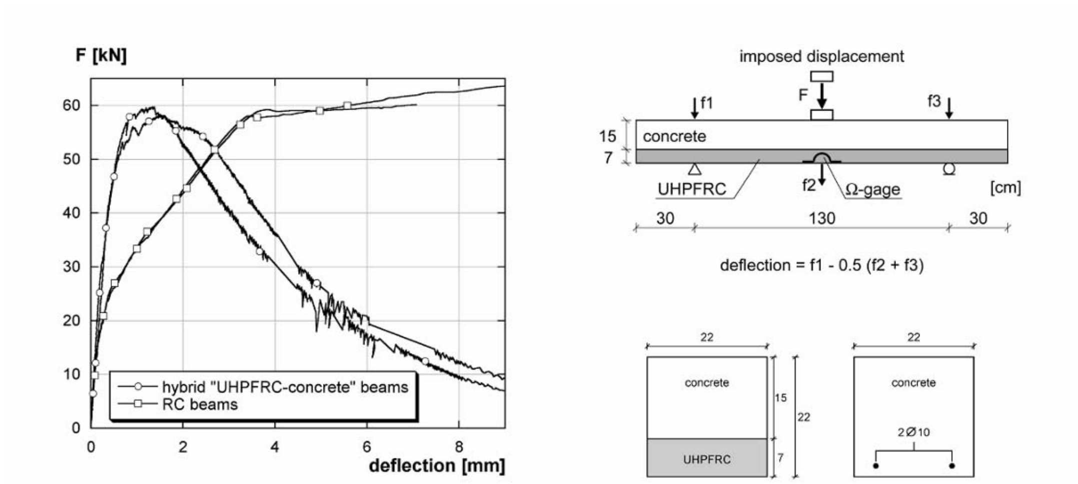


Figure 3-13: Structural response of composite "UHPFRC-concrete" beams in comparison to reinforced concrete beams (after [Denarié03])

The UHPFRC “CARDIFRC” is used as bonded strips in the tension chord for rehabilitation and improvement of existing concrete beams [Alaee03]. Reinforcement bars are incorporated in the existing concrete in the tension chord. The UHPFRC is cast separately and bonded to the concrete member with an epoxy adhesive. The tension side and in some cases also the sides of the beams are strengthened. The composite beams show monolithic behaviour under 4-point-bending until fracture. The maximum force of the composite beams is equal or higher than of the existing concrete member; however, the force-deflection curves show softening behaviour after the maximum force is reached.

The method of the use of UHPFRC as bonded strips is promising, however, the epoxy adhesive used to bond the UHPFRC to the concrete may cause problems in terms of sufficient durability and the advantage of the good bond by casting the UHPFRC directly on the substrate cannot be exploited.

The results show that UHPFRC is a promising material for the rehabilitation of concrete beams. The advantage of UHPFRC when compared to HPFRCC is their low permeability that prevents the ingress of detrimental substances. This should significantly increase the durability of composite “UHPFRC-concrete” members. However, the penetration of water to the interface zone of composite “UHPFRC-concrete” members has to be prevented by adequate design in order to prevent interface cracking as a consequence of water pressure.

4 COMPARATIVE STUDY OF UHPFRC RECIPES

4.1 Introduction

This section presents the results from a series of exploratory tests on 4 different recipes of the UHPFRC CEMTEC$_{multiscale}$®, in view of applications for the rehabilitation of highway structures.

Three aspects were more specifically investigated in order to select appropriate materials for the main test series:

- Effect of the composition (fibre mix) of UHPFRC on their workability. The *properties in the fresh state* (rheological e.g. workability) served as a basis to define the range of possible applications for specific mixes. As far as possible, self-compacting materials were sought.
- Effect of the geometry of the element to be cast (wall or plate) on the mechanical properties (tensile and flexural behaviour).
- Effect of the composition of the fibrous mix on the mechanical properties (tensile and flexural behaviour on plates).

The tests performed on fresh UHPFRC mixes were: visual inspection of the material in the drum of the mixer, spread test (slump flow with Abram's cone), and sensitivity to a slope of the substrate (inclined box).

Two different tests were performed on the hardened UHPFRC: uniaxial tensile tests with measurement of the overall pre and post-peak response, with notched specimens, and 4 point bending tests on plates with measurement of the overall pre and post-peak response. Following parameters were considered: effect of thickness on the flexural response, effect of the orientation of the specimen with respect to the direction of casting on the flexural behaviour, effect of the mode of casting (horizontal as a plate or vertical as a wall) on the response in uniaxial tension and 4 PT bending. For every mix the range of thicknesses of the specimens were selected in view of the specific application: thin protective layers or thicker layers for repair or reinforcement.

In parallel, for the sake of comparison, for each batch, characterization tests were performed on standard 4/4/16 cm specimens to determine the MOR (Modulus of Rupture) and compressive strength on the two remaining haves of the specimens after completion of the flexural tests.

Finally, preliminary permeability tests on small scale specimens as well as on composite structural members with UHPFRC helped confirm the outstanding transport properties of these materials.

4.2 Composition

Four different recipes of UHPFRC were tested, with different fibrous reinforcements (length, aspect ratio and volume percentage of fibres), for three different applications:

- Mix CM0 with only one type of macrofibres (l_f=10 mm) is a first approach to a multi-purpose UHPFRC for the rehabilitation of concrete structures. It was extensively tested and characterized by [Habel04a and b] and [Charron04]. It is self-compacting and exhibits a significant tensile hardening behaviour (up to 0.2 %) and a tensile strength of 8 to 10 MPa. It served as a reference point for the comparative study.
- Mix CM1 with only one type of short fibres (l_f=5 mm) is dedicated to thin protective layers. According to [Naaman03], with 10 % fibres such a mix is just at the limit to exhibit a strain hardening behaviour.
- Mix CM2 with two types of fibres (microfibres – steel wool, and macrofibres of 10 mm length) is foreseen for intermediate layer thickness, for repair or reinforcement purposes, with or without reinforcement bars.
- Mix CM3 with three types of fibres (microfibres – steel wool, mesofibres of 5 mm length, and macrofibres of 20 mm length) is foreseen to provide the best possible mechanical response.

The composition of each mix is summarized in Table 4.1 and given in details in Table 7.1 to Table 7.4, in appendix 1.

	CM1	**CM2**	**CM3**	**CM0**
Cement [kg/m^3]	1125.1	1300	1415.2	1051.1
SF/C [---]	0.26	0.26	0.26	0.26
Admixture[3] /Cement [%]	1	1	1	1
Steel fibers types l_f/d_f [mm]	5/0.15	Steel wool + 10/0.2	Steel wool + 5/0.15+20/0.25	10/0.2
Total vol. fibers [%[	10	9	11	6
W/C [-]	0.17	0.18	0.17	0.18
W/(C+SF) [-]	0.135	0.143	0.135	0.143

Table 4.1: Summary of the compositions of the CEMTEC$_{\text{multiscale}}$® recipes tested

The individual characteristics of the components are listed in Table 7.5, in appendix 1.

The behaviour of UHPFRC at fresh state and the texture of the hardened material on a fracture surface are shown on Figure 4-1.

[3] dry extract

Figure 4-1: a) UHPFRC at fresh state (mix CM1) and b) texture of the hardened material CM2 shown on a fracture surface.

4.3 Performance at fresh state

4.3.1 Test methods

A visual inspection was realized in the mixer's drum, at the end of the mixing sequence. The results of this visual inspection are classified in Table 4.2. Three indications were recorded:

- *Spontaneous release of entrapped air*, which is characteristic of a self-compacting material, and as much pronounced as the self compacting character is strong. The three mixes exhibited spontaneous release of air bubbles.
- *Homogeneity of the mix – segregation of fibres*: the best mixes do not show any segregation and one easily distinguishes fibres swimming close to the free surface of the fresh mix. None of the three recipes showed a noticeable segregation in the mixer.
- *Self levelling ability of the mix* in the mixer's drum: This property is associated to self compacting concretes. Only mix CM3 did not exhibit this behaviour.

	CM1	CM2	CM3	CM0
Spontaneous air release	+++	++	+-	+++
Segregation of fibres	---	---	---	---
Self levellingness	+++	++	---	+++

Table 4.2: Visual inspection of the fresh mixes, in the drum of the mixer at the end of the batching sequence

Two supplementary tests were performed to characterize the processing willingness of the fresh UHPFRC, just before casting. First of all, a slump flow test, now classical for self compacting concretes, realized with an Abram's cone, and secondly, the test of the sensitivity to a slope of the concreting surface. It is commonly accepted that a final diameter of over 600 mm from the slump flow test indicates a self compacting concrete.

4.3.2 Results and analysis

Material CM1 was clearly self-compacting whereas material CM2 was very close to it but not fully self compacting according to the slump flow test. It must be emphasized here that the slump cone has a confining effect on the fibre mixes used, that leads to a structural consolidation of the very dense fibrous skeleton. *This effect of confinement which has to be avoided in practical applications leads to a bias in the estimation of the self compacting character by means of the slump flow test.* A suitable workability test has still to be designed for UHPFRC with high amounts of fibres. On another hand, preliminary tests with similar fibrous mixes for material CM2 but with a lower dosage of cement demonstrated that the addition of microfibres (steel wool) requires a significant increase of the amount of cement and silica fume in order to reach a self compacting behaviour. The last mix tested for material CM2, according to Table 7.2, had 1300 kg/m^3 of cement and this dosage was not yet sufficient to get a final spread over 600 mm.

Mix CM3 has 3 different kinds of steel fibres (micro, meso - 5 mm length and macro – 20 mm length). Despite the full replacement of fine aggregates by cement and silica fume (cement dosage of 1400 kg/m^3), this mix was very difficult to process and cast, and impossible to test with the slump flow. The processing means available for these batching tests, usual for concrete, were obviously not adapted for such materials which are even more than material CM2 sensitive to any confinement prior to casting, which leads to an interweaving of the fibrous skeleton impossible to break afterwards. Such materials would have to be processed in a totally different way, i.e. pour onto a conveyor belt under the mixer and directly pour from the belt into the form to fill, without any confinement between the mixer and the form to fill.

The set-up for the test of sensitivity to a slope is shown on Figure 4-2. It is formed of an inclinable box of 1 m length and 30 cm width. The height of the box is variable from 50 mm to 100 mm at the lower point, nearby the pivot, to accommodate an accumulation of material at the lower point when the box is inclined. Two steel meshes of 100/100 mm, diameter 3 mm are superimposed and shifted of 50 mm, at the bottom of the box, to simulate the rough surface of a concrete after hydro jetting. A piece of wood placed under the box, opposite to the pivot, enables one to select various slopes (5, 10, and 15 %). The principle of the test is the following:

- The box is set horizontal. It is then filled with the fresh material up to until a thickness which corresponds to the foreseen application and to the used material. The box is then progressively inclined and the behaviour of the fresh material in the box is observed: movements towards the lower point, formation of an accumulation at the lower point, etc.

Figure 4-2: Test set-up for the sensitivity to a slope

The results of this test are summarized in Table 4.3. Material CM0 starts to move for small inclinations of the box and clearly does not tolerate to be applied on inclined surfaces. Surprisingly, material CM2 starts to move for a smaller inclination of the set-up than material CM1. This can be explained by the fact that for material CM1, the box was only half filled (thickness of 25 mm) prior to inclination, instead that with material CM2, the box was filled up to 50 mm. In the latter case the reinforcement bars that were at the same position in the box for the two materials, have a smaller retaining effect. This test is impossible to perform with material CM3 and presents no interest.

