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Development of Ultra High Performance Fiber Reinforced Concrete.

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Abstract

The usage of ultra-high strength concrete with high compressive and flexural strength has been significantly increasing in modern day construction. The use of locally available materials for producing Ultra High Performance Fiber Reinforced Concrete (UHPFRC) can significantly reduce the cost gap that is one of the main obstacles to the production of such concrete. This research study aims at the development of UHPFRC using locally available materials in Finland, characterized by high compressive and flexural strength properties. The study is focused on producing both white and grey UHPFRC. The research includes the use of locally manufactured cement, quartz and limestone fillers, silica fume and superplasticizers.

Water demand tests by Puntke method were carried out to optimize the filler content and type. A large series of preliminary tests were carried out to evaluate the effect of different mixture proportions and material contents on the flow and compression properties of Ultra High Performance Concrete (UHPC). The fresh and hardened properties of the UHPC and UHPFRC were studied such as flowability of the mix, compression and flexure strength. Compressive strength of 148 MPa with grey UHPFRC and 155.5 MPa with white UHPFRC were achieved using standard curing conditions. Significantly high flexural strength value of 29 MPa was achieved with grey UHPFRC. It was observed that the addition of fibers have a significant effect on the compression strength of white UHPFRC and flexure properties of grey and white UHPFRC. The flowability of the mixture was slightly reduced by the addition of fibers but was still capable of producing self-compacting UHPFRC. The specimens were cured under standard conditions. The optimum dosage of silica fume was found out to be 20 % by cement weight. Pika cement was found out to be the best cement for production of grey UHPFRC. Results obtained shows that it is possible to produce both white and grey UHPFRC under standard curing conditions by carefully selecting the local materials available and proportioning them in the right amount.

Keywords Ultra High Performance Fiber Reinforced Concrete (UHPFRC), Compressive strength, Flexural Strength, Self-Compacting Concrete.

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Adnan Syed.

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Introduction

1.1 General Background.

Concrete is the most widely used construction material around the world presently. The range of applications are as diverse as the scope of construction industry. Concrete is used for building highways, high rise buildings, dams, retaining walls, pedestrian walkaways, bridges and all types of other construction works. It is the most flexible construction material which can be combined with other materials to overcome the deficiencies of each other resulting in a more durable and efficient structure. The continuous developments in field of construction materials has made it possible to produce different types of concrete for a wide range of applications. The use of mineral and chemical admixtures to alter the properties of conventional concrete has made it possible to construct different types of shapes which were either impossible or extremely expensive with normal concrete.

Ultra high performance concrete is a recent development in the construction industry and plenty of research is going on for its development and cost reduction. Ultra high performance concrete is simply a type of concrete which is characterized by high packing density through incorporation of fine aggregates and other inert filler materials and removal of coarse aggregates from the mix recipe. The close packing of materials along with high binder content and low water to binder ratio incorporates a much larger compressive strength than normal concrete. Richard et al. (1995) stated that UHPC is a special type of concrete with a compressive strength higher than 150 MPa and has a tensile hardening behavior possible through the incorporation of short steel fibers into the mix. The flowability of the UHPC is maintained by the addition of a high range water reducing admixture as the water to binder ratio is quite low in this case. The strong properties in both compression and flexure along with self-consolidating behavior makes it a very special material for different construction uses in both architectural and structural applications. Using a combination of cement, silica fume, crushed quartz, steel fibers and the application of pressure and heat can result in the production of concrete with a compressive strength up to 800 MPa (Richard et al. 1995). The recent interest in this field is the development of an economic UHPC produced using locally available materials and without the application of any special techniques.

Otto Graf achieved a compressive strength of 70 N/mm2 in the 1950s and Kurt Walz proposed in the 1960s that a compressive strength of 146 MPa is achievable for concrete. The evolution of UHPC took place with the invention of silica fume and the removal of coarse aggregates from the mix (Ekkehard et al. 2014). The excellent strength and durability properties of UHPC makes it eligible for numerous applications in the construction industry but there are certain issues that can halt its potential acceptance:

1. UHPC is quite expensive concrete.
2. The lack of local materials use discourage the production as it can incur additional transportation costs.
3. UHPC is quite sensitive to any changes during the production phase and requires skilled workmanship to avoid any problems during the production phase.
4. Lack of standard tests for UHPC. (Erallo Technologies 2012).

The review of research-in-progress in the field of UHPC showed that it is mostly focused on the development of high strength concrete with local and easily accessible raw materials. This trend has evolved due to the limitation of high costs associated with UHPC development. The focus is more and more on how to reduce the composition of binder content and replace it with supplementary cementitious materials (SCMs) which are much cheaper. The sensitivity of UHPC to a slight change in composition, high packing density requirement, and good workability with low w/c ratio makes it a difficult task to make enormous changes. However recent research has shown good positive signs as UHPC produced with local materials has not only shown good compressive strength but has also shown excellent durability and high ductility.

1.2 Research Significance.

The aim of this research project is to develop Ultra High Performance Fiber Reinforced Concrete (UHPFRC) using locally available materials. The cost limitation of UHPC has made local producers reluctant of producing it as the transportation costs of raw materials has made it unaffordable. The research project aims at encouraging the use of local available raw materials in Finland for producing a cost efficient and high performance concrete.

To create a new cost efficient UHPC-using locally available materials and with high compressive and flexural capacity is the current goal and purpose of this thesis. Previous research indicates that using locally available materials and with different mix proportions, curing regimes concrete with compressive strength of more than 150 MPa has been constructed. The aim of this thesis is to produce UHPFRC with high compressive strength, excellent flowability and tensile hardening behavior.

The UHPFRC will be produced from both white and grey materials. This will enable its use in load bearing elements as well as in façade elements where aesthetics is a key consideration. The developed UHPC can be an alternative for conventional reinforced structures due to its high flexural strength properties. Generally, this type of concrete has a high early strength gain, so it can be of great use in pre-stressed elements.

1.3 Methodology.

The following research methodology was adopted:

- Acquisition of previous literature related to development of UHPC locally.
- Selection of suitable locally available materials for UHPC production based on the studied literature.
- Optimization of UHPC for obtaining suitable mix combinations of the material constituents, and observing the effect of variation of material constituents on the mix properties.
- Performing mechanical and rheological testing on the optimized mixes.
- Analyzing the results and deriving conclusions based on the above procedure.

1.4 Scope of Work.

The work program is summarized as:

1.4.1 Preliminary Laboratory testing.

- Water demand tests by Puntke method.
- Mini Flow tests.
- Compressive strength testing of cubes.

1.4.2 Final Laboratory testing.

- Producing UHFPRC from optimized UHPC mortars.
- Assessment of fresh concrete properties through flow table tests.
- Assessment of hardened concrete properties through compressive strength testing of cubes, and flexural testing of beams casted.

1.5 Thesis Structure.

The research study consists of the following parts as described below:

Chapter 1 (Introduction).

This chapter gives a brief description of UHPC, the significance, scope and methodology of the research project.

Chapter 2 (Literature Review).

This chapter gives a detailed description of previous research in this field, the effect of the material constituents, types and mix proportions on the behavior of mix and some examples related to application of UHPC.

Chapter 3 (Materials used and experimental setup).

A detailed description of the materials used, tests conducted, test setup, test conditions are described in this section.

Chapter 4 (Preliminary test results and discussion).

This chapter analyzes the preliminary test results carried out for developing UHPC.

Chapter 5 (Final test results and conclusion).

The test results of the developed UHPFRC, conclusion of the research study, future recommendations are given in this section.

References.

Appendices.

Chapter 2 Literature Review:

2.1 General Background

This sections contains a review of the results published in scientific literature related to ultra high performance concrete (UHPC). The effects of different material constituents on the properties of the mix, different mix compositions of the constituents and the properties and requirements related to production of UHPC are discussed in this section.

Ultra high performance concrete is a type of concrete exhibiting high strength and durability made up of binders such as Portland cement with a low w/c ratio, micro fillers for increasing the packing density, fine-grained sand, silica fume, a high range water reducing admixture to maintain the workability at low w/c ratio, coarse aggregates less than 5mm and small discontinuous steel fibers incorporated in the mix to overcome the brittle behavior of concrete.

UHPC is a diverse construction material and it can be used for a number of applications related to architectural applications where the aesthetics are a preference such as the facades of huge structures, or structural applications where the strength is a critical factor. The incorporation of steel fibers has enabled UHPC to show excellent compression and flexural strength values than normal concrete. A compressive strength of 200 MPa and a flexural strength of over 20 MPa can be easily achieved with incorporation of steel fibers and controlled curing regimes. For architectural applications Poly Vinyl Alcohol (PVA) fibers can replace the steel fibers (N. W. Paper et al. n.d.).

UHPC with fibers have greater resistance against high mechanical loads and severe environmental conditions and can enhance the durability and structural resistance of concrete structures (Brühwiler et al. 2008).The incorporation of fibers into concrete has revolutionized recent construction methods. Using a combination of cementitious materials and fibers, a high strength concrete can be produced known as ultra-high performance concrete exhibiting excellent durability and phenomenal strength characteristics. The combination of these two materials provides a structural engineer with:

(1) Extremely low permeability: prevents the concrete from chloride attack or other detrimental substances (Denari and Br 2007).

(2) Very high strength: high compressive (over 150 MPa) and flexural strengths (over 10 MPa) and considerable tensile strain hardening behaviour (Denari and Br 2007).The focus areas of modern research in the field of ultra-high performance concrete are the attainment of higher mechanical properties, alternative ingredients to achieve higher strength and durability and also a key area emerging since the past decade is preparation of UHPC with locally available materials to decrease the cost of production.

Some of the issues related to UHPC are given below:

- High costs and lack of control in production.
- Lack of local material use.
- Lack of established UHPC standards
- Sensitive to slight changes in field conditions when casted in-situ.
- Additional equipment facilities for fabrication and training of workers. (Erallo Technologies 2012).

Typical Mix constituents of UHPC:

A typical UHPC mixture is made of CEM-I cement, silica fume, ground silica, fine sand, steel fibers, high-range water-reducing admixture (HRWRA), and water.

In North America the UHPC produced for research and commercial purpose is known as ductal. Table 1 describes a typical mix proportion of ductal. (C. Paper and Gesellschaft 2015).

Table 1 Typical mix composition of UHPC mix (Ductal) used in North America.

Material	lb/yd3	kg/m3
Cement	1200	712
Silica Fume	390	231
Quartz	355	211
Fine Sand	1720	1020
Accelerator	50.5	30.0
Superplasticizer	51.8	30.7
Water	184	109
Steel Fibers	263	156

Aalborg Portland produced CRC in 1986, with a large quantity of silica fume, a water to cement ratio of 0.16 and 2-6 % of fibers. (Aarup 1986).

The following recommendations for mix proportions were developed for use with commercially available constituent materials: (Wille et al. 2011).

- Cement (moderate fineness and low C_3A content).
- Sand-to-cement ratio of 1.4 (maximum size 0.8 mm).
- Silica fume (25 % of cement weight).
- Glass powder (25 % of cement weight).
- Superplasticizer.
- Water-cement ratio of about 0.22.
- Steel fibers (2.5 % of concrete volume).

According to Aziz and Ahmed (2012):

UHPC can be produced by a concrete designer using the following basic principles:

- Eliminate coarse aggregates to have a homogenous mix.
- Optimize grain size distribution to have maximum packing density.
- Reduction in water quantity to leave some non-hydrated cement, which can act as reactive micro aggregate of high elastic modulus.
- Applying heat treatment.
- Addition of fibers.

Fibers are essential for conversion of brittle behavior of concrete while with close packing and heat treatment high values of compressive strength are achieved.

