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Characterization of the mechanical properties of Ultra High Performance Fibre-Reinforced Concretes (UHPFRC)

by
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at KU Leuven, Belgium

Summary

Ultra High Performance Fibre-Reinforced Concrete (UHPFRC) is a recent kind of concrete which incorporates characteristics of Self-Compacting Concrete (SCC), Fibre-Reinforced Concrete (FRC) and Ultra High Performance Concrete (UHPC). Usually steel fibres are used as reinforcement, but since this material is sensitive for corrosion and in addition quite dangerous when protruding outside the surface, a new kind of reinforcement is under development: polymer fibres.

As UHPFRC is not an ordinary concrete, it is necessary to analyse its behaviour. As there is almost no information available in literature about UHPFRC reinforced with polymer fibres, this thesis focusses on its tensile behaviour. This is examined by performing Barcelona tests for different kinds of dosages, changing the sand composition, water content and fibre composition. Results show that the sand composition has no clear effect on both the tensile strength of the cement matrix and the ductility. The water content has a clear effect on the tensile strength of the cement matrix: the higher the content, the lower the strength. In contrast, it has no effect on the ductility: in all cases the fibres have a good binding with the cement matrix and are mostly broken and not pulled out. Last, the fibres have no effect on the strength of the cement matrix, but even more is the effect on the ductility: results show that in case two different kinds of fibres are used, the ductility is improved. Although the results show that the amount of fibres may be increased to improve even more the ductility. This implements a decrease in workability, which can be solved by adding more water, but this implements a decrease of the strength of the cement matrix. Consequently, an intermediate solution must be found between the desired strength of the cement matrix and the ductility.

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I wish to express my deepest gratitude to my supervisor Arch. Miquel Llorens, for providing me with the opportunity to pursue my final project. I would like to thank him for his continuous support and guidance throughout the duration of this project.

Most importantly: I would like to thank my parents for allowing me to realize my own potential. All the support they have provided me over the years was the greatest gift anyone has ever given me.

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Chapter 1: Introduction

1.1 Preliminary issues[1]

Ultra High Performance Fibre-Reinforced Concrete (UHPFRC) is a quite recent kind of concrete which incorporates characteristics of Self-Compacting Concrete (SCC), Fibre-Reinforced Concrete (FRC) and Ultra High Strength Concrete (UHSC) technology.

It has a characteristic compressive strength in excess of 150 MPa and contains steel or polymer fibres in order to achieve ductile behaviour under tension and, if possible, to dispense with the need for passive reinforcement. In order to reach these properties, a high control of the materials and processes is required.

The participation of fibres provides tensile strength after the cement matrix has cracked. But in order to achieve a ductile behaviour, thorough research is still required, especially for polymer fibres.

1.2 Research objectives

The research presented in this thesis covers the aim of achieving a ductile behaviour under tension of UHPFRC reinforced with polymer fibres. As this research became one of the first experiences with UHPFRC technology at Universitat de Girona, it is only a first phase of a bigger project to reach the required ductility.

1.3 Thesis overview

This thesis consists of eight chapters that are described as follows:

Chapter 1 is an introduction that resumes the current problems, the research goals of this thesis and its organisation.

Chapter 2 is an analysis of properties of UHPFRC found in literature. After that, the components to produce UHPFRC are proposed. At last, the processes to perform both the rheological and mechanical tests are detailed.

In chapter 3 the materials and methodology used are explained. The components used for the UHPFRC dosages are defined, as well as the dosages themselves. The instrument used to produce UHPFRC, the casting process and the curing process are introduced. Finally, the computational process made to deduce the stress-strain tensile law from the test results is given.

Chapters 4, 5 and 6 show the results of the research done. Chapter 4 shows the results of the rheological tests. Chapter 5 shows the results of the Barcelona tests done after 8 days. Chapter 6 shows the results of the Barcelona tests done after 28 days and a discussion of them.

Chapter 7 shows the conclusions of the thesis. Finally, in chapter 8 some recommendations for future research are commented.

[1] For this paragraph, information is taken from: (AFGC-SETRA, January 2002) and (Torregrosa, 2013)

Chapter 2: Literature review

2.1 Concepts of UHPFRC

2.1.1 Definition

The interim recommendations by (AFGC-SETRA, January 2002) gave as first a clear definition of UHPFRC: "UHPFRC are considered the materials with cementitious matrix and characteristic compressive strength after 28 days in excess of 150 MPa, possibly attaining 250 MPa, and containing steel fibres in order to achieve ductile behaviour under tension and, if possible, to dispense with the need of passive reinforcement. They may also contain polymer fibres."

In order to achieve these properties, UHPFRC contains a high quantity of cement and a special aggregate selection. Also, a high control of the materials and processes is required.

Besides, it has excellent rheological properties in fresh state, so it is considered a Self-Compacting Concrete (SCC)

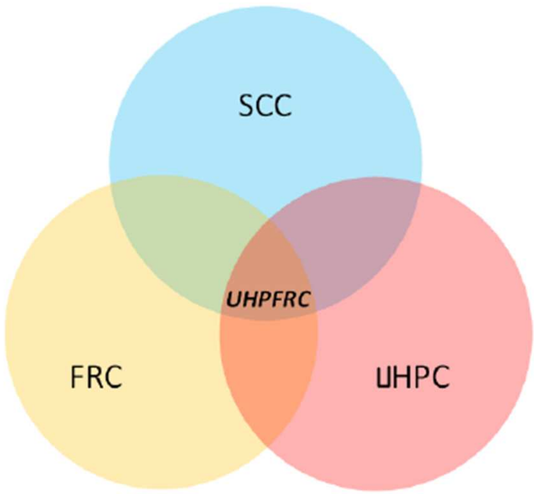


Figure 1.1: Domain of UHPFRC

2.1.2 Basic properties

The most remarkable properties of UHPFRC are the high flexural and compressive strength, its high ductility, durability, toughness, stiffness and thermal resistance. These are based in following principles taken from (Torregrosa, 2013):

- Very low W/B ratio (ratio water vs binder), between 0.15 and 0.25, which minimizes the number of capillary pores and, in addition, there is almost no connection between them. This makes deterioration of the concrete by gases or liquids almost non-existent.
- High packing density, which decreases the demand of water for the mixing. It should be obtained selecting appropriate size distribution, which requires special attention to the particle packing theory.
- Use of homogenous, high strength and reduced diameter aggregates, since micro-cracks are proportional to the aggregate size.
- The use of admixtures of high quality, in order to provide selfcompactability to the material together with a low W/B ratio. This makes that then almost all the water added takes part of the hydration reaction, which reduces the capillary pores (as told in the first principle).
- The use of fibre reinforcement to increase the ductility and the tensile, flexural and shear strength. They enter into force as soon as micro-cracks appear after the tensile strength of the matrix has been exceeded.

The most mentioned disadvantage of UHPFRC is the cost per cubic meter, which is much higher than the cost of ordinary concrete. Beside this economic disadvantage, there is also an environmental disadvantage: the production of UHPFRC requires lots of energy consumption and the emission of CO_2 is quite high. But in contrast, it has many advantages (Torregrosa, 2013):

- ✓ Much smaller volume of material is required to perform the structural elements because of the high tensile-compressive performance.
- ✓ This first advantage becomes in less mass associated to the self-weight, which reduces even more the volume of material used. This divides in many cases the dead weight respect to ordinary concrete solutions by a factor of three.
- ✓ Simpler transport.
- ✓ Quick assembly on-site.
- ✓ A long service life and less maintenance because of the high durability.

It should be remarked that because of the more slender and slight constructions, some typical structural problems like vibrations, buckling or local buckling can be more present!

2.1.3 UHPFRC manufactures and applications

As it is a new material, it has an inherent disadvantage to be cast because the current machinery and building methods require time to be adapted. Up to now, the most common way to build UHPFRC structures is by means of precast elements built with one of the few patents existent in the world market like Ductal®, CERACEM®, BCV®,…

The most common applications with UHPFRC are civil and structural engineering (footbridges, girders, decks,…), structural art (balconies, brise-soleils), elements exposed to aggressive environments (pipes, spillways,…), rehabilitation, security buildings susceptible to explosions, and industrial frame constructions. Figure 2.2 shows some of these applications.

Balconies (Hi-Con®)

Prestressed and universal beams (DURA®)

Short retaining walls (DURA®)

Box girders (Max-Goebl, Graz university)

Garden furniture (Behance®)

Facades (OGM®, DURA®)

Figure 2.2: Structural and architectural applications with UHPFRC

2.2 Material properties[2]

In this part some specifications on the mechanical performance and characteristics of UHPFRC are given. Also, durability properties are notified.

It should be mentioned that the effect of heat treatment should be considered. It consists in raising the temperature of components to a relatively high level a few hours after the concrete has set.

The main effects of heat treatment are as follows:

- Faster compressive and tensile strengths
- Delayed shrinkage and the creep effects reduce substantially after the heat treatment
- Improved durability

2.2.1 Compressive behaviour

Compressive behaviour is defined by the characteristic compressive strength and the modulus of elasticity.

The characteristic compressive strength can be obtained by a compressive behaviour test. This considers of test specimens, which are cylinders with dimensions ϕ7 x 14 cm or ϕ11 x 22 cm, that will be compressed until fracture. As the force increases, the material will behave like Hooke's law:

$$\sigma = E * \varepsilon$$

Whereby:

- σ = constraint
- E = Modulus of elasticity
- ε = deformation

At a certain moment, the yield plateau is reached ($\sigma = f_{ck}$ at this point) and the material will deform strongly without extra force. If the force increases more, at some point the material will crack.

The Modulus of elasticity (E) is specific for each material and depends on the composition of the UHPFRC, granulates, etc. Also, see further.

The design value of the compressive strength is now given as: $f_{cd} = 0{,}85 * \frac{f_{ck}}{\gamma_b}$.

As it's a Ultra High Performance Concrete (UHPC), compressive strengths up to 100 MPa, 150 MPa or more are possible.

[2] For this paragraph, information is taken from (AFGC-SETRA, January 2002), unless otherwise stated.

2.2.2 Tensile behaviour[3]

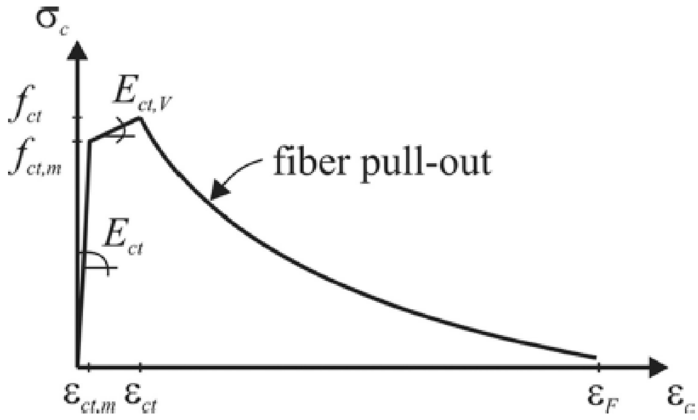


Figure 2.3: Stress-strain-diagram of UHPFRC in tension

The 'theoretical' tensile behaviour of UHPFRC is characterized by:

- an elastic stage limited by the tensile strength of the cement matrix ($f_{ct,m}$);
- a post-cracking stage characterized by the tensile strength of the composite material after the cement matrix has cracked. At this stage, several micro cracks occur until the concrete tensile strength is reached (f_{ct}). After this, macro cracks occur and the fibres break or are pulled out of the concrete, concomitant with a decrease of the stresses. At a strain of ε_f, the fibres are fully pulled out.

The tensile strength of the composite material depends a lot on the mixing and placement process (e.g. flow during concrete placing, thickness of the components,…) and the type of the structure (is it subject to direct tensile stresses or flexural tensile stresses).

2.2.2.1 Direct tensile strength

Without fibres, UHPC can exhibit a direct tensile strength in the range of 7 to 10 MPa. When steel fibres are added to the mix, the amount of the direct tensile strength could be doubled. The increase depends of course on the amount, type and orientation of the steel fibres.

As in these thesis polymer fibres are used, it is still unclear how this kind of UHPFRC will behave. As the tensile strength of polymer fibres is much lower compared to steel fibres, it is possible that the material will behave different.

2.2.2.2 Flexural tensile strength

The flexural tensile strength of UHPFRC is usually much higher than the direct tensile strength. Double amounts and even more is possible. This depends on the fibre orientation and the size of the test specimens.

[3] Some more information is taken from (Sigrist & Rauch, 2008)

2.2.3 Mechanical characteristics

2.2.3.1 Static modulus of elasticity

As the modulus of elasticity (E) depends on the composition of the concrete, the granulates, the density, etc., it is different in each case. Moreover, there is no usable simple formula and tests should be run to directly measure the modulus of elasticity. A value of around 55MPa can be considered.

2.2.3.2 Poisson's ratio

The Poisson's ratio is also different for each UHPFRC mix. A value of $\nu = 0.2$ can be considered.

2.2.3.3 Thermal expansion coefficient

The thermal expansion coefficient is also different for each UHPFRC mix. A value of $1.1*10^{-5}$ m/(m·°C) can be considered.

2.2.3.4 Creep & shrinkage

The drying shrinkage in UHPFRC is very low because of the low porosity. In addition, the autogenous shrinkage is quite large and will take place mostly after 8 to 24 hours. A value of 0.00055 (550 µm/m) can be considered. If the UHPFRC underwent a heat treatment, it will not experience any more shrinkage.

