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RECOMMENDATIONS FOR THE TAILORING OF UHPFRC RECIPES FOR REHABILITATION

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ABSTRACT

The extremely low permeability of Ultra High Performance Fibre Reinforced Concretes (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. UHPFRC provide a unique and robust solution to simplify the construction process, dramatically reduce the duration of sites, and save money with long term durability. Rehabilitations, especially with cast on site UHPFRC are among the most demanding applications for those materials and require a significant strain hardening response under tension. Achievement of tensile strain hardening, extremely low permeability and self-compacting character is indeed a challenge that few current UHPFRC recipes can satisfy. Cement-superplasticisers compatibility issues severely restrict the range of possibilities to develop new UHPFRC recipes based on locally available components with the required properties for cast in situ applications. An original concept of Ultra High Performance matrix has been developed that makes the application of UHPFRC technology feasible with a wide range of cements and superplasticisers, with outstanding mechanical and protective performance, without significant loss of workability. This concept is an extension to UHPFRC materials of the concepts of cements blended with Limestone fillers, already applied successfully to a wide range of normal or high performance concretes. In a further step, the rheology of those mixes has been adapted to enable them to support challenging 5 % slopes of the substrates at fresh state.

The development of this new technology and its portability in various countries opens very promising perspectives for the dissemination of this concept not only for rehabilitation but also for various applications of UHPFRC, prefabricated or cast-in-situ.

This document presents both a general methodology for the tailoring of UHPFRC recipes (fibrous mix and matrix) and its application to Slovene and Polish components.

TABLE OF CONTENTS

FOREWORD AND ACKNOWLEDGEMENTS

The goal of ARCHES WP 5 – "Harden Structures to last with UHPFRC" was to demonstrate on the basis of applications in Slovenia and Poland, *with products available locally to the largest extend,* that Ultra High Performance Fibre Reinforced Concretes (UHPFRC) can be successfully and price-efficiently implemented for rehabilitation in those countries, *which would be a major step forward the dissemination of this technique in New Member States (NMS).* This work is a direct continuation of WP 14 – SAMARIS (Sustainable and Advanced MAterials for Road InfraStructure) project, see http://samaris.zag.si/, based on the original concept of application of UHPFRC for the rehabilitation of reinforced concrete structures proposed at MCS by Prof. Dr. E. Brühwiler in 1999.

This report is the first of two, resulting from R&D works performed within ARCHES WP 5:

- *ARCHES D06:* Recommendations for the tailoring of UHPFRC recipes for rehabilitation
- *ARCHES D14*: Recommendations for the use of UHPFRC in composite structural members – rehabilitation Log Čezsoški bridge.

Four research centres (MCS/EPFL - Switzerland, ZAG - Slovenia, LCPC - France, IBDIM – Poland) and two industrial partners (Salonit Anhovo – Slovenia – cement producer, and TKK Srpenica – Slovenia – producer of concrete admixtures) were directly involved into the research and application works in the workpackage.

The researchers and technicians who contributed to these works under the lead of Dr. E. Denarié from MCS/EPFL (WP 5 leader) are:

For MCS/EPFL: scientists and engineers: Dr. Hamid Sadouki, Dr. John Wuest, Dr. Aicha Kamen, Mrs Agnieszka Switek, Mrs Talayeh Noshiravani, Mr Cornelius Oesterlee, Dr. Yves Houst (LTP-EPFL), Mr Philippe Simonin (LMC-EPFL); technicians: MM. Roland Gysler, Gerald Rouge, Gilles Guignet, Sylvain Demierre, Lionel Sofia-Gabrion (LMC-EPFL).

The support and advices on SEM measurements and image analyses from Dr. Emmanuel Gallucci – former LMC/EPFL collaborator are gratefully acknowledged.

For ZAG: scientists and engineers; Dr Aljoša Šajna (head of R&D works for WP 5 at ZAG), Mrs Jerneja Šuput; technicians: Mr. Vladimir Bras, Mr. Rafael Kajzer, Mr. Irfan Pašagič, Mr. Anton Kranjc; media and dissemination: Mrs. Polonca Štritof, Mr Matjaž Zupanc.

For SALONIT: Mrs Lojzka Reščič, Engineer

For IBDIM: MM Tomasz Wierzbicki, Artur Sakowski, Prof. Marek Lagoda

For LCPC: Dr. Pierre Rossi, Dr. Guillaume Habert

The support from TKK Slovenia - Mrs L. Cernilogar for supplying the superplasticiser used in the research works and for the full scale bridge application is gratefully acknowledged.

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The support of the Municipality of Bovec, Slovenia and of its Mayor, Mr Danijel Krivec for the first application of UHPFRC in Slovenia on the Log Čezsoški bridge is gratefully acknowledged.

Mr Bogomir Ipavec, engineer from Primorje – Slovenia was kind enough to accept to discover the technology of UHPFRC and apply it to the rehabilitation of the Log Čezsoški bridge.

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

Lausanne, November 27, 2009 Dr. Emmanuel Denarié

EXECUTIVE SUMMARY

Introduction

The wide dissemination of Ultra High Performance Fibre Reinforced Concrete (UHPFRC) technology, specially in very demanding applications such as cast-in situ rehabilitation works requires UHPFRC formulations from local components. However, it is extremely difficult to achieve sufficient workability just by replacing cement and plasticizer from existing optimized UHPFRC recipes by locally available ones. Insufficient workability most often either forces to increase water dosage and water/binder ratio which severely decreases all performances of UHPFRC or also prevents the use of a sufficient fibrous mix to achieve tensile strain hardening. On another hand the very low water/binder ratio of UHPFRC in the range of 0.2 or less induces a very low degree of hydration of cement grains at long term (typically 0.3 to 0.5). Thus most of the cement in Ultra High Performance Concrete (UHPC) matrices is used for packing and workability but will never contribute to hydration, at best to self healing properties. Further, most cement-superplasticisers compatibility problems are related to negative interactions between cement chemical components (typically reaction products of C_3A and sulphates) and the dispersive action of superplasticisers.

It is thus of interest to investigate possibilities to replace very significant parts of the reactive cement grains in UHPC matrices by other grains, that have a more “neutral” or even positive response towards the superplasticisers and still exhibit a morphology and size distribution close to that of the cement, without “disturbing” to a significant extend the original packing. Limestone fillers are excellent candidates for this purpose.

In this perspective, UHPFRC mixes with replacement of 50 % of the cement by limestone filler have been tested and applied successfully in this study. Strain hardening UHPFRC recipes with excellent tensile and protective properties could be produced with locally available components from Slovenia on one hand and Poland on the other hand. All properties including shrinkage and mechanical response under restraint were checked and the mixes showed properties comparable or better to the original recipes with pure CEM I, developed for similar applications, during project SAMARIS. This concept opens up very promising possibilities to produce UHPFRC with locally available components without loosing significantly on any property neither at fresh state nor at hardened state.

Methodology for mix design

The goal of the mix design is to achieve UHPFRC recipes with satisfactory properties for rehabilitation applications, with respect to three aspects summarized as **"PMW"**:

- **Requirement "P":** Protective function at serviceability: dense matrix with very low permeability to fluids and gases, very low capillary water absorption, and no macrocracking (only finely distributed microcracks, barely visible to the naked eye can be tolerated at serviceability to guarantee the continuity of the protective function of the UHPFRC).

- **Requirement "M":** Mechanical performance: high uniaxial tensile strength (in the range of 10 MPa), and deflection or tensile strain hardening response (deformability of 0.5 to 3 ‰) according to the requirements of the application foreseen (considering orientation effects of the fibres, geometry and conditions of casting such as space available in formworks, etc.).

- **Requirement "W":** Workability – rheology: acceptable mixing time, self compacting character, if required tolerance to slopes or passing ability to fill complex or narrow formworks, 2 to 3 hours minimum range of performance (from water addition in mixer) without significant loss of workability.

Guidance for the choice:

Two major kinds of applications for rehabilitation of structures can be distinguished:

(1) Prefabricated elements applied on the existing structure. in this case, provided the formworks do not have complex shapes with holes for instance, the shrinkage deformations at early age are not hindered and the dominating load case is bending during transport and local impact (shock). In such a case, deflection hardening UHPFRC with "regular "fibre dosages around 2 % vol. are likely to be sufficient.

Cast-on site applications of UHPFRC overlays on existing structures. In this case, shrinkage deformations at early age are restrained to a more or less large extent by the existing structure, which gives rise to very high tensile stresses (up to 10 MPa). To guarantee crack control with finely distributed cracks even if the matrix cracking strain is reached, the UHPFRC must exhibit a tensile strain hardening response in the structural member. This requires UHPFRC mixes with low dispersion of properties and high fibre dosages up to 6 % vol. Further in those applications, the tensile strength of the materials is also a key parameter Additions of micro fibres such as steel wool to increase the apparent tensile strength is most suited for this purpose.

<u>The methodology</u> for the design of a UHPFRC recipe can be summarized as follows:

1. Choice of the fibrous mix: length, shape, material, aspect ratio and dosage of the fibres
2. Choice of the binder, mineral additions, ultrafines (type and dosage)
3. Choice of the superplasticiser that offers the maximum water reducing efficiency for a given workability and determination of its dosage at saturation[1].
4. Choice of the aggregates and paste content according to fibre dosage and workability requirements.
5. Adjustments of Water/Fines, Ultrafines/Fines, fibrous mix, and paste content to satisfy combined requirements "PMW".

<u>Choice of fibres</u>

Key parameters for the choice of a fibre are: **length, material**, **geometry** (shape, surface condition-smoothness), **aspect ratio** and **absolute amount of fibres in the mix**.

The efficiency of the composite action between fibres and matrices is governed by the bond and by the contrast of elastic modulii between fibres and matrix.

➔ A good bond (ratio "bond/matrix cracking strength" as high as possible) and a ratio E_{fibre}/E_{matrix} >> 1 are key conditions.

➔ The bond must also not be too good to induce fibre breakage. Highly deformable UHPFRC can only be achieved with fibre pull-out mechanisms. Fibre breakage should absolutely be avoided.

<u>UHPC matrix:</u>

The major factors of influence on the performance of UHPC matrices (resistance, protective function, bond and workability for the composite) are:

- Packing density of grains
- Water/Fines – W/F ratio
- Degree of hydration of the binders α_{hydr} and confinement of hydration products
- Ultrafines/Cement[2] – U/C ratio and Ultrafines/Fines – U/F ratio
- Paste volume (% Vol.) or fine aggregate content
- Superplasticiser/Fines ratio – SP/F

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[1] When the dosage of superplasticiser is progressively increased, everything else kept constant in the recipe, the workability increases more or less. For too low or too high dosages, the effect of a change is barely noticeable, in the "efficiency range" of the superplasticiser, a change of the dosage induces a significant change of the workability. The dosage at saturation is the one after which no more significant change in workability takes place.

[2] Cement is meant here as reactive clinker particles.

Many different types of UHPFRC recipes with various matrices and fibrous mixes are currently under development worldwide. Very few or almost none however satisfy at the same time the conditions of tensile strain hardening, low permeability, high tensile and compressive strength and self compacting character needed for cast-in situ applications.

The trend is currently clearly to use local materials and by-products of the industry such as fly ash, Ground Granulated Blast Furnace Slag - GGBFS and combinations of them to replace cement, However, most often, the workability barrier linked to cement/superplasticiser compatibility issues remains an obstacle to the use of an efficient fibrous mix to achieve true tensile strain hardening and/or other drawbacks are encountered (higher shrinkage, limited availability of the materials, variability of the composition of the industrial by-products, high scatter of properties due to an insufficient fibrous mix).

A possible way to overcome this barrier is to replace cement grains by other particles of similar size and morphology but with a mineralogy providing a better compatibility with the plasticizers. Active ones such as Fly ash, latent active ones such as ground granulated slag, or inert ones such as quartz powder and limestone filler are good candidates for this.

Application to Slovenian and Polish components

The goal of the Research and Development works was to find recipes with the same fibrous mix, with comparable properties of Workability, Mechanical Performance and Protective Function ("PMW" requirements) than the SAMARIS mixes, but using to the largest possible extend components available locally in Slovenia or Poland: Cement, Superplasticiser, Quartz Sand and Silica Fume.

A further goal was to improve the slope tolerance of specific mixes for cast on site applications on structures with slopes of 3 to 5 %.

Cements (Salonit Ahnovo – Slovenia and Gorazde - Poland) and Superplasticisers Zementol Zeta Super S® (TKK) for Slovenia and Sika Viscocrete for Poland were used.

First developments were started in Slovenia. Several attempts were made with Pure CEM I 42. 5 Sulphate resistant and CEM I 52.5 R cement from SALONIT but with unsatisfactory workability despite high superplasticiser dosages. It rapidly turned out that UHPFRC recipes with such high fibre dosages and sufficient workability could not be achieved with local pure CEM I from Slovenia. The same trend was later confirmed for Polish products. Hence another way had to be found.

From there it was decided to investigate the possible replacement of large quantities of the cement used in the existing UHPFRC recipes from the SAMARIS project by limestone fillers.

The final outcome of those R&D works is three new UHPFRC recipes: for Slovenia recipes CM32_11 and CM32_13 and for Poland recipe CM33_9 with following properties:

Similar fibrous mix based on CEMTEC$_{multiscale}$® family developed at LCPC, Rossi et al. (2005), self compacting character. Mechanical and protective properties equivalent to the mixes developed during the SAMARIS project, matrix with 50 % cement replacement by limestone filler.

- Recipe CM32_11 has limited slope tolerance but can be used to fill formworks with limited space.
- Recipe CM32_13 has a slope tolerance of at least 5 % but should be used only to fill open formworks of limited height (200 mm max.) and with sufficient space (30 to 35 mm minimum) if it is needed to avoid longitudinal casting joints between kerbs and bridge decks for example.
- Recipe CM33_9 has a slope tolerance of at least 3 %. This mix was validated in the laboratory on small scale batches (25 litres) and should be further optimized on larger scale trial tests.

Mechanical performance on the basis of flexural tests on small prisms and instrumented 4 PT bending plates (500 x 200 x 30 mm), representative of the application thickness, and protective function by means of air permeability and capillary water absorption tests were also investigated for those recipes, both at EPFL and ZAG and compared to the target values. All results are within the expected limits and no significant detrimental influence of the Thixotropizing addition could be observed

Trial tests were performed at the Salonit plant in October 2008 to verify and optimize in full scale the ability of recipes to accommodate slopes of 3 to 5 %. The test were successful and 900 litres of the new material CM32_13, with only 0.3 % Thixotropizing addition were applied from a concrete truck on two inclined test surfaces of 10 m^2 with 3 and 5 % slopes in the plant. The losses in the truck were extremely small (around 50 litres). Figure 1 shows the production and application of the UHPFRC.

Figure 1: Full scale field trial, Salonit plant, Slovenia, October 2008.

Conclusions

- A methodology was proposed, validated and applied to develop local UHPFRC mixes from Slovenia and Poland, with a very large cement replacement by limestone filler.
- This concept also significantly reduces the monetary and environmental cost of UHPFRC, by decreasing to a large extend their cement content.

Both Slovenian recipes were used successfully at an industrial scale (total 15 m^3 produced) during the first application of UHPFRC in Slovenia, for the rehabilitation of the Log Čezsoški bridge in July 2009.

All recipes satisfy the original requirements of using to the largest possible extend local products and have a potential to be further improved.

1 INTRODUCTION

The wide dissemination of Ultra High Performance Fibre Reinforced Concrete (UHPFRC) technology, specially in very demanding applications such as cast-in situ rehabilitation works requires UHPFRC formulations from local components. However, it is extremely difficult to achieve sufficient workability just by replacing cement and plasticizer from existing optimized UHPFRC recipes by locally available ones. Insufficient workability most often either forces to increase water dosage and water/binder ratio which severely decreases all performances of UHPFRC or also prevents the use of a sufficient fibrous mix to achieve tensile strain hardening. On another hand the very low water/binder ratio of UHPFRC in the range of 0.2 or less induces a very low degree of hydration of cement grains at long term (typically 0.3 to 0.5). Thus most of the cement in Ultra High Performance Concrete (UHPC) matrices is used for packing and workability but will never contribute to hydration, at best to self healing properties. Further, most cement-superplasticisers compatibility problems are related to negative interactions between cement chemical components (typically reaction products of C_3A and sulphates) and the dispersive action of superplasticisers.

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In this perspective, UHPFRC mixes with replacement of 50 % of the cement by limestone filler has been tested and applied successfully in this study. Strain hardening UHPFRC recipes with excellent tensile and protective properties could be produced with locally available components from Slovenia on one hand and Poland on the other hand. All properties including shrinkage and mechanical response under restraint were checked and the mixes showed properties comparable or better to the original recipes with pure CEM I, developed for similar applications, during project SAMARIS. This concept opens up very promising possibilities to produce UHPFRC with locally available components without loosing significantly on any property neither at fresh state nor at hardened state.

In the following document firstly, a methodology is given for the design and validation of UHPFRC for cast on site applications of rehabilitation, based to the largest extend on locally available components. Secondly, two examples of applications are then given on the basis of Slovene and Polish components.

2 DEFINITIONS

More and more "UHPFRC" recipes are emerging, at the same time applications to road infrastructures are also spreading in many countries. It is thus important to clarify the definition of UHPFRC to avoid misunderstandings.

According to the French guidelines (AFGC – 2000), widely accepted, *UHPFRC are defined by*

"A compressive strength larger than 150 MPa, an ultra compact matrix and the addition of a large amount of steel fibres (typically 2 % vol. or more straight smooth steel fibres) to give the extremely brittle UHP (Ultra High Performance) matrix a sufficient deformation capability for structural applications".