2.2 Mix design of UHPC:

The introduction of different admixtures, new cementitious materials and special concrete production has complicated the mixture proportioning process. De Larrard and Sedran (2002) describes the focus on various concrete properties and the variations in results related to these properties has made it a difficult task. Optimization of particle packing density of concrete requires selection of larger particles with smaller particles filling the voids to obtain a dense and stiff particle structure (Fennis 2012). Fuller and Thompson (1907) developed the concept of grading curves and showed the effect of aggregate packing on the concrete properties. De Larrard and Sedran (2002) proposed several models related to mix design of concrete. Linear packing density model (LPDM) was presented which described the interaction between different particle sizes in the mix. The linear model was modified by introducing another model based on the concept of virtual density. Virtual density was defined as the highest packing density attainable by placing the particles one by one without any alteration in their shape. Further development led to the compressive packing model (CPM). A compaction index K was introduced to take the effect of compaction into account on the packing density. The CPM model is expressed as:

$$K = \sum_{i=1}^{n} K_i = \sum_{i=1}^{n} \frac{\frac{\phi_i}{\phi_{ix}}}{1 - \frac{\phi_i}{\phi_{ix}}}$$

The problem with these models is that the packing density is dependent on the individual fractions or the combinations of the fractions (Yu, Spiesz, and Brouwers 2013). In case of very fine materials as those that are used in production of UHPC, the measurement of packing fraction of such components is not possible. To overcome the problem of measurement of particle fractions of fine materials, (Andreasen and Anderson 1930) proposed the semi empirical equation based on an integral approach for cumulative particle fraction:

$$P(D) = (\frac{D}{D_{max}})^q \ \forall\ D \in (0, D_{max})$$

Funk (1994) modified Andreasen and Andersen Equation model by incorporating the Ds term accounting for minimum particle size shown as:

$$\frac{CPFT}{100\%} = \frac{D^n - D_s^n}{D_L^n - D_s^n}$$

Where CPFT=cumulative percent finer than

D= Particle size

D_s= Smallest particle size,

$D_{L=}$ Largest particle size

N= distribution modulus

In the above model the power “n” represents the distribution modulus. In some literatures n is denoted by “q”. Husken et al. (2008) demonstrated the effect of the distribution modulus on the particle size distribution in their research.

As it can be seen from the (figure 3) higher values of (q>0.5) leads to a coarser mix while smaller value of (q<0.25) leads to a finer mix.

The major drawback of numerical models as described by (Cwirzen et al. 2006) is that all these numerical models assumes an ideal spherical particle shape. This assumption led to supplementary experimental methods that could measure the packing density experimentally and without any dependence on the particle shape as presented by (Ledee et al. 2004). The second drawback of the numerical models described by (Cwirzen et al. 2006) was the presence of the liquid phase filling the voids between particles.

Puntke (2002) described a new method for measuring the packing density mixes containing fine aggregates, fillers and cements. In this approach the shortcomings of the numerical models; particle shape and presence of liquid phase were taken into account. The method described by Puntke (2002) determines the water demand of the dry mix including both the adsorbed and filling water. The filling water is related to the packing density of the mix while the adsorbed water is responsible for fluidity. The only drawback in this approach is that for obtaining the filling water which is the amount required for packing density, one needs to estimate the dependency of the adsorbed water on particle size distribution curve (Cwirzen et al. 2006).

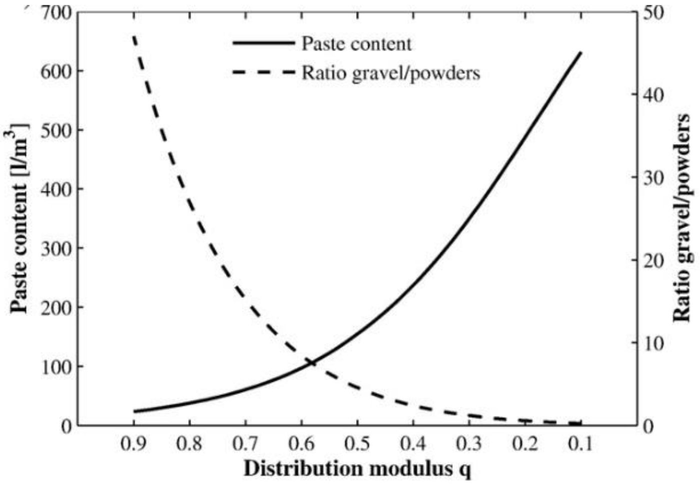


Figure 1 Distribution modulus effect on cement paste (Husken et al. 2008).

2.3 Materials for UHFPRC

2.3.1 Cement:

The basic binder used for UHPC is Portland cement. The selection of the type of cement requires special consideration as the binder content is much more than the conventional concrete requirement. Cements with low amount of calcium aluminates indicates better results for manufacturing high strength concrete (Richard et al. 1995). In terms of best rheological characteristics and good mechanical performance a high silica-modulus cement is preferred (Aitcin et al. 1991). The only problem with such high silica-modulus cement is that it sets very slowly and cannot be used in many applications where a quick set is required (Richard et al. 1995). As for particle size, cements with high Blaine fineness are not used for Reactive Powdered Concrete (RPC) manufacturing due to their high water demand (Richard et al. 1995). Schedyt et.al (2008) showed that an increase of Blaine value of different batches of same cement caused significant in the plastic viscosity and yield stress of the concrete. This led to a decrease in slump flow affecting not only the self-compacting properties of the UHPC but also causes reduction in strength due to entrapped air.

The compressive strength and fresh properties of high strength concrete is strongly related to the type of cement. For UHPC the cement selected should allow high compressive strength in combination with low water demand to also exhibit self-compacting properties. The water demand is related to Blaine fineness value and chemical composition of the cement (Hoang et al.2016).According to research carried out by (Hoang, Hadl, and Tue 2016) compressive strength of over 160 MPa are achievable only with Portland cement having a low water demand. The research was carried out with 8 different cement types and it was concluded that C3A free cements are more effective in achieving high strength with low water demand.

Dils, Boel, and Schutter (2013) carried out a research on the influence of cement type on rheology and mechanical properties of UHPC and showed that it is preferable to use a cement with a low C3A specific surface and an adequate C3A/SO24 ratio and alkali content. Bonneau et al. (2001) showed in his research that coarser cements with low C3A content showed better workability and required less superplasticizer amount than finer cements. The effect of selecting a higher cement strength class did not produced substantial difference in the mechanical properties of the mix due to the presence of a high amount of non-hydrated cement in case of UHPC (Scheydt et.al 2008).

2.3.2 Silica Fume:

Silica Fume is an amorphous polymorph of silicon dioxide, silica. It is an industrial byproduct of silicon and ferrosilicon alloys, zirconium production and has a typical diameter of 0.2 um. Silica fume is recognized as a pozzolanic material which enhances the mechanical properties of concrete. Silica Fume is also known as microsilica or condensed silica fume. Silica Fume is influenced by a high amount of SiO_2 content (normally greater than 90%) and high surface area ranging from 15000 to 25000 m^2/kg. Silica Fume serves three major functions when used in concrete:

- Filling the voids between larger cement particles and filler grains enhancing the packing density.
- The perfect spherical shape of silica fume particles introduces a lubrication effect that enhances the rheological properties of concrete.
- The lime resulting from primary hydration of cement reacts with silica fume particles causing secondary hydration (Richard et al. 1995).

According to an extensive research carried out on the effect of varying material constituents on mechanical properties of concrete by (Ibrahim et al. 2017), the compressive strength of the mix increased with increase in silica fume content from 10 % to 25 %. As the silica fume content was further increased from 25 % to 30 % no significant change was observed in the compressive strength. They further found out that although the 7 days and 28 days strength increased with increase in silica content from 20 to 25 % but the 90 days strength of both specimen were comparable. The study also showed that the drying shrinkage was maximum for the mix containing 10 % silica fume and the lowest values for drying shrinkage were observed with the mix containing 20 % silica fume. Above 20 % addition of SF an increase in drying shrinkage was reported but was still less than the initial one. Author explained this effect that inclusion of silica fume could cause refinement of pores up to a certain limit decreasing the shrinkage but as the limit is reached no further refinement can take place and an increase in drying shrinkage occurs. The silica fume with the highest surface area showed better results than other silica fumes with low surface areas in terms of durability and compressive strength (Bulvar 2016).

Richard et al. (1995) suggested that the optimum amount of silica fume for Reactive Powder Concrete (RPC) should be 25 % of the cement amount. This proportion is close to dosage required for complete consumption of lime resulting from complete hydration of cement but as in this case due to low water proportion complete hydration does not occur and so the amount is slightly more than required.

Chan and Chu (2004) carried out an experimental investigation to see the effects of silica fume content on the bond strength and pullout energy. They found out that the optimum content of silica fume for maximum bond strength and pullout energy is 20-30 %. They also observed that SF effect on UHPC is more pronounced with respect to pullout energy than bond strength. The use of silica fume in UHPC accelerates the hydration product as compared with the use of other SCMs (Yoo and Banthia 2016). They also showed that using silica fume with rise husk ash gave better results for compressive strength than using silica fume alone. The use of silica fume increases the SP demand to maintain the workability of the mix (Sabet, Libre, and Shekarchi 2013). This was explained by (Park, Noh, and Park 2005) who suggested that the greater surface area of silica fume particles allows an increase in adsorption of SP leading to a lower solution amount on the surface of cement particles and a decrease in the fluidity. The most effective mineral admixture in reducing water absorption of concrete was silica fume shown in research carried out by (Sabet, Libre, and Shekarchi 2013). A 20 % cement replacement by silica fume decreased the water absorption by over 40 %. AL Salman, Dang, and Hale (2017) carried out a research for preparation of UHPC with locally available materials. The research showed that the use of silica fume increased the strength at all ages and was independent of replacement rate. They also showed that there were slight differences in the 90 days compressive strength of the mixes containing 5% and 10 % silica fume and the values were higher than mix containing 20 % SF. They proposed that when using SCMs the 90 days strength can be regarded as the ultimate compressive strength of concrete and so a mix incorporating just 5 % of silica fume can give good strength results making it more cost effective choice. The research also proposed that the deviation of their test results from literature might be due to different curing conditions. As the mixtures in their case were cured at 21 º C, temperature and 100 % RH using large amount of silica fume will mean most of that remains unhydrated causing a decrease in compressive strength. This was in agreement with research carried out by showing the influence of temperature on hydration activity and pozzolanic reaction of silica fume. They showed that the C-S-H chains were very small after 28 days when the curing temperature was 20ºC.The research showed the strong influence of silica fume consumption on duration and treatment and an increase from 15 to 70% was found in the pozzolanic activity with change in temperature from 90 to 250ºC.

2.3.3 Fillers

Quartz fillers are crystalline crushed quartz powders with particle size ranging from 1 to 100 µm. Quartz serves two main functions when incorporated into cementitious materials:

- Improves packing density of the mix.
- Consumes portlandite by pozzolanic activity (Cwirzen et al. 2006)

For heat treated high strength concrete crushed quartz is an essential component (Richard et al. 1995). Zanni et al. (1996) showed that the pozzolanic activity of quartz fillers is highly dependent on heat treatment duration. The research stated that there was no hydration activity observed for quartz fillers at 90ºC for 8 hours. There was an increase of 10 to 25 % observed from 8 to 40 hours and 40 % increase was noted after 40 hours of treatment. This explains the strength contribution of quartz fillers in UHPC when the option of heat curing is available and quite high strengths can be achieved utilizing quartz fillers such as precast members cast with UHPC. Generally, quartz fillers are used to reduce the initial porosity of the mix enhancing its compressive strength. AL Salman, Dang, and Hale (2017) stated that due to the the smaller average diameter size of ground quartz, it fills all the possible voids between cement, sand and other hydration products resulting in a stiffer mix. This enhances the mechanical properties of the mix and decreases permeability.