		CM1	CM2	CM3	CM0
Average spread diameter (slump flow) [mm]		630	430	n.a.	600 to 700
Sensitivity to slope	**5%**	---	-+	n.a.	++
	10%	-+	++	n.a.	+++
	15%	++	+++	n.a.	+++

Legend:	
---	**no movement**
-+	**initiation of a movement on surface of fresh mix**
++	**movement and slight accumulation of material at bottom of box**
+++	**movement and marked accumulation of material at bottom of box**

Table 4.3: Results of slump flow and sensitivity to a slope tests

4.3.3 Synthesis and conclusions

The *properties in the fresh state* (rheological e.g. workability and susceptibility to a slope of the casting surface) served as a basis to define the range of possible applications for specific mixes. As far as possible, self-compacting materials were sought. Four different recipes of $CEMTEC_{multiscale}^{®}$ have been tested with various types of matrices in order to optimize their workability:

- The matrices of CM1 and CM2 could be fine tuned to obtain a self-compacting behaviour. Both mixes are robust and tolerate slopes till 5 %. CM3 was difficult to process and requires further investigations to be used.
- Further works will concentrate on CM1 and CM2.

The mobility of the fresh UHPFRC on a slope appears to be a major issue to be solved. Further, one should keep in mind that there is a scale effect on the fresh properties of cementitious materials, when the size of the mixer increases. For larger batches and mixers, the surface/volume ratio of the fresh material in the mixer diminishes and the workability increase, i.e. the mix tends to be more fluid for an equivalent composition in a larger mixer for larger batch size. This aspect has to be taken into consideration for the design of suitable recipes for on site applications using large mixers.

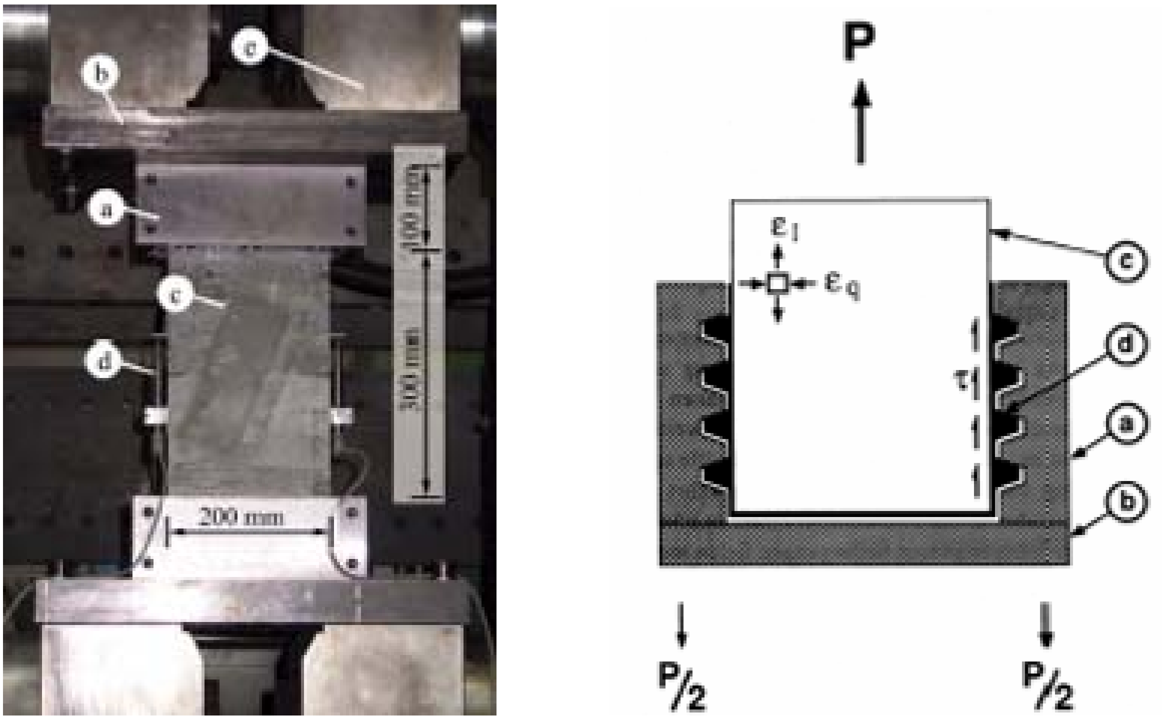
4.4 Mechanical performance

4.4.1 Introduction

24 Tensile and 60 flexural tests were performed at an age of 28 days, on specimens with various thicknesses and orientations with respect to casting. Both tests were instrumented and designed in order to obtain the full pre and post peak response of the materials. The tensile tests (on notched and unnotched plates of 20 cm width, 5 cm thickness) deliver a direct comparison of the intrinsic mechanical performance for various mixes and conditions of casting. The main results of the test are the full stress displacement curve with the limits of the hardening and softening domains which are the most reliable mechanical performance indices. However, due to the high requirements for this test, only a limited number of specimens could be tested. The flexural tests were performed as 4 PT bending on plates of 20 cm width, 42 cm span. Thickness of 10, 30, 50 and 100 mm were used to cover the range of practical applications. The result of this test is the full force-deflection curve. The interpretation of this test is less straightforward than that of the tensile test, owing to the non-linear behaviour of the UHPFRC in bending. It is however easier to perform than the tensile test and less time consuming. It helped investigate the scatter on the mechanical properties in bending and test various configurations with respect to the direction of casting and specimen thickness, to detect eventual anisotropy effects. Both tests showed a reasonable scatter of results, smaller for the tensile test.

4.4.2 Test methods

The tensile tests were realized on a universal SCHENCK testing machine with a maximum capacity of 1000 kN. The specimens were notched plates of 500 mm length, 200 mm width and 50 mm thickness, with symmetrical notches of 20 mm applied in their middle part. Four displacement transducers were used. Two on the sides of the specimen, centred on the notch, were averaged and used to control the tests. Two on the back face of the specimen were recorded independently in order to reveal possible rotations of the specimen during the test. Figure 4-3 shows the geometry of the specimen and the position of the displacement transducers controlling the test. The measurement basis is 100 mm centred on the notches. The test is controlled in close loop by the average value of the two displacement transducers with a speed of 0.02 mm/minute up to 0.5 mm (hardening domain) and 0.2 mm until the end of the test (softening domain).The specimen is fixed in a rigid way in the testing machine by a system of gluing-shaping without bonding, shown on Figure 4-3, after [Habel04a]. There is no bonding between the glue and the steel parts attached to the testing machine. Both notched and unnotched specimens were used in order to distinguish prevent premature failure of the specimen outside the measurement zone, nearby the supports.



A B

Figure 4-3: Tensile test set-up and principle, after [Habel04], A: a) metallic pieces of support, b) base plate connected to testing machine, c) specimen, d)LVDT, e), testing machine: B: a) metallic supports, b) base plate connected to testing machine, c) specimen, d) glue

The flexural tests were performed on a universal Walter & Bai testing machine with a capacity of 200 kN. The specimens are unnotched plates of 500 mm length, 200 mm width, with variable thickness (10, 30, 50, 100 mm), tested in 4 Point bending with a span of 420 mm. The supports allow a free displacement of the specimen along its longitudinal axis. The test is controlled by the stroke with a displacement speed of 0.3 mm/minute. The deflection is measured with 2 transducers attached on a measuring frame fixed on the specimen at the location of the supports, according to Figure 4-4. The displacement of the tensile chord of the specimen in the constant moment zone is recorded by means of two LVDTs attached to the bottom face of the specimen, one on each side of the specimen, with a measurement basis of 140 mm.

The characterization tests are performed on standard 4/4/16 cm specimens, in 3 PT bending, with a span of 108 mm, and compression on the remaining halves of the specimens after the flexural test.

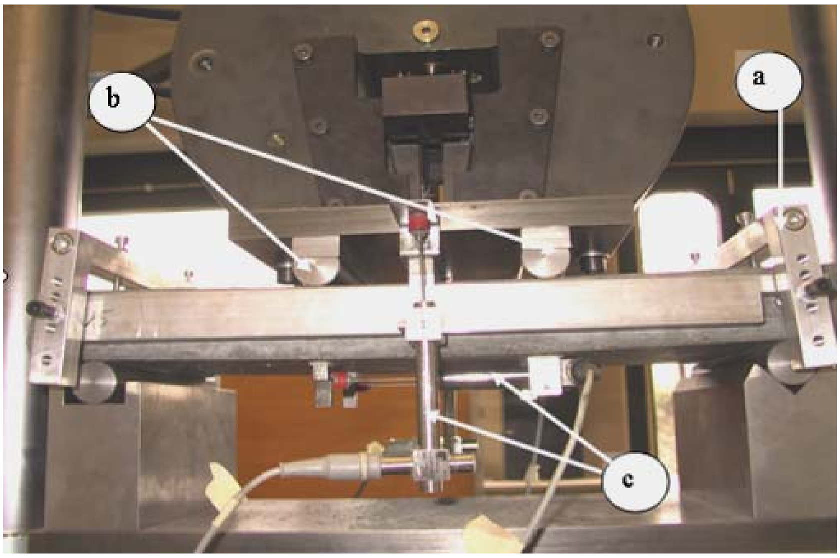


Figure 4-4: Test set-up for the 4 PT bending tests on plates, a) support of the displacement transducers, b) application of imposed displacements, c) displacement transducers

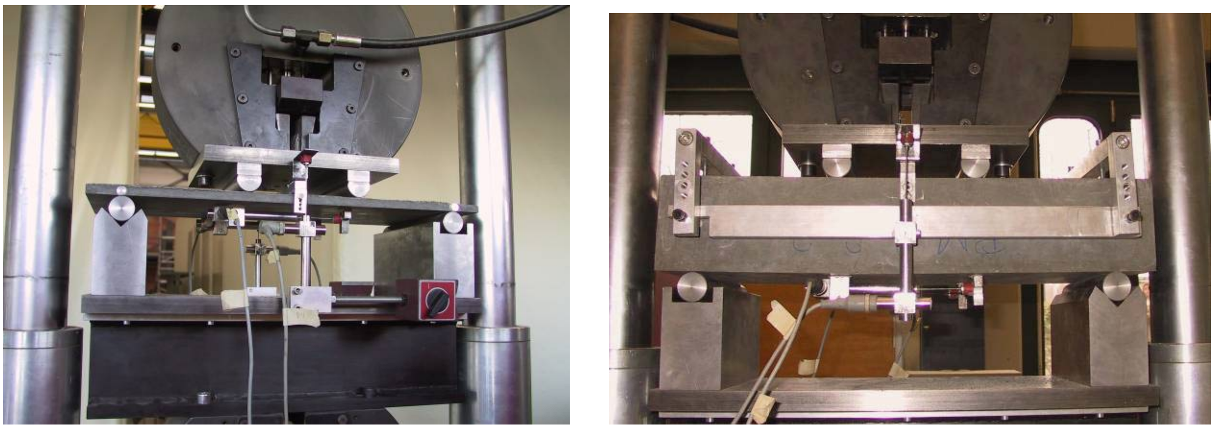


Figure 4-5: Test set-up for the 4 PT bending tests on plates of 10 and 100 mm thickness

4.4.3 Results and analysis

Table 4.4 presents the average values obtained for the tensile tests. The average curves for each set of parameters were calculated by means of the method proposed by [Brühwiler88]. Each individual curve is firstly normalized with respect to the peak force for the Y-axis, and to the displacement for the peak force, for the X-axis. The average normalized curve is then obtained by averaging the displacement for all the curves for a given force. This procedure is firstly applied pre-peak and then post peak. Finally, the so averaged "normalized curve" is multiplied for the X-axis by the average of the displacements at peak force, and for the Y axis by the average of the peak forces. The important feature of this procedure is that it preserves the specific fracture energy, i.e.: the area under the average curve is equal to the average of the areas under the individual curves.