No mention is made on the tensile or flexural response in this definition. This definition calls for two remarks:

1. It is clearly targeted to structural applications where UHPFRC are combined with prestressing in prefabricated members avoiding passive reinforcement bars, which was the original development direction followed from 1995 to 2000.
2. It opens a very wide field of possible recipes.

The definition of the ultra compact matrix is also not clear in literature. Generally speaking, UHPFRC have a water/cement ratio lower than 0.2. In this case, the compressive strength of 150 MPa is granted and the outstanding protective properties too. Cementitious materials with water/cement ratios lower than 0.3 also exhibit very low permeability to water and gases. They are however significantly higher than those of UHPFRC and most important the bond to fibres is not sufficient to enable the use of large quantities of straight steel fibres which is one of the keys to UHPFRC production in a first step.

Strain hardening responses under bending or tension are commonly achieved by reinforced or prestressed concretes. Fibre reinforced concretes too can be designed to achieve those features.

The major difference between those materials and UHPFRC is actually not in the mechanical response but rather in the properties of its matrix: very low permeability, excellent bond and workability sufficient to achieve self compacting cementitious composites adapted for industrial applications.

3 MIX DESIGN

3.1 Introduction - methodology

The goal of the mix design is to achieve UHPFRC recipes with satisfactory properties for rehabilitation applications, with respect to three aspects summarized as **"PMW"**:

- **Requirement "P":** Protective function at serviceability: dense matrix with very low permeability to fluids and gases, very low capillary water absorption, and no macrocracking (only finely distributed microcracks, barely visible to the naked eye can be tolerated at serviceability to guarantee the continuity of the protective function of the UHPFRC).

- **Requirement "M":** Mechanical performance: high uniaxial tensile strength (in the range of 10 MPa), and deflection or tensile strain hardening response (deformability of 0.5 to 3 ‰) according to the requirements of the application foreseen (considering orientation effects of the fibres, geometry and conditions of casting such as space available in formworks, etc.).

- **Requirement "W":** Workability – rheology: acceptable mixing time, self compacting character, if required tolerance to slopes or passing ability to fill complex or narrow formworks, 2 to 3 hours minimum range of performance (from water addition in mixer) without significant loss of workability.

➔ Those properties are closely linked. The mechanical performance is given by the matrix quality and the fibrous reinforcement. The fibre distribution in the structure is given by the fibrous mix design but also by the workability and the conditions of application. Finally, no protective function is granted if the material does not satisfy the mechanical requirements and exhibits numerous macrocracks[3] at serviceability in the structure.

[3] Following the definition from Rossi (2001), "Macrocracks are cracks whose length cannot be considered to be very small with respect to the size of a specimen or a structure". "Microcracks are cracks whose length can be considered to be very small with respect to the size of a specimen or a structure". They are thus not defined by absolute dimensions but rather with respect to the application.

The methodology for the design of a UHPFRC recipe can be summarized as follows:

1. Choice of the fibrous mix: length, shape, material, aspect ratio and dosage of the fibres
2. Choice of the binder, mineral additions, ultrafines (type and dosage)
3. Choice of the superplasticiser that offers the maximum water reducing efficiency for a given workability and determination of its dosage at saturation[4].
4. Choice of the aggregates and paste content according to fibre dosage and workability requirements.
5. Adjustments of Water/Fines, Ultrafines/Fines, fibrous mix, and paste content to satisfy combined requirements "PMW".

➔ Currently, UHPFRC are always prescribed by their composition. It is however the goal that in a near future, when more and more UHPFRC are locally available, prescription by performances becomes possible.

Finally, the tailoring of UHPFRC recipes to local components can be split in two phases:

(1) Choice of the fibrous mix (type, geometry and dosage) assuming that a UHPC matrix with high tensile strength and good bond can be produced (this process might need some adjustments at a later stage when a feasible matrix is defined).

(2) Determination of a matrix to achieve the required properties of workability, compacity, high tensile strength and bond to the fibres.

3.2 Fibrous mix

3.2.1 Bases

UHPFRC exhibit a very significant "Deflection Hardening" capability i.e.: there mechanical response under bending shows an increase of the force deflection curve after "first cracking[5]" with a very long non-linear domain as shown on Figure 1. This means that they "control cracking" under bending – i.e. induce a finely distributed crack pattern up to the peak load, in a way similar to reinforced concretes and much more pronounced than Fibre Reinforced Concretes (FRC).

[4] When the dosage of superplasticiser is progressively increased, everything else kept constant in the recipe, the workability increases more or less. For too low or too high dosages, the effect of a change is barely noticeable, in the "efficiency range" of the superplasticiser, a change of the dosage induces a significant change of the workability. The dosage at saturation is the one after which no more significant change in workability takes place.

[5] First cracking has a very general meaning here – for UHPFRC it means the first deviation from a linear elastic response, when the matrix tensile strength is reached.

Note that the values of the stresses indicated in MPa are calculated assuming an elastic linear stress distributions in a cross section (assumption of so–called "Modulus of Rupture" – MOR). This is a simplification helpful for demonstration or comparative purposes. It however leads to extremely high values of the "bending strength" or MOR at peak such as 50 MPa. This is very spectacular but not representative of the true mechanical performance of the UHPFRC under uniaxial tension, more in the range of 10 MPa as will be shown later.

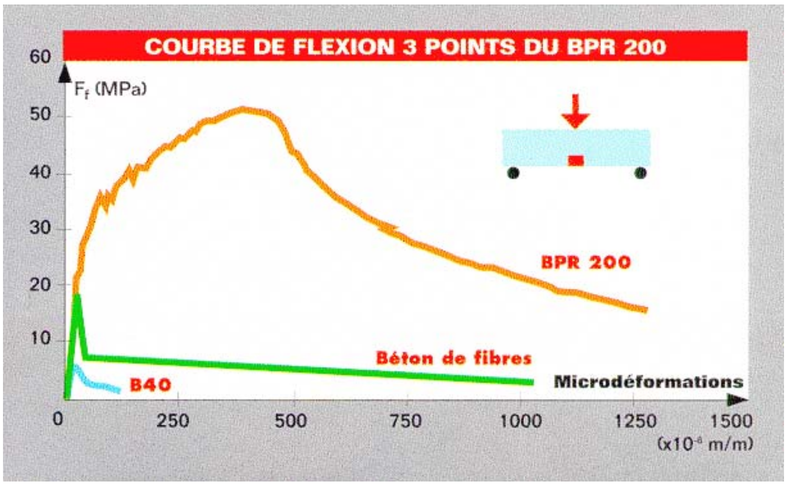


Figure 1: Flexural response of UHPFRC (BPR 200), FRC (Béton de Fibres) and concrete (B40) on 40/40/160 mm prisms, after Bouygues (1997).

Figure 2 after ITBTP (1993), presents in a very simplified way the different types of mechanical responses that can be obtained with different fibre dosages V_f. For a similar matrix and fibre type, the critical fibre volume $V_{f,crit}$ is the one for which the stresses carried after first cracking are equal to those carried by the composite before matrix cracking.

- For $V_f > V_{f,crit}$, the composite is said to be "hardening",
- for $V_f = V_{f,crit}$ "Plastic" and
- for $V_f < V_{f,crit}$, "Softening".

➔ In a "softening" fibre reinforced composite, a macrocrack appears at the peak force and it is localized until final fracture of the materials.

➔ In a "hardening" fibre reinforced composite, multiple finely distributed cracks develop progressively after first matrix cracking until the peak force, after which a crack localizes until final fracture, with a softening behaviour.

Those types of mechanical responses can be achieved in many different structural configurations such as bending or uniaxial tension. Under bending one speaks of **"deflection hardening"** response and under tension of **"tensile strain hardening"** response.

The underlying concept of critical fibre dosage $V_{f,crit}$ is exactly the same as for the choice of the minimum reinforcement in a reinforced concrete (RC) structure to control cracking-

The minimum reinforcement in RC structures to control cracking under bending is significantly lower than that necessary under a pure tensile load case. Similarly, deflection hardening is much easier to achieve that tensile strain hardening in fibrous composites.

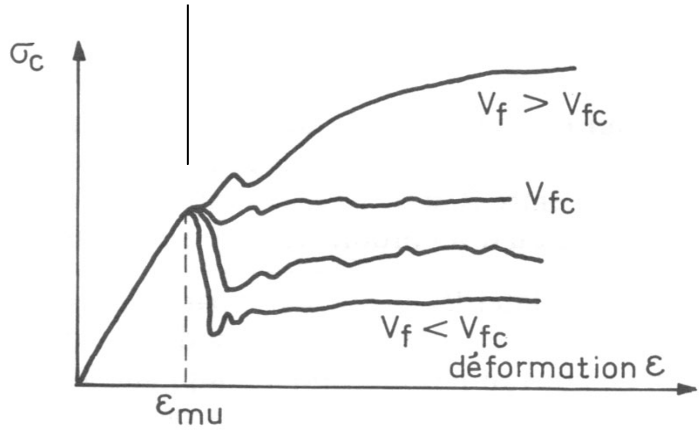


Figure 2: different types of mechanical response of a fibrous composite according to the fibre dosage V_f, after ITBTP (1993), coll.

Various types of UHPFRC exist on the market, which fulfil the requirement of deflection hardening. Very few ones have shown evidences of tensile strain hardening.

"Deflection Hardening" feature is however not automatically granted for all UHPFRC recipes as will be shown later. It depends on the fibrous mix used (type of fibres, geometry and dosage) and matrix properties (tensile strength and bond).

Bending (pure or with some axial forces) and compression are very common load cases in civil engineering applications of cementitious materials with or without rebars or prestressing and for prefabricated members. Deflection Hardening UHPFRC are well suited and open new fields of structural design for those load cases.

➔ Pure tension or dominating tensile stresses are more seldom encountered and set much higher requirements to the tensile response of UHPFRC. In order to control cracking in such cases, the materials need to exhibit tensile strain hardening: under uniaxial tension, the stresses will rise after first cracking, with a significant deformation capability (typically in the range of 0.5 to 3 ‰) characterized by finely distributed microcracks, barely visible to naked eye, before cracking localizes in a macro crack.

Figure 3 according to Namman (2003) shows the typical tensile response of a Fibre Reinforced Concrete (FRC) with a strain softening response but no strain hardening, and a UHPFRC with a tensile strain hardening, then softening response.

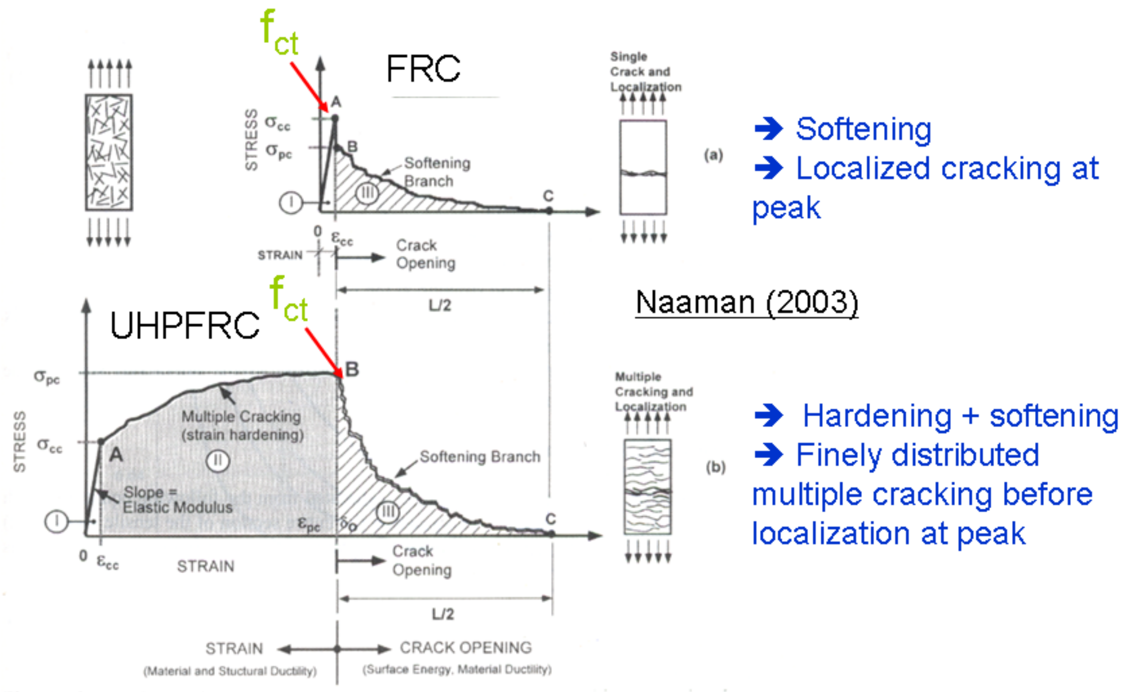


Figure 3: Tensile response of UHPFRC and FRC; adapted after Naaman (2003).

➔ *A UHPFRC material (or by extension any FRC) that exhibits a low or inexistent tensile hardening response, even if it is deflection hardening, exposed to a pure tensile load case will show localized cracking in an unacceptable way at a serviceability limit state.*

The fractured surface of a UHPFRC specimen after a tensile test shows numerous steel fibres, pulled out from the matrix, Figure 4.

Figure 4: Fractured surface of a UHPFRC specimen, CEMTEC$_{multiscale}$®, recipe CM23.

The work of pull-out of these numerous micro-reinforcements explains the extremely high specific work of fracture[6] of UHPFRC (up to 30'000 J/m^2 compared to 200 J/m^2 for normal concrete).

A significant part of the work of fracture of UHPFRC is dissipated in the bulk of the material, during the strain hardening phase, in the form of finely distributed, multiple cracks.

3.2.2 Guidance for the choice

Two major kinds of applications for rehabilitation of structures can be distinguished:

(2) Prefabricated elements applied on the existing structure. in this case, provided the formworks do not have complex shapes with holes for instance, the shrinkage deformations at early age are not hindered and the dominating load case is bending during transport and local impact (shock). In such a case, deflection hardening UHPFRC with moderate fibre dosages around 2 % vol. are likely to be sufficient.

(3) Cast-on site applications of UHPFRC overlays on existing structures. In this case, shrinkage deformations at early age are restrained to a more or less large extent by the existing structure, which gives rise to very high tensile stresses (up to 10 MPa). To guarantee crack control with finely distributed cracks even if the matrix cracking strain is reached in such a case, the UHPFRC must exhibit a tensile strain hardening response in the structural member. This requires UHPFRC mixes with low dispersion of properties and high fibre dosages up to 6 to 9 % vol. Further in those applications, the tensile strength of the materials is also a key parameter Additions of micro fibres such as steel wool to increase the apparent tensile strength is most suited for this purpose.

[6] The specific work of fracture corresponds to the energy in Joules needed to completely separate 1 m^2 of the material in two pieces, under uniaxial tension.

3.2.3 Fibres

Key parameters for the choice of a fibre are: **length, material**, **geometry** (shape, surface condition-smoothness), **aspect ratio** and **absolute amount of fibres in the mix**.

The efficiency of the composite action between fibres and matrices is governed by the bond and by the contrast of elastic modulii between fibres and matrix.

➔ A good bond ("bond/matrix cracking strength" as high as possible)

and a ratio $E_{fibre}/E_{matrix} >> 1$ are key conditions.

➔ The bond must also not be too good to induce fibre breakage. Highly deformable UHPFRC can only be achieved with fibre pull-out mechanisms. Fibre breakage should absolutely be avoided.

Fibre length: is defined by the application in order to both:

(1) maximize the mechanical performance of the material in the structure, according to the geometry to be cast (fibre length should typically be a function of the layer thickness such as not less than 1/3 to ½ of the layer thickness for horizontally cast application),

(2) accommodate the geometry to be cast: space available in formworks, rebars, details, etc.. The fibre length should typically not be larger than one third of the minimum space between two obstacles.

Orientation effects play a dominant role in the mechanical response of UHPFRC. In the worst case, the tensile strain hardening feature can vanish or contrarily, if orientation is forced in tensile specimens with narrow cross sections with respect to the fibre length, the tensile strain hardening response is largely overestimated, which can lead to severe problems in structural application with 2 to 3D orientations. At the contrary, with thin layers with a thickness in relation to the fibre length, fibres are forced to orientate in an almost 2 D plane and their efficiency is maximized.

➔ Thus a sound choice of the fibre length with respect to the application geometry is a prerequisite to optimize the tensile response of UHPFRC in structural members. The thicker the layer, the larger the fibre should be. Contrarily, for extremely thin layers (10 mm or less), short fibres such as 5 mm length can prove to be very efficient, or fibres usually providing only deflection hardening response can for the same dosage provide a tensile hardening response if most are forced to orientate in one plane.
Finally, fibre length is also a major factor for the extend of the strain hardening response. The longer it is, the longer the strain hardening domain can be, provided that a sufficient dosage can be mixed.

➔ Typical fibre length used in UHPFRC recipes varies from 5 to 30 mm.

➔ Microfibres such as steel wool have a typical length of 1 to 3 mm.

Fibre geometry: The dosage of fibres in UHPFRC is generally so high (2 % vol or more) that straight smooth fibres are the most feasible choice (also owing to the excellent bond in UHPC matrices). In very specific cases Parant (2003), hooked fibres have been used in combination with other types of straight steel fibres (multilevel fibre mixes) to extend the tensile strain hardening range. Currently almost all existing (deflection or tensile strain hardening) UHPFRC recipes are made of straight smooth steel or synthetic fibres.