Rougeau (2004) investigated the effect of micro fillers such as metakaolin, pulverized fly ash, phonolith, limestone and siliceous micro fillers on physical and mechanical properties of UHPC. They found out a mix with higher workability when limestone fillers and micronized phonolith were used. Increasing the superplasticizer dosage for metakaolin still yielded a mix with poor workability. Mercury intrusion porosimetry (MIP) tests carried out showed that when silica fume is used as a microfiller, total porosity is quite low compared to other ultra-fine materials used. The pore diameters of mixes with silica fume were also smaller than the pore diameters when other fillers were used. Sabir (2001) showed that metakaolin enhanced the early strength of concrete mixes with no detrimental effect on the concrete strength at later ages. Siddique and Klaus (2009) in his research showed similar results showing an increase in compressive strength and mechanical properties with the use of metakaolin in the mix. The research also found out that mixes made with partial replacement of cement by metakaolin reduces the effect of water penetration through capillary action, is more effective in resisting sulphate attack, reduces permeability of the mix and is more resistant to chemical actions. The incorporation of high reactivity metakaolin replacing 10-15 % cement can control alkali silica reaction. Jedidiah investigated the influence of substituting cement and silica fume with limestone fillers. The research showed that a reduction in mixing time was observed with the incorporation of limestone fillers. A slight reduction in compressive strength and high workability of the mix was observed when limestone fillers were added into the matrix.

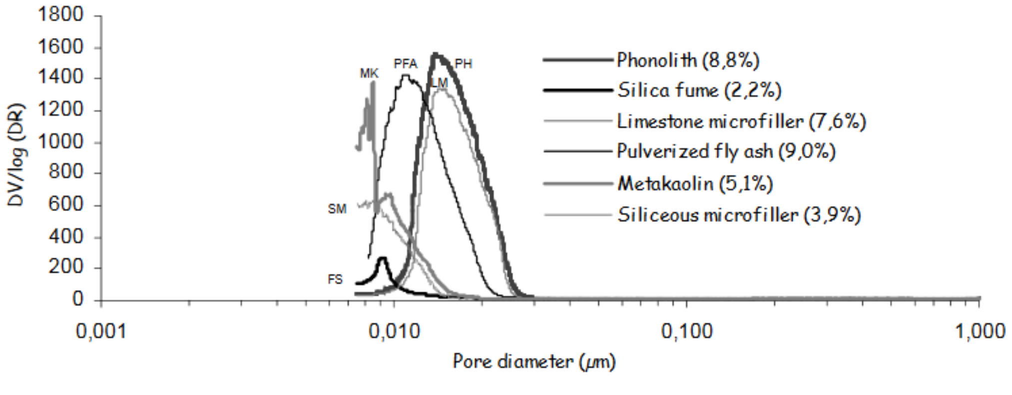


Figure 2 Mercury intrusion porosimetry analysis carried out for different ultrafine particles (Rougeau 2004).

Soliman and Tagnit-hamou (2017) studied the use of finely grounded glass powder replacing silica fume in the mix. The research showed that in order to increase the workability of the mix, 70 % of silica fume should be replaced by fine glass powder with a mean particle size of 3.8 um. The compressive strength of the same mix would show similar properties as compared with mix made up of silica fume alone but no special treatment would be required in order to achieve the strength. Kon et al. (2017) studied the effect of micro silica in hydration of UHPC. The study found out that during high temperature curing of UHPC the use of higher pozzolanic activity micro silica resulted in an increase in substitution of Al for Si in CSH chains resulting in a denser structure and an increase in compressive strength.

2.3.4 Sand and Coarse Aggregates:

Coarse aggregates in normal concrete acts as a rigid skeleton. Cracks are generated by application of force at the paste and aggregate interface. Richard et al. (1995) proposed that the size of the crack is directly proportional to the diameter of the inclusion. The reduction in size of aggregates in case of high strength concrete reduces micro cracks due to chemical, mechanical and thermos mechanical forces significantly.

Richard et al. (1995) described the role of aggregates in RPC and stated that due to reduction in sand content the aggregates does not form a rigid skeleton as it is in the case of conventional concrete, but it acts as a set of trapped inclusions in a continuous matrix. The elimination of coarse aggregates along with optimization of the granular mix results in dense and homogenous cementitious matrix exhibiting high mechanical properties (Richard et al. 1995). The larger aggregates are excluded due to the formation of interfacial transition zone and due to weaker mechanical properties (Cwirzen et al. 2006). A detailed experimental program carried out by Sobuz et al. (2016) described the effect of different sand types and coarse aggregates on the mix properties. The results showed an inverse relation between the fineness modulus and the compressive strength of the mix. The additions of coarse aggregates with CA:FA ratio of less than 0.5 did not reduced the rheological or mechanical properties if the mix. An increased amount of coarse aggregate addition however led to reductions in slump flow and compressive strength. Sobuz et al. (2016) also stated that in case of UHPC the 28 day strength is not a good and accurate representation and due to shrinkage or other reductions long term strength should be a representative. The use of coarse aggregates in the mix can cause substantial reduction in the cost. Ibrahim et al. (2017) studied the effect of increasing fine aggregate size on the properties of UHPC mix. The research findings showed that the early strength was reduced by incorporating larger aggregates but the later age strength of the control mix and the regular sand mix with larger aggregates was almost similar. This is in agreement with Sobuz et al. (2016) who proposed that 28 days strength does not accurately represent the compressive strength of UHPC. The study however showed that the rheological properties were inversely effected with increasing aggregate size. They also tested the mix by using combined sand consisting of regular sand and limestone quarry byproduct and showed that it had better mechanical properties than regular sand alone. The limestone byproduct acts as an inert filler enhancing the packing density resulting in better mechanical properties (Camiletti, Soliman, and Nehdi 2013). Liu et al. (2016) showed that the optimal content of coarse aggregates without effecting the compressive strength value was 25 %. The study also proposed that unlike UHPC without coarse aggregates, the incorporation of coarse aggregates gives a lower utilization efficiency as the fiber content is increased. This is due to the severe interlock between fibers and coarse aggregates.

Ma et al. (2004) compared two mixes, a UHPC mix with basalt coarse aggregates (2-5mm) and an RPC mix with no coarse aggregates and 20 % more paste volume than the UHPC mix. They found out that it was easier to fluidize the UHPC mix in comparison with the RPC mix without basalt aggregates. The autogenous shrinkage value of the UHPC mix was 40 % less than the RPC mix and provided lower strains at peak stress due to the stiffness of basalt aggregates in UHPC mix. Al Salman, Dang, and Hale (2017) conducted an experimental program for production of UHPC using local materials and found out that the effect of finer sand on the compressive strength rise is less pronounced in the presence of silica fume.

2.3.5 SCMs:

Supplementary cementitious materials are used in UHPC for partially replacing cement to make the mix cost effective. SCMs are also used to replace clinker in cement. Recent practices has shown a decrease in the use of clinker in cement from 85 to 77 % and is subjected to a further decrease in the future (Schneider et al. 2011). SCMs include ground granulated blast furnace slag (GGBS), fly ash, silica fume, calcined clays and natural pozzolans. The use of SCMs in concrete is not only driven by the cost perspective but the reduction of CO_2 in concrete production while using SCMs is another reason (Schneider et al. 2011). Randl et al. (2014) also presented the same view that the environment impact of concrete on environment can be reduced by replacing cement with less- energy- intensive-hydraulic concrete additives. Replacement in UHPC where there is a much a higher cement content can be even more environment friendly. Randl et al. (2014) stated that the reduced member sizes in case of UHPC are a further advantage as compared to NSC while considering the ecological point of view. The research proposed that up to 45 % of cement can be replaced by SCMs without affecting the mechanical properties substantially. Also the packing effect created by the substitution of SCMs gives an edge on the decision making while considering UHPC.

Ghafari and Costa (2012) concluded in their research program that the replacement of silica fume by GGBS did not caused any degradation of the mechanical properties and porosity of concrete. In contrast slag replacement showed a slight reduction with respect to mechanical properties but also the porosity of concrete reduced hence giving better results for autogenous shrinkage. Ibrahim et al. (2017) studied the effect of SCMs on UHPC by partial replacement of cement by GGBS and fly ash. The results showed that up to 20 % of cement replacement by fly ash enhanced the mechanical properties of UHPC at later age (90 days). The replacement by GGBS produced comparable strength as the control mixture with no SCMs at 90 days. Wu, Shi, and He (2017) studied the effect of SCM replacement of flexural and rheological properties of UHPC. The effect of SCMs on flowability is shown in figure 3.

As can be seen from figure 3, the research showed an increase in rheological properties of the mix with increasing content of SCMs. Also it can be seen that the flowability of mix replaced by fly ash shows better flow results than the mix replaced with slag. Li and Wu (2005) suggested that the better flow properties of fly ash are associated with its spherical particle shape causing a decrease in water demand. Wei, Handong, and Binggen (2003) also agreed with this statement suggesting the spherical particle shape of fly ash produces a lubricating effect and also suggested the low adsorption of highly active particles in case of high calcium fly ash helps in increasing the flow.

Wu, Shi, and He (2017) also showed the effect of SCMs on the compressive strength under standard, hot water and steam water curing. The results showed that under standard curing slag replacement reduced the compressive strength of the mix and an increase in the strength was noted with the application of heat and steam water curing. The compressive strength of the mix with any type of curing decreased with increase in content of slag. The results also agreed with (Ibrahim et al. 2017) that the early compressive strength reduced due to fly ash replacement but the later age strength was slightly increased under standard curing. The research also proposed an optimum content for fly ash and GGBS for the flexural properties of the mix. The optimum GGBS content is 40 % and the fly ash content is 20 % above which the flexural properties of the UHPC will show a decline.

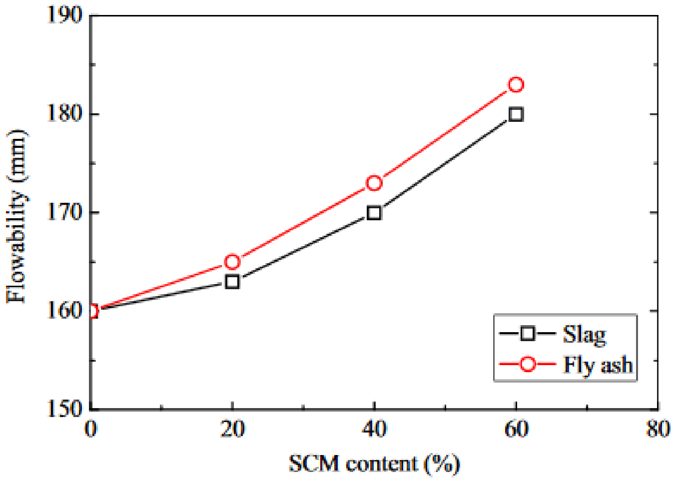


Figure 3 Effect of SCMs on flowability of UHPC mix (Wu et. Al 2017).

2.3.6 Steel Fibers:

Concrete is a brittle material and has very limited post-crack behavior with a sudden failure of the specimen. The steel fibers are incorporated into UHPC to bridge the gap between the cracks and enhance the ductility of the material (Cwirzen et al. 2006). Richard et al. (1995) proposed that an economic optimum content of 13mm long and 0.15 mm diameter steel fibers is 2 %. In case of heat treatment the research suggested the use of much shorter fibers with length of 3mm. (Ibrahim et al. 2017) used high strength /carbon steel fibers with a tensile strength of 2.16 GPa,13 mm length, 0.2 mm diameter (aspect ratio 65) in their experimental program.