The average curves for all the tests are shown on Figure 4-6. Material CM3 had the largest tensile strength, slightly higher than material CM2. Specimens with materials CM2 cast vertically and CM1 show a rather short hardening domain (<= 0.1 %). Mix CM2 cast vertically presents almost no hardening domain and a rather sudden drop of the stress after the peak. This effect is likely to be due to the unfavourable orientation of the fibres with respect to principal tensile stresses. Material CM2 cast horizontally presents the largest hardening domain. Its average magnitude of hardening is 0.39 % which is almost twice that of material CM3.

		f_t [MPa]	First crack stress [MPa]	Strain at peak stress [%]
CM1	**Average**	10.81	6.12	0.08
	Std. dev.	0.55	1.52	0.04
CM2	**Average**	12.27	5.57	0.39
	Std. dev.	0.59	0.96	0.12
CM2 vert. casting	**Average**	8.70	4.37	0.03
	Std. dev.	1.02	0.73	0.00
CM3	**Average**	12.91	5.60	0.13
	Std. dev.	1.46	0.73	0.06

Table 4.4: Results from Uniaxial tensile tests, average and standard deviation

a) b)

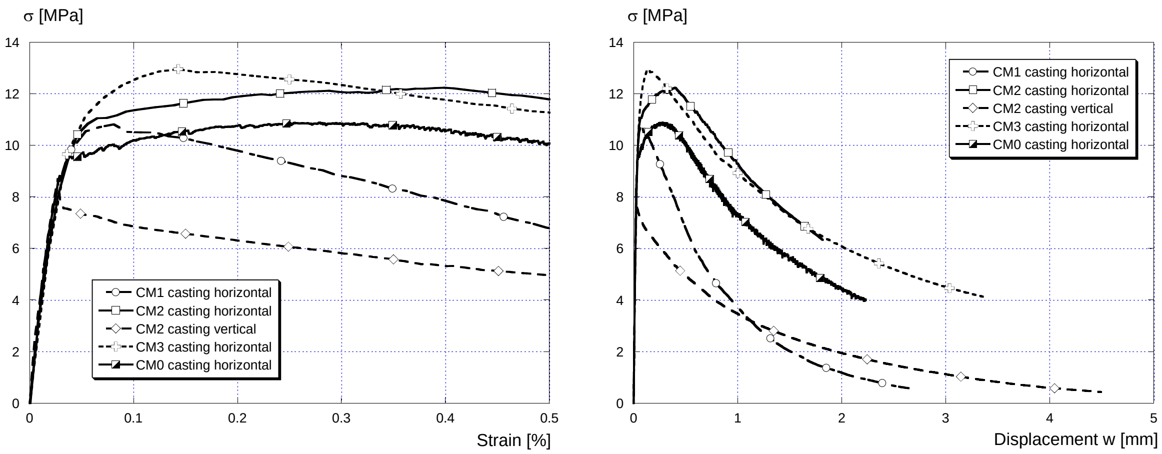


Figure 4-6: Uniaxial tensile tests, effect of material and casting conditions on a) the pre-peak response, b) the post-peak response, average curves

Figure 4-7 and Table 4.5 show the results of the flexural tests for 50 mm thick plates. Material CM 3 presents the largest peak force. For material CM2, the anisotropy effect associated to the vertical casting procedure largely diminishes the value of the peak force with respect to the material CM2 cast horizontally.. When the top casting layer is put under tension, the resistance of the specimen is smaller than when it is put under compression. The highest MOR (modulus of rupture) is reached for material CM1 with however the largest standard deviation. This effect is explained by the resistance of one plate which was significantly higher than all the others.

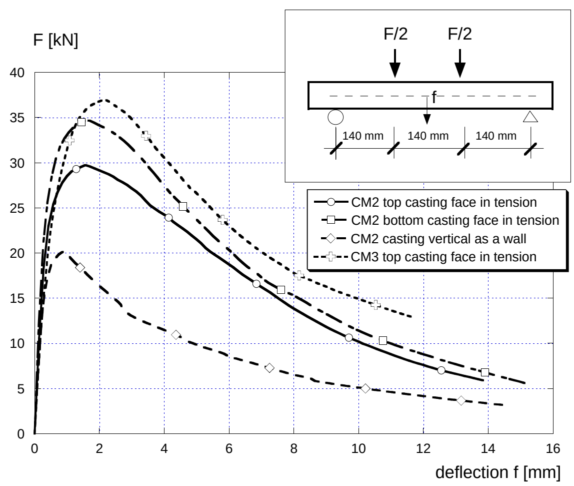


Figure 4-7: 4 PT bending test on plates (50 mm thickness), effect of material and casting conditions, average curves

		Maximum force [kN]	MOR [MPa]	First crack stress [MPa]	Deflection at peak force [mm]	Strain at peak force [%]
CM2 TCT	Average	29.32	26.51	13.51	1.62	0.49
	Std. dev.	3.33	3.71	0.83	0.44	0.11
CM2 TCT	Average	34.77	28.26	11.76	1.74	0.65
	Std. dev.	6.46	3.14	4.81	0.38	0.19
CM2 VC	Average	20.22	17.54	8.11	0.92	0.28
	Std. dev.	2.71	2.41	1.31	0.28	0.10
CM3 BCT	Average	37.02	33.13	14.61	2.19	0.66
	Std. dev.	8.93	4.38	3.42	0.61	0.21

Table 4.5: 4 PT bending tests on 50 mm thick plates (BCT : bottom casting face in tension, TCT : top casting face in tension, CV: vertical casting as a wall).

The effect of thickness on the structural response of the plates is shown on Table 4.6:

		Maximum force [kN]	MOR [MPa]	First crack stress [MPa]	Deflection at peak force [mm]	Strain at peak force [%]
CM1 10 mm	Average	1.93	38.25	7.96	7.03	0.81
	Std. dev.	0.49	8.16	2.40	0.91	0.19
CM1 CV 10 mm	Average	0.97	20.33	5.45	6.58	0.94
	Std. dev.	0.08	1.73	1.20	0.80	0.12
CM2 30 mm	Average	15.40	29.90	14.20	2.71	0.60
	Std. dev.	4.56	4.42	2.88	0.87	0.15
CM2 100 mm	Average	121.26	27.20	10.67	1.07	0.80
	Std. dev.	8.80	2.18	1.30	0.29	0.11
CM3 100 mm	Average	143.99	29.83	14.44	1.02	0.62
	Std. dev.	30.15	5.81	1.98	0.10	0.02

Table 4.6: 4 PT bending tests on plates, effect of thickness and direction of casting, average curves

- first of all, as expected, the deflection at peak load varies with the thickness: the thicker the plate, the smaller the deflection at peak load;
- Secondly, the thickness of the plates has only a non systematic minor influence on the MOR of the plates, in the range tested (30 to 100 mm). This effect was tested for mixes CM2 and CM3.

The results of the characterization tests on 4/4/16 cm prisms are shown on Table 4.7. The compressive and flexural strength follow the same trends as observed in the uniaxial tensile tests and flexural tests on plates. Material CM2 performs the best for the flexural strength (MOR). The extremely high values of the compressive strength measured for materials CM2 and CM3 can be partly attributed to the confining effect of the fibrous skeleton. Especially in material CM3, the largest fibres are 20 mm long, i.e. half the size of the compressive specimen (40 x 40 mm x ≅ 40 mm). As a consequence, these tests results should be considered only as a confirmation of the good quality of the matrix of the UHPFRC tested. However, the quantitative values are obviously exaggerated, especially in compression, with respect to what would be obtained on larger specimens (for example cylinders of 11 cm diameter and 22 cm height).

	3PT bending [MPa]	**Compression [MPa]**
CM1	47.7 ± 3.4	227.3 ± 4.3
CM2	80.3 ± 8.0	283.3 ± 14.4
CM3	52.1 ± 7.2	302.6 ± 13.0

Table 4.7: Characterization tests on 4/4/16 cm prisms, average and standard deviation

The overall performance of material CM3 in uniaxial tension does not correspond to what was expected regarding the maximum tensile stress, the magnitude of the hardening domain and the response in bending. Those bad results can however be explained by the major difficulties encountered to process the material at fresh state and cast the specimens. The tensile and flexural strength of material CM3 are rather low compared to the literature for a material with a very similar fibrous mix and matrix: 20 MPa in uniaxial tension and magnitude of hardening of 0.2 % after [Boulay03]; and MOR=50 MPa according to [Rossi02]. These discrepancies might be explained by several factors:

- No thermal treatment at early age for the specimens tested at MCS- EPFL. A thermal treatment increases the overall mechanical performances of UHPFRC in tension, bending and compression of around 30 %.
- Pure cement paste matrix with no ultra fine aggregates. Those aggregates might contribute to the bond of fibres and to the multiscale reinforcement effect of the fibres.
- Inadequate workability and difficulties of casting
- Type of macrofibres. At MCS-EPFL, only straight fibres were used instead that hooked fibres were used by Rossi et al. at LCPC, [Rossi03] and [Parant03].

Material CM2 with a bimodal fibrous reinforcement shows a resistance slightly higher than material CM0 used by [Habel04a]. The main difference between these two materials is the addition of microfibres (steel wool) which plays a major role on the control of microcracking. The magnitude of hardening of CM2 is almost twice as big as that of reference material CM0. This indicates that the addition of microfibres has a very beneficial effect on the synergy between the micro and macrofibres, and on magnitude of the hardening domain.

Material CM1 has an excellent workability. However, the magnitude of its hardening domain is small (up to 0.08 % instead of 0.4 % for CM2). This effect can be explained by the low aspect ratio of the fibres used (l_f/d_f=33) despite their high dosage of 10 % vol. After [Namman2003], in a first approximation, such a dosage is just sufficient to get a hardening behaviour with such an aspect ratio. Moreover, after [Parant2003], straight fibres of 5 mm, l_f/d_f=33 which are the only reinforcement of material CM1 are not efficient enough to control cracking induced by fatigue loading. On another hand, the tensile tests on material CM1 were realized with plates of 50 mm which are 5 time thicker than the typical layer foreseen for the application of material CM1. The 3D orientation of the fibres in this case might have caused a negative effect on the apparent tensile behaviour, which might not be representative of the real performance for a thin layer of 10 to 15 mm. This effect will have to be taken into consideration in further studies on this material for the application of UHPFRC in thin layers. The principal advantage and justification of the fibres used in CM1 is their short length, well adapted for the casting of thin UHPFRC layers, especially if cast vertically as a wall

4.4.4 Synthesis and conclusions

- The peak stresses in tension and modulus of rupture in flexure corresponded to what was expected for all materials, except CM3 which was weaker.
- The extent of the tensile hardening domains could be determined for all materials and corresponded to the expectations.
- A strong effect of the direction of the major principal stresses with respect to the direction of casting (horizontal, as a plate or vertical as a wall) was detected. This effect will have to be considered for the design and application. It is not significant for applications on slabs. It plays a significant role for application of repair layers on walls and can be mitigated to a large extent by appropriate technological procedures for casting.
- The MOR of materials CM2 and CM3, dedicated to structural reinforcements is not significantly influenced by the thickness, in the range tested (30 to 100 mm). This can be explained by the fact that in this range, for these materials, the softening domain in tension is not yet reached at the peak force in bending.