Fibre material: Deflection hardening UHPFRC with straight synthetic fibres such as PVA have already been developed and applied, such as Ductal FO® [7] but tensile strain hardening UHPFRC with a tensile strength above 10 MPa and only synthetic fibres are still a challenge expected to be solved in the next years. Fibres should of course be compatible with the matrix (AR-glass for instance is acceptable for cementitious binders but not untreated glass).

Fibre aspect ratio: the aspect ratio (length over diameter[8]) controls the stress level in the fibre before pull-out. It has a direct influence on the critical fibre dosage to achieve deflection or tensile strain hardening. The higher it is, the lower the critical volume fraction $V_{f,crit}$ will be, on an average basis. It also has a major influence on workability. The higher it is, for a similar dosage, the more difficult the workability will be. For steel fibre reinforced UHPFRC, typical aspect ratios are between 30 and 100.

Fibre amount: another extremely important parameter of fibre reinforced concrete technology is the absolute amount of fibres for the same dosage. The higher it is, the most reliable the performance of the composite will be (i.e.: smaller difference between fractile and average strength). Similar to minimal reinforcement to control cracking in RC, for the same reinforcement ratio, it is better to have multiple small diameter bars rather than few ones with large diameters, in the same cross section.

[7] http://www.ductal-lafarge.com/wps/portal/Ductal/DiscoverDuctal

[8] For fibres with a non-circular cross section, one can define an equivalent diameter for similar area.

Multilevel mixes: Finally, as shown by Rossi (1997, 2001, and 2005), a combination of different types of fibres (length, geometry, aspect ratio, dosages and materials) gives most freedom to optimize strength, deformability and workability of UHPFRC. Short fibres (like steel wool – length of a few mm - act at the material level and increase the apparent tensile strength. They dominantly have an action of the resistance of the material. Long fibres (10 mm and over), act at the structural level, they increase the deformability of the composite. Note that short or microfibers also contribute indirectly to the deformability of the composite by improving the pull-out response of the long fibres, Parant (2003).

The synergetic effect of multiple fibre types is illustrated on Figure 5 after Denarié et al. (2006). The uniaxial tensile behaviour of two different recipes of the UHPFRC $CEMTEC_{multiscale}$® type has been determined by means of a rigid fixed ends tensile test, on unnotched dogbone specimens. The average curves from five tests for each material are represented showing the range of possible strain hardening responses. Both recipes are self-compacting.

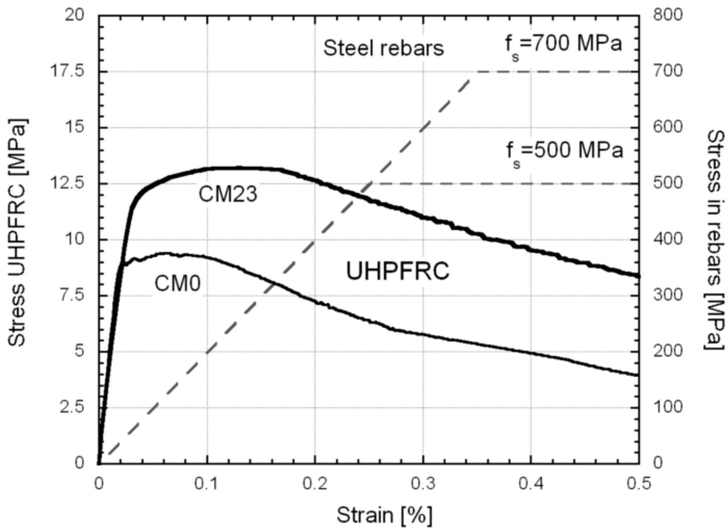
- Recipe CM0 is reinforced with a 468 kg/m^3 of a single type of 10 mm long steel fibres with an aspect ratio of 50. It has a water/binder ratio of 0.140, 1051 kg/m^3 cement, a fluid consistency (slump-flow = 700 mm) and is self-levelling.

- Recipe CM23 has more binder (1437 kg/m^3 cement) and a lower water-binder ratio (0.125). It is reinforced by a multilevel fibrous mix of macro steel fibres (10 mm long, aspect ratio 50) and microfibres (steel wool) with a total dosage of 705 kg/m^3. It can hold a slope of the substrate up to 2.5 %. The effect of the addition of microfibres is revealed by three aspects:

(1) the significant increase of the pseudo-elastic domain from 8 to above 11 MPa

(2) the increase of the strain hardening domain

(3) the increase of the load carrying capacity in the descending branch due to the indirect action of the microfibres on the progressive pull-out of the macro fibres.



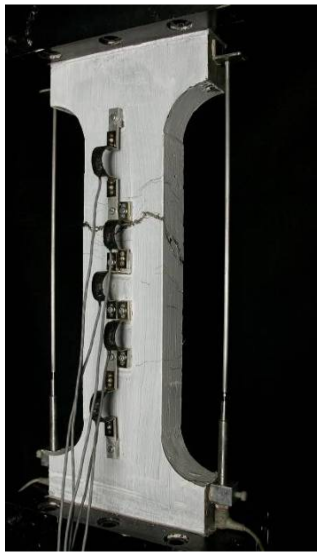


Figure 5: Tensile behaviour of two UHPFRC recipes, $CEMTEC_{multiscale}$®, unnotched tensile tests, fixed rigid boundary conditions, average curves at 28 days, Denarié et al. (2006).

3.2.4 **Dosage**

➔ *The fibre dosage is selected according to the chosen fibres in order to provide either deflection of tensile strain hardening response. The second case is much more demanding and typically requires* ***two times*** *more fibres for similar fibre types and matrices.*

The fibrous reinforcement necessary to obtain a deflection or tensile strain hardening response can be estimated by simple models such as proposed by Naaman (2003). The stress before matrix cracking is determined from the fibre volume ratio V_f, the matrix strength σmu, the fibre aspect ratio L/d, the bond τ and two coefficients α1 and α2 related to orientation and fibre bond loading before cracking. For 3D, α2=0.5 is assumed. The stress after matrix cracking is calculated in a similar way but neglecting the matrix contribution, and using three parameters λ1, λ2, λ3 related to expected pull-out length, efficiency factor in cracked state and group reduction factor.

Writing that for tensile strain hardening, the stress carried by the composite after cracking should be larger or equal to the one that was carried before cracking, yields:

$$V_f \geq V_{f,crit} = \frac{1}{1 + \frac{\tau}{\sigma_{mu}} . \frac{L}{d} .(\lambda_1 \lambda_2 \lambda_3 - \alpha_1 \alpha_2)} \qquad (1)$$

The two major parameters in this equation are:

- the aspect ratio L/d
- the ratio "bond over matrix strength" τ/σ_{mu}.

According to Namman, (2003), for straight smooth steel fibres, the bond over matrix strength ratio is typically around 1 to 1.5. For normal concretes: tensile strength is between 2 and 4 MPa and bond of smooth steel fibres = 4.2 MPa after Bentur and Mindess (2007).

➔ For UHPFRC, bond of straight smooth steel fibres is a function of fibre diameter. For diameters between 0.1 and 0.2 mm the bond is in the range of 6 to 8 MPa, after Orange et al. (2000), and Wuest (2007) and the matrix cracking strength is in the range of 6 to 10 MPa, so the ratio τ/σ_{mu} for UHPFRC is smaller than for usual FRC (bond around 4.2 MPa after Bentur et al, (2007)) with steel fibres and is in the range of 0.6 to 1.2. Thus one can assume an average value of 1 in a first approach, keeping in mind that the higher the tensile strength of the matrix is, the more difficult it will be to provide a fibrous mix satisfying the tensile strain hardening condition proposed by Naaman. This effect is particularly important to consider with UHPC matrices with a high tensile strength around 10 MPa.

Figure 6 after Naaman (2003) graphically illustrates equation (1). As an example, let us consider the case of two types of smooth steel fibres: slender fibres such as 13/0.16 mm - aspect ratio = 80), and fibres with a moderate aspect ratio of 50 such as 10/0.2 mm, assuming a ratio τ/σ_{mu} of 1 and a 3D orientation. For the slender fibres 13/0.16 one gets a critical fibre content of **4.8 %** and for the 10/0.20 fibres **7.4 %**. Considering the influence of the orientation to be inversely proportional to the orientation coefficient μ_o, one gets for the 2D case:

$$V_f(2D) = V_f(3D) * \frac{\mu_0(3D)}{\mu_0(2D)} = V_f(3D) * \frac{0.5}{0.635} \qquad (2)$$

- for the 13/0.16 mm fibres $V_{f,crit}$ /2D) = **3.9 %**
- for the 10/0.20 mm fibres $V_{f,crit}$ /2D) = **5.9 %**

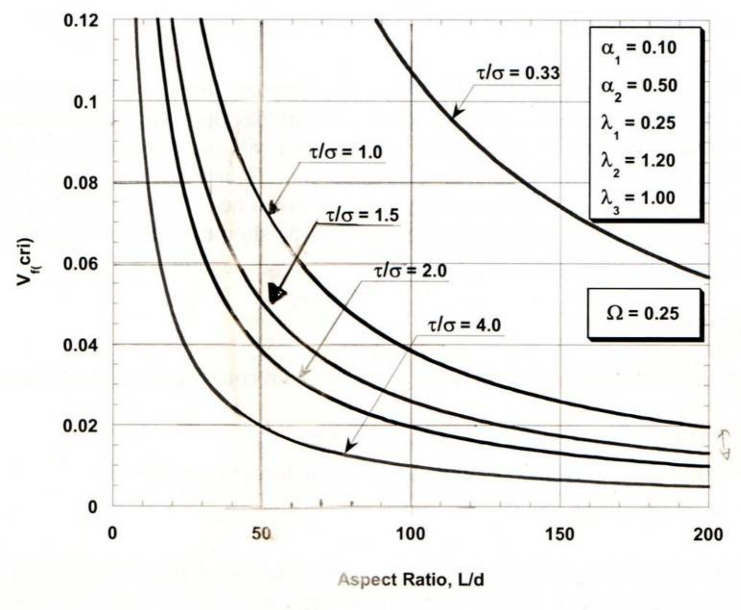


Figure 6: Domains for tensile strain hardening composites ($V_{f,crit}$ as function of L/d and τ/σ) after Naaman (2003).

Caution: The Naaman model however does not predict either the extend of the strain hardening deformability obtained, or the scatter of this performance. It is only a pre-design tool delivering informations on the "possibility" to achieve either deflection or tensile strain hardening responses. Laboratory tests are mandatory to confirm those predictions.

Naaman (2003) followed the same approach to determine the critical fibre dosage under bending. In this case, the criterion is that the moment in the cross section after cracking should be equal or larger than the moment before cracking. Figure 7 illustrates graphically the results obtained with such a criteria for a 3D orientation.

➔ Comparing Figure 6 and Figure 7, one immediately notices that for a similar geometry and τ/σ_{mu} ratio, the fibre dosage required to achieve deflection hardening is **around two times smaller** than that to achieve tensile strain hardening.

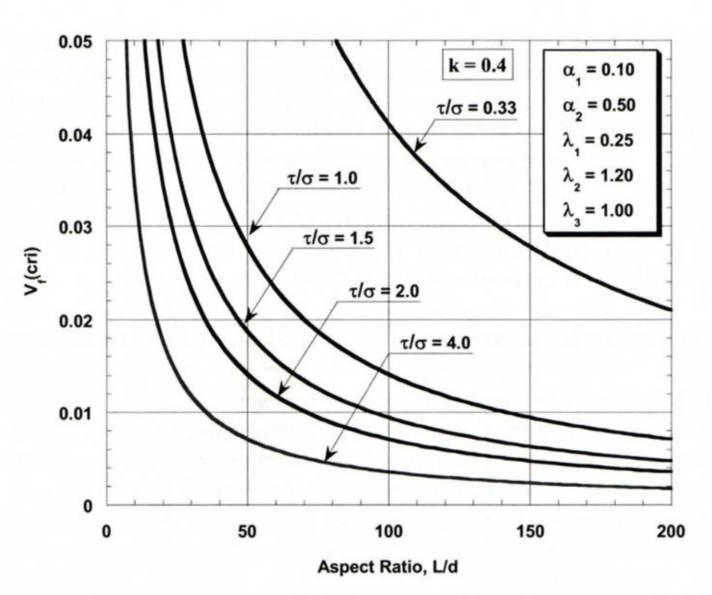


Figure 7: Conditions for deflection hardening response for Fibre Reinforced cementitious composites, after Naaman (2003).

Following Naaman's approach there is virtually an infinite number of possible fibrous mixes (combination of fibre aspect ratio and dosage) to achieve, for a given matrix (strength and bond) deflection or tensile strain hardening. However, for decreasing fibre dosages and increasing fibre aspect ratios (a priori more economical) the difference between the average performance and the characteristic one (such as deformation capability) rapidly increases. So the most efficient mix is not the cheapest one for the average performance but for the characteristic performance

One finds here in the background the well known effect from Fibre reinforced Concrete (FRC) technology:

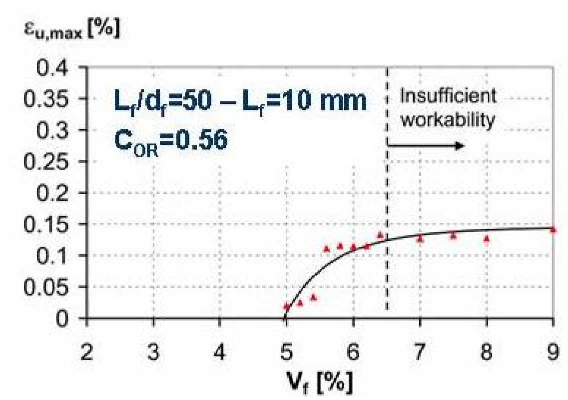
➔ The absolute amount of fibres is one of the most important properties to guarantee a high level mechanical performance with low scatter. The same applies for minimal reinforcement in RC structures. For a similar reinforcement ratio in a cross section, a high number of rebars with a small diameter is more efficient to control cracking that a low number of rebars with a large diameter.

The sensitivity of the tensile strain hardening response as a function of the chosen fibrous mix is illustrated by the results of the model from Wuest (2008) that can simulate the mechanical response of a UHPFRC under tension as a function of its matrix and fibrous mix (fibre type, dosage and coefficient of orientation).

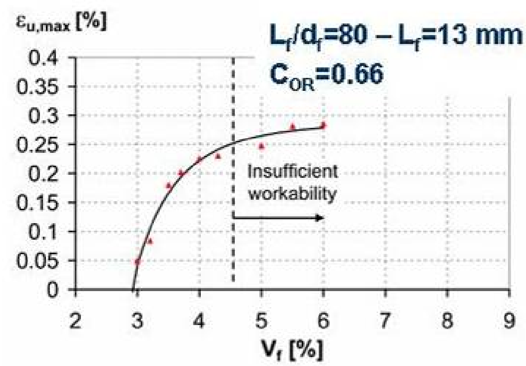
This model was able to predict very accurately the response observed in uniaxial tensile tests for different kinds of UHPFRC and also ECC with synthetic fibres.

In a further step, the model was applied to investigate the effect of the fibre dosage on the extend of the tensile hardening response $\varepsilon_{u,max}$ for different fibre types. The results are illustrated on Figure 8 for two types of fibres that lead a priori, according to the Naaman approach to a tensile strain hardening response for respectively between 5 and 7 % and 3 and 5 % vol.

➔ The mix with less fibres with a higher aspect ratio (13 mm length, diameter 0.16 mm) , case b), although it delivers a larger strain hardening for a high dosage, is much more sensitive in its applicability range of workability. For those fibres, mixes with 3 to 3.5 % are practicable for workability reasons. For a dosage of 3.5 %, a change of 0.5 % vol., fibres in the dosage can decrease the extent of hardening by a factor of two and eventually make it disappear completely. At the contrary, for fibres 10 mm long, aspect ratio 50, with a dosage of 6 %, totally compatible with a wide range of workability, a decrease of 0.5 % of the fibre dosage does not significantly decrease the hardening domain, however, before 5.2 % vol. fibres, no tensilehardening is expected.



Case a)



Case b)

Figure 8: Extend of the tensile strain hardening domain as a function of fibre dosage for two fibre types with different length and aspect ratio, calculated, after Wuest et al. (2008) – C_{OR}=coefficient of orientation.

3.3 UHPC matrix

3.3.1 Bases

UHPFRC were originally developed with focus on the optimization of their ultra dense matrix, with a special attention to the increase of the compressive strength, above 200 MPa, Bache (1989), de Larrard et al. (1989, 1994), Richard et al. (1995), Roux et al. (1995).

This lead to a dramatic decrease of the intrinsic permeability, by optimization of the packing of grains with micro fillers such as quartz flour and silica fume and decrease of the water/binder ratio.

Many different types of UHPFRC recipes with various matrices and fibrous mixes are currently under development worldwide. Very few or almost none however satisfy at the same time the conditions of tensile strain hardening, low permeability, high tensile and compressive strength and self compacting character needed for cast-in situ applications.

The trend is currently clearly to use local materials and by-products of the industry such as fly ash, Ground Granulated Blast Furnace Slag - GGBFS and combinations of them to replace cement, Cwirzen et al., (2008), Durand (2007), Formagini et al. (2005), Habel et al. (2008), Jacobsen et al. (2008), Kim et al. (2008), Schmidt et al. (2005), Yang et al. (2009), Yazici (2007), Yungsheng et al. (2008).

➔ However, most often, the workability barrier linked to cement/superplasticiser compatibility issues remains an obstacle to the use of an efficient fibrous mix to achieve true tensile strain hardening and/or other drawbacks are encountered (higher shrinkage, limited availability of the materials, variability of the composition of the industrial by-products, high scatter of properties due to an insufficient fibrous mix).