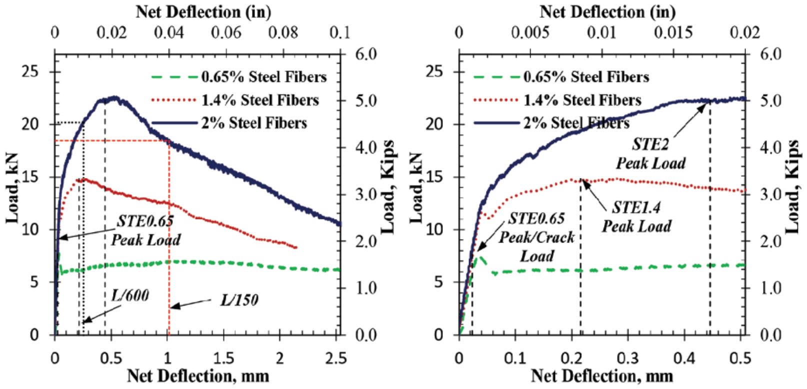
Wille and Naaman (2012) carried out a detailed research on the fibers embedded in HSC and UHPC matrix. The results showed a significant increase in the shear stress results accompanied by hardening of bond stress vs slip curve. In an earlier research carried out by Wille and Naaman (2010) the increase of bond stress vs slip curve was examined by microscopic analysis and the results suggested that the increase may be explained by following 3 factors: 1) wedge effect of abraded particles, 2) scratching of fiber surface, and 3) deformed steel fibers end after cutting. The study also showed that by enhancing the bond between cementitious matrix and fibers through introduction of fine sand particles and silica fume a bond strength of 20 MPa was achieved showing the high tensile behavior and ductility of UHPC with fiber reinforcement. According to Wille and Naaman (2012) an increase in the strength of the matrix compressive strength, fiber geometry, and fiber volume fraction up to a certain range increases the tensile strength and tensile strains at peak stress values. The tests showed that a 28 days compressive strength of up to 292 MPa, tensile strength up to 37 MPa and a strain of 1.1 % at peak stress were observed with a high strength fiber content of 8 % dispersed in an UHPC cementitious mix without any special heat or pressure treatment. Wu et al. (2016) carried out a research to examine the effect of steel fiber content and shape on mechanical properties of concrete.

The results showed that hooked end and corrugated fibers had a much greater impact on the compressive and tensile strengths rather than the straight fibers. The incorporation of 3 % hooked and corrugated fibers increased the compressive strength by 48 % and 59 % at 28 days as compared with straight fibers. The research also described the impact of fiber content on peak loads and showed that though the fibers doesn't have a significant effect on the first crack strength. It greatly enhanced the peak load and peak deflection values. This explains the conversion of brittle behavior into ductile when incorporation of fibers occurs in UHPC. The toughness is largely increased giving a large area under the deflection curve.

According to Sahmaran and Yaman (2007) smooth and small diameter steel fibers reduced the water amount required for workability of self-compacting high strength concrete. The increase in compressive strength was influenced by small dimensions and large fiber volume of fibers delaying the micro crack formation and preventing its propagation once they are formed. Ibrahim et al. (2017) showed that by addition of 0.65 % of fibers improved the compressive strength by 30 MPa. The test results also described the increase in peak load as the fiber content increases from 0.65 to 2 % (figure 4).As seen from the figure when 0.65 % fibers are added the peak load is less than the cracking load and as significant increase in the peak load is observed as the fiber amount increases to 2 %. Addition of further fiber content decreased the strength rate and only 10 MPa improvement was note for every 0.65 % fiber addition. (Wu et al. 2016) described that the incorporation of combination of macro and micro steel fibers can lead to tensile strain hardening behavior of the mix. The tensile strength of UHPFRC increased in a linear manner with an increase of fiber content from 0 to 5 % (Kang et al. 2010). The incorporation of fiber content from 2-5 % increased the cylinder compressive strength of specimen by 3.7 to 25 %, flexural strength increased upto 100 % and shear strength up to 260 % as compared with no fiber content (Kazemi and Lubell 2013).

Ibrahim et al. (2017) noted the effect of steel fibers on drying shrinkage and showed that the shrinkage reduced by 27 % when 2% of the fibers were incorporated into the mix. Garas, Kahn, and Kurtis (2009) showed that the use of fibers can reduce the drying shrinkage by over 100 %.

Wille, Joo, and Antoine (2011) showed that by using 1 % of high strength fibers, strain-hardening behavior of the mix can be established. The formation of multiple cracks during strain hardening behavior will lead to a high ductility



(a) Load vs. net deflection

(b) Relationship showing first crack

Figure 4 (a) Effect of Steel Fibers on Load vs net deflection (b) Relationship showing first crack (Ibrahim et al. 2017).

2.3.7 Superplasticizers:

A high range water reducing admixture is necessary to achieve required workability of the UHPC mix. Super plasticizers enhances the workability of mix at low water to cement ratio hence for UHPC where the water to binder ratio is quite low they are a necessary ingredient.(Plank et al. 2009) studied the effect of two types of polycarboxylates (PCEs) on a cement and silica mix with low water to cement ratio. Methacrylate ester copolymers dispersed well in cement while allylether copolymers dispersed well in silica fume. The research proposed the use of a blended polycarboxylate copolymer to provide better dispersion in both cement and silica. Ma et al. (2008) worked on the effect of addition process of superplasticizers in UHPC. The study suggested the stepwise addition of superplasticizers reduces the viscosity of the mix and increases the workability of the mix. They showed that the delayed addition of the second part increases these properties for cement with high activity index. They proposed a cement/superplasticizer combination for which the superplasticizer addition won't be affected by time such as cement which hydrates slowly.

2.4 Special Treatments

2.4.1 Application of heat:

The application of heat enhances the microstructure of the UHPC mix and increases its mechanical properties (Cwirzen et al. 2006). Ingo et al. (2008) proposed early age heat treatment at 90ºC can greatly accelerate the reaction of silica fume and a 7-day compressive strength of up to 225 MPa can be achieved through this technique. Muller et al. (2008) stated that heat treatment results in a denser microstructure of the UHPC mix which explains the increase in compressive strength. The research also proposed that quartz filler and fly ash reacts better when heat or pressure treatment is applied. Wu, Shi, and He (2017) carried out a research to find out the effect of curing conditions on the mechanical properties of UHPC incorporated with SCMs. The study showed an increase in compressive and flexural strength when the mix was steam cured and hot water cured than the mix, which was cured under standard conditions. Ibrahim et al. (2017) found out that the 28 days compressive strength values were almost similar for mixes that were cured at 23,38 and 90ºC respectively. The compressive strength values were more pronounced at high temperatures of 140 and 200ºC. This probably was because of the high temperatures activating the quartz powder and other fillers which would act inert without heat treatment. The application of heat curing makes these fillers active by taking part in the hydration reactions resulting in longer C-S-H chains giving a denser microstructure and resulting in higher compressive strength. Binder, Wang, and Wu (2015) agreed with this statement and proposed that heat curing is beneficial for the reaction between the CH from hydration of cement and other cementitious materials thus increasing the C-S-H chain length. Wang et al. (2012) stated that at a curing temperature of 250°C the C-S-H chains dehydrates resulting in xonotlite.

Yoo and Banthia (2016) suggested that standard curing conditions could also result in higher strengths if carried out for longer durations. The study suggested that a compressive strength of 200 MPa could be achieved through standard wet curing at 20°C for 91 days. Bulvar (2016) showed that the standard and hot water curing after 56 days has less pronounced effect and the compressive strength gain rate decreases substantially.

Zanni et al. 1996) investigated the effect of heat treatment on UHPC using NMR technique. The results showed that the pozzolanic activity of quartz and silica fume depends on the temperature and duration of the curing procedure. A temperature rise from 90 to 250°C increased the pozzolanic activity of silica fume from 15 to 70 %. The duration of treatment also affected the pozzolanic activity of quartz as nothing was observed when treated for up to 8 hours but there was a significant rise as the treatment was continued for more than 8 hours.

2.4.2 Application of pressure:

Richard et al. (1995) explained the effect of pressure on the compression strength of reactive powder concrete. The increase of pressure increases the density of the mix and thus increases the compressive strength of the mix. The application of confining pressure has the following three effects on the concrete mix; (a) reduces the entrapped air, (b) removes excess water via formwork, (c) compensates for the porosity resulting from chemical shrinkage. Justs et al. (1995) carried out an experimental research program to find out about the impact of pressure application on UHPC. The results indicated an increase in the compressive strength, a decrease in porosity and an increase in the density of the mix. An application of 10 MPa of pressure should the most promising effect on the strength rate value. By increasing the pressure upto 50 MPa a slower gain in the concrete strength value was notice, 48 % as compared to 31.4 % just by applying 10 MPa. The increase of compressive strength vs hardening pressure is shown in figure 5. The figure clearly shows the high strength gain rate for hardening pressure value from 0-10 MPa and a slower strength gain rate for further increase as found out by (Justs et al. 1995).

Ipek et al. (2011) also conducted a research program for finding out the effect of pre-setting pressure on the properties of UHPC mix. The results showed that with a 4 % fiber content and a pre-setting pressure of 25 MPa twice the compressive strength value was achieved than without any presetting pressure. The increase of pre-setting pressure to 100 MPa still yielded a higher compressive strength value but the strength rate dropped significantly. The results also indicated an increasing value for Young’s modulus with increasing pressure

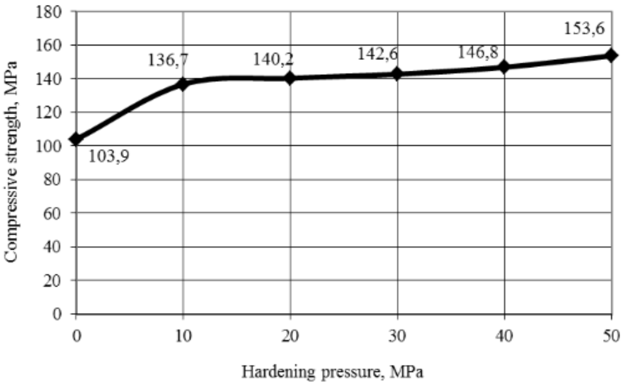


Figure 5 Increase of hardening pressure vs. compressive strength (Justs et al. 1995).

2.5 Advantages of using UHPC

Ultra High Performance Concrete (UHPC) has better mechanical properties, higher durability and resistance to external attacks than normal conventional concrete. The cost limitation of UHPC is the only issue that hinders its use as it is way more expensive than conventional concrete. The use of locally available raw materials and conventional techniques for the production of UHPC is a prime research topic in modern concrete research field. UHPC incorporated with fibers has the advantage of reducing the crack width, stopping the crack propagation and converting the brittle behavior of concrete into a ductile one. Another advantage of UHPC is that a structural member can be constructed without reinforcement by using UHPC incorporated with steel fibers that has enough strength properties in both compression and flexure so to resist the effect of external loads. This is useful for the construction of architectural façade elements where the irregular shapes of the members make it difficult to be constructed with reinforced concrete.

UHPC mix designs shows much higher strength values, increased durability to chemical and environmental attacks due to the high density of the mix achieved through close packing and low porosity than conventional concrete. As UHPC has self-compacting properties it is much easier to be handled and placed than conventional concrete. UHPC has also shown excellent resistance to blast and impact loadings thus is the prime choice for nuclear stations or other high security regions (NPCA).

2.6 Applications of UHPC

UHPC has a wide range of applications credited to the excellent strength and durability properties associated with it. Buitelaar (2004) carried out a detailed study on the development and applications of UHPC in the previous three decades. Some of the practical applications are listed below:

Wear protection:

UHPC has been used as a wear protection material for hydraulic, pneumatic transportation and aggressive material storage systems. The advantages of using UHPC as a wear protection material is its high impact and temperature resistance and the ease of designing the wear resistance system using UHPC.

Concrete Repair:

UHPC has been successfully employed as a repair material for dams where cavitation erosion had created holes in the basin, toe, inlet and spillways of the dams. In Netherlands, a solution was invented for repair of foundation piles by applying a protective layer made of UHPC. UHPC can be also used for the treatment of thin covers of concrete, and strengthening of concrete by shotcreting procedure.