The long-term creep coefficient can be considered 0.8 if there is no heat treatment. If there is a heat treatment, the creep will reduce significantly; a value of 0.2 may be considered.

2.2.3.5 Impact strength

UHPFRC has, like most fibre-reinforced concretes, a high energy-dissipation capacity. Also, because of its high tensile strength, the cracking and structural integrity can be controlled. This endures even for quite strong impacts.

When concrete is subjected to an impact, it experiences high rates of localised strain. These high rates of strain cause in porous materials, such as concrete, an increase in tensile and compressive strength. This results in tensile strength increases up to 2 times and compressive strength increases of 1.5 times for 'common' rates of accidental loading and impact on civil engineering structures.

2.2.4 Durability

UHPFRC is not only far stronger than conventional concrete, it also has outstanding qualities in terms of durability. This means UHPFRC can have interesting special applications, such as for structures in highly aggressive environments, waste storage, etc.

Because of the gain in durability, a reduction in thickness of structural elements is possible. Moreover, the outstanding durability makes it possible to consider a decrease in concrete cover.

If we consider the possible damage mechanism, there are in fact two possibilities: mechanical effects in the form of imposed strain and stress (creep, shrinkage, fatigue,…) or physico-chemical mechanisms (agents, radiation,…).

The latter depend on:

- The transfer properties of the material such as porosity, permeability, etc. This aspect is dealt with in section 2.2.4.1.
- The reactivity of the different constituents: portlandite, admixtures, fibres, etc. Section 2.2.4.2 concerns identification of the possible kinds of damage that could result from specific features of UHPFRC and the associated indicators.

Finally, the fire performance of UHPFRC is notified in section 2.2.4.3.

2.2.4.1 "Conventional" damage mechanisms and associated durability indicators

For the following aspects, measuring methods and thresholds for defining UHPFRC classes will be given:

- Water porosity
- Oxygen permeability
- Chloride-ion diffusion factor
- Portlandite content

Water porosity

The method used is the AFREM recommendation (Association Française Réflexes et Mouvements). The test involves determining the mass of a dry specimen, its saturated mass and its apparent volume.

The water porosity of UHPFRC varies between 1.5 and 6 %.

Oxygen permeability

Again, the AFREM recommendations are used. The test involves measuring the steady-state volumic flowrate of gases passing through a sample of a material based on hydraulic binders under a constant pressure gradient. Using Darcy's law, the permeability to gas can be deduced.

The oxygen permeability of UHPFRC is less than 10^{-19} m^2 and is below the threshold of the AFREM method.

Chloride-ion diffusion factor

There is no recommendation method to determine this factor.

The following diffusion factor for UHPFRC was obtained from a free diffusion test with the tracer 'tritium': $2*10^{-14}$ m^2/s

Portlandite content

The portlandite content is measured by thermographic analysis, comparing water losses between 400°C and 550°C.

The potential portlandite content of UHPFRC is 0 kg/m^3.

Conclusion

All these durability indicators, clarify that UHPFRC has an improvement in durability.

2.2.4.2 Indicators associated with specific features of UHPFRC (reinforced with polymer fibres)

Stability of admixtures

The admixtures are superplasticizers which are polyelectrolytes or water-soluble polymers. None of these products are toxic when normal dosages are used, i.e. 0.5 to 2% by weight of the cement content. A typical value for UHPFRC is 1.4%.

Rather than the dosage, it is the stability of the concrete that guarantees the stability of the admixtures. Therefore, UHPFRC are in a much better position than ordinary concrete and the long-term stability of admixtures in it should not be concerned.

Resumption of hydration

Because of the low water content, there is a limitation on hydration reactions. This results in some residual anhydrite and gypsum. Research found that none of these constitute a danger for the durability of UHPFRC.

Durability of polymer fibres

Polymer fibres are sensitive to both oxidation and ultraviolet light. as long as the concrete is not cracked, UHPFRC provides a good degree of protection against these kinds of damage because of its low porosity. In this case, both oxygen and ultraviolet light are able to come into contact with the fibres. Therefore, there are some products to protect the fibres and can be simply added to the mix.

2.2.4.3 Fire performance

Like all concretes, UHPFRC is non-combustible and makes no contribution to the development of a fire. In addition, it has a low thermal conductivity of about 1.6 W/(m·K). But during a fire, its mechanical performance changes, generally with a loss of strength.

As there is no standard for the fire performance of UHPFRC, there should be made a verification of its fire performance in the event that the structure made with UHPFRC is subject to detailed specifications relating to the risk of fire.

2.3 Components to produce UHPFRC[4]

An UHPFRC dosage is a composition of binders, aggregates, water, PCE admixture and fibres. In this chapter all of them are described and commented.

2.3.1 Binders

The binders are a combination of cement and additions. The latter can contain Silica Fume (SF), Fly Ash (FA), Quartz Flour (QF) or other active additions. The total amount of binder weight generally ranges between 1100 and 1300 kg/m³.

2.3.1.1 Cement

The cement content used to produce UHPFRC is very high compared to ordinary concrete (mostly between 700 and 1100 kg/m³). This implies a noticeable increase of heat hydration and autogenous shrinkage.

Different cement types could be used: type I-42.5 and type I-52.5 are both commonly used. The water demand for the former is more reduced, as the specific surface of the particles is smaller. This results in a decrease in the W/B-ratio which could derive in higher strengths (see further).

The cement content normally represents between 60 and 80% of the binder content.

2.3.1.2 Silica Fume

Silica Fume is often used in UHPFRC dosages as it has a positive effect in the hardened state due to its pozzolanic properties. Besides, it implies a decrease of the workability of the fresh concrete.

Its optimum content in UHPFRC has been found between 20 and 30% over the cement weight. But in some cases this amount could be too high, as the workability decreases too much.

2.3.1.3 Fly Ash

Fly Ash provides an enhancement of the workability of the fresh concrete and can substitute cement well when the W/B-ratio is very low, as is the case for UHPFRC.

Flay Ash can replace cement in contents up to 40% providing similar or even higher long term compressive strengths. But it is not often used in UHPFRC mixes, as it is difficult to guarantee a supply with constant properties, which is necessary when producing this kind of concrete.

[4] For this paragraph, all information has been found in (Torregrosa, 2013)

2.3.1.4 Quartz Flour

Actually, Quartz Flour is only a filler, but sometimes it is considered as binder in the W/B-ratio. It provides higher compacity to the structure.

Generally, most of the dosages contain Quartz Flour, with a typical addition of 25 - 30%.

2.3.2 Aggregates

Generally, aggregates are divided into coarse aggregates (diameter higher than 4 mm) and fine aggregates (also named sands).

The smaller the aggregates, the larger the surface to be enveloped with the cementitious paste, which includes a higher cement content and consequently a higher cost and autogenous shrinkage. The advantage of coarse aggregates is their low specific surface (which implements lower cement content), however both the fibre orientation and rheology of the mixture will be affected.

It has been proven that a great compacity is reached with a combination of two coarse and fine sands, in a proportion of 70-30% respectively.

2.3.3 Water

Water is necessary for the hydration of the cement. This basic principle is that water not used for the cement hydration has to be as low as possible. Then the capillary porosity ant their connection will be minimal, which increases the strength and the durability.

A second reason to avoid high water content is the possibility of sedimentation of the coarse aggregates and fibres. The density of the coarse aggregates is higher than the density of fresh concrete and the density of polymer fibres is lower than the density of fresh concrete.

But this reduction of water, includes the danger that not every cement particle is able to contact with water molecules to hydrate. Besides, when the water amount is too low, the workability decreases strongly and the entrapped air is not able to rise to the surface.

2.3.4 W/B ratio

In fact, this is not a component, but it is quite important to focus on this parameter. As it gives a ratio between the water and the binders, it is considered one of the ruling parameters to analyse concrete.

This ratio may not be too low to guarantee a good flowability so the entrapped air can come out and also to provide the hydration of the binders. The ratio may also not be too high, as a high W/B ratio decreases the strength and promotes the sedimentation of the aggregates or fibres as told in previous paragraph.

The typical ratio for UHPFRC is much lower than ordinary concrete and varies around 0.20.

Another ratio often used, is the W/C ratio. Here, only the cement is considered and not the other active additions. It is higher than the W/B ratio, often around 0.25 – 0.30 for UHPFRC.

2.3.5 PCE admixture

Superplasticizers (polycarboxylate based plasticizers – PCE) are used to reduce the water content up to 40%. Most commonly known are the liquid plasticizers, with a content over the binder weight normally between 2 and 3.5%.

2.3.6 Fibres

Fibres are added to the concrete mix in order to obtain the required ductility and avoiding brittle failures. The content mostly varies around 2% by volume.

The most common fibres used in UHPFRC are steel fibres with a tensile strength more than 2000 MPa. But in this thesis, only polymer fibres are considered.

(Yu, Spiesz, & Brouwers, 2015) showed that the improvement of the mechanical properties depends on different fibre hybridizations. Results from their studies gave the highest flexural and compressive strengths for a volumetric ratio of long fibres to short fibres of 3:1. The reason might be that short fibres can efficiently bridge microcracks, while long fibres are more efficient in resisting the development of macrocracks.

The study of Yu et al. also showed that the strain softening behaviour of the concrete is less ductile for short fibres. The reason for this is their low binding force with the concrete matrix, which makes them easy to pull out after reaching the concrete tensile strength. It should be remarked that polymer fibres with hydrophilic properties have a higher binding force with the concrete matrix, which makes them more difficult to pull out. Moreover, as their tensile strength is lower compared to steel fibres, it is possible that polymer fibres will never pull out and always break.

To resist higher values of strain, long fibres are added to the mix, which are more capable for bridging microcracks. To reach an even higher binding force between the fibres and the concrete matrix, hooked fibres are used. But it should be noticed that this is only optional for steel fibres or polymer fibres with hydrophobic properties.

2.4 Rheological tests

There are several different methods to perform rheological tests. As UHPFRC is self-compacting, the slump flow test is mostly recommended. The procedure to apply is developed in the norm EN-12350-8 (EN-12350-8, 2010). Also, the time required for the slump to reach a diameter of 500 mm (t_{500}) can be measured with the slump flow test. This alternative is less time-demanding and also used in these thesis.

The methodology is as follows:

- A base plate is used to let the concrete flow and is wetted before performing the test. For these tests, the base plate is just the floor covered with a plastic foil.
- An Abrams cone (open at the top and at the bottom - 30 centimetres high, 17 centimetres top diameter, 25 centimetres base diameter) is placed in the centre of the flow table and filled with fresh concrete in two equal layers. Each layer is tamped 10 times with a tamping rod.
- After waiting for 30 seconds, the cone is lifted, allowing the concrete to flow. At this moment, a timer is started and will be stopped as soon as the concrete reaches a slump diameter of 500 mm. This gives the t_{500} time. The lower t_{500}, the higher the flowability.
- After the timer has reached 5 minutes, the diameter of the liquid concrete is measured again. The higher this diameter (D_{max}), the higher the flowability.

2.5 Design methods to analyse the tension behaviour[5]

2.5.1 Introduction

There are different constitutive models to determine the tensile behaviour of FRC. By most of them, the parameters are determined from the results of a flexural tests on beams. As the setup and load configuration provide a simplified control and assessment of the response of the material, and, moreover, the internal forces can be easily derived, the beam test has become the reference for the systematic quality control of FRC. But the beam test shows some drawbacks: the shape and size of the

[5] All information for this paragraph has been found in (Blanco, Pujadas, Cavalaro, Fuente, & Aguado, 2014)

specimen and its production process favour a preferential alignment of the fibres along the axis of the beam, which tends to an increase of the mechanical properties. Second, the area of the beam that is subjected to cracking is quite small, which reduces the total amount of the non-elastic energy mobilised and contributes to increase the scatter in the results. Finally, the weight of the specimen and the equipment required complicate the test procedure and the limit number of elements characterised per batch.

The panel test has been proposed as an alternative test to avoid the favourable orientation and the scatter, but the size of the specimen increases the setup complexity even more.

The Barcelona test has been proposed as an intermediate between both tests. It is simpler to perform, less time-demanding and more sustainable than the others in terms of volume and concrete consumed. It might show some disadvantages regarding the control of crack initiation and the estimation of the internal stress distribution.

Its acceptance in practice is still hindered by the absence of simplified formulation to derive the tensile constitutive models from the test results.

2.5.2 Description of the Barcelona test

The Barcelona test is a double punch test (DPT) performed on Fibre Reinforced Concrete (FRC) specimen. It has been standardized in Spain in 2010 (UNE 83515-2010). The specimen has a cylindrical shape with a diameter (2b) of 150 mm and a height (2h) of 150 mm. At the centre of the top and the bottom surfaces of the specimen, cylindrical steel punches with a diameter (2a) of 37,5 mm and a height of 24 mm are placed. The piston of the press applies a constant relative displacement rate of 0,5 ± 0,05 mm per minute. Force and vertical displacement are both measured.