A trend is also to try to try replace costly silica fume used for packing density by other micro-fillers such as metakaolin, nano sized limestone filler, pulverized fly ash or slag, Rougeau et al. (2004), Staquet et al. (2004), Yamada et al. (2008).

The major factors of influence on the performance of UHPC matrices (resistance, protective function, bond and workability for the composite) are:

- Packing density of grains
- Water/Fines – W/F ratio
- Degree of hydration of the binders α_{hydr} and confinement of hydration products
- Ultrafines/Cement[9] – U/C ratio and Ultrafines/Fines – U/F ratio
- Paste volume (% Vol.) or fine aggregate content
- Superplasticizer/Fines ratio – SP/F

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[9] Cement is meant here as reactive clinker particles.

Definitions

- Fines = particles smaller than 0.125 mm (similar definition as in EN 206 for concretes). Cement (C) and mineral additions (fillers, fly ash), are most common fines. In what follows, Limestone filler will be noted as "LF"
- Ultrafines = particles with a diameter D90 (90 % fractile) smaller than 5 µm. Silica fume (SF) is a typical ultrafine.
- Degree of hydration: percentage of cement grains that will be hydrated in the mix at long term. After the model from Powers adapted by Jensen et al. (2001) and applied by Habel (2004) and Kamen (2007) to UHPFRC, and confirmed by various experimental results, in pure CEM I UHPFRC recipes, with no mineral additions, this value is between 30 and 50 %. In normal concretes, complete hydration (100 %) is possible for a Water/Binder ratio higher than 0.42.
- Paste = Fines + Ultrafines + added water + superplasticiser + air

3.3.2 Packing density of grains

Packing density of grains is controlled by the mixing of grains of different sizes, similar to normal concretes, but at a much finer scale. Figure 9 after Roy (1987) illustrates the progressive increase of packing density of cement particle mixes with the use of a superplasticiser and the addition of ultrafine particles acting as micro fillers. This principle was proposed already in 1980 by Bache to achieve first generations of UHPFRC with so called DSP matrices.

➔ Since then various theoretical models and experimental works have confirmed the fact that the most efficient combination of fines and ultra fines needs a very large difference in diameters (around a factor of 100), such as obtained by using silica fume (D50[10] around 0.5 µm) - cement (D50 around 50 µm) mixes.

The rheology plays of course a critical role in the achievable packing densities. The progressive development of more and more efficient superplasticisers clearly made those theoretical concepts achievable in practice.

➔ Finally, as shown by de Larrard (1994), the optimum Ultrafines/Fines ratio to achieve maximum compacity is around 37% Vol. (1/3 of ultrafines – 2/3 of fines).

Many current UHPFRC recipes follow this rule which was already found on an empirical basis by Féret (1896) for mixes of sands and gravels:

"Maximum compacity is obtained for mixes with no intermediate aggregates and with 1/3 fine aggregates and 2/ 3 coarse ones".

[10] D50 = median diameter

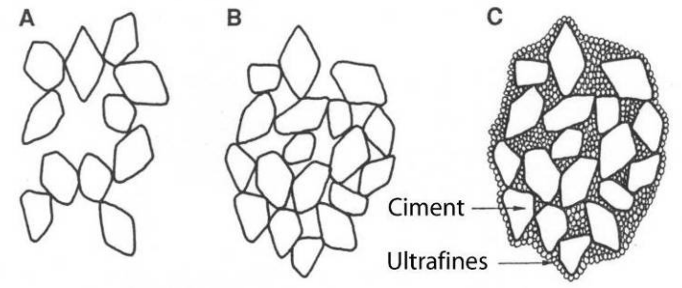

Figure 9: Compacity of mixes of cement grains and ultrafine particles after Roy (1987); a) flocculated cement grains in ordinary hardened cement pastes, b) deflocculated cement grains under the action of a superplasticiser, c) with superplasticiser and ultrafine particles.

3.3.3 Water/Fines ratio

In a first step, the Water/Binder ratio might seem to be the most important parameter related to the mechanical and protective performance of cementitious materials. However, when coming to very low Water/Binder ratios, such as in UHPFRC, a dominant part of the binder is unhydrated and can thus be replaced advantageously to a large extend by other particles, cheaper, more sustainable with respect to environment, or with other advantages.

Bornemann et al. (2002) showed that it is possible to replace significant amounts of the cement in UHPC mixes by fine quartz sand of close size and distribution, while keeping the absolute water added constant, without significantly decreasing the compressive strength. The workability was even improved as demonstrated by the lower superplasticisers dosage required to achieve equivalent consistency.

Following Schmidt (2005a) it thus makes sense to define on a more general basis for UHPFRC the Water/Fines as the governing factor for the mechanical performance. This rule finds however its limits when the degree of hydration of the binders in the mix becomes close to 100 %. This would happen for a Water/Cement factor of around 0.42 in a concrete without silica fume, according to Powers, and around 0.50 with 20 % mass silica fume, according to the model by Jensen et al. (2001). The latter case would correspond to a level of replacement of cement grains by inert particles of around 66 % in mass for a Water/ Fines of 0.2). Any further replacement would decrease the effective content of hardened cement paste (also called gel) and most probably decrease also the mechanical performances in an unacceptable way. This aspect will be discussed later into more details to define optimum levels of cement replacement.

➔ The Water/Fines ratio also governs the workability to a large extend and also the risk of segregation of the fibres if the mix is too liquid.

Further, the Water/Binder ratio and by extension Water/Fines ratios also play a very important role on the magnitude of the shrinkage of UHPFRC. When those ratios remains lower than 0.2, the shrinkage is not significantly higher than in normal concretes. However, when they increase above 0.20 up to 0.30, the shrinkage also increases in a significant way, as shown by Loukili et al. (1996).

➔ Thus, as far as possible, it is better to keep the Water/Fines ratio lower than 0.2 in UHPFRC matrices and the lowest possible, considering the necessary rheology to obtain a self compacting character and adapted to the conditions of application.

Finally, it is worth mentioning that despite the fact that the Water/Binder or Water/Fines ratio of UHPFRC is dramatically smaller than in usual concretes (0.120 to 0.20 typically instead of 0.4 to 0.6), the absolute water quantity used in the mix remains in the same range (150 to 250 litres per m^3). Hence, the only reason for the extremely low Water/Binder or Water/Fines ratio in UHPFRC is the very high paste content around 50 to 90 % with a very high fines content..

3.3.4 Degree of hydration of the binders α_{hydr} and confinement of hydration products

The quantity of water needed for hydration of a cement is a function of its mineralogical composition. Typical values for CEM I are 23 to 25 % in mass or 0.25 of the cement mass content. However, the hydration process is a complex phenomena not limited to stoechiometric chemical aspects.

Powers et al. (1947) showed that the hydration process is also influenced by the development of porosity and self desiccation phenomena that control the relative humidity in pores. After this model, a complete hydration of cement grains can occur only for water/binder ratios of around 0.42, much larger than the 0.25 predicted by the purely stoechiometric considerations (this value depends on the type of system considered – closed or open to external moisture sources). Waller (2000) and Jensen et al. (2001) extended this model to systems with silica fume. Habel (2004) and Kamen (2007) used those models to predict the maximum degree of hydration in two types of UHPFRC. The values obtained (around 30%) for closed systems correspond to experimental measurements. Hence, as also confirmed by various other authors, the degree of hydration in UHPFRC is very low and most cement grains are not hydrated at long term.

If cement is progressively replaced by inert particles in a UHPC matrix, as far as only unhydrated cement grains from the original recipe are replaced, no detrimental consequences on the mechanical performance of the material should be observed.

This effect was demonstrated by various authors on concretes. Nehdi et al. (1996), studied combinations of limestone filler, cement and silica fume in high performance mortars with cement replacement by filler up to 25 % mass. They determined most cost effective mixes with respect to the compressive strength performance. Benz et al. (2001), Benz (2006), numerically simulated the hydration process and predicted compressive strength of mixes with low w/c ratios (0.25 to 0.38) and replacement of coarse cement particles by inert fillers up to 31 % mass. The result of their works clearly outlines and justifies the interest to replace not used cement by inert particles in low w/c mixes with low degrees of hydration. This was confirmed by Bonavetti et al. (2003), who experimentally investigated the effect of cement replacement by limestone filler up to 20 % mass on the hydration process (gel-space ratio and degree of hydration) in pastes with w/c=0.25 to 0.50 and low slump concretes with w/c=0.30 and 0.34.

It was also demonstrated on UHPC by Bornemann et al. (2002) who showed that it is possible to replace significant amounts of the cement in UHPC mixes by fine quartz sand of close size and distribution without significantly decreasing the compressive strength. The workability was even improved as demonstrated by the lower superplasticisers dosage required to achieve equivalent consistency.

➔ The maximum acceptable level of cement replacement by inert particle is actually the one for which the degree of hydration of the remaining cement grains reaches 100 %. This would happen for a Water/Cement factor of around 0.42 in a concrete without silica fume, according to Powers, and around 0.50 with 20 % mass silica fume, according to the model by Jensen et al. (2001). The latter case would correspond to a level of replacement of cement grains by inert particles of around 66 % in mass for a Water/Fines of 0.2). Any further replacement would decrease the effective content of hardened cement paste (also called gel) and most probably decrease also the mechanical performances in an unacceptable way.

➔ In this context, one might wonder why for example a UHPC matrix with a Water/(Cement +Inert Fines) = 0.2 and degree of hydration of 100 %, with a cement replacement of 66 %, thus a Water/Cement ratio of 0.42, would not exhibit the same "poorer" level of mechanical performance as a pure cement paste with a similar Water/Cement ratio of 0.42.

The answer to this question is found in the morphology of the microstructures of those two different materials. In the UHPC matrix, the cement paste **is diluted** in a much larger volume and the hydration products nucleate on inert grains, in a **confined space**. Cyr et al. (2003), Lawrence et al. (2003) showed that the addition of inert particles to cement mixes accelerated the hydration process by the nucleation of hydration products. Both effects lead to a much better level of performance of the microstructure and hydration products. This dilution effect corresponds to and explains the positive effect[11] of decreasing the MPT (Mean Paste Thickness) under the compressive strength performance, observed by de Larrard (1994) on UHPC mixes.

[11] this effect is also discussed later for the choice of the paste content.

➔ Consequently, the replacement of large amounts of cement in UHPC matrices (up to 60 % for a Water/Fines of 0.2 in a first approach) by inert particles of similar size and morphology than the cement grains, without disturbing to a large extend the original packing density, is not likely to significantly impair either the mechanical performance or the protective function of UHPFRC.

This opens very promising perspectives with respect to a more sustainable use of cements and also for breaking the workability barrier often encountered when designing UHPFRC recipes form local components, as will be shown later.

3.3.5 Ultrafines/Cement

The choice of ultrafines type and dosage is guided by three aspects:

- Compacity of the mix
- Rheology – workability
- Bond of the matrix to the fibres

Usually, in UHPFRC, the ratio between fines and ultrafines is between 20 and 40 % in volume. This corresponds to the optimum compacity of a binary mix of fine and coarse grains as shown already empirically by Féret in 1896, then by de Larrard et al. (1994).

Figure 10 from Schmidt et al. (2008) presents the calculated packing density and measured viscosity of quartz powder slurries. Two different powders were used: Q2 with a specific surface of 3600 cm^2/g after Blaine is representative of fine particles in UHPFRC mixes (cement and fillers). Q1 has a specific surface of 18'000 cm^2/g similar to most silica fumes which are the most common ultrafines used.

Two major conclusions can be drawn from these results:

1. As expected, the maximum packing density is reached for around 30 % vol. of the ultrafine powder Q1 (according to Féret and de Larrard, the optimum is at 1/3 =36 % vol.). At 25 % vol. of powder Q1, the packing density is still close to the maximum. For a silica fume/cement mix, converted in mass (considering the different specific weights respectively 2200 and 3100 kg/m3 for a CEM I and silica fume), this leads to 25 % * 2200/3100 = **18 % mass**. For comparison, in original UHPFRC recipes developed by de Larrard et al. (1994) and later in many other UHPFRC mixes, the silica fume/cement dosage is close to **26 %** mass which corresponds to 37 % vol.

2. The minimum viscosity of the mix is obtained for the optimum packing density which calls back the concrete formulation method form LCPC – Baron Lesage (1980) based on the assumption *that the optimum concrete mix is the one for which the choice of the granular skeleton leads to the optimum workability.* The same approach seems to apply to mixes of fines and ultrafine powders. Further, the viscosity is almost constant and close to the minimum for a quantity of ultrafine powder Q2 between 20 and 40 % vol.

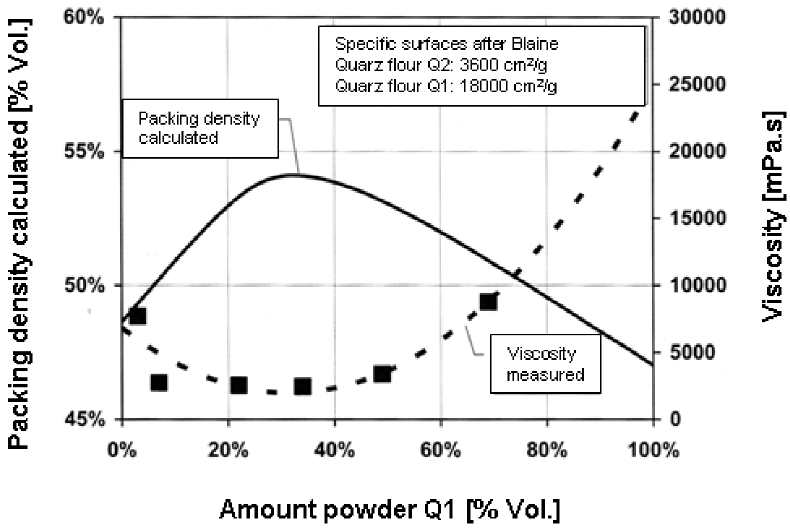

Figure 10: Calculated packing density and measured viscosity of quartz powders (Q1, Q2) slurries with 1.5 % superplasticiser and Water/Powders =0.26, Schmidt et al. (2008).

Recent proposals were made to use nano sized limestone fillers to replace silica fume in UHPFRC mixes, Yamada et al. (2008). However, the most common choice for ultrafines in UHPC matrices remains silica fume for its combined action as microfiller, hydration accelerator (due to its fineness) and pozzolanic reactant.

The second aspect that needs to be considered is bond of the matrix to the fibres. Chan et al. (2002) tested various UHPFRC recipes with different silica fume contents from 0 to 40 % of the cement mass. The bond strength and pull-out energy reach maximum values for silica fume dosage of 20 % mass of cement and are more or less constant up to 30 %. At 40 % a decrease is observed. Hence, the optimum silica fume/cement dosage is around 20 % mass.

Finally, according to AFGC (2000), after a dosage of 20 % mass of silica fume over cement, all Portlandite - $Ca(OH)_2$ is consumed and the pozzolanic reactions can barely go on.

➔ Consequently, **a silica fume/cement dosage of 20 % mass** appears to be an optimum choice.

The type of silica fume and its specific surface play also a significant role on the workability of UHPC mixes. Silicafumes from the zirconium industry, purer (white) and with a lower specific surface are most suited to develop UHPFRC. Grey silica fumes from the Ferro-Silicium industry, with higher specific surfaces (18 to 20 000 cm^2/g) are also a choice to consider if they are available locally but their water demand is often a barrier to achieve satisfactory mixes.

3.3.6 **Paste volume – aggregates content**

De Larrard et al (1994) demonstrated the close link between rheology and compacity in the quest for largest possible packing density to achieve highest possible mechanical performance. The maximum possible packing density of a set of particles (typically 0.74 for monosized spheres perfectly arranged) is never reached in practice. Wall and loosening effects act when different classes of particles of different sizes interact. Finally, the effective packing density achievable for a given mix of particles is a function of the "effort" needed to obtain it which can be characterized by a "viscosity". This is the basis of the "Solid Suspension Model" that links the viscosity of a mix to the viscosity of the suspension and to the ratio of the effective packing density to the maximum possible one.

Further, de Larrard also empirically demonstrated that the MPT "Mean Paste Thickness" which is the mean largest distance between two "aggregates" in the compacted mix is inversely correlated to the compressive performance (factor Kg equal to a relative compressive strength considering the water binder ratio) as shown on Figure 11. Accordingly, to reduce the MPT means to increase the specific surface of the aggregates which means decreasing their maximum diameter.

➔ Considering also the packing of the other particles found in UHPC matrices; cement and fillers and Ultra fines that should not be loosened by the aggregates, this approach leads to the choice of "aggregates" – fine sand - with a size distribution from 0.1 to 0.5 mm, most often encountered in UHPFRC recipes.

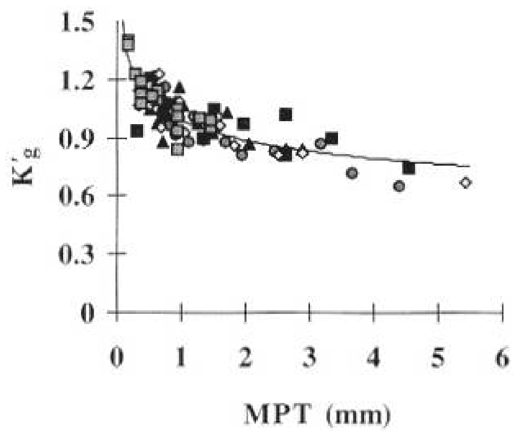

Figure 11: Relative compressive performance as a function of the Mean Paste Thickness, after de Larrard et al. (1994).