Offshore:

The filling of offshore materials using UHPC can result in increased resistance against increased wave load, weakening of structure due to accident or aggressive environment or fatigue. UHPC strengthens the bearing strength of the filling due to excellent strength properties. Also by using UHPC, slender members would further decrease the deal load and the impact of wave load. UHPC has also been employed in offshore windmills. UHPC can be grouted in the bedrock and casing to strengthen the structure and it can also be grouted in the connections to obtain more rigid fixation of both the structure and individual connections.

Security industry:

UHPC can be applied for building security barrier systems, blast resistant structures. The security barrier systems has been successfully tested against the specified standards and such systems have been successfully implied. UHPC also has shown great results to blast testing and impact loads.

Prefab systems:

UHPC can be used for creating huge ductile structures with slender member sizes and pleasing aesthetics. Recent applications of UHPC includes construction of galleries and stairs but its potential can be seen in the near future by constructing the entire prefab structural system using it.

Industrial floors and pavements:

High early strength, greater wear resistance and resistance to wet sub base conditions makes UHPC as an excellent material for flooring applications. It has been successfully applied as a topping material for various industries such as food industry.

2.7 Structures made of UHPC:

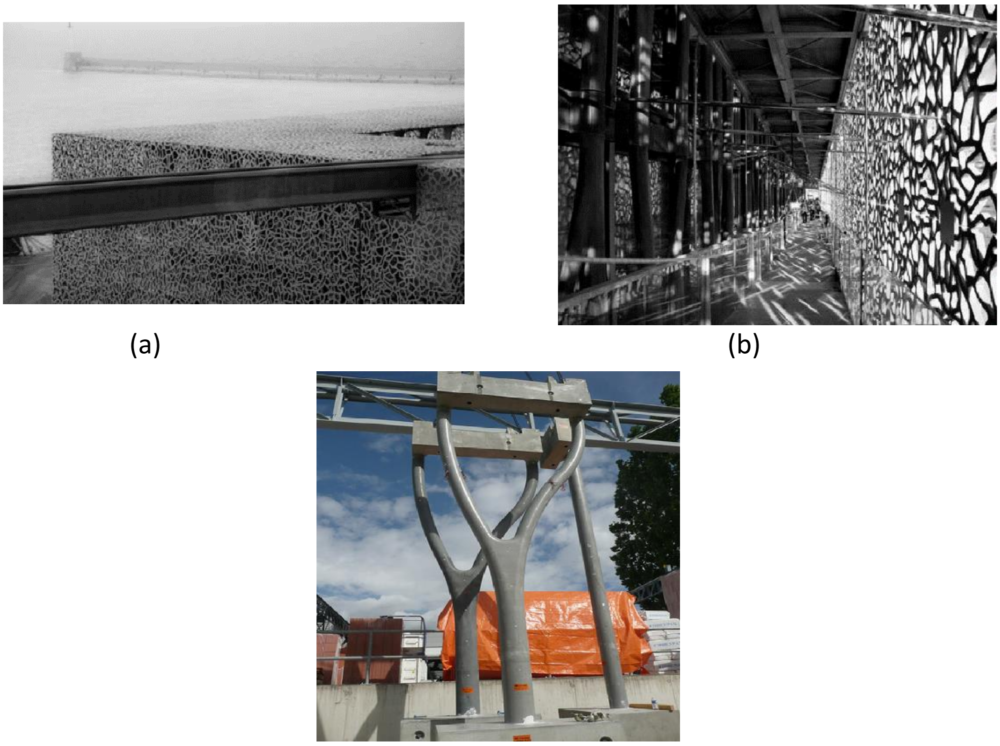
MuCEM (Musée des Civilisations de l'Europe et de la Méditerranée)

Rudi Ricciotti, a pioneer of the architectural application of UHFPRC showed the capability of UHPC in architectural and structural design. He wanted to test the capability of UHFPRC in the design for a whole building through this project. The museum has five levels above the ground and two under. The entrance to the museum is through a 76 m span, 1.8m high footbridge made up of UHFPRC.

UHFPRC is applied in two structural elements in the building; columns of museum façade and the latticework in the second skin. The main supporting structure in the façade of the museum is made of 309 arboreal UHPFRC poles. There are three different families of trees fabricated in 20 different casts with varying height and diameter. The configuration can be straight or upside down thus giving a varied pattern in the façade. Due to incorporation of metallic fibers no passive reinforcement was needed. The trees were composed of straight lines, Y-shapes and N-shapes, height varying from 2.89 to 8.79 m and diameter from 25 to 40 cm.

A peripheral beam was cast on top of the poles to support the floors of the museum. Due to financial reasons floor were cast of prefabricated elements of C60 concrete and required additional post tensioning.

The latticework is constructed of 384, 6 by 3 meter prefab panels. They are attached to each other by stainless steel bi-articulated joints to allow the panels to warp and expand freely. The strands are branches of UHPC in trapezium shape. The overall thickness of the panels is 7 to 8 centimeters. The latticework is self-supporting in the vertical direction and is attached to the main structure with stainless steel rods to take horizontal loading. On the roof the panels are laid out on a metallic framework. This framework is supported by exterior UHPC brackets. The walkways around the museum are also suspended from this construction. The latticework is a fine example of the architectural application of UHPC for durable façade elements.(Paper *et al.*,NPCA).



(a) (b)

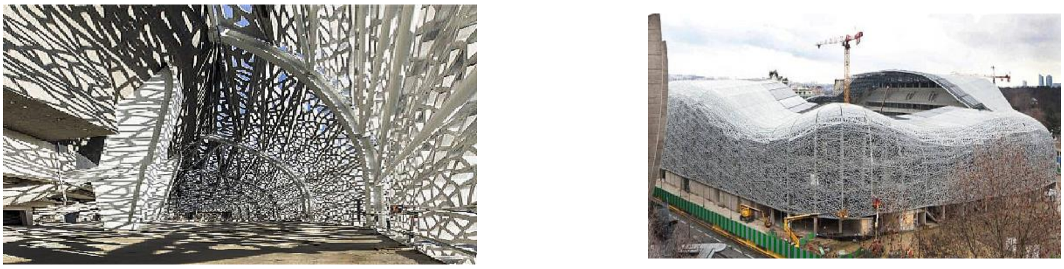
(c)

Figure 6 (a) One of the slenderest pathways linking the MuCEM to the Fort Saint-Jean has neither arch nor cable (b) Arboreal UHFPRC poles in main supporting façade of the structure. (c)Tree like UHPC columns in MuCem. (Lafrage).

Stade Jean Bouin:

The Stade Jean Bouin in Paris, France was redesigned and rebuilt to host up to 20,000 spectators in such a fashion to reduce its impact on the urban surroundings as much as possible. Ruddy Ricciotti presented the solution to this technically difficult objective, by creating a precast UHPC lattice-style façade system that is light and airy as shown. This included a 23000 m^2 envelope, including a 12000 m^2 roof, made of 3,600 self-supporting triangular UHPC panels, each approximately 8 to 9m long by 2.5m wide and 0.45 m thick.

This envelope provides a complete cover to the stadium in an amorphic fashion protecting the spectators from the elements and providing an acoustic screen in consideration of surrounding neighborhood. This is a unique project, first of its kind and is another prime example of the architectural use of UHPC. (Paper *et al.,* NPCA).



(a) (b)

Figure 7 (a) Stade Jean Bouin, open lattice façade allowing sunlight to filter through. (b) 23000 square meter UHPC lattice envelope and roof (NPCA).

Runway, Haneda Airport, Tokyo Japan:

The extension of Tokyo's Haneda airport is an excellent example showing the durability and less weight solutions can be economically implemented by using Ultra High performance fiber reinforced concrete. The new runway was constructed on reclaimed land in Tokyo bay because of lack of space on shore. The substructure near the mouth of the river was constructed of steel driven 70 m below in water.

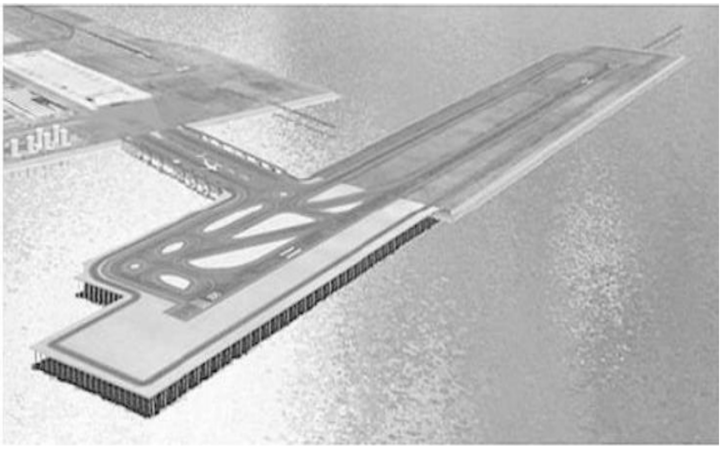


Figure 8 New Haneda Airport runway, Tokyo (Fehling et al.).

Stainless steel jackets were added to deal with severe climatic conditions exposing the substructure to corrosion. The platform was constructed of UHPC elements supported on steel platform. The primary reasons for choosing UHPC were; light weight of the structure minimizing the substructure cost and 100 years design life of the structure.

The total area of platform is 200,000 m^2. The precast slab had dimension of 7.8×3.61m. The elements were ribbed in the direction of the shorter span and different concreting techniques were employed to get optimum fiber orientation with respect to anticipated loading. The fiber reinforced ribbed UHPC slabs has a depth of just 135 mm designed for max. Wheel loads of 320 kN. Employing UHPC resulted in 50 % reduction of the overall weight of the structure as compared with conventional concrete. (Fehling et al. 2014 UHPC).

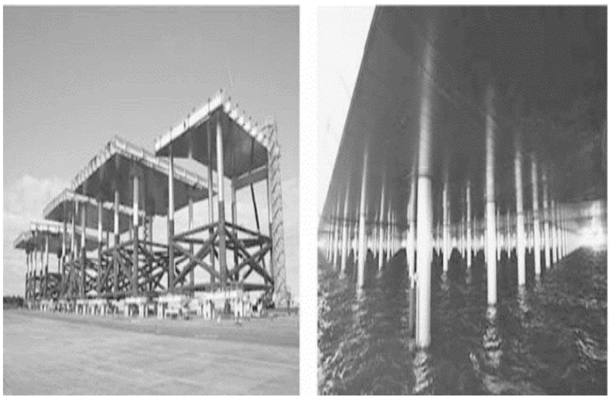

(a) (b)

Figure 9 (a) Stainless Steel Jackets (b) UHPC element details. (Fehling et al.).

Glenmore/Legsby Pedestrian Bridge

Glenmore Pedestrian Bridge is a single span, 53m long bridge with 8 lanes of traffic. The bridge has a drop-in, 33.6 m long girder made up of UHPFRC with a T-shape section. The girder has a depth of 1.1 m at the mid span with a 3.6 m wide deck weighing 100 tons. The bridge has two cantilevered abutment that are made of high strength concrete. The steel fibers used have an aspect ratio of 65 and are post tensioned with 15 mm strands. Total number of 42 strands are used. A passive reinforcing system was constructed by using Glass fiber-reinforced plastic bars. (Paper *et al.*,NPCA).

Figure 10 Glenmore Pedestrian Bridge. (NPCA).

Chapter 3 Materials and Experimental Program

3.1 Introduction:

This chapter describes the experimental program and the constituent materials that were used in this research to produce UHPFRC.