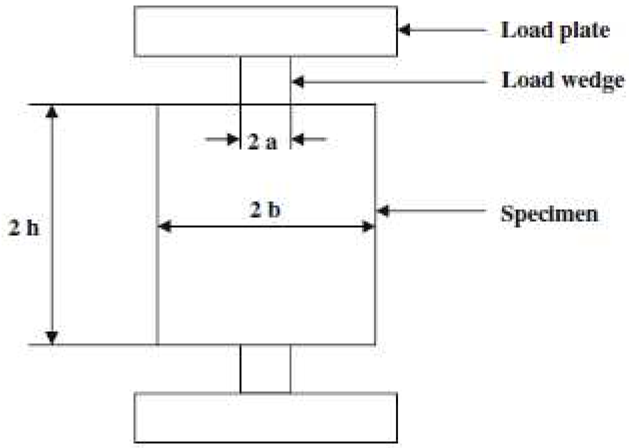


Figure 2.4: Definition of geometric parameters used in the Barcelona test (Malatesta, Cea, & Borrell, 2012)

The applied load produces a tensile stress field inside the specimen. At first, the stresses are borne by the concrete matrix. This happens until the tensile strength of the cement matrix is reached. At this moment, a transition stage occurs: 2 to 4 radial cracks are abruptly formed perpendicular to the stress field and two wedges are formed under the punches where the load is applied. Those wedges are the bottom of cones and have the same diameter as the punches. Once the cracks have appeared, the fibres become responsible for bearing the tension stresses. In this moment, part of the elastic energy is released and the specimens enter a kinematic stage in which the conical wedges slide into the specimen. This vertical displacement (δp) causes the lateral displacement (δL) of the concrete segments with the corresponding crack opening.

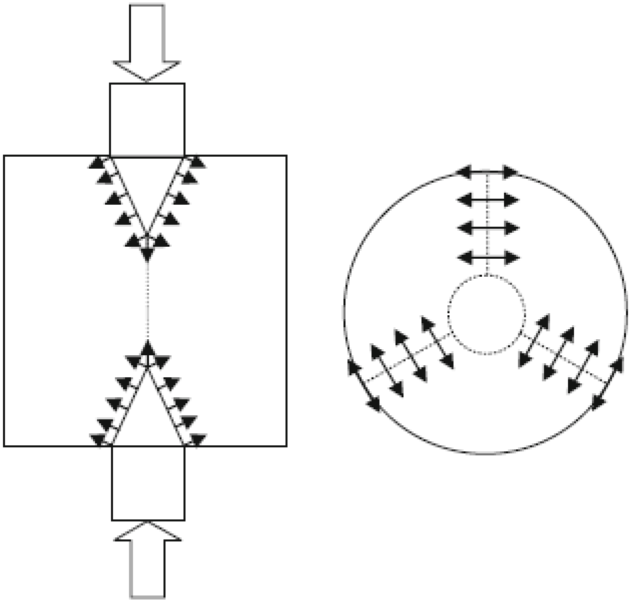


Figure 2.5: Compressive wedges and tensile stresses developed within a specimen subjected to the Barcelona test (Malatesta, Cea, & Borrell, 2012)

2.5.3 Differences compared to the flexural test

The total cracked surface in the Barcelona test is up to 2.2 times more than in the flexural test. Because of this, the total non-elastic energy mobilised in the Barcelona test will be higher, which favours smaller scatter in the post-cracking results.

In the Barcelona test, the biggest part of the elastic energy is released abruptly when the cracks occur and only a small part is released during the post cracking stage. On the contrary, in the flexural test the release occurs at a much slower rate during almost the whole post cracking stage since the crack depth increases gradually during the test. This means that the results obtained at a sectional level will reflect better the contribution of the fibres.

Chapter 3: Materials and Methodology

3.1 Components used

3.1.1 Cement

Type: I 52.5 R

Origin: CIMENTS DE CATALUNYA, SA · Riudellots de la Selva, Spain

Main features:

- Initial setting time: 150 minutes
- Strength: 2 days: 37 MPa, 28 days: 62 MPa
- Composition: Clinker 96%, minor components: 4%

Figure 3.1: Photo of cement used

3.1.2 Silica fume (SF)

Description: MasterRoc MS 610

Origin: BASF Construction Chemicals España, S.L. · L'Hospitalet de Llobregat, Barcelona, Spain

Figure 3.2: Photo of silica fume used

3.1.3 Fine sand

Grain size: 0 – 0.5 mm

Origin: Casellas Xirgu · Girona, Spain

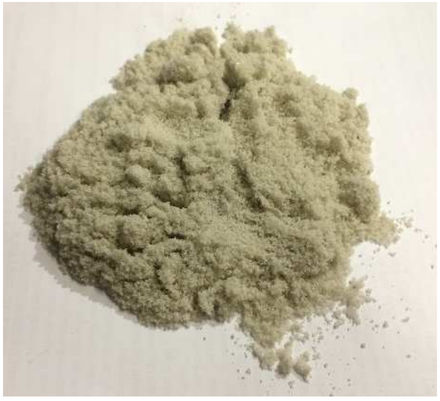


Figure 3.3: Photo of fine sand used

3.1.4 Coarse sand

Grain size: 0 – 4 mm

Origin: Casellas Xirgu · Girona, Spain

Figure 3.4: Photo of coarse sand used

3.1.5 PCE admixture

Description: MasterGlenium SKY 886 (superplasticizer)

Origin: BASF Construction Chemicals España, S.L. · L'Hospitalet de Llobregat, Barcelona, Spain

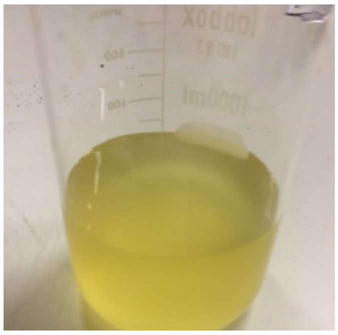


Figure 3.5: Photo of PCE admixture used

3.1.6 Fibre type 1

Description: MasterFiber 400

Origin: BASF Construction Chemicals España, S.L. · L'Hospitalet de Llobregat, Barcelona, Spain

Main properties:

- Polyvinyl acetate fibres (PVA)
- As this fibre is hydrophilic, there is a chemical bonding between the cement matrix and the fibres.
- Length: 18 mm
- Equivalent diameter: 0.20 mm
- Tensile strength: 750 MPa
- Elastic Modulus: 7100 MPa

Figure 3.6: Photo of MasterFiber 400

Figure 3.7: Photo of MasterFiber 246

3.1.7 Fibre type 2

Description: MasterFiber 246

Origin: BASF Construction Chemicals España, S.L. · L'Hospitalet de Llobregat, Barcelona, Spain

Main properties:

- Polypropylene fibres (PP)
- As this fibre is hydrophobic, there is NO chemical bonding between the cement matrix and the fibres. However, because of the shape of these fibres, there is a physical bonding between them.
- Length: 40 mm
- Equivalent diameter: 0.75 mm
- Tensile strength: 448 MPa
- Elastic Modulus: 3640 MPa

3.2 Dosages

3.2.1 First assumption

The aim of this project is to achieve a ductile behaviour of the UHPFRC under tension. Therefore, different dosages were developed, changing the sand composition, the fibre composition and the water content.

For the composition of the different dosages, different sources were consulted: (Malatesta, Cea, & Borrell, 2012), (Torregrosa, 2013) and (Yu, Spiesz, & Brouwers, 2015).

Based on these, 8 different dosages were developed. They can be found in Table 3-5 on page 17.

3.2.2 Calculation of tap water

As UHPFRC requires only a small amount of water, it is important to weigh the right amount of water.

Both sand types contain an amount of water. This has to be measured so less tap water has to be added. This is done by means of a drying test: the wet sand is put into an oven at 200°C and completely dried. The weight loss correspondents to the amount of water, which is evaporated.

Fine sand

The results of the drying process for the fine sand can be found in Table 3-1.

Table 3-1: Results of the drying process for the fine sand

dosage nr	**sand wet (g)**	**sand dry (g)**	**water percentage (%)**
1	19.338	19.174	0.8%
2	19.338	19.174	0.8%
3	19.338	19.174	0.8%
	16.348	15.824	3.2%
4	16.348	15.824	3.2%
5	22.328	21.444	4.0%
6	22.328	21.444	4.0%
*7**	28.748	25.273	12.1%
*7***	26.329	21.788	17.2%
8	31.404	27.885	11.2%

Remarks:

- There were 5 different sand bags, for each bag the water percentage is measured.
- For dosage nr. 3 fine sand of two different bags is used.
- Dosage nr. 7: this dosage was very fluid after mixing the components. Because of this, a second dry test was done to see if the first dry test was correct. The results show that the real water percentage (**) was higher than the water percentage used to make the concrete (*). This explains the high flowability of this dosage (see chapter 4: results of the slump flow test). This fact is taken into account for the final dosages.

Coarse sand

The results of the drying process for the coarse sand can be found in Table 3-2.

Table 3-2: Results of the drying process for the coarse sand

dosage nr	**sand wet (g)**	**sand dry (g)**	**waterpercentage (%)**
1	20.315	20.216	0.5%
2	20.315	20.216	0.5%
3	20.315	20.216	0.5%
4	20.315	20.216	0.5%
5	27.140	27.091	0.2%
6	27.140	27.091	0.2%
7	30.889	30.846	0.1%
8	30.889	30.846	0.1%

Remarks:

- There were 3 different sand bags, for each bag the water percentage is measured.
- The water content of the coarse sand is a lot more reduced than these of the fine sand. This can be explained by the lower absorption capacity of the coarse sand.

3.2.3 Addition of water to reach the liquid state

For dosages 1, 2, 3 and 4 some more water had to be added in order to reach the liquid state. The composition was 90% water and 10% PCE (in mass %).

For dosage nr. 7, the extra amount of water because of the fine sand is taken into account.

Table 3-3: Adjusted values for water and PCE

dosage nr	**real amount water per m³**	**real amount PCE per m³**
1	183.2	21.9
2	183.2	21.9
3	187.3	22.4
4	189.4	22.6
5	210	21
6	210	21
7	272.2	21
8	210	21

3.2.4 Final dosages

The final dosages take into account the real amounts of water and PCE used. They can be found in Table 3-6. The corresponding W/B and W/C ratios can be found in Table 3-4.

Table 3-4: W/B and W/C ratios for the different dosages

dosage nr	**W/B ratio**	**W/C ratio**
1	0.204	0.262
2	0.204	0.262
3	0.208	0.268
4	0.21	0.271
5	0.233	0.3
6	0.233	0.3
7	0.302	0.389
8	0.233	0.3

Table 3-5: First assumption for the dosages

	Content of components (kg/m³)							
dosage nr	**Cement**	**Fine sand**	**Coarse sand**	**Silica fume**	**PCE**	**Water**	**PVA fibre**	**PP fibre**
1	700	975	325	200	21	175	25	-
2	700	780	520	200	21	175	25	-
3	700	975	325	200	21	175	20	5
4	700	780	520	200	21	175	20	5
5	700	975	325	200	21	210	25	-
6	700	780	520	200	21	210	25	-
7	700	975	325	200	21	210	20	5
8	700	780	520	200	21	210	20	5

Table 3-6: Final dosages used

	Content of components (kg/m³)							
dosage nr	**Cement**	**Fine sand**	**Coarse sand**	**Silica fume**	**PCE**	**Water**	**PVA fibre**	**PP fibre**
1	700	975	325	200	21.91	183.2	25	-
2	700	780	520	200	21.91	183.2	25	-
3	700	975	325	200	22.37	187.3	20	5
4	700	780	520	200	22.60	189.4	20	5
5	700	975	325	200	21	210	25	-
6	700	780	520	200	21	210	25	-
7	700	975	325	200	21	272.23	20	5
8	700	780	520	200	21	210	20	5

3.3 Mixer type & process

The mixer used is a tilting drum mixer (see Figure 3.8). It is non-forced and inside are discontinuous paddles. There is no relative movement between the paddles and the drum; mixing takes place by lifting part of the material and then letting it fall. The drum's rotatory speed is around 25 r.p.m., and the power of the engine is 0.25 kW. The maximum volume of UHPFRC that can be cast is around 20 litres, so 4 cylinders (= 1 dosage) can be cast at once (this takes 21.2 litres).

Figure 3.8: Drum mixer mixing UHPFRC

Figure 3.9: Addition of the fibres during mixing

The mixing time is quite long compared to other mixer types, as the non-forced mixing requires that particles disperse by rubbing each other. The mixing process is taken from (Torregrosa, 2013) and summarized in Table 3-7:

Table 3-7: Mixing process for the drum mixer

Phase	Minutes	Process	Aspect
1	0 – 2	Aggregates and binder are mixed	Dry
2	2 – 6	Addition of water + 50% of the PCE and mixing	Dry – Slumps
3	6 – 20	Addition of the remaining PCE and mixing	Slumps – Plastic – Fluid
4	20 – 26	Addition of the fibres and mixing	Fluid

Remark: as mentioned in 3.2, in some cases there was added some more water in order to obtain the fluid state. This happened during phase 3, and in order to be assured of obtaining a homogenous mixture, this phase took place some more than 14 minutes.

3.4 Slump flow test

For each kind of dosage, one slump flow test is done following (EN-12350-8, 2010) and as described in chapter 2.4.

Figure 3.10: Slump flow test

Figure 3.11: Cylindrical mold filled with UHPFRC

3.5 Casting process

After the concrete has been mixed, some of it was used to perform the slump flow test. After waiting several minutes to let the air bubbles rise to the surface, the concrete was poured in cylinders with a diameter of 150 mm and a height of 300 mm. So every cylinder delivers 2 specimens to perform the Barcelona test.

3.6 Curing process

After casting, the cylindrical molds filled with the fresh concrete were stored for 24 hours at 20±2°C and after approximately 2 hours covered with water in order to avoid that the water inside the specimen evaporates.