Various authors reported developing UHPFRC recipes with coarse aggregates up to several mm to save on the paste content. However, the quantity of those coarse aggregates remains small in the recipe and preserves the other principle of UHPFRC technology: *avoid a closely packed granular skeleton that hinders the deformations of the paste.*

Applying the concepts of the solid suspension model also leads to the conclusion that to improve the workability of a suspension (i.e. decrease its viscosity or even yield stress), it is necessary to give more space between the particles; i.e. increase the paste content and decrease the aggregates content. This effect is well known from concrete technology and is one of the key factors to achieve self-compacting concretes. In fibre reinforced concretes technology, the effect is the same. Fibres are inclusions that hinder the workability of the mix, in a way comparable to aggregates of D_{max}=fibre length. In order to preserve the workability, to compensate for the addition of the fibres, one needs to decrease the amount of coarse aggregates (increase the Sand/Gravel ratio).

In UHPFRC mixes the approach is the same however the "coarse aggregate" is here the fine sand 0.1 to 0.3 (0.5) mm.

➔ For a given workability, there is a direct complementarity between the fibre dosage in the UHPFRC and the aggregate content in volume. If one increases, the other has to decrease and vice-versa. More generally speaking, the paste (cement + fillers + ultrafines+ water and superplasticiser) content is the first parameter to select to influence the workability of a UHPFRC mix or to accommodate a change of the fibrous mix.

➔ Typical paste contents of UHPFRC vary between 55 and 90 %, compared to 30 % for normal concretes and 35 to 38 % for SCC.

3.3.7 **Superplasticiser/Fines**

The lack of compatibility between cement and superplasticisers is the major cause of failure in the design of new UHPFRC recipes. The level of performance needed to achieve very low Water/Cement ratios such as in UHPFRC is indeed very often not possible to achieve with local components.

During the very first chemical reactions between cement grains and water, at mixing, various hydration products of sulphates (from Gypsum) are formed. With sufficient Sulphate content in the cement, AFt phase is formed and it is unlikely that it can absorb the superplasticiser molecules in its structure. At the contrary, with low sulphate contents the AFm phase is formed with a high likelihood that it can absorb the superplasticiser in its structure and thus hinder to a large extend the steric dispersive action of polycarboxylate based superplasticisers used for UHPFRC production.

Cements with low Sulphate contents are thus very likely to require more superplasticiser for the same dispersive action, Aitcin et al. (1994). At the contrary, cements with an optimal quantity of sulphates vs. C3A such as CEM I 52.5 HTS from le Teil (Lafarge) are best suited for the most efficient interaction with superplasticisers, thus enabling the realization of mixes with extremely low water/cement ratios with a self compacting character needed for UHPFRC production.

Generally speaking, cements with low C3A content (Sulphate resistant) should exhibit a better compatibility with superplasticisers and should be tried first. However, many other factors of the cement mineralogy also come into play in this interaction and an excellent performance is seldom achieved.

➔ Typical SP/C or SP/F ratios in UHPFRC are much higher than in usual concretes or SCC, and in the range of 2 to 4 % mass (liquid + dry extract). A study of the efficiency of superplasticisers as a function of their dosage is an important step in the design of a UHPFRC formulation. The superplasticiser dosage at saturation (no more noticeable effect on workability after an increase of the dosage) is a key factor. Further, it is worth trying quite soon different superplasticiser available locally, from different brands, to try overcoming workability barriers.

The high superplasticiser dosages in UHPFRC also induce a significant delay of setting (from 12 to 36 hours typically). This can be accepted or overcome by the use of accelerating admixtures if needed.

In most cases, other ways to improve the efficiency of superplasticisers with local cements have to be found to solve compatibility issues. A possible way to overcome this barrier is to replace cement grains by other particles of similar size and morphology but with a mineralogy providing a better compatibility with the plasticizers. Active such as Fly ash, latent active such as ground granulated slag, or inert particles such as quartz powder and limestone filler are good candidates for this.

➔ The action of the superplasticiser is to disperse the fine particles in the fresh mix, by electro static action or steric hindrance for most recent ones (Polycarboxylates). They have an action on cement grains but not on silica fume particles much finer and negatively charged. Thus a positive interaction has to be sought with inert particles with possibly a neutral potential in dispersion, such as limestone fillers. Limestone fillers also chemically react with calcium aluminates in cement pastes to form Afm phases. This contribution is however very small in absolute quantities and can be neglected. Hence, in a first step, limestone fillers can be considered as inert towards the cement.

➔ If cement replacement by inert mineral additions is selected as an option in UHPFRC mixes, the superplasticiser dosage should be considered with respect to the total fines = cement + Inert Filler.. Filler grains should also be dispersed, even if it is easier than for cement grains with mineralogy incompatible with the superplasticiser.

➔ Finally, the action of superplasticisers is limited in time (typically 1 to 3 hours of constant workability) since water addition, and their efficiency depends on the temperature at application. High temperatures (more than 30°C) of the fresh mix should be avoided as far as possible or preliminary validation tests should be performed.

➔ *It is important to mention that the superplasticiser dosage in UHPC matrices is so high (typically total 2 to 4 % mass of cement or fines) that the water contained in this admixture (typically 65 to 70 %) plays a major role in the overall water content (often 10 %). This aspect should not be forgotten for the mix design and preparation of batches.*

3.4 Slope tolerance

The tolerance to a slope of a fresh cementitious material is related to its rheological behaviour. One can distinguish two fundamental rheological parameters:

- The yield stress τ which can be compared to static friction. This is the threshold value for putting the material into motion.
- The dynamic viscosity μ which can be compared to dynamic friction. This is a measure of the effort required to make the material go on moving.

The effect of the yield stress on slope tolerance under the action of gravity is illustrated by Figure 12, from de Larrard (1999). The yield stress opposes the gravity force that tends to make the material move downwards.

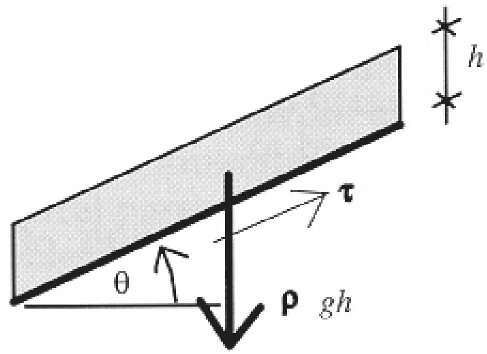

Figure 12: Equilibrium of a fresh material on an inclined substrate, after De Larrard (1999).

Normal concretes with low to no content in superplasticiser (workability classes S1, S2) exhibit a yield stress higher than zero and can support slopes. The value of the yield stress is very well inversely correlated with the Slump value. The larger the slump, the lower the yield stress. The extended addition of super plasticizers decreases significantly the yield stress of concretes. In self compacting concretes, the yield stress is almost zero and slump is maximum and is no more a reliable measure. The “slump flow” test rather uses the final diameter and time to reach 500 mm diameter (t_{500}) as rheological indications. Those are however closely related to the viscosity rather than to the yield value.

Self compacting concretes can be made tolerant to slopes to some extend but the combination of a self compacting character with tolerance to slopes up to 5 % is a very challenging task.

4 APPLICATION

4.1 Mix design

The starting basis was given by the mixes CM22 and CM23 developed for cast on site applications of rehabilitation, validated in the laboratory, and used in a full scale industrial application on a bridge in Switzerland during the SAMARIS project, Denarié et al. (2006a and 2006b).

The same patented fibrous mix of the $CEMTEC_{multiscale}$® family, originally developed at LCPC by Rossi et al. with total 706 kg/m^3 of micro (steel wool) and macro steel fibres 10 mm long, 0.2 mm diameter was used.

Note: $CEMTEC_{multiscale}$® *fibrous mixes are covered by the French patent applications #FR2806403 and #FR2806404 (both published on 9th September 2001) and by the PCT patent application WO0168548 (published on 9th September 2001)*[12].

The steel wool was from the same producer as during the SAMARIS project (GERVOIS – France) but the macrofibres were taken from a different producer (BEKAERT – Belgium or Slovakia) instead of Redaelli Tecna - Italy). Their dimensions were similar but the steel used for the wire had a lower tensile strength of 2000 MPa instead of 3000 MPa, still largely sufficient with respect to the maximum stresses that occur in the fibres at pull-out (in the range of 600 to 800 MPa). The macrofibres are coated with brass for the wire drawing process.

A closer examination of the macrofibres from the two producers shows that the fibres from Redaelli Tecna are slightly torqued along their longitudinal axis due to their cutting process. At the contrary, the BEKAERT fibres are almost perfectly straight.

The tolerance on fibre length and diameter indicated by BEKAERT is around 10 % which could in the worst case lead to variations of the length of 10 % and aspect ratios from 41 to 61, for an expected average of 50. This theoretical variation is quite high and could explain some differences in workability and mechanical performance observed in inter laboratory comparative tests or between different fibre deliveries. From a general point of view however, also validated by large scale batches realized during the full scale application on the Log Čezsoški Bridge in Slovenia, in July 2009, the repeatability of the workability over a large amount of batches was excellent. Further, measurements were done at EPFL and ZAG on samples of macrofibres and no significant variations of geometry with respect to the specified 10/0.2 mm could be observed.

Cements (Salonit Ahnovo – Slovenia and Gorazde - Poland) and Superplasticisers Zementol Zeta Super S® (TKK) for Slovenia and Sika Viscocrete for Poland were used.

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[12] The detailed composition of the fibrous mix is patent protected and is available upon request, with a license of exploitation.

➔ The goal of the works was to find recipes with the same fibrous mix, with comparable properties of Workability, Mechanical Performance and Protective Function ("PMW" requirements) than the SAMARIS mixes, but using to the largest possible extend components available locally in Slovenia or Poland: Cement, Superplasticiser, Quartz Sand and Silica Fume.

➔ A further goal was to improve the slope tolerance of specific mixes for cast on site applications on structures with slopes of 3 to 5 %.

First developments were started in Slovenia. Several attempts were made with Pure CEM I 42. 5 Sulphate resistant and CEM I 52.5 R cement from SALONIT but with unsatisfactory workability despite high superplasticiser dosages. It rapidly turned out that UHPFRC recipes with such high fibre dosages and sufficient workability could not be achieved with local pure CEM I from Slovenia. The same trend was later confirmed for Polish products. Hence another way had to be found.

➔ In this context, the idea emerged (justified by the low degree of hydration of UHPFRC mixes) to break the workability barrier by replacing large quantities of cement grains by other particles of close size and morphology but less detrimental with respect to the interaction with the superplasticiser.

At this stage, limestone fillers appeared as a suitable choice for various reasons:

- Easy availability, cheap
- Good potential interaction with superplasticiser
- Well known positive effect on workability of various types of concretes

Limestone fillers have been indeed used as partial replacement of cement (5 to 20 %) for a long time, Bertrandy et al. (1991). The major advantages of this "quasi inert" mineral addition are the following:

- Improvement of workability
- Improvement of surface rendering of concretes (colour and limitation of air voids)
- Worldwide availability – low cost
- Synergetic use with other industries (road construction, paper, etc.)
- Reduction of CO_2 emissions associated to cementitious binders
- Acceleration of the hydration reaction by nucleation effect

They are currently accepted up to 35 % cement replacement in European standards (EN 197-1). In Switzerland, the majority of cements sold are for some years type II ones including Limestone fillers up to 20 % mass. In Self compacting concretes, Limestone fillers bring a significant improvement of the workability that contributes to the overall concept of the material, El Hilali et al. (2006). Finally, it was also recently proposed (following the principles of “Sand concretes” associated to the concepts of optimum packing density) to use high to very high (up to 50 %) dosages of mineral additions (fly ash and GGBFS) to produce low cost-sustainable binders for concretes with low to moderate compressive strength and high flowability, Su et al. (2003). The durability and drying shrinkage characteristics of those materials are however not clear and should be further investigated.

➔ *To the best of the author knowledge, no works mention yet an application or a concept of combining all advantages of high levels of replacement of cement by limestone filler (50 % - eventually 40 to 65 % mass) to break the "workability barrier" in the formulation of top level self compacting Ultra High Performance Fibre Reinforced Concretes with tensile Strain hardening, made of locally available components (cement, superplasticiser, among others).*

A major advantage of limestone fillers is their worldwide availability in large quantities and the "simplicity" of their chemical composition.

➔ *From there it was decided to investigate the possible replacement of large quantities of the cement used in the existing UHPFRC recipes from the SAMARIS project by limestone fillers.*[13]

Figure 13 presents the sieve analysis of all dry components, except fibres, used in the formulations described in the sequel. Following methods were used: for the quartz sand, standard sieving. For the cements and limestone fillers, laser granulometry under water, for the silica fume: X-Ray monitored gravity sedimentation (liquid). For all components except silica fume and quartz sand, % volume passing is indicated. For silica fume and quartz sand % mass passing is shown.

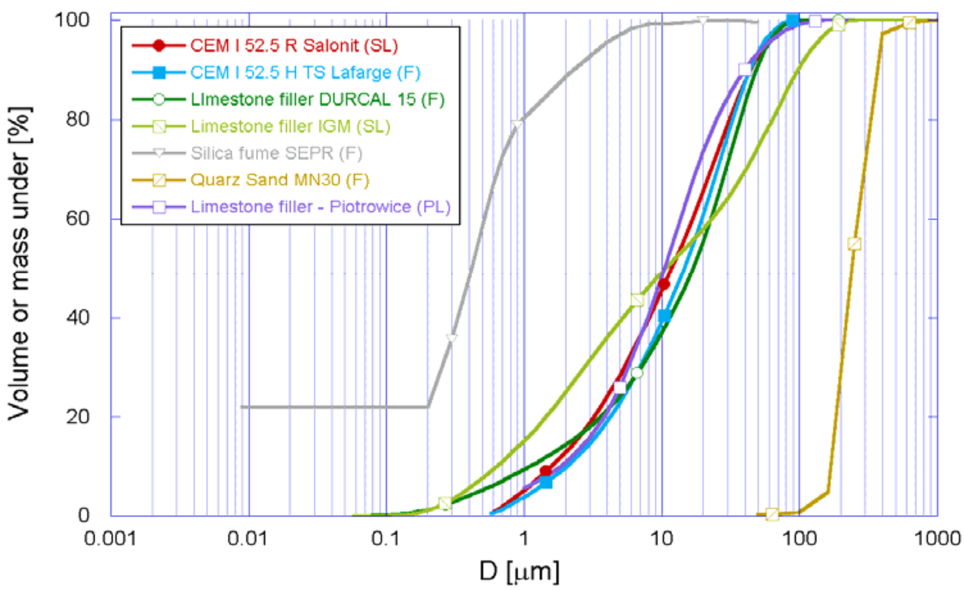


Figure 13: Sieve analysis of dry components except fibres.

[13] Detailed UHPFRC recipes are given in Appendix 5

4.2 Development steps 1 and 2 - Slovenia

4.2.1 Mixes

In a first step a limestone filler of very high quality from OMYA (Durcal 15), with a sieve curve very close to that of the Salonit CEM I 52.5 cement was used to validate the concept of cement replacement at EPFL/MCS. A cement replacement of **50 % in mass** was selected to stay under the level of full hydration of the remaining cement grains: i.e.: the masses of cement and limestone filler in the mix are equal to 745 kg/m^3.

➔ Note that the cement replacement in volume is even higher than 50 %, proportional to the ratio of the specific weights = 50 % *3.12/2.7=58 % vol.

The white silica fume (from SEPR) used for the SAMARIS recipes was used again with a Silicafume/Cement dosage kept constant at **26 % mass** as it already exceeds the theoretical amount of 20 % for which all Portlandite is consumed and the pozzolanic reaction is stopped. This choice means a significant decrease of the absolute silica fume content in the mix from originally 392.8 kg/m^3 down to 193.7kg/m^3, positive from and economical and a rheological point of view and a priori not detrimental for mechanical or protective performances as shown in § 3.3.5.

The amount of paste resp. quartz sand was kept similar to the SAMARIS mix CM23 at 120 litres/m^3, resp**. 80 kg/m^3**.

The superplasticiser dosage was kept at **3.3 %** as in SAMARIS recipe CM23 but with respect to the Fines = Cement + Limestone filler in mass.

Finally, the Water/Fines ratio was equal to the Water/Cement ratio of mix CM23 = **0.155**.

➔ Thus the absolute water contents of the two mixes CM24 with limestone filler and CM23 was more or less equivalent. However, in the mix CM24, the Water/Cement ratio becomes much higher = **0.31.**

Table 1 summarizes the two recipes. Mix CM23 used Lafarge Cement CEM I 52.5 HTS and Superplasticiser Optima 175 from Chryso.

	CM24	CM23
Components	Mass [kg/m^3]	Mass [kg/m^3]
Cement	745.1	1433.7
Silica fume	193.7	372.8
Limestone filler	745.1	
Sand 0.1 - 0.5 mm	80.4	80.4
Water added	199	189.1
Micro + macro fibres	706.5	706.5
Superplasticizer	49.2*	47.3*

Table 1: Comparison of recipes CM23 (SAMARIS basis) and CM24 (new)

➔ The corresponding matrix and UHPFRC had comparable or better performance at fresh state than the CM 23 one and the protective and mechanical functions were also similar or better as will be shown later. Thus the concept of cement replacement was validated[14].

In a second step, it was decided to try using more locally available components. Silica fume is not produced in Slovenia and has to be imported. The grey silicafumes imported in Slovenia gave unsatisfactory results from a workability point of view and it was decided to go on with the SEPR white silica fume from France.