The research work was carried out in two parts. The first part of the research program was composed of preliminary laboratory tests carried out to obtain optimized mix compositions for both grey and white UHPC. The determining factors during the preliminary laboratory tests were the minimum water demand of the aggregate combination, the compressive strength and the mini flow of the mix. Preliminary mixes were cast with Hobart mixtures. Puntke test was used for the determination of an appropriate combination of fine aggregates and fillers that would correspond to the lowest water demand and the highest packing density. The water demand values were then compared with compressive strength of the cubes and the flow results obtained through mini cone test and a correlation was established between the three values.

The preliminary tests also included the investigation of the influence of different mix components on the rheological and mechanical properties of the mix. This investigation was useful in getting an appropriate amount of the mix components which will lead to a mix with excellent rheological properties and high compressive strength. The influence of the following components on the rheology and mechanical properties of the mix was evaluated during this phase:

- Silica fume type and dosage.
- Cement type.
- Superplasticizer type and dosage.
- Cement replacement by SCMs with different dosage rates.
- Influence of Coarse aggregate.
- Influence of different filler types and dosage.

The final tests included more extensive tests, and were actually an extension of preliminary laboratory tests. The preliminary test results gave optimized UHPC mixes with respect to maximum strength, maximum flow and also mixes with excellent strength and flow values were obtained. These mixes were then incorporated with fibers to obtain UHPFRC and the fresh and hardened concrete properties of the mixes were analyzed in this phase. The tests included the slump flow tests, compressive strength testing of cubes and flexure testing of beams. The compressive and tensile strength properties of the obtained UHPFRC were analyzed in this phase. The research program was focused on both white and grey UHPFRC.

3.2 Materials:

UHPC is produced using cement, silica fume, quartz fillers and fine sand. The cement and silica fume constitutes the binder component of the mix while quartz fillers and fine sand constitutes the aggregate component of the mix. Due to a very low water to binder ratio superplasticizer is also added to the mix. The effect of steel fibers and coarse aggregates is also studied in this research project. White cement and limestone fillers are also used to produce white UHPC. The detailed description of these materials is described in this section.

3.2.1 Cement

Cement is the basic binder of UHPC paste and is present in much larger proportions than in conventional concrete. Cement holds the fine aggregate materials together and reacts with the mineral components in the hardened concrete mass. In this research four types of cements produced by Finnish manufacturer Finnsementti were used. Grey UHPC was casted with Plus, Pika and SR cement while white UHPC was cast with white cement. All four cements conformed to the standard SFS-EN 197-1: 2011.

- Pika cement is a very fast hardening Portland cement CEM I 52,5R. It is used for construction where formwork has to be removed quickly due to its higher early strength gain. It is most favorable type of cement used for ultra-high strength concrete due to its excellent compressive strength properties. Pika cement was the main cement used for casting grey UHPC.
- White cement was used for making white UHPC. The purpose of developing white UHPC was to develop a concrete with high compression strength and excellent flexural strength properties for irregular shapes like façade of a building. The aesthetics and strength both would be fulfilled by using this type of concrete. White cement has greater early initial setting time than other cement types. It has the highest early age strength gain and has very low amount of inert constituents.
- SR cement (Sulfate resisting) is classified as ‘CEM I 42.5 N-SR3’, Portland cement with a small percentage of limestone as inert constituent. It is composed of 95 % clinker and has slightly higher strength than plus cement. SR-cement is used in structures exposed to high levels of sulfate ions as: harbors constructions, waste water systems, dams, underground water pipes, foundations, sewers, irrigation canals and treatment plants. It is appropriate cement for using at the structures that require resistance against chemical effects such as sea water and sulfate environment
- Plus cement is the most commonly used cement for general construction purpose in Finland. Plus cement has 15-25% of blast furnace slag by composition. It has 65-79% clinker and is classified as ‘CEM II/B-M (S-LL) 42.5 N’ Portland cement. This type of cement is classified as ordinary strength class cement.

Table 2 Chemical composition of Pika, white, Plus and SR cement.

Clinker Components	**Pika**	**White**	**Plus**	**SR**
CaO	63-65%	69%	63-65%	64-66%
SiO_2	20-22%	24%	20-22%	20-22%
Al_2O_3	4-5.4%	2.1%	4-5.4%	3.1-3.7%
Fe_2O_3	2.8-3.3%	0.3%	2.8-3.3%	3.9-4.2%
MgO	2.5-3.2&	0.7%	2.5-3.2%	2.7-3.5%
C_3A	Nil	<5%	Nil	<3.0 %
SO_3	3.5-3.9%	1.8-2.3%	3.0-3.3%	2.5-2.9%
Cl	0.08%	0-0.04%	<0.08%	<0.08%

Table 3 Physical properties of Pika, white, Plus and SR cement.

Physical Property	**Pika**	**White**	**Plus**	**SR**
Fineness (Blaine value) (m^2/kg)	510-600	390-420	420-470	380-410
Soundness (mm)	0-2	0-2	0-1.5	0-3.5
Initial setting time (mins)	120-180	110-160	150-210	160-200

Table 4 Compressive strength properties of Pika, white, Plus and SR cement with time.

Compressive strength	**Pika**	**White**	**Plus**	**SR**
1-day (MPa)	28-32	19-25	10-14	13-16
7-days (MPa)	41-46	53-65	34-39	43-48
28-days (MPa)	48-60	66-76	46-52	54-59

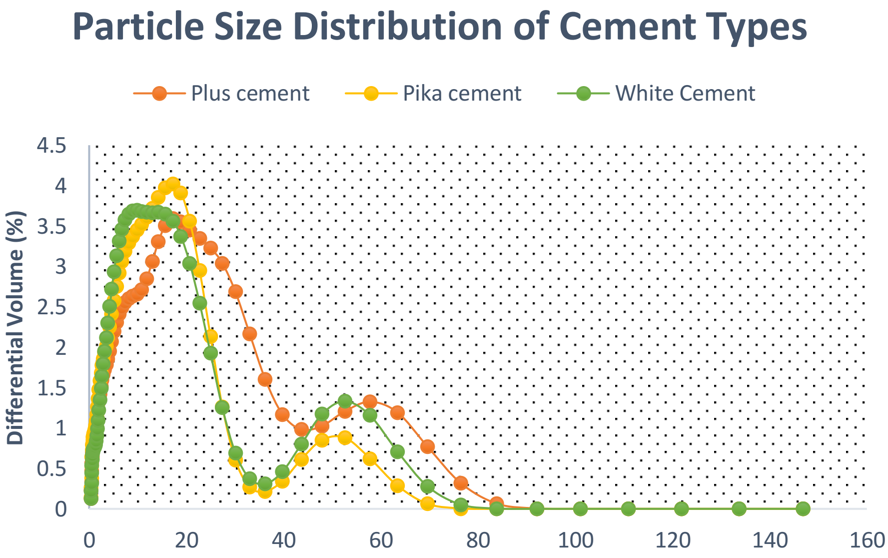


Figure 11 Particle size distribution of Cement types obtained through Laser Analyzer.

3.2.2 Silica fume

In this research program three types of silica fume were used. The first type was densified grey colored ultrafine amorphous powder silica, Elkem Microsilica Grade 920E D. It has a minimum 85 % SiO_2 content and is suitable for all concrete works where silica fume is required. The second type of silica fume used was also a product of Elkem microsilica known as Grade 940 U. It was an undensified powder and was regarded as a highly reactive pozzolan by the manufacturer. Elkem 940 U had a higher SiO2 content of more than 90 %. The third type of silica fume Elkem microwhite was used for the production of white UHPC. It contains slightly higher content of carbon as compared with the grey silica fume, and was used for producing white UHPC. The detailed physical and chemical properties of the above-mentioned products as specified by the manufacturer are given below:

Grade 920 E

Table 5 Physical and chemical properties of densified Silica fume 920 E.

Component	**Value**
SiO_2	Minimum 85 %
SiO_3	Maximum 2 %
Cl	Maximum 0.3 %
Free CaO	Maximum 1.0 %
Free Si	Maximum 0.4 %
Loss on ignition	Maximum 4 %
Specific Surface Area	15-30 m2/g
Pozzolanic Activity Index, 28 days	Minimum 100 %
Specific Gravity	2.2-2.3
Bulk Density	150-700 kg /m3

Grade 940 U

Table 6 Physical and chemical properties of undensified Silica Fume 940 U

Component	**Value**
SiO_2	Minimum 90 %
Loss on ignition	Maximum 3 %
Coarse particles >45 um	Maximum 1.5 %
Bulk Density (U)	200-350 kg/m3
Specific Gravity	2.2-2.3
Specific Surface area	15-30 m^2/g

Microwhite

Table 7 Physical and chemical properties of Elkem Michrowhite Silica.

Component	**Value**
SiO_2	92-95 %
C	2
Cl	<0.3
CaO	0.6
Bulk Density	200
Loss on ignition	98.5 %
Specific Gravity	2.2-2.3

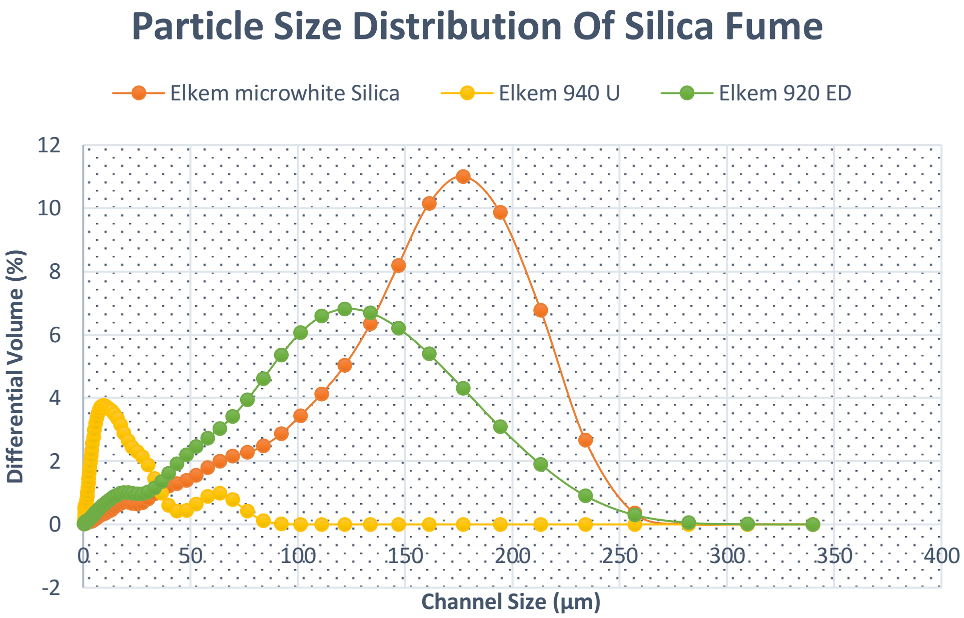


Figure 12 Particle size distribution of Silica fume types obtained through Laser Analyzer.