Figure 3.12: Demolding of the cylinders

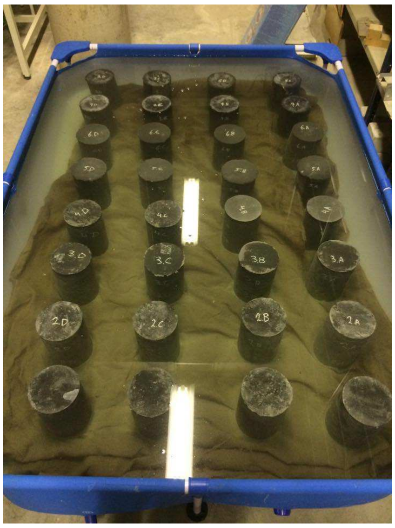


Figure 3.13: Storage of the cylinders in water

After 24 hours, the cylinders were demolded and stored in water with a temperature of again 20±2°C. Thirty minutes before testing, the specimens were extracted from the water and cut into 2 test specimens for the Barcelona test.

Figure 3.10: Cutting of cylinders giving two specimens

3.7 Hardened state tests: Barcelona test

For each dosage, 4 cylinders are made. This equates to 8 specimens that can be used for the Barcelona test. Two of them are tested after 8 days and the other six are tested after 28 days. The numbering is as follows: Number of dosage (1 to 8) – "." – number of cylinder (A to D) – "." – down or upside of the specimen. Example: 7.B.up equals to the upper side of cylinder B for dosage number 7. Cylinders with letter A are tested after 8 days, those with letters B, C and D after 28 days.

During the test, both the applied force and vertical displacement are measured. The tests at 8 days were stopped as soon as the force fell down to 0.5-0.6 tons.

Figure 3.15: Specimen during Barcelona test

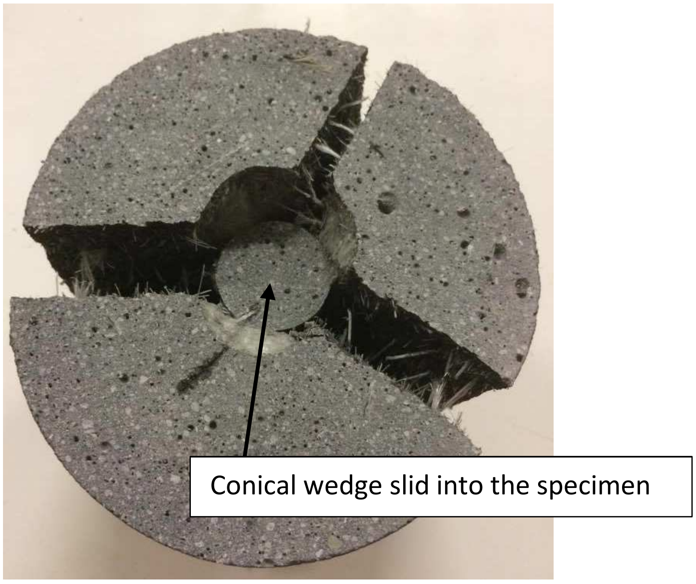


Figure 3.16: Specimen after Barcelona test

3.8 Computational process[6]

3.8.1 Formulation to estimate the stress (σ)

Blanco et al. (2014) found that the tensile stress (σ) resisted by the FRC depending of the load applied by the press (F_p), can be written as:

$$\sigma = \frac{F_P}{2*\pi*A} * \frac{\cos(\beta)-\mu_k*\sin(\beta)}{\sin(\beta)+\mu_k*\cos(\beta)} \qquad (N/mm^2)$$

Where:

- F_p: the load applied by the press. This is measured during the testing. (N)
- A: the area of the cracked radial surface = $\frac{d*h}{4} - \frac{d\prime^2}{4*\tan(\beta)}$ (mm^2)
- μ_k: kinetic friction coefficient (-)
- β: the failure angle of the material (-)

3.8.2 Formulation to estimate the strain (ε)

Blanco et al. (2014) found that the strain in the specimen may be written as:

$$\varepsilon = \frac{n*\delta_P}{\pi*R} * \tan(\beta) * \sin(\frac{\pi}{n}) \qquad \text{(-); often in (‰)}$$

Where:

- n: the number of cracks (mostly 2 to 4)
- δ_p: the displacement of the conical wedges that slide into the specimen. This is measured during the testing. (mm)
- R: the radius of the specimen (mm)
- β: the failure angle of the material (-)

This equation can also be written in terms of increments:

$$\Delta\varepsilon = \frac{n*\Delta\delta_P}{\pi*R} * \tan(\beta) * \sin(\frac{\pi}{n})$$

3.8.3 Values of failure angle (β), friction coefficient (μ) and number of cracks (n)

The value of the failure angle (β) can be found by means of the internal friction angle of the material (ϕ), as β = 90° - ϕ. This friction angle can be found in literature or by looking at the cracking surface of the conical wedge. As l is the length of the conical wedge and d' the diameter (= 37,5 mm, as the diameter of the steel punch), the value of ϕ can be calculated as: $\tan\varphi = \frac{l}{\frac{d\prime}{2}}$.

About the kinematic friction coefficient (μ_k), there is only very limited information available in literature. It is considered to be smaller than the static friction coefficient (μ_s). For this, the values found in Table 3-8 may be considered.

[6] All information for this paragraph has been found in (Blanco, Pujadas, Cavalaro, Fuente, & Aguado, 2014).

Table 3-8: Friction coefficient for plain concrete

Interface roughness	Friction coefficient μ (-)
Smooth interface	0.5 - 0.7
Rough interface	0.7 - 1.0
Very rough interface	1.0 - 1.4

For an initial approximation, a μ_k equal to 0.7 will be used, but more studies are required to characterize this coefficient more precisely.

The number of cracks (n) can be determined experimentally by an observation of the specimens after the test.

Chapter 4: Results of the slump flow test

The slump flow is both measured like the norm EN-12350-8 (value D_{max}) and the less time-demanding alternative (value t_{500}). The results can be found in Table 4-1. Since for all the dosages D_{max} is higher than 500 mm, all of them are self-compacting (SCC).

It seems that there is a clear relationship between the 2 values: the higher the slump diameter, the lower the time required to reach a diameter of 500 mm.

For the dosages with two types of fibres (dosages 3, 4, 7 and 8), the slump flow is more reduced compared to the dosages with only one type of fibres. The explanation is that the PP fibre is long and thick, which prevents the concrete to flow. Only for dosage number 7 this statement is incorrect, but as earlier mentioned, there was too much water added to this mix because of the miscalculation of the water content of the sand.

Table 4-1: Results of the slump flow test

dosage nr	t_{500} (s)	D_{max} (mm)
1	*20s*	*595*
2	15s	680
3	*90s*	*520*
4	endless	500
5	*20s*	*570*
6	7s	630
7	*3s*	*860*
8	10s	590

Figure 4.1 shows the relationship between the W/C ratio and D_{max}. As expected, for higher W/C ratios, the slump diameter increases.

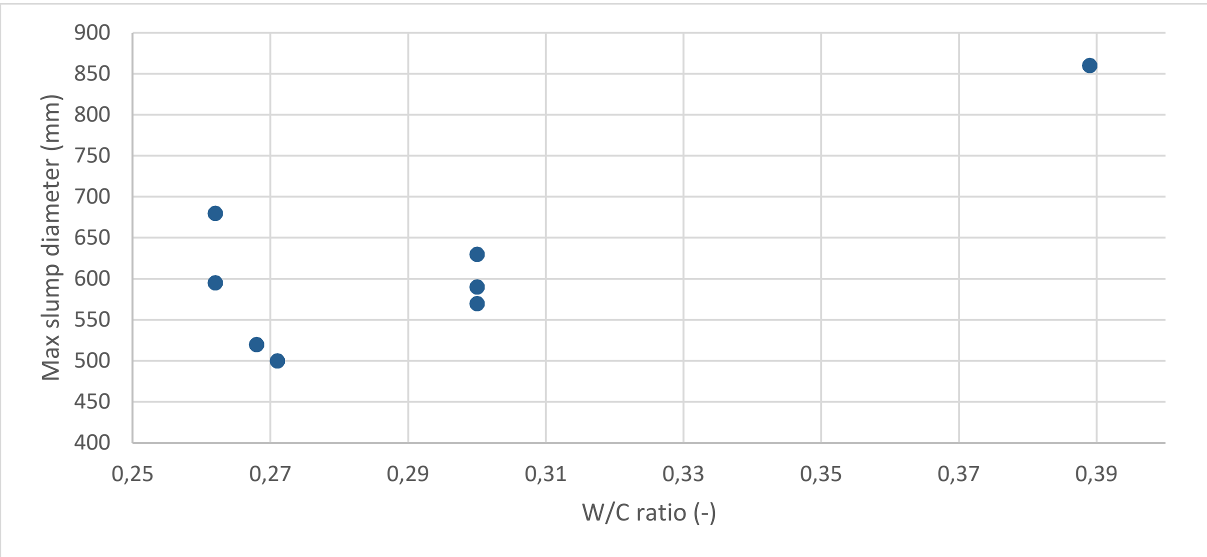


Figure 4.1: Maximum slump diameter versus the W/C ratio for every dosage

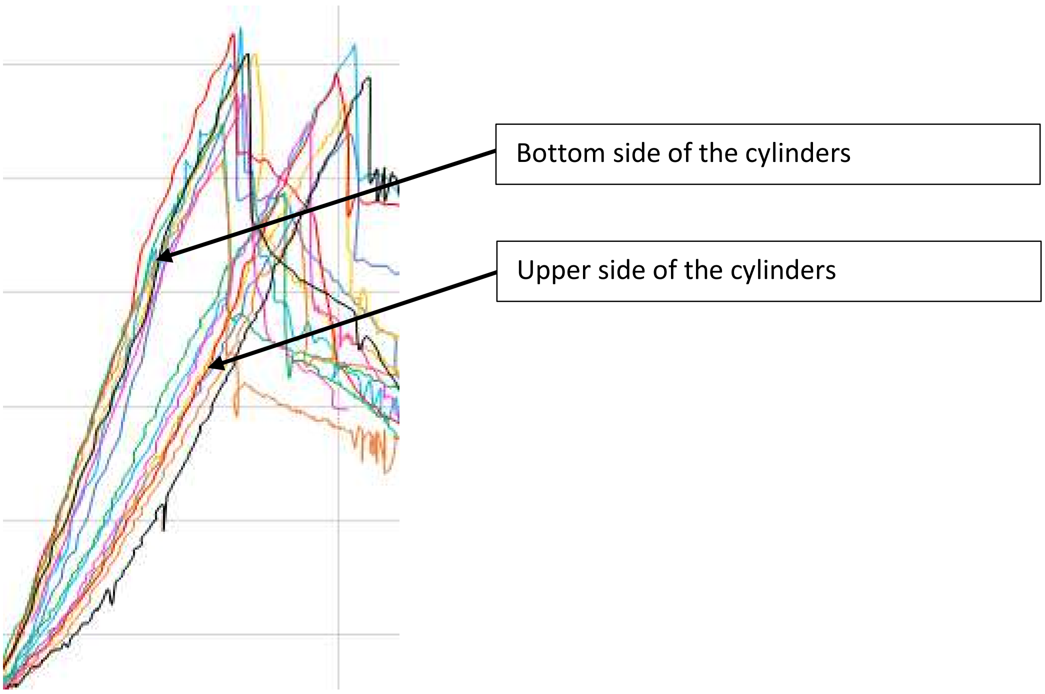
Chapter 5: Results after 8 days

5.1Results

As mentioned earlier, for each dosage 2 specimens were subjected to the Barcelona test after 8 days. The results are shown in Figure 5.1 and Figure 5.2. These results are not used for the final conclusion, the tests were only done to get acquainted with the Barcelona test.

(1) The tests at 8 days were stopped as soon as the force fell down to 0.5-0.6 tons. For some of the specimens (e.g. 4.A down and 7.A down), this took more than 30 minutes.

(2) There is a remarkable difference between the upper and bottom side of the cylinders. The elastic modulus seems less for the upper side than for the bottom side. The reason could be the rough surface of the upper side.



(3) The value of the failure angle (β) has been measured by means of taken the cones out of the specimens. The results are shown in Table 5-1. The mean value for β is 24.85°.