However, Limestone fillers are available in Slovenia and it was decided to try to optimize mixes to use them in the new UHPFRC recipes. After several attempts, the IGM filler from Zagorje with a size distribution close to that of the cement was tried. It has significantly more fine particles (lower than 10 μm) than the Durcal 15 from Omya and thus a higher water demand for similar workability, but also a benefit from the packing density point of view as it can compensate to some extend a decrease of the silica fume content in this range of sizes (0.1 to 10 μm). For the level of performance required (Water/fines ratio of 0.170 maximum), the mixes done with the IGM filler and the same bases as for mix CM24 (SF/C=0.26, SP//(C+LF)=3.3%, Sand=80 kg/m^3) yielded an insufficient workability.

From there, a first attempt was to decrease the macro fibre dosage from 6 to 5 % vol. (Mixes CM27 and CM29). This lead to unsatisfactory mechanical performance (actually, 5 % macrofibres are not sufficient to obtain a strain hardening response – see § 3.2.4 - Figure 8, and Figure 15.

4.2.2 **Test results**

The following properties were checked and compared with the large database of UHPFRC properties available at MCS/EPFL:

- Workability of UHPC matrices with mini slump cone tests[15], and of UHPFRC with slump flow tests.
- Mechanical performance on the basis of flexural tests on small prisms and 4 PT bending plates instrumented, (500 x 200 x 30 mm) representative of the application thickness.
- Protective function by means of air permeability and capillary water absorption tests.
- Delayed response at early age by means of TSTM (Temperature Stress Testing Machine) in free and restrained conditions.

Mixes type CM22/CM23 with Lafarge cement and superplasticiser from Chryso (defined and applied successfully during project SAMARIS) were the target.

14 A patent application was filled by Dr. Denarié and Dr .Y. Houst from EPFL for this concept in July 2009.

15 Detailed description is given in Appendix 1

Three different new mixes were investigated with different fibre macro contents and Water/(Cement + Additions) ratio, as shown in Table 2. All blended mixes had the same limestone filler dosage: LF/C = 1 in mass and contain the same dosage of microfibers (steel wool). Mix CM24 has a superplasticiser dosage of 3.3 %, all others 3.6 % (total= water + dry extract). Mixes CM27 and CM29 have a lower dosage of macrofibres (5 instead of 6 % vol.).

Reference	Water/(Cement+ Filler)	Cement	Limestone Filler	Macrofibres 10/0.2 mm [% Vol.]
CM22	0.165	Lafarge CEM I 52.5 HTS	None	6
CM23	0.155	Lafarge CEM I 52.5 HTS	None	6
CM24	0.155	Salonit CEM I 52.5 R	Durcal 15 (Omya)	6
CM27	0.155	Salonit CEM I 52.5 R	IGM	5
CM29	0.165	Salonit CEM I 52.5 R	IGM	5

Table 2: Mixes: references and investigated materials

The workability barrier encountered when using pure local cements is illustrated on Figure 14. The mini slump cone test is applied to two UHPC matrix mixes. One with pure CEM I 52.5 from Salonit and the other with 50 % Fines mass of the same cement and 50 % of Durcal 15 Limestone filler. Both mixes have similar superplasticiser dosages (2.5 % total mass Cement + Filler) and very close Silicafume dosages (200 or 210 kg/m^3). The results are shown in Table 3.

➔ Case A: impossible to achieve sufficient workability when fibres are added

➔ Case B: excellent workability, comparable to reference UHPFRC mixes with Lafarge cement – perfectly adapted for addition of fibres at high dosages

Figure 14: Mini-slump cone test on UHPC matrices. Comparison of the final spread of two mixes with or without cement replacement by limestone filler.

Mini-slump[16]**:** determination of (1) t_{250} = time to flow at 250 mm diameter, (2) $D_{1,2}$ = diameters when flow is stopped, in two perpendiculars directions, (3) If applicable, s = slump with respect to top of mini-cone.

CASE	Cement [kg/m^3]	Limestone Filler [kg/m^3]	Silica fume (SF) [kg/m^3]	SF/C [---]	t_{250} [s]	$D_{1,2}$ [mm]	$D_{average}$ [mm]	Slump [mm]
A	1614	0	210	0.13	∞	170/170	170	90
B	770	770	200	0.26	9,3	390/410	400	n.a.

Table 3: Mini cone workability test results – influence of cement replacement by limestone filler

Mechanical performance: Figure 15 presents the comparative performances of the reference mix CM23 and several mixes developed with Slovenian cement from Salonit, for the flexural tests on 4 PT bending plates (span: 420 mm)[17].
Materials with only 5 % fibres (CM27 and CM29) cannot achieve the level of performance of the reference mix CM23. However, material CM24 with 6 % fibres achieves an equivalent level of performance with respect to mix CM23. It is worth mentioning that there is no significant difference between the performances of mixes CM27 and CM29. As a consequence,

16 Detailed reference is given in Annex 1.

17 Test set-up described in Appendix 2.

the major factor of influence on the flexural response appears to be the fibre dosage rather than the Water/(Cement + Filler) ratio, between 0.155 and 0. 165.

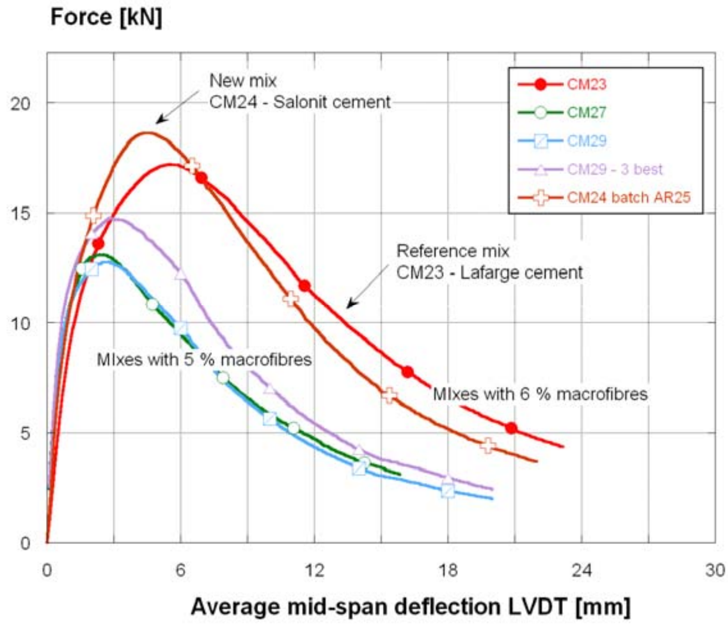


Figure 15: Comparative results of flexural tests on plates, average curves.

Protective function: Table 4 shows the comparative results of capillary absorption and air permeability tests (average values) for the various types of UHPFRC investigated and for usual concretes as a reference point. All mixes developed with Slovenian cement and Superplasticiser (CM24, 27, 29) are clearly in the range of very low air permeability and capillary water absorption. Their long term protective function is granted.

Reference	Air permeability $[10^{-16}\ m^2]$	Capillary water absorption coefficient $[g/m^2.h^{0.5}]$
Bad concrete	2	1200
Good concrete	0.03	400
CM23	0.003	45 (EPFL meas.)
CM24	0.008	53 (EPFL meas.)
CM27	n.a	23 (ZAG meas.)
CM29	n.a	23 (ZAG meas.)

Table 4: **Comparative transport properties (average values).**

Delayed response at early age: Figure 16 shows the development of stresses at early age in a partially restrained testing set-up (TSTM - degree of restraint: 50 % - stroke control) for two materials: reference mix CM22 with Lafarge cement and mix CM29 with Salonit CEM I 52.5. Time 0 is 2 hours after contact between water and binders. Mix CM29 has lower induced stresses at early age, which is fully beneficial for the application in composite UHPFRC concrete construction.

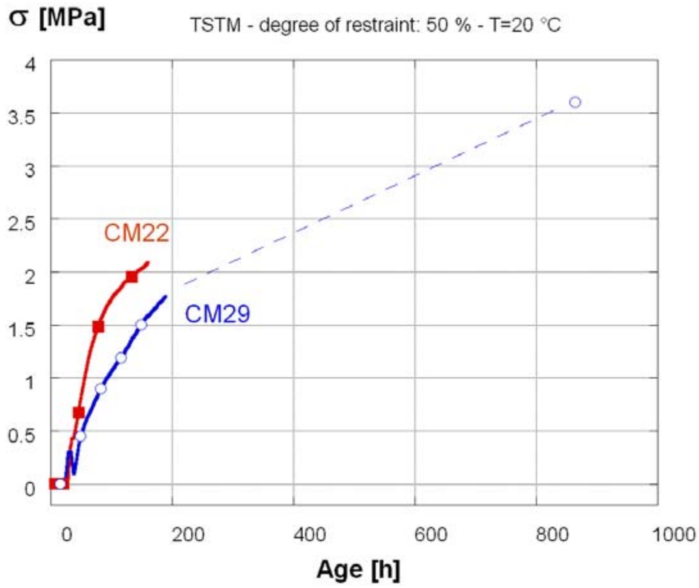


Figure 16: Comparative results of restrained shrinkage tests at early age.

4.3 Development steps 3 and 4 - Slovenia and Poland

4.3.1 Mixes

In a further step, in agreement with the concepts described in § 3.3, several remaining degrees of freedom in the matrix recipe were mobilized successfully to achieve a new family of recipes in Slovenia, (CM32) with a good workability with the intended fibrous mix and a Water/Fines ratio of 0.170 that lead to satisfactory mechanical and protective properties similar to material CM22 used in the SAMARIS project but with superplasticiser from TKK as CM22_TKK for reference.

- First of all, the paste content was maximized and all remaining sand was removed. This is welcome from a practical point of view as quartz sand is expensive and it represents one more component to deal with on sites. Further, the limestone filler plays the role of inert inclusion in a dominant way in the mix. Thus the need of aggregates such as quartz sand becomes questionable in such blended binders UHPFRC..
- Secondly, the superplasticiser dosage was further increased to 3.6 % mass of the fines = Cement + Limestone filler.

- Finally, the Silicafume/Cement dosage was reduced to 20 % instead of 26 %.

The obtained recipe type CM32 responds to the goal of maximizing the use of local components.

In a final step, the recipe CM32 was modified (CM32_10) to accommodate slopes of 5 % by means of the addition of a thixotropizing admixture (SIKA Extender - short polyethylene fibres in form of a white powder) normally used in industrial floors with resins.

4.3.2 Test results

The effect of the addition of a thixotropizing admixture (SIKA Extender) was tested on pure UHPC matrices at EPFL with mini cone workability measurements. Mix CM32M_04 gives the basic requirements for a non slope tolerant mix. At 0.2 % addition, no change is noticed. However between 0.3 and 0.4 % and further to 0.5 % the change is very important. The optimum dosage of the admixture for the UHPFRC recipe is thus likely to be in this range.

Material	Thixotropizing admixture [% mass C+LF]	t250 [s]	Final diameter [mm]
CM32M_04	0	6.5	380
CM32M_05	0.2	6.4	380
CM32M_06	0.4	20	300
CM32M_07	0.5	34	280

Table 5: Effect of thixotropizer Sika Extender on Mini cone workability.

On this basis, slope tolerant UHPFRC mixes were developed at EPFL and validated. Similar mixes with Slovenian components were tested in the laboratory at EPFL and ZAG and showed a tolerance to slopes of 3 % (MCS-EPFL) and 3 up to 5 % (ZAG). On the same basis, a slope tolerant UHPFRC mix based on Polish cement and Limestone Filler was also developed and validated at EPFL. The following table summarizes the recipes used. All mixes had 9 % steel fibres including micro and macro fibres and used CEM I 52.5 R cements blended with limestone filler (Slovenia: Salonit and Poland: Gorazde). French SEPR Silica fume, no quartz sand.

The sieve curve of the Polish filler (Piotrowice) was very close to that of the cement used and thus the water demand of the mix was significantly lower than for Slovenia mixes for similar workability. This made the determination of a slope tolerant mix more difficult and after several trials with a superplasticiser available in Poland (Sika Viscocrete) required: (1) to come back to the TKK superplasticiser, and (2) to comeback to a Silicafume/Cement dosage of 26 % to further thixotropize the mix.

Reference	Water/(Cement+ Filler)	Cement	Silicafume/Cement [mass]	Thixotropizing addition
CM32_10	0.170	Salonit	0.20	0.5 %
CM32_11	0.170	Salonit	0.20	No
CM33_9	0.160	Gorazde	0.26	0.5 %

Table 6: Mixes: references and investigated materials.

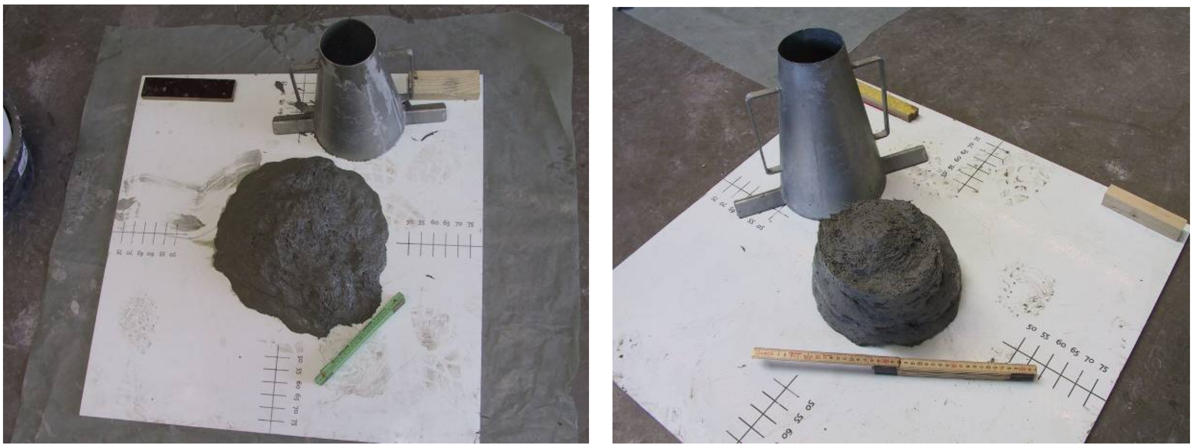
The following example shows how a UHPFRC type CM32 is modified with a thixotropizing addition to make it tolerant to a slope of 3 %. An unconfined slope tolerance test developed at EPFL/MCS is performed. The material is first poured in a wood frame applied on an inclined rough support. The frame is then carefully removed and the behaviour of the fresh UHPFRC is observed.

Figure 17 a), without the addition, the material flows and the 30 mm thickness of the UHPFRC layer cannot be preserved. At the contrary, Figure 17b), with the thyxotropizing addition, the material remains in place and the thickness of 30 mm is preserved.

a) b)

Figure 17: Unconfined slope tolerance test, imposed slope = 3 %, a) CM32_11 without thyxotropizing addition, b) CM32_10 with (tests at EPFL/MCS).

A closely related trend is observed on companion slump tests realized on the same two mixes Figure 18 a). For the UHPFRC without the Thixotropizing addition, the slump test leads to a collapsed block with no distinct shape. Only the very high fibre content prevents further spread of the fresh material. Figure 18 b) at the contrary, with Thixotropizing addition, the slump tests shows a typical “tower” shape, which is characteristic of a material with a significant yield value, able to sustain slopes such as normal concretes.



a) b)

Figure 18: Slump tests without (CM32_11) (a) or (b) with (CM32_10) thyxotropizing addition (EPFL/MCS).

Similar tests were performed at ZAG on identical recipes and gave comparable results with even a slope tolerance of 5 % for mix CM32_10.

a) b)

Figure 19: Unconfined slope tolerance test, imposed slope = 5 %, a) CM32_11 without Thixotropizing addition, b) CM32_10 with (tests at ZAG).

Table 7 summarizes the results of the slump tests (EPFL/MCS + ZAG) - one hour after contact water/binders – temperatures: fresh mix = 30 °C, air: 22 °C (EPFL).

Mix	Slump [mm]	Final diameters [mm]
CM32_10 with Thixotropizing addition	120 (EPFL) 175 (ZAG)	240/250 (EPFL) 250/370 (ZAG)
CM32_11 without Thixotropizing addition	175 (EPFL)	370/420 (EPFL) 390/420 (ZAG)

Table 7: Results from slump tests at ZAG and EPFL

In small scale laboratory tests (batches of around 25 litres) the thixotropic character of the mixes type CM32_10 was clear. However, their workability is no more in the range of self-compacting concretes. On the basis of previous experiences in SAMARIS project with closely related materials, it was expected that for larger scale batches, the workability should be significantly improved, with the same thixotropic properties.

Further, given the stiffer character of the fresh thixotropic UHPFRC mixes, the bond to the substrate might be a concern. Pull-off tests performed at ZAG clearly demonstrated that this was not the case and that the slope tolerant mixes CM32_10 had excellent bond properties to the concrete substrate.

Trial tests were performed at the Salonit plant in October 2008 to verify and optimize in full scale the ability of the new CM32 recipes to accommodate slopes of 3 to 5 %. The test were successful and 900 litres of the new material CM32_13, with only 0.3 % Thixotropizing addition were applied from a concrete truck on two inclined test surfaces of 10 m^2 with 3 and 5 % slopes in the plant. The losses in the truck were extremely small (around 50 litres). Figure 20 shows the production and application of the UHPFRC.

Figure 20: Full scale field trial, Salonit plant, Slovenia, October 2008.

Mechanical performance on the basis of flexural tests on small prisms and instrumented 4 PT bending plates (500 x 200 x 30 mm), representative of the application thickness, and protective function by means of air permeability and capillary water absorption tests were also investigated for those recipes, both at EPFL and ZAG and compared to the target values. All results are within the expected limits and no significant detrimental influence of the thixotropizing addition could be observed, as shown on Figure 21.