3.2.3 Aggregates

Fine sand having a particle diameter from 0.1-0.6 mm was used as an aggregate for producing UHPC. The UHPC with coarse aggregates involved coarse aggregates with sizes ranging from 0.5-1.4, 1-2 and 2-3 mm. The particle size distribution of fine sand obtained through laser analyzer is shown below:

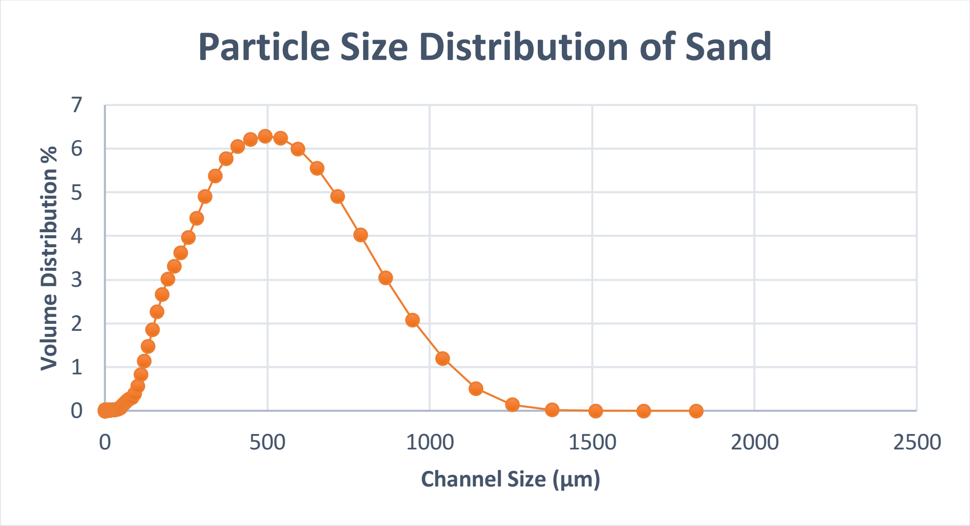


Figure 13 Particle size distribution of sand (0.1-0.6 mm) obtained through laser analyzer.

Other data related to fine sand obtained through the laser analyzer is described in the table below:

Table 8 Statistical size analysis of fine sand (0.1-0.6 mm) obtained through laser analyzer.

Property	**Value (µm)**
Mean	460
Median	425
Mode	517
S.D.	244
D10	172
D50	425
D90	807

3.2.4 Fillers

Two groups of fillers were used; limestone and quartz fillers. Quartz fillers were used with grey UHPC while limestone fillers were used for producing white UHPC.

Quartz Fillers:

Quartz fillers were used for making grey UHPC. Two types of quartz fillers produced by Sibelco Europe were used; FFQ 45 Quartz and NFQ 0-0.2 quartz.

FFQ 45 Quartz:

The FFQ 45 quartz is produced from pegmatite ore using flotation technique. The mica is first removed and then the feldspar and quartz are separated into two different products. The dried products are further cleaned by high magnetic separation to remove the remaining iron containing minerals before grinding.

The chemical composition of FFQ 45 quartz specified by the product sheet is shown in table x. The mineralogical composition of FFQ 45 quartz is 96 % quartz and 4 % feldspar. FFQ 45 quartz has a specific gravity of about 2.6 kg/dm^3 and a bulk density of about 1.4 t/m^3

Quartz NFQ 0-0.2:

The second type of quartz filler used was the NFQ 0-0.2 quartz. NFQ quartz is produced from Nilsiä quartzite ore using flotation technique after crushing, grinding and classification. It is used as a raw material in glass-, steel and building material industry. It is composed of 99 % quartz and has a specific gravity of approximately 2.65 kg/dm^3.The chemical composition as specified by the developer is presented in the tables below:

Table 9 Chemical properties of FFQ 45 and Nilsia Nfq 0-0.2 quartz fillers.

Component	**FFQ 45**	**Nilsiä NFQ 0-0.2**
SiO2	98.7%	99.4%
Al203	0.7%	0.3%
K2O	0.12%	0.06%
Fe2O3	0.03%	0.03%
CaO	0.04%	100 ppm
Na20	0.14%	-
L.O.I	-	0.2%

Table 10 Statistical Size analysis of FFq 45 quartz filler obtained through laser analyzer.

Property	**Value (um)**
Mean	16.9
Median	12.1
Mode	19.7
S.D	15.9
Variance	253.7
D10	1.5
D50	12.1
D90	40.3

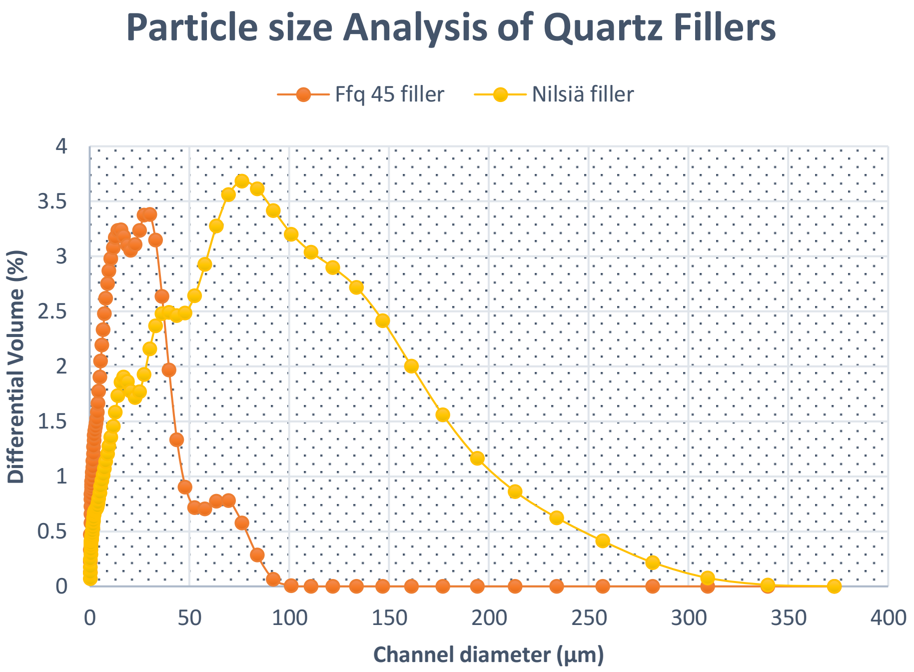


Figure 14 Particle size distribution of Quartz Fillers obtained through Laser Analyzer.

Limestone fillers:

Seven different types of limestone fillers were used for producing white UHPC. They included three different calcites, two Parfill fillers, Tytyri 63 filler and Wollastonite. The description of these fillers is given below:

Calcite Fillers:

Nordkalk C-Series products are micronised calcium carbonate products ($CaCO_3$) that are made from high-quality calcite marble. Using optical separation and foam flotation, impurities are removed from calcites. The enhanced calcite is dried and ground to the desired particle size in an enclosed fine grinding circuit. All of Nordkalk's C-Series products are manufactured in Lappeenranta Finland and their special characteristic is a high degree of whiteness.

Table 11 Physical Properties of Calcite Fillers.

Nordkalk C fillers	C2	C5	C7
Average grain size (d50) µm	2.5	5	7
Cutpoint (d98) µm	10	20	30
Lightness (Ry) %	95	95	94
Oil absorption value g/100g	25	19	17

Parfill Fillers:

Nordkalk Parfill white limestone fillers are an economic way to replace some of the cement in concrete production. With limestone fillers, the concrete will be lighter in colour with less variation and there will be less shrinkage. The chemical composition of the two Parfill fillers used as specified by the manufacturer is given below:

Table 12 Chemical Properties of Parfill Fillers.

Component	Parfill 80	Parfill H80
CaO	50.5%	49%
SiO_2	4.8%	7.4%
Al_2O_3	1.1%	1.6%
Fe_2O_3	0.38%	0.59%
MgO	1.6%	1.8%
K_2O	0.28%	0.41%
Na_2O	0.17%	0.25%
MnO	0.015%	0.021%

Nordkalk wollastonite and Tytyri 63 filler:

These two products were also manufactured in Finland by Nordkalk. The chemical composition of Tytyri 63 filler is described below.

Table 13 Chemical Properties of Tytyri 63 filler.

Component	Tytyre 63
CaO	36.9%
SiO_2	12.4%
Al_2O_3	1.5%
Fe_2O_3	1.1%
MgO	11.1%
K_2O	0.29%
Na_2O	0.12%
MnO	0.035%

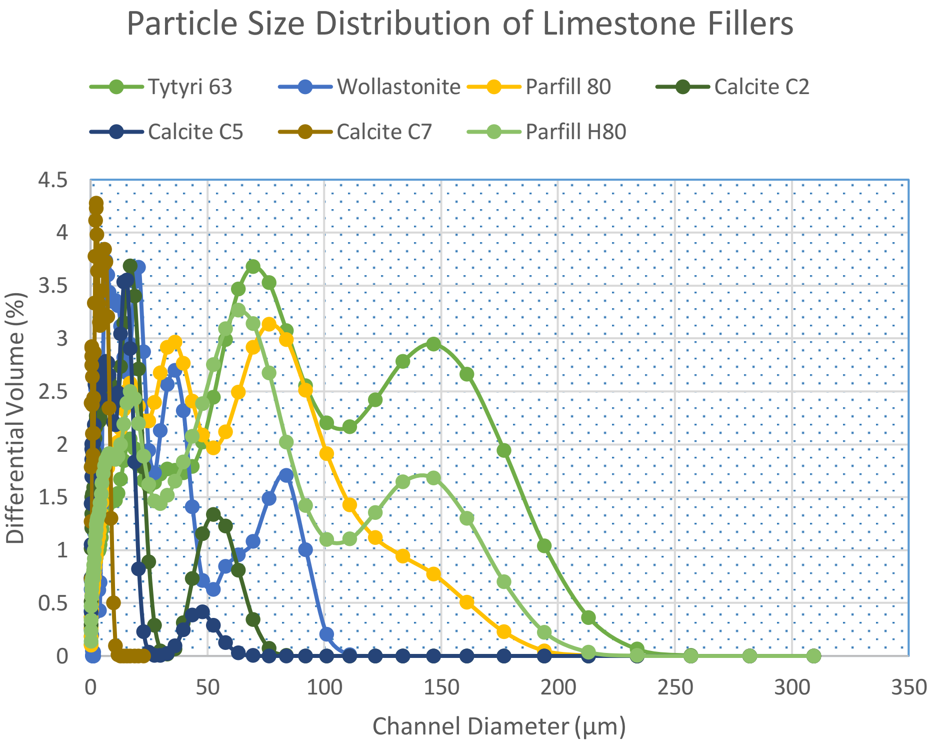


Figure 15 Particle size distribution of Limestone Fillers obtained through Laser Analyzer.

3.2.5 Steel Fibers:

Copper coated steel fibers designed for producing reactive powdered concrete were used for making UHPFRC. The steel fibers used has a length of 13 mm and thickness of 0.2 mm. The extension strength of the steel fibers is 2850 MPa.

Figure 16 Copper coated steel fibers used for producing UHPFRC (Aspect ratio=65).

3.2.6 Superplasticizer

The superplasticizer that was used during this research study was Master Glenium Sky 600 manufactured by BASF.

3.3 Production and Mixing Procedure:

The production of test concrete was divided into two parts, initial preliminary laboratory studies and main testing. The initial laboratory tests were carried out by casting small quantities of concrete using Hobart mixers. The main testing was carried out by casting concrete using Eirich mixer. The mixing procedure adopted for both testing procedures is described below:

Mixing Procedure:

Preliminary tests using Hobart Mixer:

- Slow dry mixing of all the materials for 3 minutes.
- Addition of superplasticizer and mixing for 1 minute.
- Addition of water and slow mixing until the sample turned to a fluid state.
- High Speed mixing for 3 minutes.

The mixing time usually varied from 10 to 15 minutes for grey UHPC while for white UHPC it varied from 13-18 minutes.

Main tests using Eirich Mixer:

- Dry mixing of materials for 1 minute.
- Addition of superplasticizer and water and slow wet mixing for 3 minutes.
- Addition of fibers.
- High Speed mixing for 3 minutes.

The mixing time varied from 7 to 15 minutes. The Eirich mixer was programmed so as if the mixture hadn't turned into fluid state, there was an option for extending the mixing time before ending it.

Curing:

No special curing technique was applied for the production of test samples. The samples were demoulded after 24 hours and stored in a water basin under standard curing conditions till the specified date for testing. The concrete was cured under water at a temperature of 20 degree Celsius.

3.4 Testing:

Laboratory tests were carried out for both fresh and hardened concrete. Fresh concrete was tested for mini flow and flow table tests while hardened concrete tests included compressive strength and flexure strength tests.