4.5 Protective function

Comparative air and water permeability tests were performed between $\text{CEMTEC}_{\text{multiscale}}^{®}$ and concrete, on tensile specimens and on hybrid structural elements. The outstanding protective properties of the UHPFRC $\text{CEMTEC}_{\text{multiscale}}^{®}$, *without any thermal treatment*, towards ingress of aggressive substances were confirmed by air permeability tests, as shown on Figure 4-8. Water permeability tests by Charron et al. [Charron04] confirmed this trend and revealed the acute hydrophilic behaviour of $\text{CEMTEC}_{\text{multiscale}}^{®}$.

a) b)

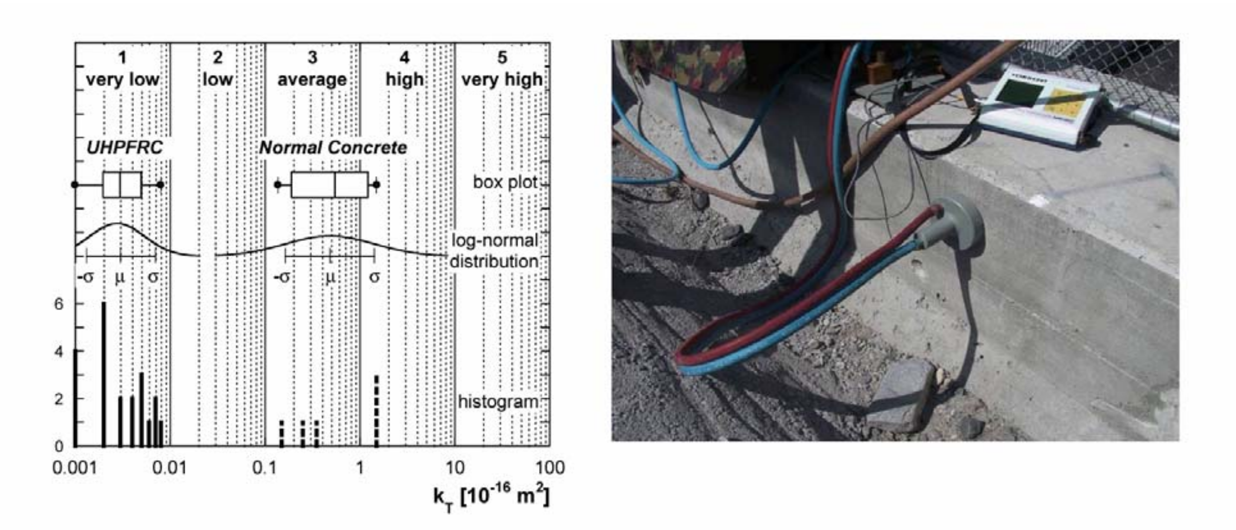


Figure 4-8: Air permeability tests (Torrent method). A) Comparative tests between concrete and UHPFRC, on composite beams, after [Habel04a], b) test setup.

5 CONCLUSIONS OF THE PRELIMINARY STUDIES

Milestone M4 On the basis of the literature study, experimental tests and numerical simulations [Habel04b], [Charron04], following phenomena were identified as most significant:

In fresh state: effect of the fibrous mix on the workability, effect of a slope of the casting surface, effect of curing. Further, the effect of the size of the batch and of the mixer on the apparent workability has to be considered when planning full scale tests.

In hardened state: effect of the direction of casting (vertically as a wall or horizontally, as a plate) and of the layer thickness on the mechanical and physical properties; at early age: effect of viscoelasticity (relaxation) and of thermo-mechanical phenomena and autogenous shrinkage linked to hydration of binders; at long term: effect of viscoelastic behaviour (relaxation and creep), effect of sustained loading or fatigue loading, effect of damage on the permeability of UHPFRC. The acute hydrophilic behaviour of UHPFRC, due to its extremely low water/binder ratio, and high quantity of unhydrated cement grains plays a very significant role in the water transport in permeability tests. Permeability tests with liquids inert towards cement hydration have to be performed to have a sound overview of the transport properties of UHPFRC in damaged state. Due to the very low permeability of the UHPFRC, the drying shrinkage should not be a significant cause of deformations at long term.

Milestone M12 *Selection of materials for main tests series* (subtask 14.1.2).

On the basis of the literature study and experimental works, it was decided to focus the study of WP 14 on a special class of HPFRCC, that are the only ones to offer at the same time a very low permeability and a significant tensile strain hardening behaviour. These materials are called UHPFRC (Ultra High Performance Fibre reinforced Concretes). This terminology will be used in all what follows during the project, to describe the Advanced Cementitious Materials set forward in WP 14. Three different types of UHPFRC will be used for the main test series:

1. For the application of UHPFRC as thin protective layers on horizontal surfaces, on bridge decks, under cyclic loading due to traffic, materials CM0 or CM2 with a larger "magnitude of hardening"[4] might be preferred to material CM1.
2. For the application of UHPFRC as thin protective layers on vertical surfaces, on tunnels or galleries, without cyclic loading due to traffic, material CM1 with short fibres of 5 mm might be the most appropriate.
3. For medium layers with protective and eventual structural function (with or without reinforcement bars), material with short steel fibres of 10 mm can be used, with steel wool (recipe CM2), and without (recipe CM0) .
4. For prefabricated elements, CM2, or if very high mechanical performance required, further investigations on CM3 needed.

[4] Definition: see footnote 2, page 12

6 REFERENCES

[Aarup04] Aarup B., *CRC - A Special Fibre Reinforced Reinforced High Performance Concrete*, RILEM Symposium, Advances in Concrete Through Science and Engineering, March 22-24, Evanston, USA, March, 2004, 6 p, CD-ROM.

[Abrishami97] Abrishami H. H., Mitchell D., *Influence of Steel Fibers on Tension Stiffening*, ACI Structural Journal, Vol. 94, No. 6, November-December, 1997, pp 769-776.

[Acker01] Acker P., *Micromechanical analysis of creep and shrinkage mechanisms*, Creep, Shrinkage and Durability Mechanics of Concrete and other Quasi-Brittle Materials (Concreep 6), Ed. by F-J. Ulm, Z. P. Bazant and F. H. Wittmann, Boston, USA, August, 2001, pp 15-25.

[Acker01a] Acker P., Ulm F. J., *Creep and shrinkage of concrete: physical origins and practical measurements*, Nuclear Engineering and Design, Vol. 203, No. 2, 2001, pp 143-158.

[AFGC02] Association Française du Génie Civil, *Bétons fibrés à ultra-hautes performances (Ultra high performance fibre-reinforced concretes)*, SETRA - Service d'études techniques des routes et autoroutes, AFGC, France, January, 2002, 152 p.

[Alaee03] Alaee F. J., Karihaloo B., *Retrofitting of Reinforced Concrete Beams with CARDIFRC*, ASCE Journal of Composites for Construction, Vol. 7, No. 3, August, 2003, pp 174-186.

[Alford85] Alford N. McN., Birchall J. D., *The properties and potential applications of Macro-Defect-Free Cement*, Symposium on very high strength cement-based materials, Ed. by J. F. Young, Materials Research Society symposia proceedings, Vol. 42, Pittsburgh, USA, 1985, pp 265-276.

[Alkubaisy75] Al-Kubaisy M.A., Young A.G., *Failure of concrete under sustained tension*, Magazine of Concrete Research, Vol. 27, No. 92, September, 1975, pp. 171-178.

[Altoubat02] Altoubat S. A., Lange D., *The Pickett effect at early age and experiment separating its mechanisms in tension*, Materials and Structures, Vol. 35, No. 248, May, 2002, pp 211-218.

[Attiogbe88] Attiogbe E.K., Darwin D., *Strain due to submicrocracing in cement paste and mortar*, ACI Materials Journal, Vol. 85, No. 1, USA, January-February, 1988, pp 3-11.

[Bache87] Bache H. H., *Introduction to Compact Reinforced Composite*, Nordic concrete research, No. 6, pp 19-33, 1987.

[Baker61] Baker A. L. L., *Note for discussion at Monaco*, Comité euro-international du béton (CEB), Bulletin d'information No. 30, Lausanne, Switzerland, 1961.

[Bangham37] Bangham D. H., *The Gibbs adsorption equation and adsorption on solids*, Transactions of the Faraday Society, London, England, Vol. 33, 1937, pp 805-811.

[Barcelo01] Barcelo L., Boivin S., Acker P., Toupin J., Clavaud B., *Early age shrinkage of concrete: back to physical phenomena*, Concrete Science and Engineering, Vol. 3, No. 10, June, 2001, pp 85-91.

[Barcelo02] *Chemical shrinkage*, Early Age Cracking in Cementitious Systems, Report of Technical Committee 181-EAS: Early age shrinkage induced stresses and cracking in cementitious systems, Ed. by A. Bentur, RILEM Report 25, France, July, 2002, pp 21-25.

[Bazant72] Bazant Z., Najjar L. J., *Nonlinear water diffusion in nonsaturated concrete*, Materials and Structures, Vol. 5, No. 25, 1972, pp 3-20.

[Bazant72a] Bazant Z. P., *Numerical determination of long-range stress history from strain history in concrete*, Materials and Structures, Vol. 5, No. 27, 1972, pp 135-141.

[Bazant74] Bazant Z., Wu S.T., *Rate-type creep law of aging concrete based on Maxwell chain*, Materials and Structures, Vol. 7, No. 37, 1974, pp 45-60.

[Bazant83] Bazant Z. P., Oh B., *Crack band theory for fracture of concrete*, Materials and Structures, Vol. 16, No. 93, 1983, pp 155-177.

[Bazant85] Bazant Z., Chern J.C., *Concrete creep at variable humidity constitutive law and mechanism*, Materials and Construction, Vol. 18, No. 103, 1985, pp 1-20.

[Bazant87] Bazant Z., Chern J.C., *Stress-Induced Thermal and Shrinkage Strains in Concrete*, ASCE Journal of Engineering Mechanics, Vol. 113, No. 10, 1987, pp 1493-1511.

[Behloul03] Behloul M., Kicul C. L., *Ductal®* Seonyu footbridge, Structural concrete, Journal of the fib, Vol. 4, No. 4, December, 2003, pp 195-201.

[Bekaert99] Bekaert A., Behloul M., Dugat J., Adeline R., Lacombe H., *Centrale EDF de Cattenom - Du béton de poudres réactives (BPR) pour le nucléaire*, Travaux, No. 752, April, 2001, pp 69-72 (in French).

[Bentur02] Bentur, A., *Terminology and definitions,* Early Age Cracking in Cementitious Systems, Report of Technical Committee 181-EAS: Early age shrinkage induced stresses and cracking in cementitious systems, Ed. by A. Bentur, RILEM Report 25, France, July, 2002, pp 13-15.

[Bernard00] Bernard O., *Comportement à long terme des éléments de structure formés de bétons d'âges différents*, Doctoral Thesis, No. 2283, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, 2000, 190 p. (in French).

[Bernard00a] Bernard O., *Comportement à long term des éléments de structure formés de bétons d'âges différents*, Test report, EPFL-MCS96.01.01, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, November, 2000, 238 p (in French).