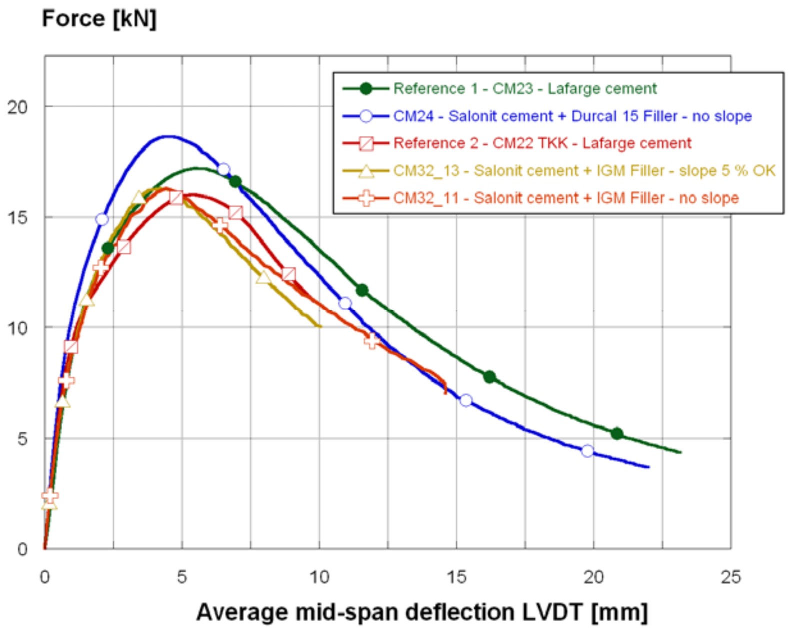


Figure 21: Comparative results of flexural tests on plates, average curves.

The degree of hydration of three UHPFRC: CM22 (Lafarge CEM I 52.5 HTS cement – no limestone filler) and CM32_13 (with thixotropizing addition) and CM32_11 (without thixotropizing addition) with SALONIT CEM I 52.5 cement and IGM Slovenian limestone filler, have been determined my means of image analysis of Scanning Electron Microscope (SEM) images, Stutzmann (1991), Scrivener (2004).

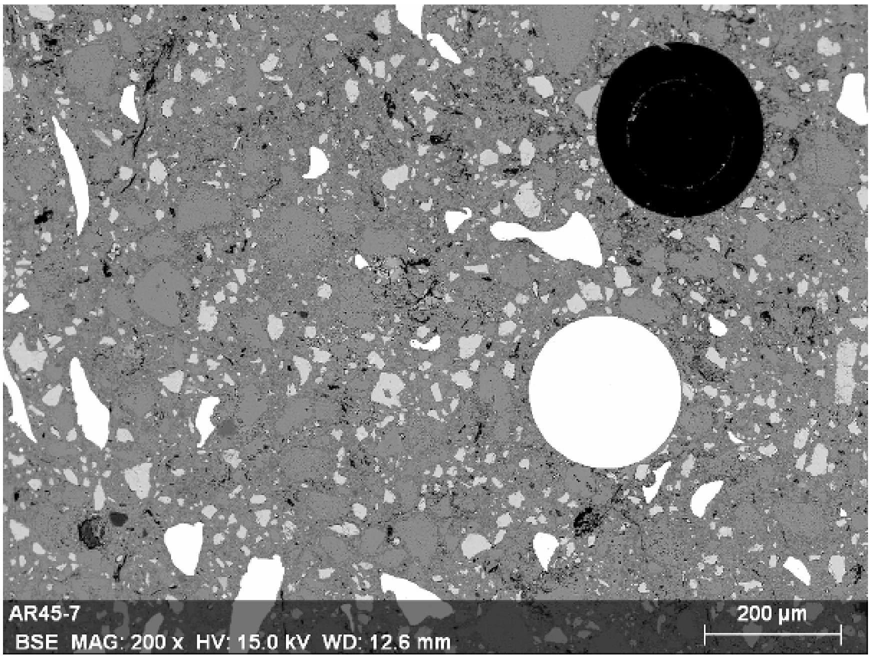
The samples were taken in 500/200/30 mm plates moist cured for 28 days at 20 °C and stored in the testing facilities until an age of 3 month at 60 % RH and 20°C.

The detailed results are given in Appendix 9. On Figure 22a) one can clearly distinguish the medium grey limestone filler and the small amount of unhydrated cement particles (light grey). On image b) the large quantity of unhydrated cement grains (light grey) is obvious.

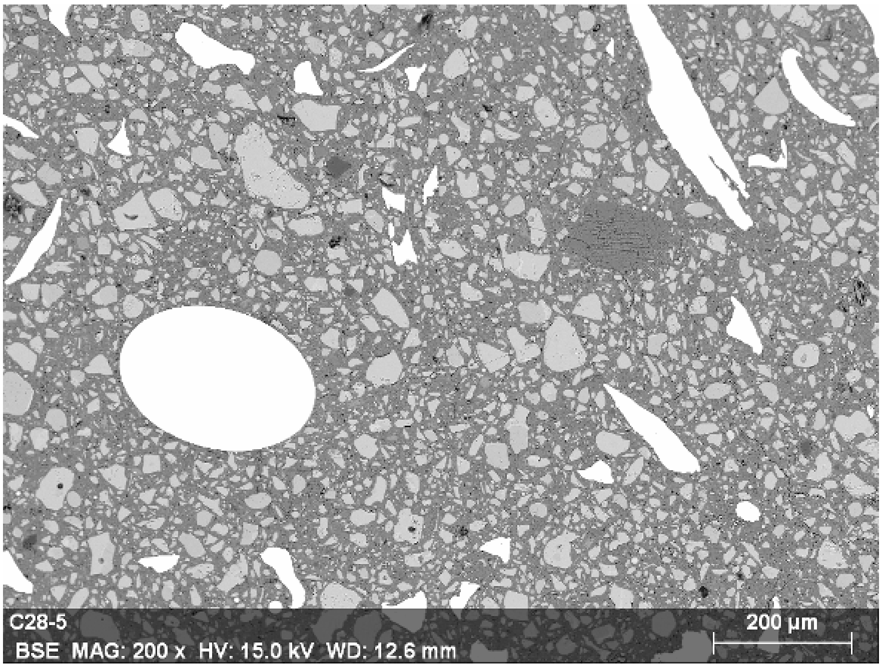
The degrees of hydration of cement determined by this method are:

- CM 22_TKK : **42.1 % ± 5.7**
- CM32_13 : **57.7 % ± 6**
- CM32_11 : **60.6 % ± 6.7**

As expected, the mixes with limestone filler have a much higher degree of hydration, of cement, close to 60 %. Comparatively, the model from Jensen et Hansen (2001) gives for such a recipe (W/(C+LF) =0.17 - LF/C=1 - W/C=0.34 and SF/C=0.2) a degree of hydration of **0.61** in a closed system and 0.75 in an open one. This is close to the measured values.



a)



b)

Figure 22: SEM images of UHPFRC after 3 month age: a) mix CM32_13 with 50 % cement replacement by limestone filler; b) mix CM22_TKK with 100 % cement, shown at same scale. White circles or ellipses are macro steel fibres. White irregular shapes are micro steel fibres. Black circle is an air bubble.

5 CONCLUSIONS

- A methodology was proposed, validated and applied to develop local UHPFRC mixes from Slovenia and Poland, with a very large cement replacement by limestone filler.
- Following this concept, the effective water/cement ratio of the mix is significantly increased and the degree of hydration at the same age too, without affecting the UHPFRC performance. The limestone fillers grains just replace unhydrated cement, with a dramatic improvement of workability, thus allowing the realization of UHPFRC well suited for cast insitu applications of rehabilitation, with virtually any locally available cement and superplasticiser.
- This concept also significantly reduces the monetary and environmental cost of UHPFRC, by decreasing to a large extend their cement content.

The final outcomes of those R&D works are for Slovenia recipes CM32_11 and CM32_13 and for Poland recipe CM33_9 with following properties:

Self compacting character, mechanical and protective properties equivalent to the mixes developed during the SAMARIS project.

- Recipe CM32_11 has limited slope tolerance but can be used to fill formworks with limited space.
- Recipe CM32_13 has a slope tolerance of at least 5 % but should be used only to fill open formworks of limited height (200 mm max.) and with sufficient space (30 to 35 mm minimum) if it is needed to avoid longitudinal casting joints between kerbs and bridge decks for example.
- Recipe CM33_9 has a slope tolerance of at least 3 %. This mix was validated in the laboratory on small scale batches (25 litres) and should be further optimized on larger scale trial tests.
- Both Slovenian recipes were used successfully at an industrial scale (total 15 m^3 produced) during the first application of UHPFRC in Slovenia, for the rehabilitation of the Log Čezsoški bridge in July 2009.
- Finally all recipes satisfy the original requirements of using to the largest possible extend local products and have a potential to be further improved.

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List of Figures

List of Tables

APPENDIX 1 – MINI CONE TEST

Figure 23 shows the test set-up and dimensions of the cone. The selected geometry was inspired form the one used by Roussel et al. (2003). A circle of 250 mm diameter is drawn on the test plate, centred on the location of the cone, in the middle of the plate.

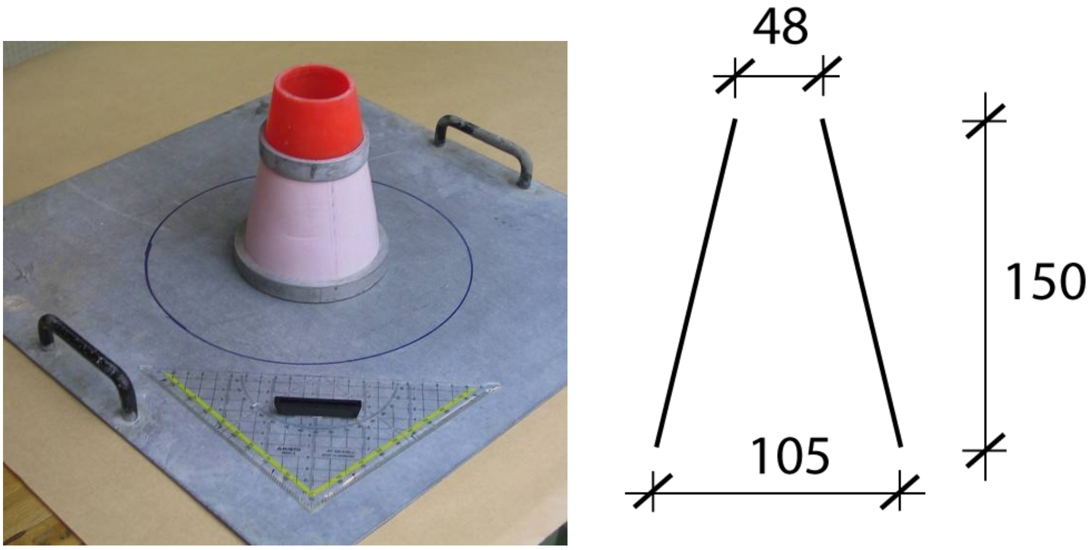


Figure 23: Mini cone test set-up and geometry (dimensions in mm).

<u>Procedure:</u>

- The plate and inner face of the cone are pre-wetted.
- The material is poured into the cone, pressed tightly on the plate to avoid any leakage of the fresh material between the base of the cone and the plate.
- The cone is lifted vertically within a few seconds. As soon as the lifting of the cone begins, a chronometer is started and stopped when the flowing material reaches the circle indicating a diameter of 250 mm marked on the plate.
- After the flow has stopped; the final diameter of the material disk is recorded in two perpendicular directions.

<u>Test results:</u>

(1) t_{250} = time to flow at 250 mm diameter in seconds, precise to one tenth.

(2) $D_{1,2}$ = diameters when flow is stopped, in two perpendiculars directions in mm,

(3) If applicable, s = slump with respect to top of mini-cone in mm.

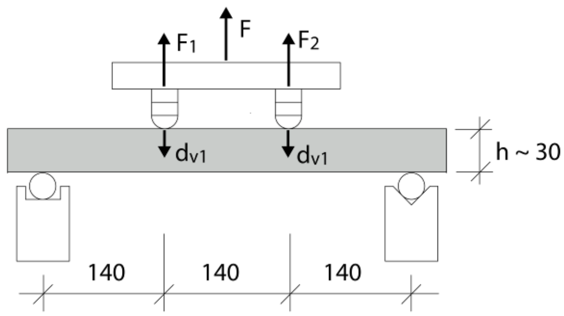
(4) Time at which the measurement is started with respect to the time of water addition into the mixer, t_{meas}.

(5) Ambiant temperature Text °C, and (6) temperature of the fresh material tested Tmix °C.

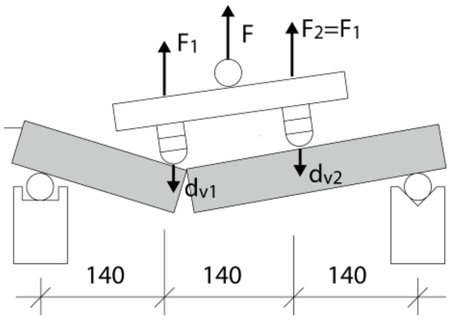
Interpretation of results:

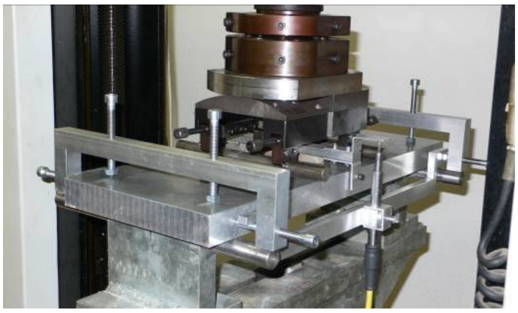
- The final diameter is representative of the flowing ability of the mix (slump flow for self compacting concretes).
- The time to reach 250 mm is closely linked to the dynamic viscosity of the mix and follows a similar approach than the T_{500} for slump flow tests on self compacting concretes.
- The combination of those two values gives a rheological characterization of the mix.

APPENDIX 2 – FLEXURAL TEST



Set-up at MCS – no hinge on the loading platen





Set-up at ZAG with multiple hinges

Figure 24: Flexural tests set-ups for 4 PT bending test on thin rectangular plates (dimensions in mm).

The flexural tests were performed at EPFL on a universal Walter & Bai testing machine with a capacity of 200 kN and at ZAG on a Zwick testing machine.

The specimens are unnotched plates of 500 mm length, 200 mm width, with a thickness of 30 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.

The plates are tested with upper casting face subjected to tension (lower face – positive moment) + surfacing to provide even surfaces for the supports. Thin Lead strips (2 mm thick, 30 mm wide) under load application points were used at MCS-EPFL.

Companion characterization tests are performed on standard 40/40/160 mm specimens, in 3 PT bending, with a span of 108 mm, and compression on the remaining halves of the specimens after the flexural test.

APPENDIX 3 – AIR PERMEABILIY TESTS

Torrent et al. (1992), (1995) proposed the Torrent Permeability Tester – TPT, described in Figure 25. This two-chamber device has been validated and used extensively for more than 10 years in Switzerland and other countries. Its application is recommended and described in the most recent Swiss codes for reinforced concrete structures, SIA 262 (2003), SIA 262/1 (2003). Its main advantages are its fully non-destructive character and its ease of operation. The two-chamber design of the permeability cell guarantees an air-intake perpendicular to the concrete surface in the zone of the central chamber. The air permeability index *kT* is calculated automatically by the device, according to the model from Torrent et al. (1995), on the basis of the air flow in the inner chamber, where the pressure measurements are made. The standard duration of a test is 12 minutes. The effect of the degree of moisture saturation of moist concretes is taken into consideration by the subsequent measurement of the electrical resistivity ρ according to Wenner, in the same zone. The very low moisture content of UHPFRC exempts from determining the electrical resistivity and the classification can be done on the basis of the air permeability.

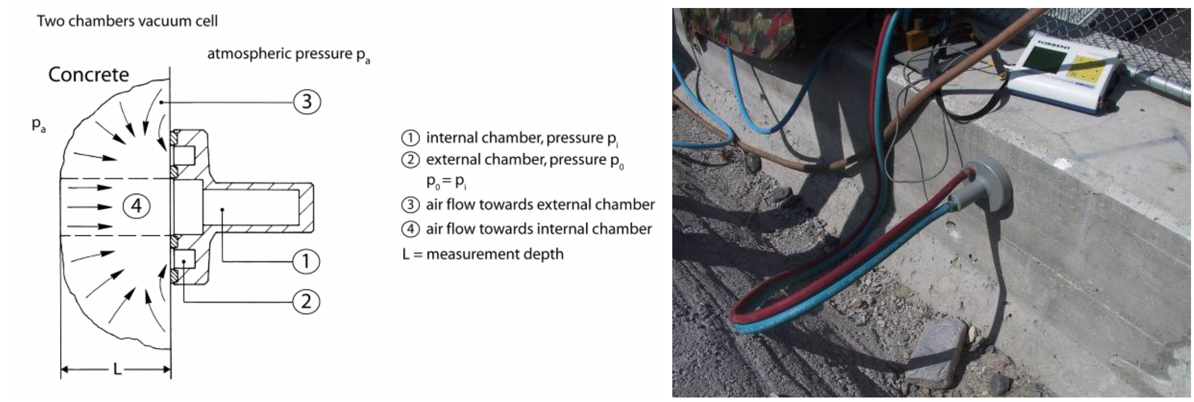


Figure 25: Torrent air permeability tester.