Table 5-1: Results for the failure angle (β)

1.A.down	27°	5.A.down	26.3°
1.A.up	26.1°	5.A.up	25.7°
2.A.down	23.5°	6.A.down	21.8°
2.A.up	27.5°	6.A.up	26.3°
3.A.down	25.4°	7.A.down	23.3°
3.A.up	27.9°	7.A.up	24°
4.A.down	26.2°	8.A.down	21.6°
4.A.up	21.3°	8.A.up	23.7°

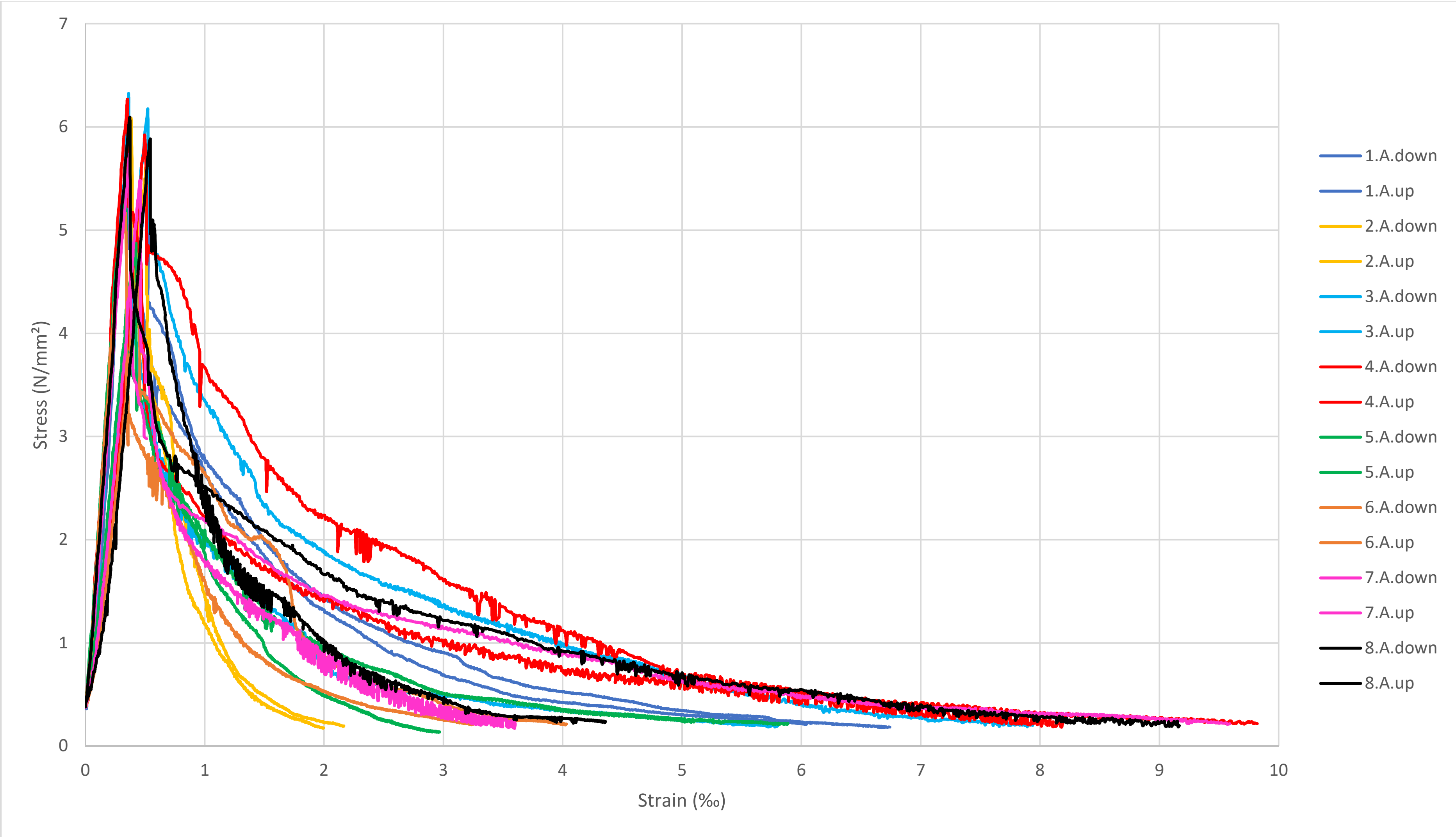


Figure 5.1: Results after 8 days

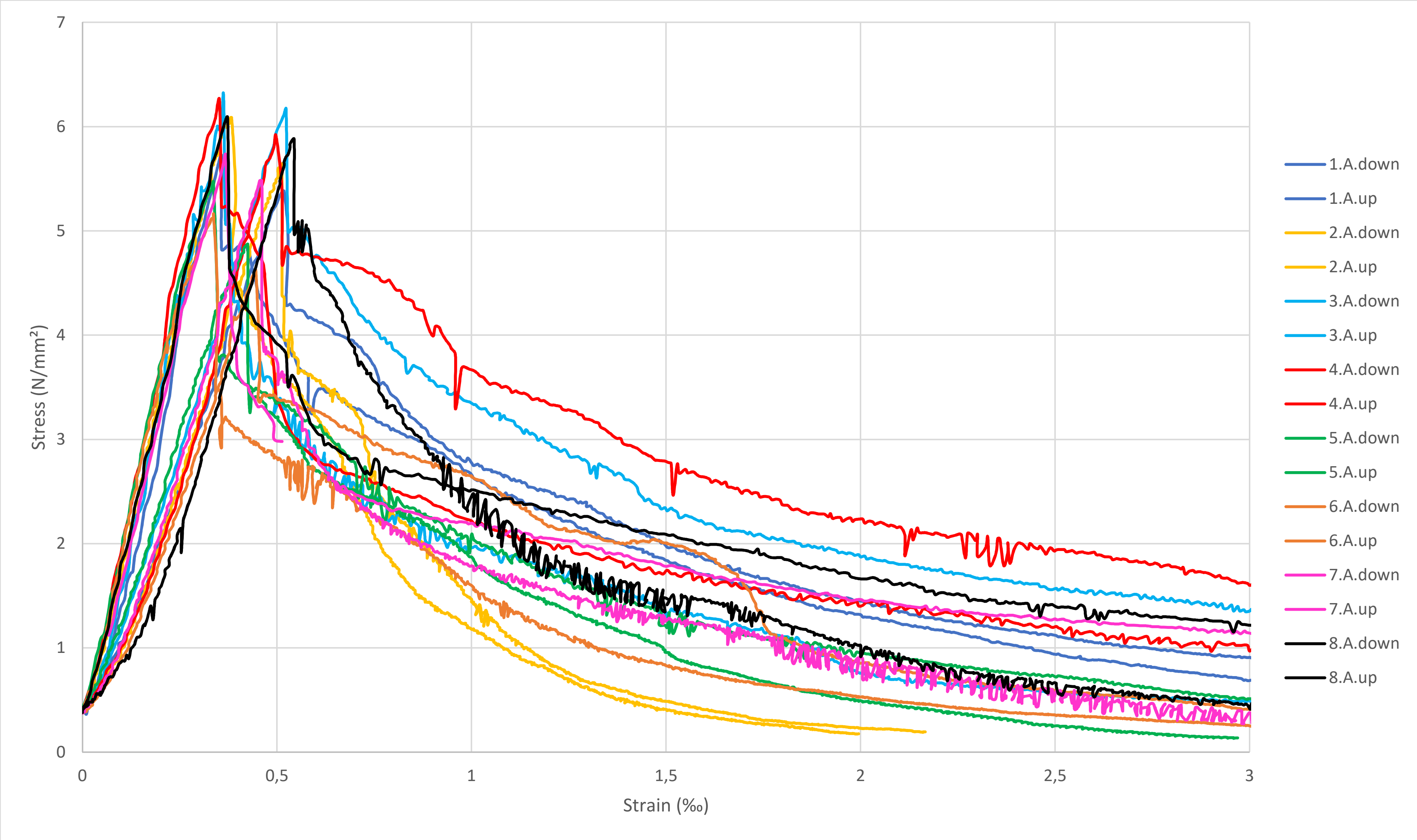


Figure 5.2: Results after 8 days: detail of the first part

(4) The number of cracks was as expected 2, 3 or 4, as shown in Figure 5.3.

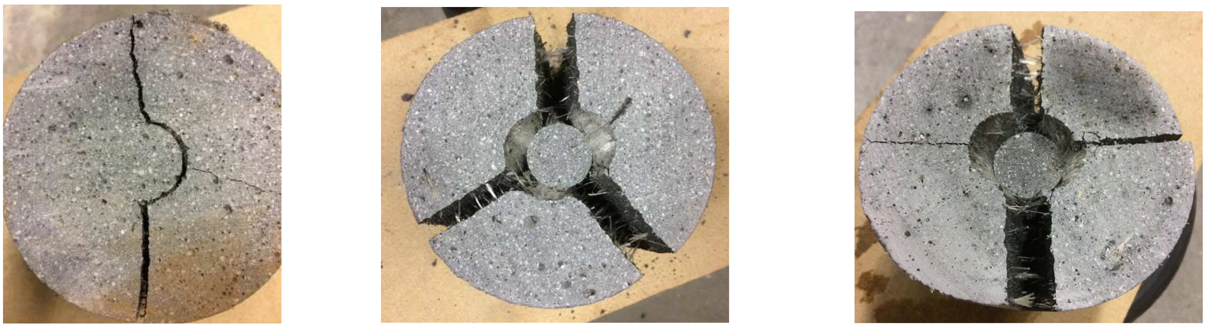


Figure 5.3: Different number of cracks: 2, 3 and 4

5.2Conclusions made after 8 days

Different things will be done differently for the tests after 28 days:

(1) The tests will be stopped as soon as the vertical displacement reaches 6 mm (this equals to 12 minutes) or as soon as the force falls down to 0.5 tons. The results after 8 days show that after a vertical displacement of 6 mm (which correspondents to a strain around 3 ‰), the behaviour doesn’t change that much and doesn’t give extra information.

(2) The difference in Elastic modulus during the elastic section of the curves will not be taken into account to make the final conclusions.

(3) The value of the failure angle (β) will not be measured anymore. It will be supposed 25° in any case, as the mean value (24.85°) is very close to this value. Also, a failure angle of 25° is predicted as a good estimation in (Blanco, Pujadas, Cavalaro, Fuente, & Aguado, 2014).

Chapter 6: Results after 28 days

6.1All graphics per dosage (together with their content)

5.1.1 Dosage 1

Content of components (in kg/m³):

Cement	Fine s	Coarse s	SF	PCE	Water	PVA fibre	PP fibre
700	975	325	200	21,91	183,2	25	-

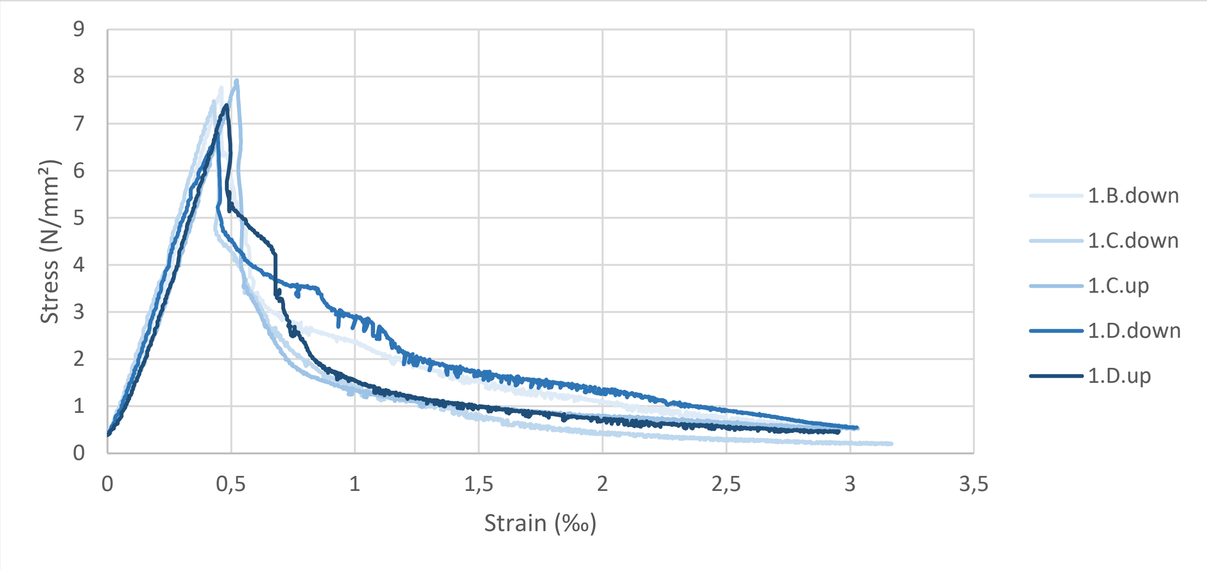


Figure 6.1: Results of dosage 1

Remark: specimen 1.B.up was broken by accident before testing.