[Bernard01] Bernard O., Denarié E., Brühwiler E., *Comportement au jeune âge du béton et limitation de la fissuration traversante des structures hybrides*, Report VSS, 1997/064 (82/97), Swiss Federal Roads Authority, Swiss Association of Road and Transportation Experts, Lausanne, Switzerland, October, 2001, 116 p. (in French).

[Bernard02] Bernard O., Brühwiler E., *Influence of autogenous shrinkage on early age behaviour of structural elements consisting of concretes of different ages*, Materials and Structures, Vol. 35, No. 235, November, 2002, pp 550-556.

[Bernard03] Bernard O., Brühwiler E., *The effect of reinforcement in the new layer on hygral cracking in hybrid structural elements*, Materials and Structures, Vol. 36, No. 256, March, 2003, pp 118-126.

[Bissonnette00] Bissonnette B., Pigeon M., *Le comportement viscoélastique du béton en traction et la compatibilité déformationelle des réparations*, Materials and Structures, Vol. 33, No. 226, March, 2000, pp 108-118 (in French).

[Bonneau97] Bonneau O., Lachemi M., Dallaire E., Dugat J., Aïtcin P-C., *Mechanical Properties and Durability of Two Industrial Reactive Powder Concretes*, ACI Materials Journal, Vol. 94, No. 4, July-August, 1997, pp 286-290.

[Boulay03] Boulay C., Arca A., Tailhan J-L., Rossi P., Sananes J., *Comportement mécanique d'un nouveau composite cimentaire à écrouissage positif. II : Caractérisation du comportement en traction uniaxiale*, Bulletin des Laboratoires des Ponts et Chaussées, No. 243, LCPC, France, March-April, 2003, pp 19-30 (in French).

[Brenni95] Brenni P., *Il comportamento al taglio di una struttura a sezione mista in calcestruzzo a getti successivi*, IBK-Report, No. 211, Swiss Federal Institute of Technology (ETHZ), Zürich, Switzerland, September, 1995, 150 p. (in Italian).

[Broquet99] Broquet C., *Comportement dynamique des dalles de roulement des ponts en béton sollicités par le trafic routier*, Doctoral thesis, No. 1964, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, 1999, 171 p. (in French).

[Brühwiler88] Brühwiler E., *Bruchmechanik von Staumauerbeton unter quasi-statischer und erdbebendynamischer Belastung*, Doctoral thesis, No. 739, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, 1988, 169 p. (in German).

[Brühwiler00] Brühwiler E., Bernard O., Wolf S., *Beton-Beton Verbundbauteil bei der Verbreiterung eines Brückenüberbaus - Massnahmen zur Begrenzung der Rissbildung im neuen Beton*, Beton- und Stahlbetonbau, Vol.95, No. 3, March, 2000, pp 158-166 (in German).

[Brühwiler04a] Brühwiler E., Denarié E., Wälchli T., Maitre M., Conciatori D., *Dauerhafte Kunstbauten bei geringem Unterhalt (Ouvrages d'art durables à entretien minimal)*, final draft, Report VSS, 2000/173 (88/00), Swiss Federal Roads Authority, Swiss Association of Road and Transportation Experts, Lausanne, Switzerland, April, 2004 (in German).

[Brühwiler04b] Brühwiler E., Habel K., Denarié E., *Advanced reinforced concrete for the improvement of bridges*, Second International Conference on Bridge Maintenance, Safety and Management (IABMAS'04), Kyoto, Japan, October, 2004.

[Brunauer73] Brunauer S., Yudenfreund M., Odler I., Skalny J., *Hardened Portland Cement Pastes of Low Porosity, VI. Mechanism of the Hydration Process*, Cement and Concrete Research, Vol. 3, No. 2, 1973, pp 129-147.

[Brunauer73a] Brunauer S., Skalny J., Odler I., Yudenfreund M., *Hardened Portland Cement Pastes of Low Porosity, VII. Further Remarks about Early Hydration. Composition and Surface Area of Tobermorite Gel. Summary*, Cement and Concrete Research, Vol. 3, No. 3, 1973, pp 279-293.

[Byfors82] Byfors J., *Mechanical properties*, International Conference on Concrete at Early Ages, Vol. 2, Ecole Nationale des Ponts et Chaussées (ENPC), Paris, France, April, 6-8, 1982, pp 13-33.

[Carino94] Carino N. J., *The Maturity Method: Theory and Application*, Cement, Concrete and Aggregates, Vol. 6, No. 2, 1984, pp 61-73.

[Casanova94] Casanova P., Le Maou F., Renwez S., Rossi P., *Calcul du béton de fibres métalliques: poutre en flexion simple*, Bulletin de liaison des laboratoires des ponts et chaussées, No. 191, France, May-June, 1994, pp 73-85 (in French).

[CEB204] CEB, *CEB-FIP Model Code 1990*, Comité euro-international du béton (CEB), Bulletin d'Information 204, Lausanne, Switzerland, July, 1991.

[CEB242] CEB, *Ductility of reinforced concrete structures - Synthesis Report and Individual Contributions*, Comité euro-international du béton (CEB), Bulletin d'Information 242, Lausanne, Switzerland, May, 1998, 332 p.

[Charif98] Charif H., Mivelaz P., *Construction de la nouvelle usine GENEX 4 à Genève*, Report 497.023-3.2, ESM Charif & Mivelaz, St Sulpice, Switzerland, 1998 (in French).

[Charron02] Charron J-P., Marchand J., Bissonnette B., Pigeon M., *Test device for studying the early-age stresses and strains in concrete*, American Concrete Institute Fall Convention, Ed. by O. M. Jensen, D. P. Bentz and P. Lura, Phoenix, USA, 2002, 17 p.

[Charron03] Charron J-P., *Contribution à l'étude du comportement au jeune âge des matériaux cimentaires en conditions des déformations libre et restreinte*, PhD thesis, CRIB, University Laval, Québec, Québec, Canada, April, 2003, 373 p. (in French).

[Charron04] Charron J-P., Denarié E., Brühwiler E., *Permeability of UHPFRC under high stresses*, RILEM Symposium, Advances in Concrete Through Science and Engineering, March 22-24, Evanston, USA, 2004, 12 p. CD-ROM.

[Chausson97] Chausson H., Granju J.-L., *Optimized design of fiber reinforced thin bonded overlays*, 5th International Symposium on Brittle Matrix Composites, Warsaw, Poland, October, 1997, pp 133-142.

[Cheyrezy95] Cheyrezy M., Maret V., Frouin L., *Microstructural analysis of RPC (Reactive Powder Concrete)*, Cement and Concrete Research, Vol. 25, No. 7, July, 1995, pp 1491-1500.

[Cheyrezy97] Cheyrezy M., *Structural Applications of RPC*, International Conference - New technologies in structural engineering, Vol. 1, Lisbon, Portugal, July, 1997, pp 5-14.

[Cheyrezy01] Cheyrezy M., Behloul M., *Creep and Shrinkage of Ultra-High Performance Concrete*, Creep, Shrinkage and Durability Mechanics of Concrete and other Quasi-Brittle Materials (Concreep 6), Ed. by F.-J. Ulm, Z. P. Bazant and F. H. Wittmann, Boston, USA, August, 2001, pp 527-538.

[Cosenza91] Cosenza E., Greco C., Pecce M., *Nonlinear design of Reinforced Concrete Continuous beams*, Structural Engineering International, Vol. 1 No. 1, February, 1991, pp 19-27.

[Courard99] Courard L., *Contribution à l'analyse des paramètres influençant la création de l'interface entre un béton et un système de réparation*, University of Liège, Collection des Publications de la Faculté des Sciences Appliquées, No. 192, Liège, Belgium, 1999, 198 p. (in French).

[DeLarrard94] De Larrard F., Sedran T., *Optimization of Ultra-High-Performance Concrete by the Use of a Packing Model*, Cement and Concrete Research, Vol. 24, No. 6, June, 1994, pp 997-1009.

[DeLarrard99] De Larrard F., *Concrete mixture Proportioning - A scientific approach*, Modern concrete technology 9, E & FN SPON, London, England, 1999, 421 p.

[Denarie00] Denarié E., *Etude expérimentale des couplages viscoélasticité-croissance des fissures dans les bétons de ciment*, Doctoral Thesis, No. 2195, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, 2000 207 p. (in French).

[Denarie01] Denarié E., Brühwiler E., *Comportement d'Eléments de Structure Hybrides formés de béton Traditionnel et de Matériaux Cimentaires Avancés*, Regroupement Francophone pour la Recherche et la Foration sur le Béton ($(RF)_2B$), Québec, Canada, August, 2001, 4 p. (in French).

[Denarie03] Denarié E., Habel K., Brühwiler E., *Structural behavior of hybrid elements with Advanced Cementitious Materials (HPFRCC)*, RILEM Proceedings PRO 30, 4th International Workshop on High Performance Fiber Reinforced Cement Composites (HPFRCC-4), Ed. by A. E. Naaman and H. W. Reinhardt, Ann Arbor, USA, June, 2003, pp 301-312.

[Denarie04] Denarié. E., *personal communication*, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, 2004.

[DeSchutter96] De Schutter G., Taerwe L., *Degree of hydration-based description of mechanical properties of early age concrete*, Materials and Structures, Vol. 29, No. 190, July, 1996, pp 335-344.

[DeSchutter00] De Schutter G., *Fictitious degree of hydration method for the basic creep of early age concrete*, Materials and Structures, Vol. 33, No. 230, July, 2000, pp 370-380.

[DeSchutter02] *Short-term mechanical properties*, Early Age Cracking in Cementitious Systems, Report of Technical Committee 181-EAS: Early age shrinkage induced stresses and cracking in cementitious systems, Ed. by A. Bentur, RILEM Report 25, France, July, 2002, pp 101-109.

[DeSchutter02a] *Visco-elastic response*, Early Age Cracking in Cementitious Systems, Report of Technical Committee 181-EAS: Early age shrinkage induced stresses and cracking in cementitious systems, Ed. by A. Bentur, RILEM Report 25, France, July, 2002, pp 111-120.

[Ducret97] Ducret J-M., *Etude du comportement réel des ponts mixtes et modélisation pour le dimensionnement*, Swiss Federal Institute of Technology (EPFL), Doctoral thesis, No. 1738, Lausanne, Switzerland, 1997, 185 p. (in French).

[Dugat96] Dugat J., Roux N., Bernier G., *Mechanical Properties of Reactive Powder Concretes*, Materials and Structures, Vol. 29, No. 188, May, 1996, pp 233-240.

[Dupont03] Dupont D., *Modelling and experimental validation of the constitutive law (σ-ε) and cracking behaviou rof steel fibre reinforced concrete*, Doctoral thesis, Faculty of Applied Science, Catholic University of Leuven, Leuven, Belgium, October, 2003, 256 p.

[EC01] *Eurocode 1,* Draft pr EN 1990 - Eurocode: Basis of Structural Design, European Committee of Standardization (CEN), Stage 34, Brussels, Belgium, December, 2000, 88 p.

[Emberson96] Emberson N. K., Mays G. C., *Significance of property mismatch in the patch repair of structural concrete, Part 3: Reinforced concrete members in flexure*, Magazine of Concrete Research, Vol. 48, No. 174, March, 1996, pp 45-57.

[Emborg89] Emborg M., *Thermal stresses in concrete structures at early ages*, Doctoral thesis, Division of structural engineering, Lulea University of Technology, 189:73 D, Lulea, Sweden, 1989, 285 p.