Figure 26 shows the permeability classes and a comparison of the air permeabilities of UHPFRC and two types of concretes. The UHPFRC cast in the laboratory and on site, SAMARIS D22 (2005), exhibit excellent protective properties with a very low permeability.

Following recommendations can be made for the application of the air permeability tests to UHPFRC:

- Careful preparation of set-up (30 minutes under vacuum) + several calibrations on steel plate.
- Target value of air permeability after Torrent at least 7 days: 0.020 10^{-16} m^2 for 65 % fractile, for outstanding protective function.
- Minimum number of measurements on different locations on same element: 6. If only one is not OK on 6: the measured area complies. If more than one are not OK: 6 other measurements on other locations. If only one is not OK; the measured area complies, otherwise, not.

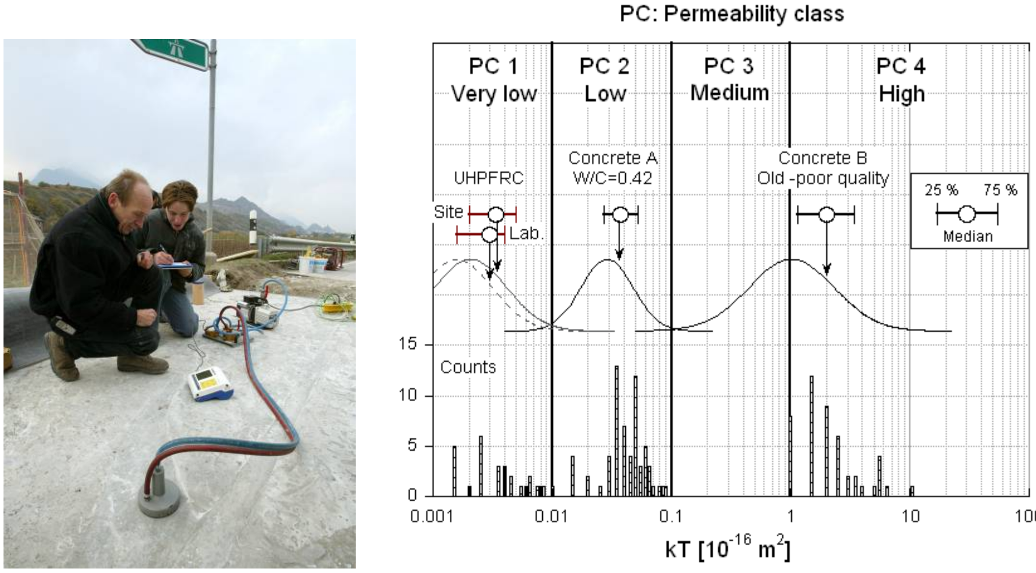


Figure 26: Air permeability measurements on a UHPFRC overlay cast on site and results

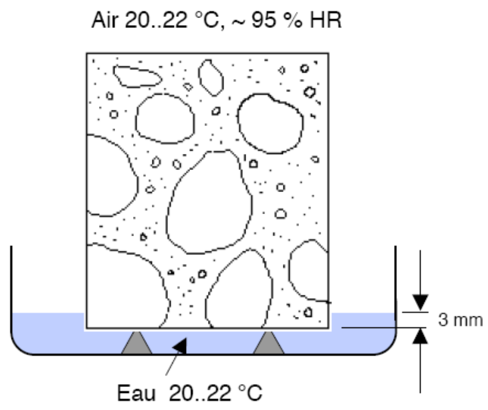
APPENDIX 4 – WATER CAPILLARY ABSORPTION + TOTAL POROSITY UNDER VACUUM

Absorption capillaire: principe

- Les échantillons sont séchés à l'étuve durant 48 heures à la température de 50 °C, puis entreposés à l'atmosphère du laboratoire pendant au moins 12 heures.
- Le fond est immergé sur une profondeur de 3 mm
- L'absorption est déterminée par pesées successives au cours du temps

Remarques:

- Selon la norme SIA, 5 échantillons sont requis pour cet essai
- Sur la base de ces mesures, on peut calculer la porosité, les masses volumiques apparentes et absolues, le coefficients d'absorption capillaire selon DIN 52617, la porosité selon SIA 162/1-7 et la perméabilité à l'eau selon SIA 262/1.



Absorption capillaire: interprétation des mesures selon DIN 52617

- La détermination du coefficient d'absorption capillaire α correspond à l'essai décrit par la norme DIN 52617.
- La masse d'eau absorbée est proportionnelle à la racine du temps selon la loi:

$$m_{(t)} = \alpha \cdot S \cdot \sqrt{t}$$

avec: $m_{(t)}$: masse d'eau absorbée
α: coefficient d'absorption en gr/m2.√h
S: Surface en contact avec l'eau

- Le coefficient est calculé avec l'eau absorbée entre 1 et 24 heures pour obtenir de meilleures valeurs comparatives car l'absorption entre 0 et 1 heure est très variable.
- La norme ne fixe pas d'exigences pour le béton.

Selon l'expérience du LMC, l'échelle des valeurs suivante peut être proposée (le point blanc représente la valeur du coefficient α à 24 heures déterminé par les essais):

31 200	400	600	800	1000	1200	1400	1600	1800
○								
très faible	faible		moyenne		forte		très forte	

APPENDIX 5 – UHPFRC RECIPES

Note: The UHPFRC recipes used in this study belong to the family CEMTEC$_{multiscale}$® developed by Dr. P. Rossi – LCPC Paris, and modified at MCS-EPFL for the application to rehabilitation. CEMTEC$_{multiscale}$® *fibrous mixes are covered by the French patent applications #FR2806403 and #FR2806404 (both published on 9th September 2001) and by the PCT patent application WO0168548 (published on 9th September 2001).*[18]

The concept of UHPFRC matrices with cement replacement by limestone filler at high dosages, developed at MCS/EPFL during the project and applied to Slovene and Polish components is currently in the process of being patented by Dr. E. Denarié and Dr. Y. Houst (EPFL).

UHPFRC CM24 (fibrous mix type CEMTEC$_{multiscale}$®)

➔ Original mix used for the validation of the concept – no slope tolerance

Components	Origin	Mass [kg/m^3]
Cement	CEM I 52.5 R – SALONIT Anhovo (SL)	745.1
Silica fume	Silice thermique SEPR (F)	193.7
Limestone filler	Durcal 15 – Omya (F)	745.1
Sand 0.1 - 0.5 mm	Fontainebleau MN 30 (France)	80.4
Water added		199
Micro + macro fibres	Steel wool (Gervois) + OL 10/20 (BEKAERT)	706.5
Superplasticiser	Zementol Super S - TKK (SL)	49.2*

*: total= liquid + dry extract

18 The detailed composition of the fibrous mix is patent protected and is available upon request, with a license of exploitation.

UHPFRC CM32_11 (fibrous mix type $CEMTEC_{multiscale}$®)

➔ Final mix with Slovenian cement, Filler and Superplasticiser, no slope tolerance, for casting horizontal surfaces or vertical faces in formworks.

Components	Origin	Mass [kg/m^3]
Cement	CEM I 52.5 R – SALONIT Anhovo (SL)	766.6
Silica fume	Silice thermique SEPR (F)	153.3
Limestone filler	“Fine” IGM – Zagorje (SL)	766.6
Water added		224.8
Micro + macro fibres	Steel wool (Gervois) + OL 10/20 (BEKAERT)	706.5
Superplasticiser	Zementol Super S - TKK (SL)	55.2*

*: total= liquid + dry extract

UHPFRC CM32_13 (fibrous mix type $CEMTEC_{multiscale}$®)

➔ Final mix with Slovenian cement, Filler and Superplasticiser, thixotropic, slope tolerance to 5 % +.

Components	Origin	Mass [kg/m^3]
Cement	CEM I 52.5 R – SALONIT Anhovo (SL)	762.5
Silica fume	Silice thermique SEPR (F)	152.5
Limestone filler	“Fine” IGM – Zagorje (SL)	762.5
Water added		223.6
Micro + macro fibres	Steel wool (Gervois) + OL 10/20 (BEKAERT)	706.5
Thyxotropizing admixture	Sika Extender T	4.6
Superplasticiser	Zementol Super S - TKK (SL)	54.9*

*: total= liquid + dry extract

UHPFRC CM33_9 (fibrous mix type $\text{CEMTEC}_{\text{multiscale}}$®)

➔ Final mix with Polish cement, Filler and Slovenian Superplasticiser, slope tolerance up to 3 % proven

Components	Origin	Mass [kg/m^3]
Cement	CEM I 52.5 R – Gorazde (PL)	756.7
Silica fume	Silice thermique SEPR (F)	196.8
Limestone filler	Piotrowice (PL)	756.7
Water added		206.7
Micro + macro fibres	Steel wool (Gervois) + OL 10/20 (BEKAERT)	706.5
Thyxotropizing admixture	Sika Extender T	7.6
Superplasticiser	Zementol Super S - TKK (SL)	54.5*

*: total= liquid + dry extract

Reference mixes for comparison of properties

UHPFRC CM23 (fibrous mix type $\text{CEMTEC}_{\text{multiscale}}$®)

➔ Mix applied on the Bridge over river La Morge, Switzerland, 2004 - SAMARIS project

Components	Origin	Mass [kg/m^3]
Cement	CEM I 52.5N HTS – Le Teil - Lafarge (F)	1433.7
Silica fume	Silice thermique SEPR (F)	372.8
Sand 0.1 - 0.5 mm	Fontainebleau MN 30 (France)	80.4
Water added		189.1
Micro + macro fibres	Steel wool (Gervois - F) + Tecnafibres 10/20 – (Redaelli tecna - I)	706.5
Superplasticiser	Chrysofluid Optima 175 (F)	47.3*

*: total= liquid + dry extract

UHPFRC CM22_TKK (fibrous mix type $\text{CEMTEC}_{\text{multiscale}}$®)

➔ Mix derived from mix CM22 applied on the Bridge over river La Morge, Switzerland, 2004 - SAMARIS project, modified with Slovenian superplasticiser from TKK (originally Chrysofluid Optima 175) and fibres OL 10/20 from Bekaert (originally Redaelli Tecna 10/20).

Components	Origin	Mass [kg/m^3]
Cement	CEM I 52.5N HTS – Le Teil - Lafarge (F)	1392.4
Silica fume	Silice thermique SEPR (F)	362.0
Sand 0.1 - 0.5 mm	Fontainebleau MN 30 (France)	80.4
Water added		204.3
Micro + macro fibres	Steel wool (Gervois - F) + OL 10/20 (BEKAERT)	706.5
Superplasticiser	Zementol Super S - TKK (SL)	34.8*

*: total= liquid + dry extract

APPENDIX 6 - MATERIALS AND SUPPLIERS

Component	Type	Supplier
Cement	CEM I 52.5 R	SALONIT ANHOVO Anhovo, Vojkova 1 SI-5210 Deskle, Slovenija **Mrs Lojzka Reščič** **lojzka.rescic@salonit.si**
Limestone filler	IGM fine (Mean diameter 13 µm)	IGM Zagorje - industrija gradbenega materiala, d.o.o. Savska cesta 1 1410 Zagorje ob Savi - Slovenia **tajnistvo@igm.si**
Microsilica	SEPR (mean diameter 0.5 µm) Specific surface 12 m^2/g, SiO2 > 93.5 %, white	SEPR, B.P. 40, F-84131 Le Pontet Cedex, France **Mr J.M. Detalle** **jean-marie.detalle@saint-gobain.com**
Steel fibres	Straight l_f=10 mm, d_f=0.2 mm Type OL 10/20	NV Bekaert SA, Bekaertstraat 2 B-8550 Zwevegem **Mrs C. Deprez** **Catherine.Deprez@bekaert.com**
Steel wool	Crushed steel wool . ref. FbGV2 Code LALACD.BR	Gervois, 1, rue Boucher de Perthes, F-80580 Pont-Remy, France, **Mr. Riquiez or Mrs Pallier** **gervois01@hexanet.fr**
Superplasticiser	Zementol Zeta Super S®	TKK , Srpenica 1 5224 Srpenica – Slovenia **Mrs L. Cernilogar** **l.cernilogar@tkk.si**
Thixotropizing admixture	Sika Extender (Sika Stellmittel)	SIKA SISTEMI ZA LEPLJENJE IN TESNENJE D.O.O. Prevale 13 - 1236 Trzin - Slovenia **info@si.sika.com**

APPENDIX 7 - PRECAUTIONS FOR THE PRODUCTION AND USE OF CEMTEC$_{MULTISCALE}$®

- The compatibility between the cement, the superplasticiser and the silica fume to achieve the target values of workability, mechanical performances and protective function should be tested on small scale batches before realising larger batches.
- The concrete mixer can be cautiously pre-wetted before the filling with the raw components of the UHPFRC.
- The barrel of the concrete truck should not be pre-wetted before the filling with the fresh UHPFRC.
- Safety precautions to be followed are identical to those prescribed for the production of normal concretes with silica fume.
- During all steps of the production and casting of the UHPFRC and after its hardening, special care has to be taken to protect the skin and eyes of the personal from injury by protruding short steel fibres (10 mm long). During the handling of 10 mm long short steel fibres, during the mixing and pouring of the UHPFRC, and during the cleaning of the batching equipments (mixer, etc.) and of the moulds and forms when the UHPFRC has hardened, it is mandatory to protect the eyes of the operators with fully covering glasses from accidental projection of fibres in the face. Further, the aspect ratio of the 10 mm long steel fibres makes them especially prone to penetrate under the skin. For this reason, the use of thick protection gloves is mandatory during all steps of the production process of UHPFRC.
- The duration of mixing of the 10 mm long steel fibres has to be, according to the performances of the mixer, sufficient to insure a uniform dispersion of the fibres in the UHPFRC, but short enough in order to avoid the formation of agglomerates of fibres.
- The presence of protruding steel fibres on the surface can constitute a danger during the handling of hardened UHPFRC specimens (for the personal and for the lifting equipments such as slings). Hardened UHPFRC specimens shall be cautiously examined before manipulation.
- Free surfaces of fresh UHPFRC shall be protected from desiccation as soon as possible. Due to its extremely low W/B ratio, and to the small thickness of the layers applied for rehabilitation applications, UHPFRC overlays are very sensitive to desiccation. A plastic foil shall be applied on the fresh UHPFRC as soon as possible after casting. A moist curing (daily spraying of water) of 8 days shall then be applied as soon as the material is hardened (around 30 hours after contact between binders and water for the UHPFRC recipes described in this report).

APPENDIX 8 - BATCHING SEQUENCE OF CEMTEC$_{MULTISCALE}$® RECIPES TYPE CM32 AND CM33

- Add cement, microsilica, steel wool and thixotropizing admixture (if applicable) in dry mixer.
- Mix for 2 minutes, then stop mixer.
- Add limestone filler and mix for one minute then stop mixer.
- Add fine quartz sand if applicable and mix for 30 seconds.
- Add all water followed by all superplasticiser while mixer runs.
- Let mixer run until getting a homogeneous mix, with fluid consistency (duration around 8 minutes for mixes type CM32 or CM33, depending on mixer type).
- If the mixer has to be stopped for feeding, add half the quantity of short steel fibres (10 mm).
- Mix for 30 seconds until all fibres are properly coated and dispersed.
- Stop mixer and add second half of the fibres.
- Otherwise (preferably) add fibres continuously while mixers turns
- Mix until all fibres are properly coated and dispersed.
- Total mixing time around 12 minutes.

Note: the first batch, in a dry mixer, always shows a stiffer consistency than subsequent batches with the same UHPFRC. One can cautiously pre-wet the mixer before the first batch, to avoid this effect.

APPENDIX 9 – DEGREE OF HYDRATION BY SEM

SEM = Scanning Electron Microscopy

Methodology: The investigated samples are extracted from UHPFRC specimens. Every sample is cut, pre-polished, impregnated in epoxy resin and polished with diamond suspensions until a roughness lower than 50 μm is achieved. Once polished, more than 150 randomly selected images, without overlapping, are taken by means of backscattered Scanning Electron Microscopy with a resolution of 300 nanometres. The unreacted cement in the samples is determined by image analysis. The degrees of hydration were calculated from those measurement results and the original UHPFRC formulations.

Two calculation approaches were followed

- The first one considers the global UHPFRC formulation: the raw unhydrated cement content determined by image analysis is linked to the initial volumetric dosage in the recipe.

- The second one only considers the hydraulic binder fraction: the unhydrated cement dosage is linked to the paste content (excluding aggregates and steel fibres).

The two methods deliver similar results although the first one is slightly less accurate (higher standard deviation due to anisotropic orientation of fibres in the investigated cross sections).

Nb. The standard deviations correspond to the statistical dispersion of the measurements for each field and not to the uncertainty of the method (< 1%)

Results

Sample	C28-5 *	AR45-7	AR47-9
Material	CM22_TKK	CM32_13	CM32_11
Fields analysed	248	135	132
Corresp. surface. (mm^2)	26.29	14.31	13.99
vol% $_{aggregates}$	2.96 ± 5.86	0.89 ± 6.29	-
vol% $_{cement}$	27.71 ± 4.06	11.01 ± 1.64	10.29 ± 1.69
vol% $_{fibres}$	9.99 ± 12.23	8.34 ± 10.98	10.95 ± 12.09

degree of hydration			
method 1 (%)	40.38 ± 8.74	56.88 ± 6.44	60.05 ± 7.03
method 2 (%)	42.10 ± 5.74	57.68 ± 6.01	60.60 ± 6.73

* for specimen C28-5, 2 seriesof around 150 measurements were performed. The above mentionned results take into consideration the full 300 measurements.

After Gallucci, LMC-EPFL (2008)