5.1.2 Dosage 2

Content of components (in kg/m³):

Cement	Fine s	Coarse s	SF	PCE	Water	PVA fibre	PP fibre
700	780	520	200	21,91	183,2	25	-

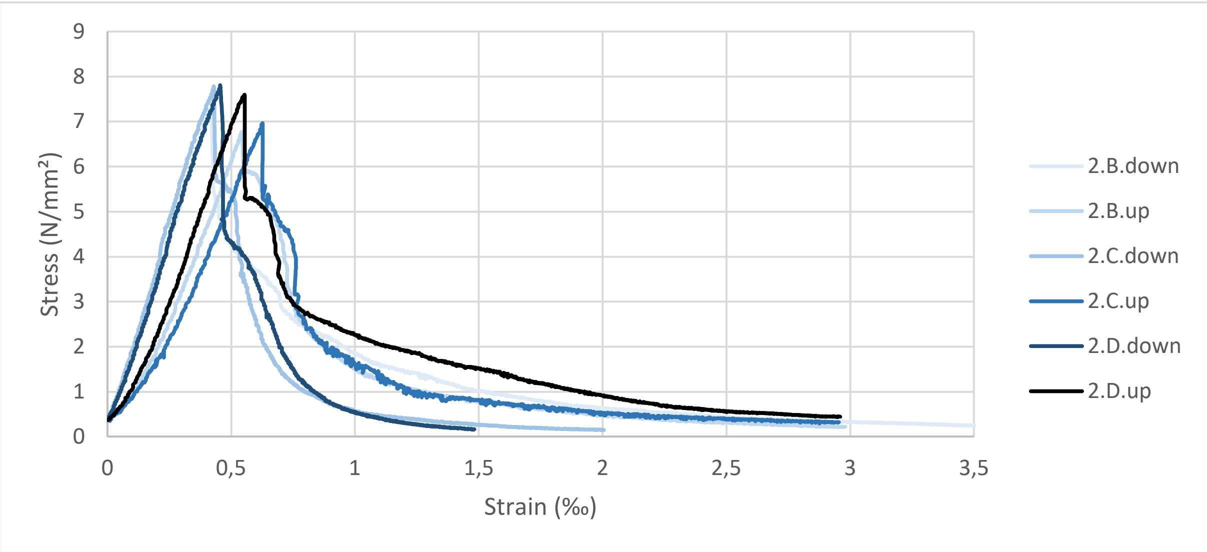


Figure 6.2: Results of dosage 2

5.1.3 Dosage 3

Content of components (in kg/m³):

Cement	Fine s	Coarse s	SF	PCE	Water	PVA fibre	PP fibre
700	975	325	200	22,37	187,3	20	5

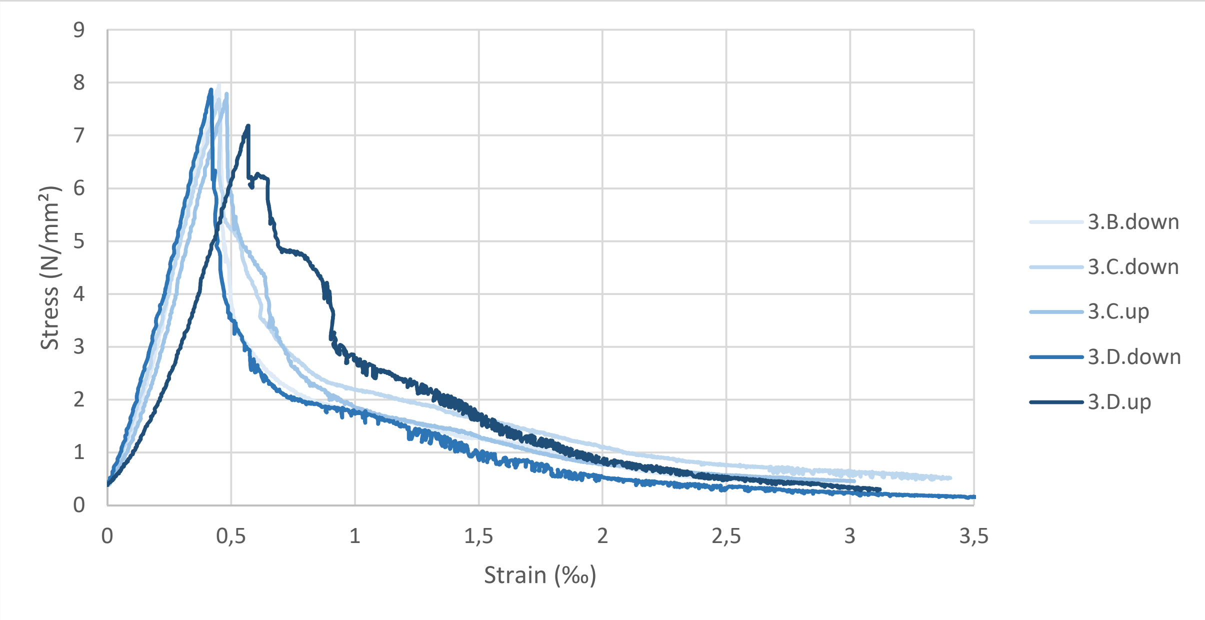


Figure 6.3: Results of dosage 3

Remark: specimen 3.B.up was broken by accident before testing.

5.1.4 Dosage 4

Content of components (in kg/m³):

Cement	Fine s	Coarse s	SF	PCE	Water	PVA fibre	PP fibre
700	780	520	200	22,60	189,4	20	5

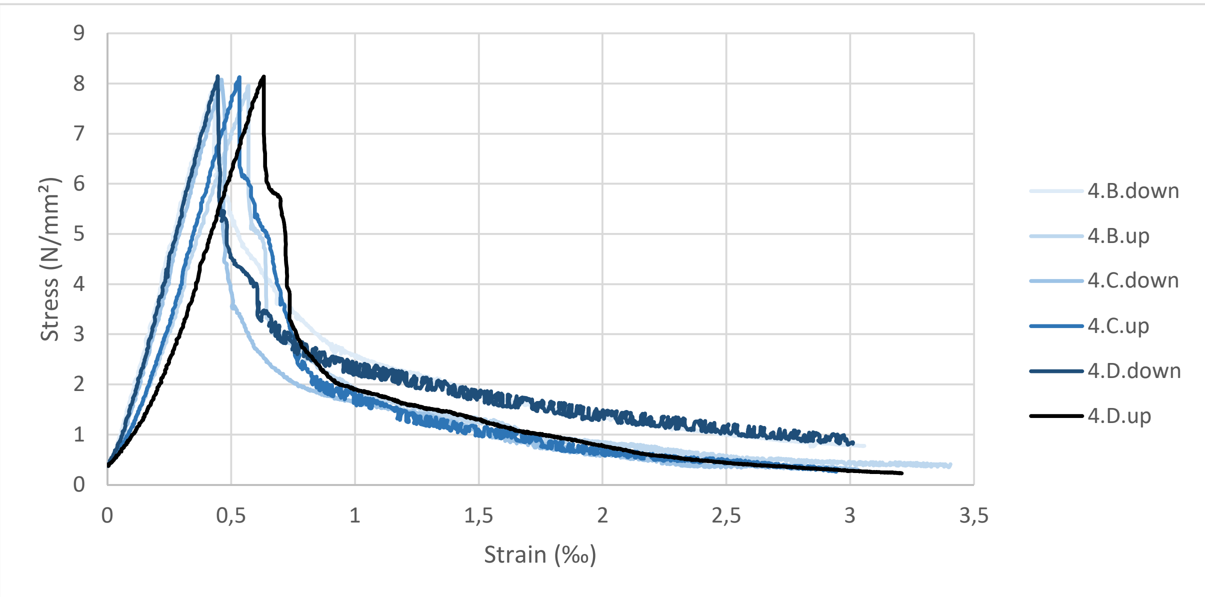


Figure 6.4: Results of dosage 4

5.1.5 Dosage 5

Content of components (in kg/m³):

Cement	Fine s	Coarse s	SF	PCE	Water	PVA fibre	PP fibre
700	975	325	200	21,00	210,0	25	-

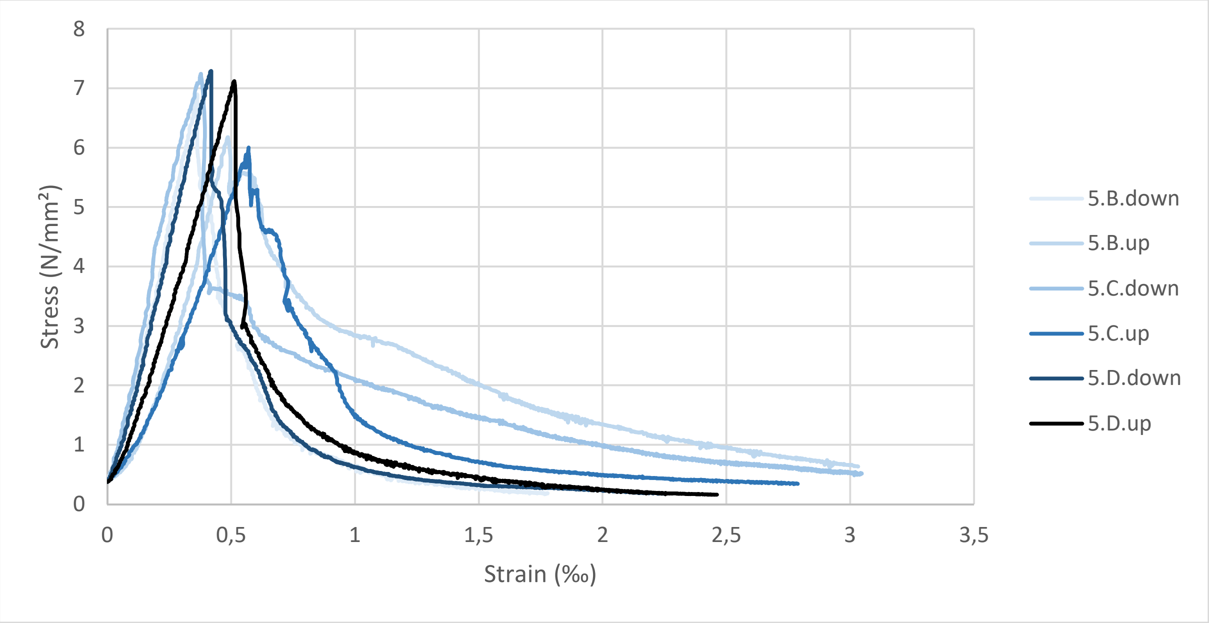


Figure 6.5: Results of dosage 5

5.1.6 Dosage 6

Content of components (in kg/m³):

Cement	Fine s	Coarse s	SF	PCE	Water	PVA fibre	PP fibre
700	780	520	200	21,00	210,0	25	-

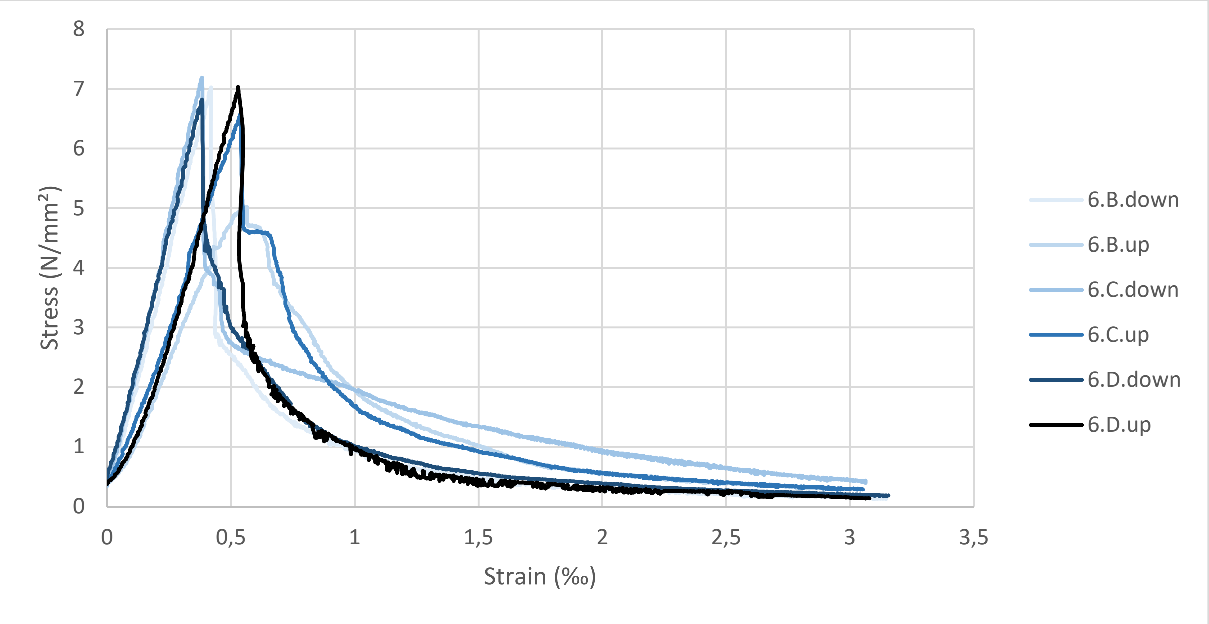


Figure 6.6: Results of dosage 6

5.1.7 Dosage 7

Content of components (in kg/m³):

Cement	Fine s	Coarse s	SF	PCE	Water	PVA fibre	PP fibre
700	975	325	200	21,00	272,2	20	5

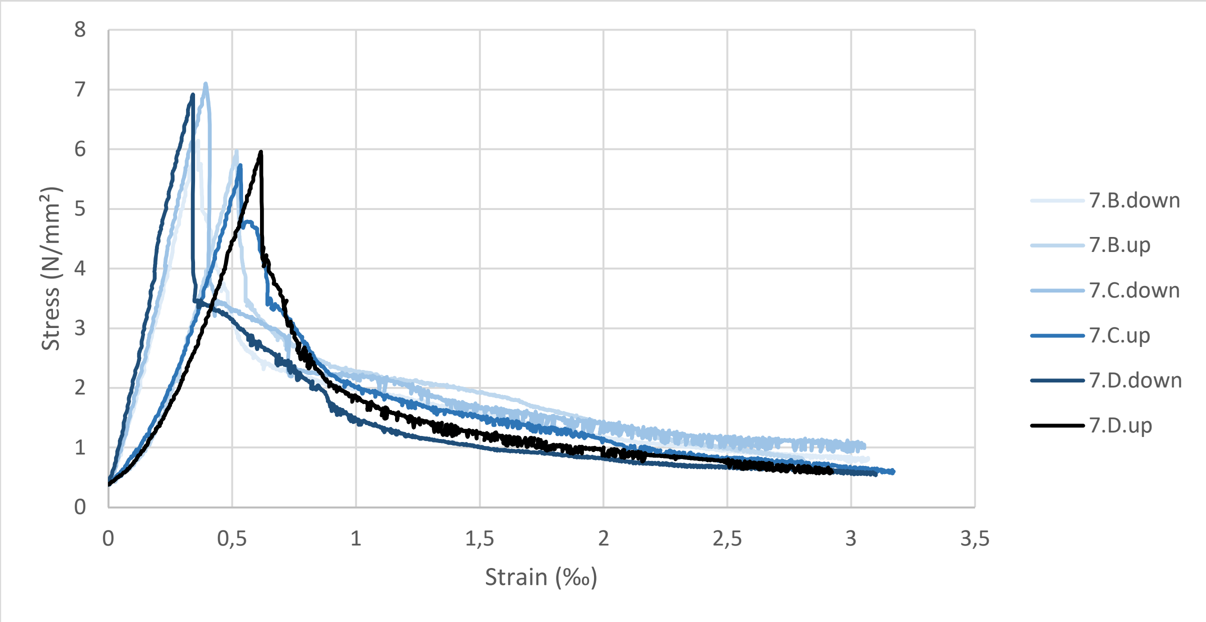


Figure 6.7: Results of dosage 7

5.1.8 Dosage 8

Content of components (in kg/m³):