[Emmons00] Emmons P. H., Vaysburd A. M., McDonald J. E., Poston R.W., Kesner K., *Selecting Durable Repair Materials: Performance Criteria*, Concrete International, Vol. 22, No. 3, March, 2000, pp 38-45.

[EN206] *EN206, Beton - T*eil 1: Festlegung, Eigenschaften, Herstellung und Konformität, EN 206-1:2000, SIA, Zürich, Switzerland, 2000, 83 p. (in German).

[Feldmann68] Feldmann R. F., Sereda P. J., *A model for hydrated Portland cement paste as deduced from sorption-length change and mechanical properties*, Materials and Structures, Vol. 1, Nr. 6, 1968, pp 509-520.

[Femmasse04] *Finite Element Modules for Materials Science and Structural Engineering*, website, Retrieved: April 20, 2004, from http://www.femmasse.com.

[Ferraris87] Ferraris C.F., Wittmann F.H., *Shrinkage mechanisms of hardened cement paste*, Cement and Concrete Research, Vol. 17, No. 3, 1987, pp. 453-463.

[fib10] *Bond of reinforcement in concrete: state-of-art report prepared by Task Group Bond models*, Fédération Internationale du Béton (fib), fib Bulletin, No. 10, Lausanne, Switzerland, August, 2000, 427pp.

[Fischer02] Fischer G., Li V. C., *Influence of Matrix Ductility on Tension-Stiffening Behavior of Steel Reinforced Engineered Cementitious Composites (ECC)*, ACI Structural Journal, Vol. 99, No. 1, January-February, 2002, pp 104-111.

[Gamble78] Gamble B. R., Parrott L. J., *Creep of Concrete in Compression during Drying and Wetting*, Magazine of Concrete Research, Vol. 30, No. 104, September, 1978, pp 129-138.

[Gartner89] Gartner E. M., Gaidis J. M., Grace W. R., *Hydration mechanisms I*, Materials Science of Concrete I, Ed. by J. Skalny, American Ceramics Society, Westerville, USA, 1989, pp 95-125.

[Gibbon98] Gibbon G. J., Ballim Y., *Determination of the thermal conductivity of concrete during the early age stages of hydration*, Magazine of Concrete Research, Vol. 50, No. 3, September, 1998, pp 229-235.

[Goto71] Goto Y., *Cracks formed in concrete around deformed tension bars*, ACI Journal Proceedings, Vol. 68, No. 4, April, 1971, pp 244-251.

[Granju01] Granju J.-L., *Debonding of Thin Cement-Based Overlays*, ASCE Journal of Materials in Civil Engineering, Vol. 13, No. 2, March-April, 2001, pp 114-120.

[Guandalini04] Guandalini S., Muttoni A., *Essais de poinçonnement symétrique des dalles en béton armé sans armature à l'effort tranchant*, Test report, 00.03-R1, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, 2004, to be published (in French).

[GuenotDelahaie97] Guénot-Delahaie I., *Contribution à l'analyse physique et à la modélisation du fluage propre du béton*, Doctoral thesis, Laboratoire Central des Ponts et Chaussées (LCPC), France, April, 1997, 180 p. (in French).

[Guerrini00] Guerrini, G.L. *Applications of high-performance fibre-reinforced cement-based composites*, Applied Composite Materials, **7**, 2000, pp. 195-207.

[Haardt91] Haardt P., *Zementgebundene und kunststoffvergütete Beschichtungen auf Beton*, Doctoral thesis, Massivbau und Baustofftechnologie, University of Karlsruhe, Karlsruhe, Germany, 1991, 201 p. (in German).

[Habel00] Habel K., Bernard O., Brühwiler E., *The Numerical Investigation of Delamination in Hybrid Reinforced Concrete Elements*, 3rd International PhD Symposium in Civil Engineering, fib, Ed. K. Bergmeister, Vol. 2, Vienna, Austria, October, 2000, pp 221-228.

[Habel04a] Habel K., *Structural behaviour of "UHPFRC - concrete" elements*, Test report, MCS99.04, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, 2004.

[Habel04b] Habel K., Structural behaviour of composite UHPFRC-concrete elements, Doctoral thesis n° 3036, Swiss Federal Institute of Technology, Lausanne (EPFL), Switzerland, 2004.

[Hamza96] Hamza A. M., Naaman A. E., *Bond Characteristics of Deformed Reinforcing Steel Bars Embedded in SIFCON*, ACI Materials Journal, Vol. 93, No. 6, November-December, 1996, pp 578-588.

[Hansen86] Hansen T. C., *Physical structure of hardened cement paste. A classical approach*, Materials and Structures, Vol. 19, No. 114, 1986, pp 423-436.

[Hauggaard99] Hauggaard A.B., Damkilde L., Hansen P. F., *Transitional Thermal Creep of Early Age Concrete*, ASCE, Journal of Engineering Mechanics, April, 1999, pp 458-465.

[Helbling87] Helbling A., Brühwiler E., *Eine neue Halterung für Zugversuche mit Beton-Probekörper*, Material und Technik, No. 4, Switzerland, 1987, pp 103-107 (in German).

[Hillerborg83] Hillerborg A., *Analysis of a single crack*, Fracture mechanics of concrete Ed. by F.H.Wittmann, Elsevier science Publishers B.V., Amsterdam, Netherlands, 1983, pp 223-249.

[Holschemacher03] Holschemacher K., Dehn F., *Ultrahochfester Beton (UHFB) - Stand der Technik und Entwicklungsmöglichkeiten*, Ultrahochfester Beton, Innovationen im Bauwesen - Beiträge aus Praxis und Wissenschaft, Ed. by G. König, K. Holschemacher, F. Dehn, Bauwerk, Berlin, Leipzig, Germany, 2003 pp 1-12 (in German).

[Hua95] Hua C., Acker P., Ehrlacher A., *Analyses and Models of the Autogenous Shrinkage of Hardening Cement Paste, I. Modelling at macroscopic scale*, Cement and Concrete Research, Vol. 25, No. 7, 1995, pp 1457-1468.

[Jennings00] Jennings H. M., *A model for the microstructure of calcium silicate hydrate in cement paste*, Cement and Concrete Research, Vol. 30, No. 1, 2000, pp 101-116.

[Jennings04] Jennings H. M., *Colloid model of C-S-H and implications to the problem of creep and shrinkage*, Materials and Structures, Vol. 27, No. 265, January-February, 2004, pp 59-70.

[Jensen95] Jensen O. M., *Thermodynamic limitation of self-desiccation*, Cement and Concrete Research, Vol. 25, No. 1, January, 1995, pp 157-164.

[Jensen96] Jensen O. M., Hansen P. F., *Autogenous deformation and change of the relative humidity in silica fume-modified cement paste*, ACI Materials Journal, Vol. 93, No. 6, 1996, pp 539-543.

[Jensen01] Jensen O. M., Hansen P. F., *Autogenous RH-change and deformation - Exercise*, Behaviour and Performance of Early Age Concrete, Shortcourse organized by D. A. Lange and H. Stang, Technical University of Denmark (DTU), Lyngby, Denmark, July, 2001, 5 p.

[Jensen01a] Jensen O. M., Hansen P. F., *Autogenous deformation and RH-change in perspective*, Cement and Concrete Research, Vol. 31, No. 12, December, 2001, pp 1859-1865.

[Jones02] Jones M. R., Zheng L., Newlands M. D., *Comparison of particle packing models for porportioning concrete constituents for minimum voids ratio*, Materials and Structures, Vol. 35, No. 249, June, 2002, pp 301-309.

[Kabele97] Kabele, P., Li, V.C., Horii, H., Kanda, T. and Takeuchi, S., *Use of BMC for ductile structural members*, in Proc. of 5th Int'l Symposium on Brittle Matrix Composites (BMC-5) (Eds: Brandt, A.M., Li, V.C. and Marshall, I.H.) BIGRAF and Woodhead Publ., Warsaw, Poland, 1997, pp. 579-588.

[Kada02] Kada H., Lachemi M., Petrov N., Bonneau O., Aïtcin P.-C., *Determination of the coefficient of thermal expansion of high performance concrete from initial setting*, Materials and Structures, Vol. 35, No. 245, January-February, 2002, pp 35-41.

[Kendall83] Kendall K., Howard A. J., Birchall J. D., *The relation between porosity, microstructure and strength, and the approach to advanced cement-based materials*, Philosophical Transactions of the Royal Society of London, A 310, London, England, 1983, pp 139-153.

[Kim03] Kim K.-H., Jeon S-E., Kim J.-K., Yang S., *An experimental study on thermal conductivity of concrete*, Cement and Concrete Research, Vol. 33, No. 3, 2003, pp 363-371.

[Kosa91] Kosa K., Naaman A. E., Hansen W., *Durability of Fiber Reinforced Mortar*, ACI Materials Journal, Vol. 88, No. 3, May-June, 1991, pp 310-319.

[Kranz99] Kranz St., *Lokale Schwind- und Temperaturgradienten in bewehrten, oberflächennahen Zonen von Betonstrukturen*, Doctoral thesis, Heft 35, Massivbau und Baustofftechnologie, University of Karlsruhe, Karlsruhe, Germany, 1999, 377 p. (in German).

[Krstulovic95] Krstulovic-Opara, N., Haghayeghi, A.R., Haidar, M. and Krauss, P.D. *Use of conventional and high-performance steel-fibre reinforced concrete for bridge deck overlays*, ACI Materials Journal, **92**(6), 1995, pp. 669-677.

[Krstulovic96] Krstulovic-Opara N., Toutanji H., *Infrastructural repair and retrofit with HPFRCC*, High Performance Fiber Reinforced Concrete Composites 2 (HPFRCC 2), Ed. by A. E. Naaman and H. W. Reinhardt, RILEM, Proceedings 31 Ann Arbor, USA, June, 1996, pp 423-442,.

[Krstulovic97] Krstulovic-Opara N., Dogan E., Uang C.-M., Haghayeghi A. R., *Flexural Behavior of Composite R.C.-Slurry Infiltrated Mat Concrete (SIMCON) Members*, ACI Structural Journal, Vol. 94, No. 5, September - October, 1997, pp 502-512.

[Laplante94] Laplante P., Boulay C., *Evolution du coefficient de dilatation thermique du béton en fonction de sa maturité aux tout premiers âges.*, Materials and Structures, Vol. 27, No. 174, USA, 1994, pp 596-605.

[Laube90] Laube M., *Werkstoffmodell zur Berechnung von Temperaturspannungen in massigen Betonbauteilen in jungen Alter*, Doctoral thesis, University of Braunschweig, Braunschweig, Germany, May, 1990, 251 p. (in German).

[Lemberg96] Lemberg M., *Dichtschichten aus hochfestem Faserbeton*, Deutscher Ausschuss für Stahlbeton, (DAfStb), Beuth Verlag GmbH, No. 465, Berlin, Germany, 1996, pp 1-163 (in German).

[Li00] Li V. C., Horii H., Kabele P., Kanda T., Lim Y. M., *Repair and retrofit with engineered cementitious composites*, Engineering fracture mechanics, Vol. 65, No. 2-3, 2000, pp 317-334.

[Lim98] Lim, Y.M. and Li, V.C., *Characterization of interface fracture behaviour in repaired concrete infrastructures*, in *Fracture Mechanics of Concrete Structures,* Proceedings FRAMCOS3, AEDIFICATIO Publishers, Freiburg, Germany, 1998, pp.1817-1828.