Cement	Fine s	Coarse s	SF	PCE	Water	PVA fibre	PP fibre
700	780	520	200	21,00	210,0	20	5

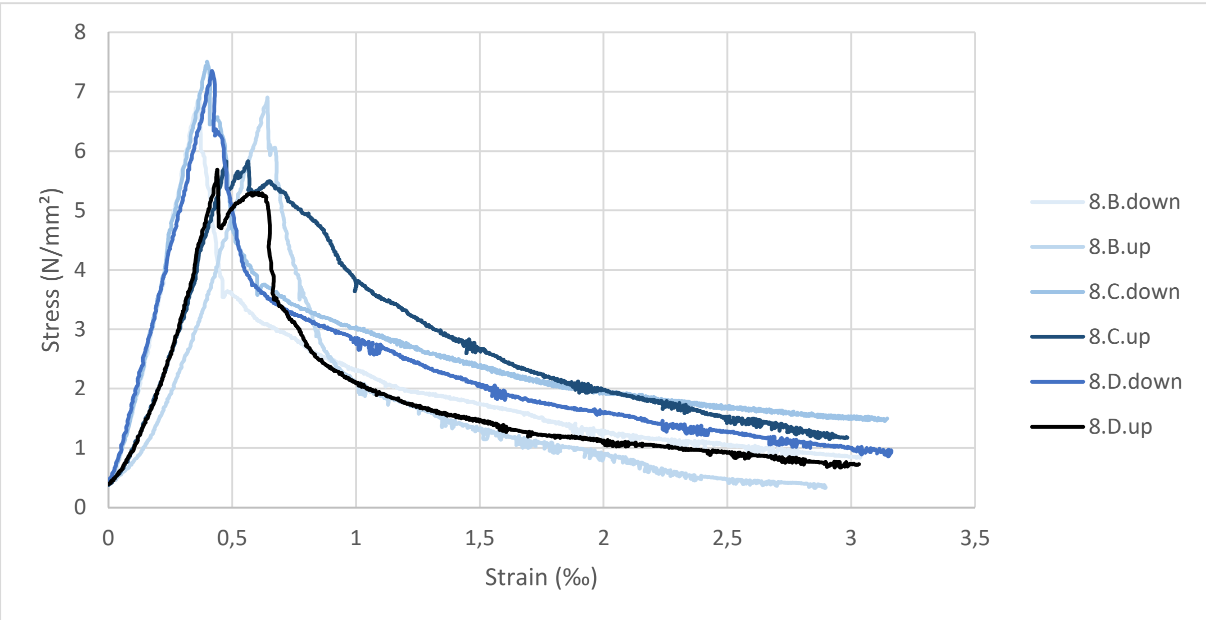


Figure 6.8: Results of dosage 8

6.2 Description of some graphics to explain the behaviour of UHPFRC

Specimen 3.D.up is used to explain the behaviour of UHPFRC. Dosage 3 (Figure 6.9) is used as example because it contains two different kinds of fibres (same for dosages 4, 7 and 8).

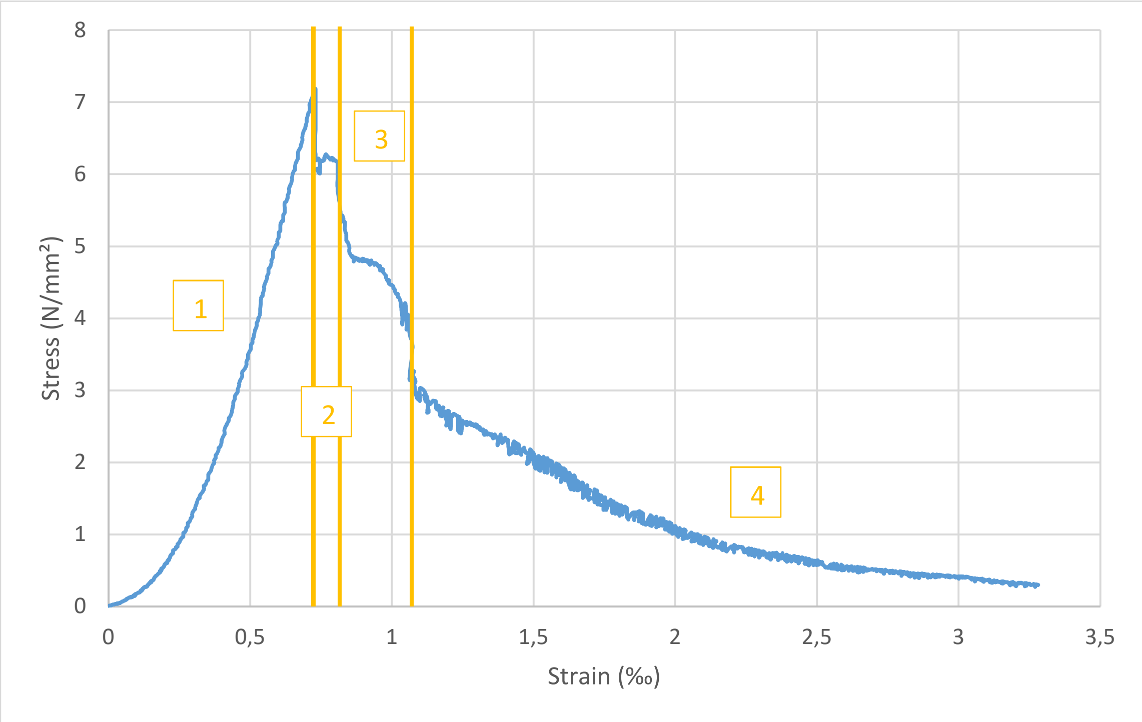


Figure 6.9: Stress-strain curve for specimen 3.D.up as typical curve for UHPFRC reinforced with hybrid fibres

Phase 1 is an elastic stage limited by the tensile strength of the cement matrix ($f_{ct,m}$). For specimen 3.D.up, $f_{ct,m}$ is around 7.20 MPa.

After $f_{ct,m}$ is reached, in any case there is a 'vertical falldown'. The stress drops sharply without the strain changing. After this falldown, the PVA fibres start to work (phase 2). The specimen is now characterized by 2,3 of 4 vertical cracks, which are equally wide across the entire height of the specimen (Figure 6.10).

Figure 6.10: Crack equally wide across the entire height of the specimen

After stage 2, there is another falldown before entering stage 3, where the PP fibres start to work. During this stage, the cracks stay equally wide across the entire height of the specimen.

Figure 6.11: Crack more wide at the top than at the bottom

At the end of this stage, there is another (mostly less impressive) falldown. After this, the strain softening behaviour of UHPFRC starts (phase 4). This phase is characterized by cracks which are not equally wide anymore across the entire height of the specimen (Figure 6.11). In this figure, the fibres at the top are all broken, while at the down bottom they are still working to keep the parts together.

For the dosages with only one type of fibres, the behaviour is different: phase 3 won't be there as there are no polypropylene fibres present. Specimen 6.C.up is used as example in Figure 6.12.

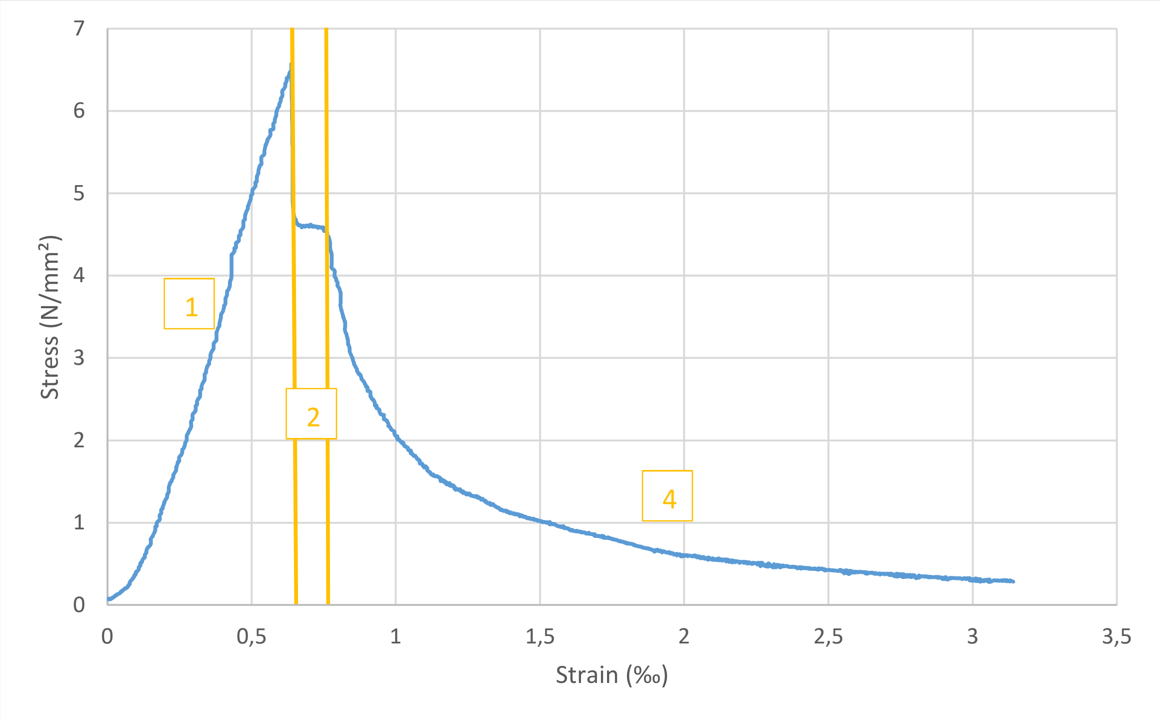


Figure 6.12: Stress-strain curve for specimen 6.C.up as typical curve for UHPFRC reinforced with 1 type of fibres

In some cases, the fibres do not work: the strain softening process starts immediately after the tensile strength of the cement matrix has been exceeded. Specimen 6.B.down shows this behaviour (Figure 6.13).

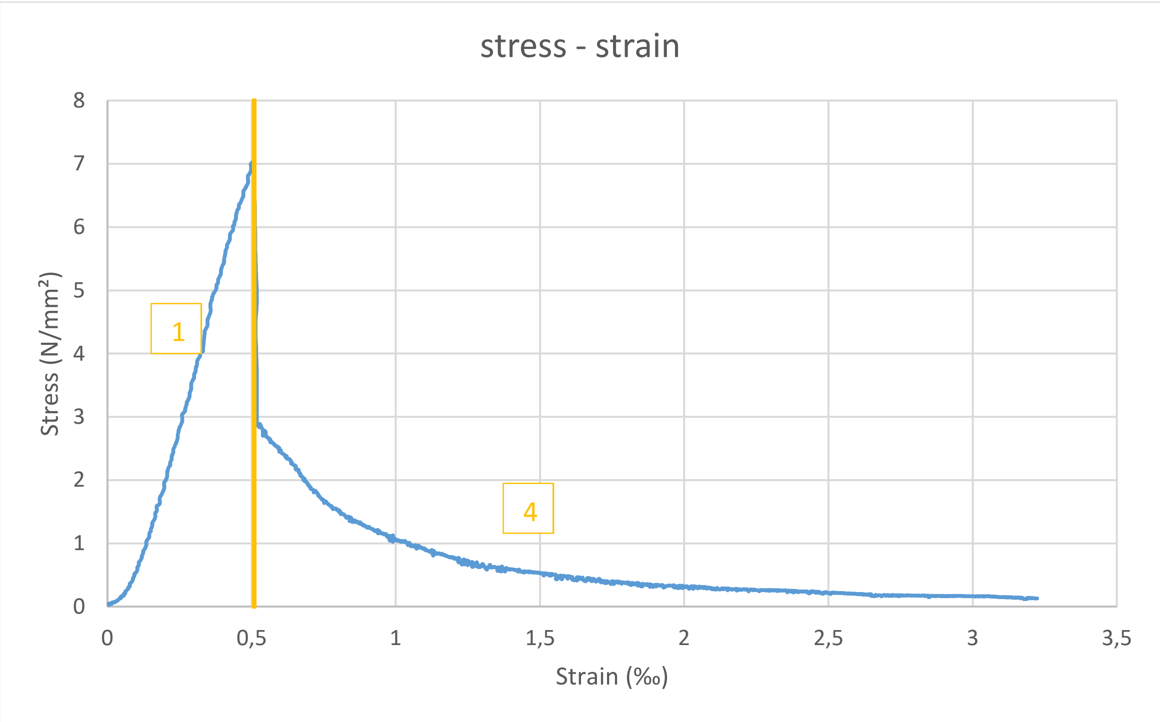


Figure 6.13: Stress-strain curve for specimen 6.B.down as typical curve for UHPFRC where the fibres don't work

6.3Comparison of the tensile strength of the cement matrix ($f_{ct,m}$)

The tensile strength of the cement matrix ($f_{ct,m}$) for each specimen, as well as the average for each dosage, can be found in Table 6-1.