[Lim02] Lim Y. M., Kim M. K., Kim J. H. J., Shin S. K., *Is ductility important for repair application?*, Proceedings of the JCI international Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC) - Application and Evaluation (DFRCC-02), Takayama, Japan, October, 2002, pp 199-208.

[Locher76] Locher F. W., Richartz W., Sprung S., *Erstarren von Zement - Teil 1: Reaktion und Gefügeentwicklung (Setting of cement - Part 1: Reaction and development of structure)*, Zement, Kalk, Gips, Vol. 29, No. 10, October, 1976, pp 435-442 (in German).

[Loukili96] Loukili A., *Etude du retrait et du fluage de Bétons à Ultra-Hautes Performances*, Doctoral thesis, Ecole Centrale Nantes, Nantes, France, November, 1996, 155 p (in French).

[Martinola01] Martinola G., Sadouki H., Wittmann F. H., *Numerical model for minimizing risk of damage in repair systems*, ASCE Journal of Materials in Civil Engineering, Vol. 13, No. 2, March-April, 2001, pp 121-129.

[Martinola02] Martinola G., Bäuml M. F., Wittmann F. H., *Modified ECC applied as an effective chloride barrier*, Proceedings of the JCI international Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC) - Application and Evaluation (DFRCC-02), Takayama, Japan, October, 2002, pp 171-180.

[Massicotte03] Massicotte B., *Design of SFRC members in flexure: application to a building floor*, Dimensionato de estruturas de betão reforçado com fibras de aço, Ed. by J. Barros, P. Rossi, B. Massicotte, DEC-UM, Portugal, 2003, p. 4.1-4.17.

[Matsumoto00] Matsumoto, T. and Mihashi, H., *JCI_DFRCC summary report on DFRCC terminologies and application concepts*, Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC) - Application and Evaluation (DRFCC-2002), Takayama, Japan, Oct. 2002, pp. 59-66.

[Mihashi03] Mihashi H., Nishiwaki T., de B. Leite J.P., *Effectiveness of crack control on durability of HPFRCC*, in RILEM Proceedings PRO 30, 4th International Workshop on High Performance Fiber Reinforced Cement Composites (HPFRCC-4), Ed. by A. E. Naaman and H. W. Reinhardt, Ann Arbor, USA, June, 2003, pp. 437-450.

[Mensi88] Mensi R, Acker P., Attolou A, *Séchage du béton: analyse et modélisation*, Materials and Structures, Vol. 21, No. 121, 1988, pp 3-12 (in French).

[Morin01] Morin V., Cohen Tounedji F., Feylessoufi A., Richard P., *Superplasticizer effects on setting and structuration mechanisms of ultrahigh-performance concrete*, Cement and Concrete Research, Vol. 31, No. 1, 2001, pp 63-71.

[Morin02] Morin V., Cohen-Tenoudji F., Feylessoufi A., Richard P., *Evolution of the capillary network in a reactive powder concrete during hydration process*, Cement and Concrete Research, Vol. 32, No. 12, 2002, pp 1907-1914.

[Muttoni97] Muttoni A., Schwartz J., Thürlimann B., *Bemessung von Betontragwerken mit Spannungsfeldern*, Birkhäuser, Basel, Switzerland, 1997, 145 pp (in German).

[Naaman02] Naaman A. E., *Toughness, ductility, surface energy and deflection-hardening FRC composites*, Proceedings of the JCI international Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC) - Application and Evaluation (DFRCC-02), Takayama, Japan, October, 2002, pp 33-57.

[Naaman03] Naaman A.E., *Strain hardening and deflection hardening fibre reinfirced cement composites*, in RILEM Proceedings PRO 30, 4th International Workshop on High Performance Fiber Reinforced Cement Composites (HPFRCC-4), Ed. by A. E. Naaman and H. W. Reinhardt, Ann Arbor, USA, June, 2003, pp 95-113.

[Neville70] Neville A., *Creep of Concrete: Plain, Reinforced and Prestressed*, North-Holland Publishing Company, Amsterdam, the Netherlands, 1970, 622 p.

[Neville95] Neville A., *Properties of concrete*, Adison Wesley Longman Limited, 4th edition, Harlow, England, 1995.

[Odler72] Odler I., Yudenfreund M., Skalny J., Brunauer S., *Hardened Portland Cement Pastes of Low Porosity, III. Degree of Hydration. Expansion of Paste, Total Porosity*, Cement and Concrete Research, Vol. 2, No. 4, 1972, pp 463-480.

[Odler72a] Odler I., Hagymassy J., Bodor E. E., Yudenfreund M., Brunauer S., *Hardened Portland Cement Pastes of Low Porosity, IV. Surface Area and Pore Structure*, Cement and Concrete Research, Vol. 2, No. 5, 1972, pp 577-589.

[Ong97] Ong, K.C.G., Paramasivam, P. and Subramaniam, M., *Cyclic behavior of steel-fiber mortar overlaid concrete beams*, Journal of Materials in Civil Engineering, **9**(1), 1997, pp. 21-28.

[Orange00] Orange G., Dugat J., Acker P., *DUCTAL: New Ultra High Performance Concretes. Damage, Resistance and Micromechanical Analysis*, Fifth RILEM Symposium on Fiber-Reinforced Concretes (FRC) (BEFIB 2000), Ed. by P. Rossi and G. Chanvillard, Lyon, France, September, 2000, pp 781-790.

[Parant03] Parant E., *Mécanismes d'endommagement et comportements mécaniques d'un composite cimentaire fibré multi-échelles sous sollicitations sévères: fatigue, choc, corrosion*, Doctoral thesis, Laboratoire Central des Ponts et Chaussées (LCPC), France, December, 2003, 245 p. (in French).

[Pfyl03] Pfyl Th., *Tragverhalten von Stahlfaserbeton*, Doctoral thesis, IBK-Report, No. 279, Swiss Federal Institute of Technology (ETHZ), Zürich, Switzerland, February, 2003, 140 p. (in German).

[Pickett42] Pickett G., *The Effect of Change in Moisture-Content on the Creep of Concrete Under a Sustained Load*, Research Laboratory of the Portland Cement Association, Bull. 11, Detroit, USA, March, 1942, 80 p.

[Pigeon92] Pigeon M. , Saucier F. , *Durability of repaired concrete structures*, International Symposium on Advances in Concrete Technology, Ed. by V. M. Malhotra, Athens, Greece, May, 1992, pp 741-773.

[Powers48] Powers T. C., Brownyard T. L., *Studies of the Physical Properties of Hardened Portland Cement Paste*, Research Laboratories of the Portland Cement Association, Bull. 22, Detroit, USA, March, 1948, 356 p.

[Randl00] Randl N., Wicke M., *Schubübertragung zwischen Alt- und Neubeton*, Beton- und Stahlbetonbau, Vol. 95, No. 8, August, 2000, pp 461-473 (in German).

[Reich97] Reich R., Cervenka J., Saouma V. E., *MERLIN, A Three-Dimensional Finite Element Program Based on a Mixed-Iterative Solution Strategy for Problems in Elasticity, Plasticity, and Linear and Nonlinear Fracture Mechanics*, EPRI Report, Palo Alto, USA, 1997.

[Richard95] Richard P., Cheyrezy M., *Composition of Reactive Powder Concretes*, Cement and Concrete Research, Vol. 25, No. 7, October, 1995, pp 1501-1511.

[RILEM02] RILEM TC 181-EAS, *Early Age Cracking in Cementitious Systems*, RILEM report, Technical Committee 181-EAS: Early age shrinkage induced stresses and cracking in cementitious systems, Ed. by A. Bentur, Report 25, France, July, 2002, 337 p.

[Roelfstra89] Roelfstra P. E., *A numerical approach to investigate the properties of concrete - numerical concrete*, Doctoral Thesis, No. 788, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, 1989.

[Rossi87] Rossi P., Acker P., Malier Y., *Effect of steel fibres at two different stages: the material and the structure*, Materials and Structures, Vol. 20, No. 120, 1987, pp 436-439.

[Rossi97] Rossi P., *High Performance Multimodal Fiber Reinforced Cement Composites (HPMFRCC): The LCPC Experience*, ACI Materials Journal, Vol. 94, No. 6, November - December, 1997, pp 478-483.

[Rossi02] Rossi P., *Development of new cement composite material for construction*, Innovations and Developments in Concrete Materials and Construction, Proceedings of the International Conference, University of Dundee, Ed. by R. K. Dhir, P. C.Hewlett and L. J. Csetenyi, Dundee, Scotland, September, 2002, pp 17-29.

[Roux96] Roux N., Andrade C., Sanjuan M. A., *Experimental Study of Durability of Reactive Powder Concretes*, ASCE Journal of Materials in Civil Engineering, Vol. 8, No. 1, February, 1996., pp 1-6

[Roy72] Roy D. M., Gouda G. R., Bobrowsky A., *Very high strength cement pastes prepared by hot pressing and other high pressure techniques*, Cement and Concrete Research, Vol. 2, No. 3, 1972, pp 349-366.

[Roy73] Roy D. M., Gouda G. R., *High strength generation in cement pastes*, Cement and Concrete Research, Vol. 3, No. 6, 1973, pp 807-820.

[Rüsch60] Rüsch H., *Researches towards a general flexural theory for structural concrete*, ACI Journal Proceedings, Vol. 57, July, 1960, pp 1-28.

[Sadouki97] Sadouki H., Van Mier J. G. M., *Simulation of hygral crack growth in concrete repair systems*, Materials and Structures, Vol. 30, no. 203, November, 1997, pp 518-526.

[Saucier90] Saucier F., *Contribution à l'étude de la durabilité de l'adhérence des réparations en béton*, PhD thesis, University Laval, Québec, Québec, Canada, December, 1990, 144 p. (in French)

[Schachinger03] Schachinger I., Schmidt K., Heinz D., *Zeitabhängiges Verformungsverhalten von UHFB*, Ultrahochfester Beton, Innovationen im Bauwesen - Beiträge aus Praxis und Wissenschaft, Ed. by G. König, K. Holschemacher, F. Dehn, Bauwerk, Berlin, Leipzig, Germany, 2003, pp 67-77 (in German).

[Schenkel98] Schenkel M., *Zum Verbundverhalten von Bewehrung bei kleiner Betondeckung*, Doctoral Thesis, IBK-Report, No. 237, Swiss Federal Institute of Technology (ETHZ), Zürich, Switzerland, September, 1998, 162pp. (in German).

[Schläfli99] Schläfli M., *Ermüdung von Brückenfahrbahnplatten aus Stahlbeton*, Doctoral thesis, No.1998, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, 1999, 113 p. (in German).

[Schneider92] Schneider B., *Development of SIFCON through applications*, Proceedings of the International Workshop, "High Performance Fiber Reinforced Cement Composites (HPFRCC), Ed. by H. W. Reinhardt and A. E. Naaman, E & FN Spon, RILEM Proceedings 15, Stuttgart, Germany, June, 1992, pp 177-194.

[Schrader92] Schrader K. E., *Mistakes, Misconceptions, and Controversial Issues Concerning Concrete and Concrete Repairs, part 1, 2, 3*, Concrete International, Vol. 14, No. 9, 10, 11, September, October, November, 1992, pp 52-56, 48-52, 54-59.

[Scrivener89] Scrivener K., *The Microstructure of Concrete*, Materials Science of Concrete I, Ed. by J. Skalny, American Ceramics Society, Westerville, USA, 1989, pp 127-161.