Table 6-1: Tensile strength of the cement matrix for all the specimens and average for each dosage (MPa)

	1	2	3	4	5	6	7	8
B down	7.76	7.42	7.96	7.93	6.9	7.02	6.14	6.98
B up	/	6.77	/	7.95	6.17	5.02	5.97	6.90
C down	7.47	7.79	7.68	7.97	7.24	7.18	7.09	7.50
C up	7.92	6.96	7.78	8.12	5.29	6.57	5.73	5.82
D down	6.79	7.80	7.86	8.14	7.29	6.81	6.91	7.34
D up	7.39	7.59	7.18	8.13	7.12	7.03	5.95	5.67
Average	**7.47**	**7.39**	**7.69**	**8.04**	**6.67**	**6.61**	**6.30**	**6.70**

Between the dosages with different sand ratio, there is no remarkable difference. Neither for the dosages with different fibres.

However, there is a clear difference between the dosages with a different water content. The lower the water content (equals to lower W/B or W/C ratio), the higher the tensile strength of the matrix. Dosages 1 to 4 have a lower water content than the others, while their tensile strength of the cement matrix is around 10 to 20 % higher. Figure 6.14 clarifies this:

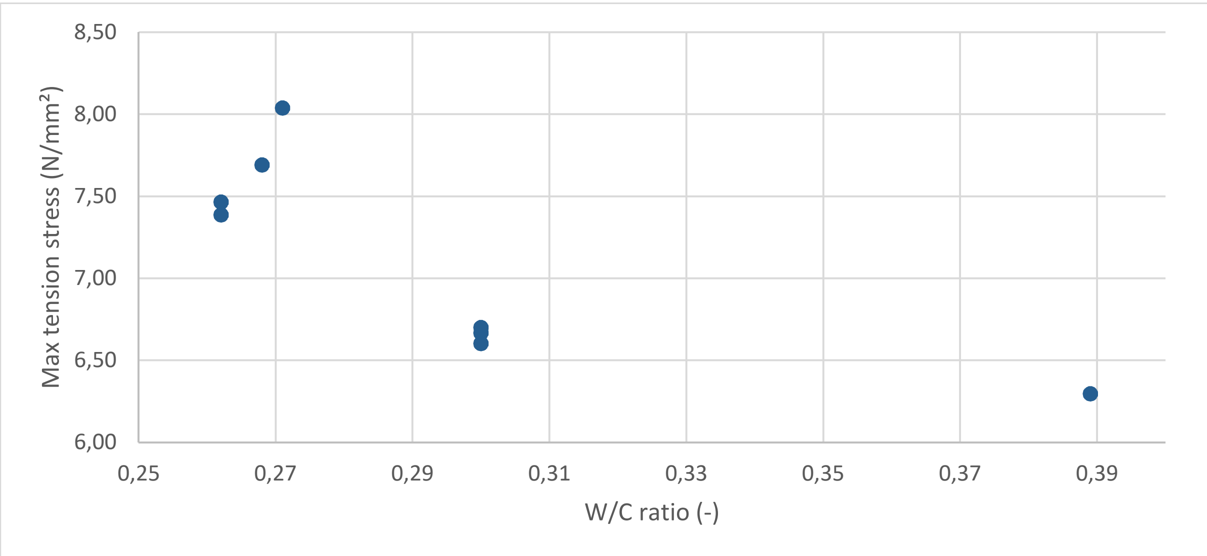


Figure 6.14: Average tensile strength of the cement matrix versus the W/C ratio for every dosage

Remark: dosage number 7 had a very high water content, which correspondents to the lowest tensile strength of the cement matrix of all dosages. However, the value is not that much lower as actually expected.

6.4 Comparison between the dosages with different ratio fine sand / coarse sand

As can be seen in Figures 6.1 to 6.8 in paragraph 5.1, there is no clear difference between the dosages with different sand content (the even number of dosages compared to the uneven ones).

It clarifies that aggregates are not the ruling parameter in UHPFRC. Cement content, W/C ratio and fibre content are a lot more important.

6.5 Comparison between the dosages with different water content

Dosages 1 to 4 have to be compared to dosages 5 to 8 to watch the influence of the water content.

As described in paragraph 5.3, it is clear that for higher water contents, the strength of the concrete decreases. In contrast, there is almost no difference in the post-cracking stage. In all cases, the fibres were broken and never pulled out, which means that the binding between the fibres and the cement matrix is quite good.

Therefore, addition of water will not have any influence on the post-cracking stage (as long as it is not too much of course), but will only decrease the strength of the cement matrix.

6.6 Comparison between the dosages with different fibre content

The dosages 1, 2, 5 and 6 contain only one type of fibre: the short straight fibres with hydrophilic properties. Dosages 3, 4, 7 and 8 contain two types of fibres: the one just mentioned and the longer notched fibres with hydrophobic properties.

As mentioned in paragraph 5.2, in some cases the dosages with two types of fibres give a clear efficiency of both fibre types. The short straight fibres start to work after the tension strength of the cement matrix has been reached. After these fibres start to break, the longer notched fibres start to work. The dosages with only the short straight fibres go into the phase of the strain softening behaviour as soon as these fibres start to break.

Both cases are proposed in Figure 6.15: on the left side are two examples of dosages with only one type of fibre and on the right side two examples of dosages with two types of fibres. The two graphs on top have a quite high tensile strength of the cement matrix, for the bottom ones this is much lower. It shows that for concretes with a high strength, the "falldown" - after the tensile strength of the cement matrix has been reached - is clearly noticeable. For less strong concretes, this falldown is not as much, and, in addition, the ductile behaviour is both longer and stronger (especially in case of 2 types of fibres).

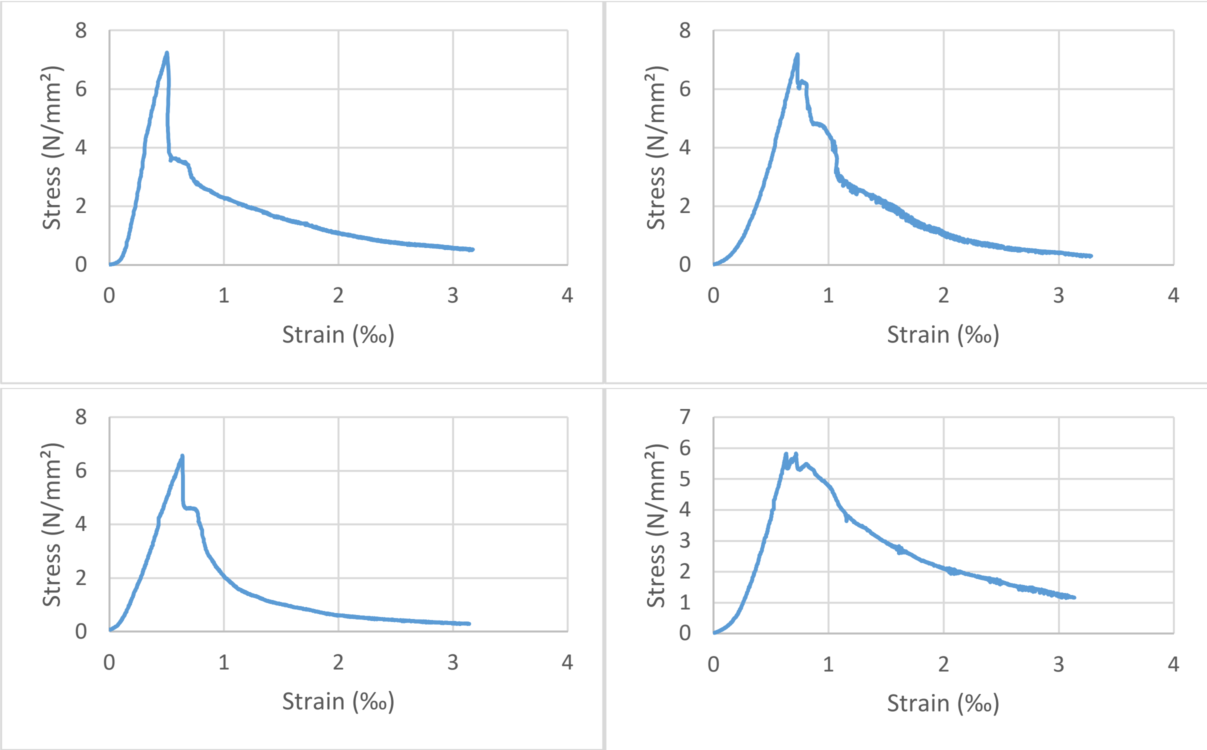


Figure 6.15: Specimens (from left to right and from top to down): 5.C.down ; 3.D.up ; 6.C.up ; 8.C.up

6.7General results

Some findings can be made for all the specimens:

- There are big differences in the results for the same dosages. The scatter is quite big, but can't be explained unambiguously. Different causes are possible:
  - difference between the first and the last cylinder during casting;
  - insufficient care of the specimens
  - other unknown causes…
- The zone where the fibres work (phases 2 and 3 referred to 5.2) is still quite short.
- Some of the specimens were examined after the Barcelona test. This clarified that all of the fibres were broken and not pulled out.
  However one big problem is that the short straight fibres are not completely dispersed. Some of them are stuck together as can be seen in Figure 6.16. This can be explained by the hydrophilic properties of the fibres. As they are exposed to air, they come in contact with water and start to stick together.
  The right figure in Figure 6.16 shows that after adding the fibres to the liquid concrete mix, the fibres that are stuck together don't separate. A close study shows that these groups of fibres are not broken but pulled out of the cement matrix. This is a very important issue for UHPFRC reinforced with polymer fibres with hydrophilic properties.


Figure 6.16: Fibres stuck together: before adding to the mix (left) and inside the hardened specimens (right)

- Some specimens were cut after the Barcelona test to see if all the components were completely dispersed. This showed that all of them are well dispersed and no segregation is noticeable.

Chapter 7: Conclusions

First of all, it can be concluded that the scatter between specimens of the same dosage is quite big. A specific explanation for this is hard to find. But it is known that this is quite common for UHPFRC.

Besides, in some cases there are hopeful results. The sand composition, water content and fibre composition were changed. The results show that the difference in sand composition does not have a clear effect on both the strength of the cement matrix and the ductile behaviour of UHPFRC. The difference in water content has a clear effect on the strength of the cement matrix: the higher the water content, the lower the strength. In contrast, a change in the water content has no effect on the ductile behaviour, as in all cases the fibres are broken and never pulled out. The change in fibre composition has the biggest and most clear effect on the ductile behaviour: a fibre composition of two different kinds of fibres shows the best results, but the ideal ratio between them should still be investigated.

Results show that for UHPFRC specimens with a lower strength of the cement matrix (because of a higher water content for example), the falldown after the maximum tensile is more reduced. In addition, when more water is added, the content of fibres could be increased (while the concrete stays self-compacting), which could possible improve the ductile behaviour.

So, to conclude which is the best dosage, we arrive at dosages 7 and 8, as for these dosages the water content is more and consist of two kinds of fibres.

Apart from the results, two things can be concluded: first, the formulas proposed by (Blanco, Pujadas, Cavalaro, Fuente, & Aguado, 2014) are very good approaches to estimate both the stress and the strain. The mean values for the failure angle (β), friction coefficient (μk) and the number of cracks (n) can be used for every specimen. Respectively, they are: 25° ; 0.7 and 3.

Second, by looking at the inside of the specimens, it became clear that the short straight fibres are not completely dispersed. This causes that these groups of fibres are not broken but pulled out of the cement matrix. The reason is the hydrophilic properties of these kinds of fibres, as they start to bind as soon as they come in contact with water (which is present in the air and causes this).

Chapter 8: Recommendation for future work

The investigation aimed to study the ductile behaviour of UHPFRC reinforced with polymer fibres. Hence, a few limitations arise due to the lack of full depth investigation in one specific concept. Therefore, more future work is recommended based on the findings of this preliminary investigation. The following is a list of suggestions for future work:

- Fabricate more specimens for one dosage and pay more attention during fabricating. This is in order to avoid a huge scatter in the results.
- Associated to avoid the big scatter, it could be useful to perform both Barcelona tests and beam tests in the future and compare them. Although, the scatter should be less in the Barcelona test, as explained in (Blanco, Pujadas, Cavalaro, Fuente, & Aguado, 2014).
- If the main aim is to reach a good ductility, the most important factor are the fibres. The biggest recommendation based on this investigation, is to add more fibres; both PVA and PP fibres. This in order to increase the zone where the fibres work.

  However problems could arise in terms of the workability. Therefore, more water should be added, but this will decrease the strength of the cement matrix. Consequently, an intermediate solution must be found. Another solution could be just increasing the PCE amount, so the W/C ratio stays low.
- Finding a solution for fibres with hydrophilic properties to prevent them from being stuck together when they are added to the liquid concrete.
- Finally, it is very important to dwell on the fact that the properties of UHPFRC depend on the shape of elements. Long thin elements will react differently under tension than robust elements. Moreover, the shape of elements could have influence on its properties as the fibre orientation will be affected because of the flow of fresh concrete. For example: if a beam is filled with concrete at one side, the direction of the fibres will be mostly in the direction which the concrete flows.

  Therefore, it is appropriate to develop protocols to monitor the fabrication of specific elements, as well as to develop prototypes for the behaviour of specific elements in UHPFRC.

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