[Sedran94] Sedran T., de Larrard F., Angot D., *Prévision des mélanges granulaires par le modèle de suspension solide, I - Fondements théoriques et étalonnage du modèle*, Bulletin de liaison des laboratoires des ponts et chaussées, No. 194, France, November-December, 1994, pp 59-70 (in French).

[Shah99] Shah, S.P., Peled, A., Aldea, C.M. and Akkaya, Y., *Scope of high performance fibre reinforced cement composites*, in High Performance Fiber Reinforced Cement Composites (HPFRCC3), (Eds: Reinhardt, H.W., Naaman, A.E.), RILEM Publishers, 1999, pp. 113-129.

[SIA260] *SIA 260,* Grundlagen der Projektierung von Tragwerken (Swisscode 0), SIA, Zürich, Switzerland, 2003, 44 p. (in German).

[SIA261] *SIA 161, Einwirkungen* auf Tragwerke (Swisscode 1), SIA, Zürich, Switzerland, 2003, 110 p. (in German).

[SIA262] *SIA 262, Betonbauten (Swisscode 2)*, SIA, Zürich, Switzerland, 2002, 76 p. (in German).

[SIA469] *SIA 469, Erhaltung von Bauwerken*, SIA, Zürich, Switzerland, 1997, 20 p. (in German).

[Siebel03] Siebel E., Müller Chr., *Geeignete Zemente für die Herstellung von UHFB*, Ultrahochfester Beton, Innovationen im Bauwesen - Beiträge aus Praxis und Wissenschaft, Ed. by G. König, K. Holschemacher, F. Dehn, Bauwerk, Berlin, Leipzig, Germany, 2003, pp 13-24 (in German).

[Sigrist95] Sigrist V., *Zum Verformungsvermögen von Stahlbetonträgern*, Doctoral thesis, IBK-Report, No. 210, Swiss Federal Institute of Technology (ETHZ), Zürich, Switzerland, 1995, 160 p. (in German).

[Silfwerbrand87] Silfwerbrand J., *Effekter av differenskrympning, krypning och fogytans egenskaper på bärförmågan hos samverkanplattor av gammal och pågjuten betong (Effects of differential shrinkage, creep and properties of the contact surface on the strength of composite concrete slabs of old and new concrete)*, Research Report, No. 147, TRITA-BST-0147, Institutionen för Byggnedsstatik, Royal Institute of Technology, KTH, Stockholm, Sweden, 1987, 131 p. (in Swedish).

[Silfwerbrand90] Silfwerbrand J., *Improving concrete bond in repaired bridge deck*, Concrete International, Vol. 12, No. 9, September, 1990, pp 61-66.

[Silfwerbrand97] Silfwerbrand J., *Stresses and Strains in Composite Concrete Beams Subjected to Differential Shrinkage*, ACI Structural Journal, Vol. 94, No. 4, July-August, 1997, pp 347-353.

[Tazawa98] Tazawa E., *Autogenous shrinkage of concrete*, Proceedings of the International Workshop organized by JCI (Japan Concrete Institute), Hiroshima, Japan, June, E & FN SPON, London, 1998, 411 p.

[Torrent92] Torrent R., *A two-chamber vacuum cell for measuring the coefficient of permeability to air of the concrete cover on site*, Materials and Structures, Vol. 25, No. 150, 1992, pp 358-365.

[Trausch01] Trausch J-L., *Verhalten der grenzflächennahen Zone von Instandsetzungs- und Schutzsystemen für Stahlbeton*, Doctoral thesis, Swiss Federal Institute of Technology (ETHZ), Building Material Reports, No. 13, Aedificatio Publishers, Zürich, Switzerland, 2001, 209 p. (in German).

[VanBreugel92] Van Breugel K., *Numerical Simulation of Hydration and Microstructural Development in Hardening Cement-Based Materials*, Heron, Vol. 37, No. 3, the Netherlands, 1992, 62 p.

[VanMier97] Van Mier J. G. M., *Fracture Processes of Concrete - Assessment of Material Parameters for Fracture Models*, CRC press, Boca Raton, USA, 1997, 448 p.

[Vandewalle00] Vandewalle L., *Cracking behaviour of concrete beams reinforced with a combination of ordinary reinforcement and steel fibers*, Materials and Structures, Vol. 33, No. 227, April, 2000, pp 164-170.

[Vaysburd01] Vaysburd A. M., Sabnis G. M., Emmons P. H., McDonald J. E., *Interfacial bond and surface preparation in concrete repair*, The Indian Concrete Journal (ICJ-journal), January, 2001, pp 27-33.

[Viviani04] Viviani, M., *personal communication*, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, 2004.

[Waller00] Waller V., *Relations entre composition des bétons, exothermie en cours de prise et résistance à la compression*, Doctoral thesis, Laboratoire Central des Ponts et Chaussées (LCPC), Nantes, France, May, 2000, 317 p. (in French).

[Warner98] Warner J., Bhuyan S., Smoak W. G., Hindo K. R., Sprinkel M. M., *Surface preparation for overlays*, Concrete International, Vol. 20, No. 5, May, 1998, pp 43-46.

[Weimann03] Li V. C., Weimann M. B., *Hygral Behavior of Engineered Cementitious Composites (ECC)*, International Journal for Restoration of Buildings and Monuments, Vol. 9, No. 5, 2003, pp 513-534.

[Weiss02] Weiss, J., *Experimental determination of the 'time zero'* t_0 *(maturity-zero* M_0*)*, Early Age Cracking in Cementitious Systems, Report of Technical Committee 181-EAS: Early age shrinkage induced stresses and cracking in cementitious systems, Ed. by A. Bentur, RILEM Report 25, France, July, 2002, pp 195-206.

[Wheat93] Wheat, D.L., Fowler, D.W. and Al-Negheimish, A.I., *Thermal and fatigue behaviour of polymer concrete overlaid concrete beams*, Journal of Materials in Civil Engineering, **5**(4), 1993, pp. 460-477.

[Wittmann82] Wittmann F. H., *Creep and shrinkage mechanisms*, Concrete and shrinkage in concrete structures, Ed. by Z. P. Bazant and F. H. Wittmann, John Wiley & Sons, 1982, pp 129-162.

[Wittmann83] Wittmann F. H., *Structure of concrete with respect to crack formation*, Fracture mechanics of concrete, Ed. by F.H.Wittmann, Developments in Civil Engineering 7, Elsevier science Publishers B.V., Amsterdam, Netherlands, 1983, pp 43-74.

[Wuest04] Wuest J., *Etude Exploratoire des Propriétés Mécaniques de Bétons de Fibres Ultra Performants de Structures*, Diploma thesis, MCS, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, March, 2004, 137 p. (in French).

[Yuan94] Yuan Y. , Marosszeky M., *Restrained shrinkage in repaired reinforced concrete elements*, Materials and Structures, Vol. 27, No. 171, 1994, pp 375-382.

[Yudenfreund72] Yudenfreund M., Odler I., Brunauer S., *Hardened Portland Cement Pastes of Low Porosity, I. Materials and Experimental Methods*, Cement and Concrete Research, Vol. 2, No. 3, May, 1972, pp 313-330.

[Yudenfreund72a] Yudenfreund M., Skalny J., Mikhail R. S., Brunauer S., *Hardened Portland Cement Pastes of Low Porosity, II. Exploratory Studies. Dimensional Changes*, Cement and Concrete Research, Vol. 2, No. 3, May, 1972, pp 331-348.

[Yudenfreund72b] Yudenfreund M., Hanna K, M., Skalny J., Odler I., Brunauer S., *Hardened Portland Cement Pastes of Low Porosity, V. Compressive Strength*, Cement and Concrete Research, Vol. 2, No. 6, 1972, pp 731-743.

[Zhu91] Zhu Y., *Evaluation of bond strength between new and old concrete by means of fracture mechanics method*, Doctoral thesis, Royal Institute of Technology (KTH), Bull. 157, Stockholm, Sweden, May, 1991, 102 p.

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7 APPENDIX 1 – UHPFRC RECIPES

Component	Vol. Percent of fibres [%]	ρ [kg/m³]	Mass [kg/m³]	Volume [l/m³]
Powders			1922.2	
Cement		3140	1125.1	358.3
Silica Fume		2200	292.5	133.0
(Fine sand + quartz)		2680	504.6	188.3
Added water		1000	165.3	165.3
Steel wool		7850		
Fibres 5 mm		7850		
Fibres 10 mm		7850		
Fibres 20 mm		7850		
Admixture		1055		35.2
Dry extract 30%			11.1	
Liquid part 70%			26.0	26.0
Total water		1000	191.3	191.3
Air				20.0
Total	**10**		2909.6	1000.0

Table 7.1: Composition of material CM1

Component	Vol. Percent of fibres [%]	ρ [kg/m³]	Mass [kg/m³]	Volume [l/m³]
Powders			1846.2	
Cement		3.140	1300.0	414.0
Silica Fume		2.200	338.0	153.6
(Fine sand + quartz)		2.680	208.2	77.7
Added water		1.000	204.0	204.0
Steel wool		7.850		
Fibres 5 mm		7.850		
Fibres 10 mm		7.850		
Fibres 20 mm		7.850		
Admixture		1.055	42.9	40.7
Dry extract 30%			12.9	
Liquid part 70%			30.0	30.0
Total water		1.000	234.0	234.0
Air				20.0
Total	**9**		**2799.5**	**1000.0**

Table 7.2: Composition of material CM2

Component	Vol. Percent of fibres [%]	ρ [kg/m³]	Mass [kg/m³]	Volume [l/m³]
Powders			1783.1	
Cement		3.140	1415.2	450.7
Silica Fume		2.200	368.0	167.3
(Fine sand + quartz)		2.680		0.0
Added water		1.000	207.9	207.9
Steel wool		7.850		
Fibres 5 mm		7.850		
Fibres 10 mm		7.850		
Fibres 20 mm		7.850		
Admixture		1.055	46.7	44.3
Dry extract 30%			14.0	
Liquid part 70%			32.7	32.7
Total water		1.000	240.6	240.6
Air				20.0
Total	**11**		**2901.2**	**1000.1**

Table 7.3: Composition of material CM3

Component	Vol. Percent of fibres [%]	ρ [kg/m^3]	Mass [kg/m^3]	Volume [l/m^3]
Powders			1846.2	
Cement		3.140	1051.1	334.7
Silica Fume		2.200	273.3	124.2
(Fine sand + quartz)		2.680	732.5	273.3
Added water		1.000	164.6	164.6
Steel wool		7.850		
Fibres 5 mm		7.850		
Fibres 10 mm		7.850	468	59.6
Fibres 20 mm		7.850		
Admixture		1.055	35.1	33.3
Dry extract 30%			10.5	
Liquid part 70%			24.6	
Total water		1.000		189.2
Air				10.2
Total	**6**		**2724.7**	**1000.0**

Table 7.4: Composition of material CM0

Component	Type
Cement	CEM I 52.5 N CE PM-ES-CP 2, Lafarge, Le Teil
Silica fume	SEPR (average diameter 0.5 μm) Specific surface 12 m^2/g, SiO2 > 93.5 %
Fine sand + quartz	SIFRACO (SiO_2>5%), D_{max} < 0.5 mm
Steel fibres	Steel wool (micro fibres) from Gervois Straight, l_f=5 mm, d_f=0.15 mm Straight l_f=10 mm, d_f=0.2 mm Straight l_f=20 mm, d_f=0.25 mm
Superplasticizer	Chrysofluid OPTIMA 175

Table 7.5: Description of the individual components of the UHPFRC