3.4.1 Fresh concrete tests:

The fresh properties of UHPC were measured through flow tests. For the preliminary studies only the mini cone flow table test was used while for the main tests both mini cone test and standard flow table test were carried out. The testing standards and procedure are described below.

Flow table test EN 12350-5-2009:

The flow table test is a standard test used for measuring the flow properties of concrete. The test principle is to measure the consistency of fresh concrete by measuring spread of concrete on a flat plate.

Flow table: It consists of a moving table made up of flat plate with a plane area of 700 mm×700 mm.

Mould: It is a metallic plate not readily attacked by cement paste and should be at least 1.5 mm thick. The base diameter is equal to 200 mm, top diameter is equal to 130 mm and the height is equal to 200 mm.

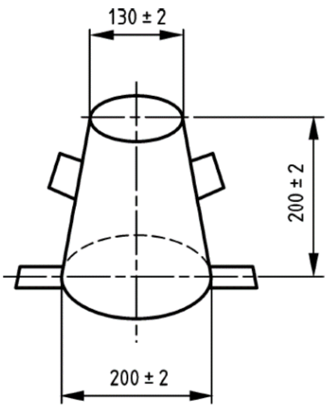


Figure 17 Standard sized mould used for conducting flow table test.

Test Procedure:

The table was placed on a flat and horizontal surface. The table and mould were cleaned and moistened before testing. The mould was filled in two layers, levelled with the help of tamping rod. After filling the mould excess concrete was struck off and the top surface was levelled. The mould was vertically lifted over a period of 1 s to 3 s. The maximum spread value was measured in two directions with maximum spread. No lifting of table was used for measuring the spread value.

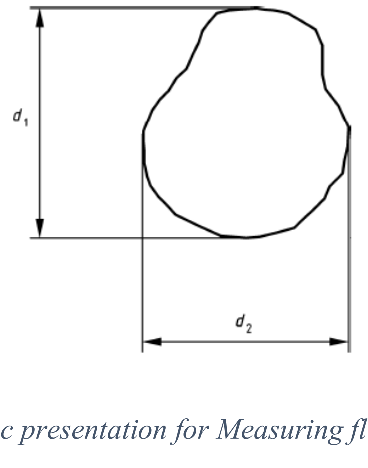


Figure 18 Schematic presentation for Measuring flow value.

Mini Flow table test:

The flowability of UHPC mixtures were evaluated through mini flow tests. The mini flow test is the most widely adopted test procedure for measuring the flow properties of UHPC and self-compacting concrete. The principle of mini flow test is the same as the flow table test but has a smaller mould. The test arrangement is shown in figure a below. The spread value was measured in two perpendicular directions and the average value gave the flowability of the UHPC mix. The base diameter of the mould is equal to 100 mm, top diameter is equal to 70 mm and the height of the cone is 60 mm as shown in the figure below.

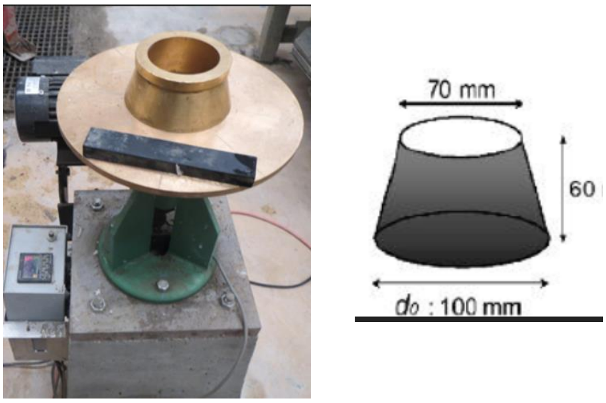


Figure 19 Mini flow table test apparatus and dimensions of the mould.

3.4.2 Hardened concrete tests

The preliminary tests included the measurement of compressive strength only while the final tests included measurement of both compressive strength and flexure strength of the UHPC mix. The standard test procedures implied for measuring these properties are described below:

Compressive strength of Concrete (EN 12390-3):

Principle: Specimens are loaded to failure in a compression testing machine conforming to EN 12390-4. The compressive strength is calculated from the maximum load sustained by the specimen.

Apparatus: Compression testing machine.

Specimen Preparation: For the compressive strength testing, 100 ×100 ×100 mm^3 cube samples were prepared. The mould was covered with plastic sheets after casting and the samples were demoulded after 24 hours. The samples were cured under water at standard conditions. The compressive strength was evaluated at 7 days and 28 days of concrete age. For each casting 6 cubes were prepared, three cubes for 7 days testing and 3 cubes for 28 days testing. The average of the three results was termed as the compressive strength of the sample.

Procedure: The bearing plate was cleaned and the excessive moisture was removed from the sample. The weight of the sample and volume was measured. The specimen was centered with respect to lower platen to an accuracy of 1 % of cube size. Loading rate was selected as per standard to be 0.6 N/mm^2. The cubes were loaded till failure and the compressive strength value was noted from the testing machine. Three samples were tested for each mix and the mean value was termed as the compressive strength of the mix.

Flexural Tests:

The flexural strength of the UHPC and UHFPRC mixtures was calculated using two different methods.

Determination of Flexural Strength of Hardened Mortar EN 1015-11

Principle: The flexural strength of mortar is determined by three point loading of hardened moulded mortar prisms, specimens to failure.

Apparatus: Testing machine conforming to EN 1015-11.

Loading Rate: The load is applied without shock at a uniform rate in the range of 10 N/s to 50 N/s so that failure occurs within a period of 30 s to 90 s.

Specimen Preparation: Three prisms of 40mm×40mm×160mm were made from each UHPC mix casted. The samples were kept in moulds covered with plastic sheets for 24 hours and were demoulded and transferred to water basin. They were cured under water with standard temperature and curing conditions and were tested at 28 days age of concrete.

Testing Procedure:

The testing machine has two supporting steel rollers of length between 45-50 mm and a diameter of 10 mm spaced 100 mm apart, and a third steel roller of same length and diameter located centrally between the supporting rollers. The specimen is kept on the supporting rollers, and the uniform loading is applied until failure. The maximum value of the loading in N and the flexural strength of the specimen is displayed on the screen at failure. The flexural strength is calculated from the maximum load using the following formula.

$$f = 1{,}5\frac{Fl}{bd^2}$$

Where b and d are the internal mould dimensions.

Flexural Strength Test (EN 12390-5):

Flexural strength of the samples was measured using the standard test defined in EN 12390-5.

Principle: Prismatic samples are subjected to bending moment through application of load to upper and lower rollers. Maximum load sustained is recorded and flexural strength is measured.

Apparatus: Testing machine conforming to EN 12390-4.

Loading rate: A constant stress between 0.04MPa-0.06 MPa.

Specimen Preparation: 100mm×100mm×500mm beams were made from each UHPC mixtures casted. The samples were kept in moulds covered with plastic sheets for 24 hours and were demoulded and transferred to water basin. They were cured under water with standard temperature and curing conditions and were tested at 28 days age of concrete.

Testing Procedure: The device for applying force consists of:

- Two supporting rollers.
- Two upper rollers carried by articulated cross member dividing the applied load equally.

The test specimen was placed in the machine centered and in such a way that the longitudinal axis of the specimen was perpendicular to the longitudinal axis of upper and lower rollers. The load was

$$f_{\mathrm{cf}} = \frac{F \times I}{d_1 \times d_2^2}$$

applied at a constant stress of 0.04 N/mm^2 . After the application of initial load, applied load was increased continuously at a rate of 1.0 % until no further load was sustained. The flexural strength was calculated by the following equation.

Where f_{cf}	is the flexural strength of the specimen, in MPa.
F	is maximum load, in N.
I	is the distance between supporting rollers.
D1 and d2	are lateral dimensions of the specimen, in mm.

4 Preliminary Laboratory Tests

4.1 Mix Design:

The optimization procedure of UHPC is a complex task due to the fact that it contains a large amount of binders, fillers and superplasticizers. In order to develop an optimization procedure, a large number of tests were carried out, and relationships were developed between water demand through Puntke tests, rheological properties through flow test and mechanical properties through compressive strength tests. The basic concept was to develop a mix, with excellent compressive strength and suitable flowability. The effect of different composition of material constituents on the flow and compressive strength were also analyzed. The water demand of different filler/aggregate combinations was determined using Puntke tests. The compressive strength was determined according to the European standard EN 1250-3 and the rheological properties of the mix were determined through mini cone test. Both grey and white UHPC were produced and are described in detail in this section.

Puntke Tests:

Puntke (2002), developed a procedure to determine the water demand of dry particle system. The water demand of dry particle system is used to calculate the packing density of the mix. The water demand determined using this test consists of filling water and adsorbed water. The adsorbed water determines the fluidity of the mix and the filling water determines the packing density.

The water demand is found by taking a small amount of the dry powder (50-100g) in a beaker and thoroughly mixing it. Water is added and the container is dropped from a certain height repeatedly until visible moistening of the surface of the material is absorbed. If wetting does not take place, more water is added and the container is dropped again in the same fashion. The water demand of the individual filler components and the mix containing all the components was calculated. The water demand calculation is required for calculating the packing density of the mix, which results in obtaining the appropriate amount of material components for the mix.

4.2 Optimization procedure of UHPC

The first step in the optimization procedure was the calculation of water demand of different combinations of binary mixes to get an appropriate amount of filler/aggregate ratio. The water demand of the mix containing all the mix components was also calculated. The minimum water demand gives the maximum packing density of the mix leading to selection of appropriate amounts of the mix components. The water demand tests were carried out for quartz and limestone fillers. For the same combinations of sand and filler reference concrete was produced. The reference concrete had a constant mix proportion of all other components.

The mix composition of the reference mix is given in the table 14 below. The proportions of the reference mix were varied according to filler/aggregate content for optimization of fine aggregates. Puntke tests served a basis of providing an appropriate filler/aggregate amount for maximum packing density, and was verified through the evaluation of mechanical and rheological properties of the mix cast on the basis of water demand test.

Table 14 Mix proportions by cement weight of the reference mixture for preliminary tests.

Material	Composition by cement weight	Composition (kg/m3)
Pika cement	1	817
Elkem 940 U Silica fume	0.25	205
FFq 45 quartz filler	0.25	205
Sand	1	817
Water	0.25	205
Superplasticizer	0.05	41

The reference concrete were produced using Hobart mixers. Rheological properties were calculated through mini cone test. Concrete cubes 100×100×100 mm^3 were produced and compressive strength was evaluated using the procedure defined in EN 1250-3. All the specimens were cured at standard conditions and no heat or pressure treatment was done. The curing procedure included covering the specimen with a plastic sheet after casting, demoulding after 24 hours and storage in a water basin until the test date. The same procedure was carried out for ternary mix combinations.

In this research study both grey and white UHPC were studied. The grey concrete was manufactured using grey cement, grey silica fume and quartz fillers. White UHPC was manufactured using a combination of white cement, micro white silica fume and limestone fillers.

4.3 Preliminary Test results for binary mixes:

4.3.1 FFQ 45 quartz filler

The results of Puntke tests carried out for FFQ 45 quartz filler is shown in figure 15. Puntke test was carried out for mixture of filler/sand combination as well as for mix containing all the components. The water demand of filler/sand combination gives an approximation of the optimum filler/sand ratio leading to maximum compressive strength. The results showed that the optimum amount of quartz fillers with respect to lowest water demand for FFQ 45 quartz was 40 percent quartz filler and 60 percent sand. The increase in the amount of quartz filler attributed to a decrease in flow as shown by the mini flow table test of the prepared samples. This was due to the increased amount of water adsorbed on the surface of quartz fillers (Cwirzen et.al 2006). The compressive strength increased with increasing the filler/sand ratio and the highest result was obtained for a combination of 60 % sand and 40 % FFQ 45 quartz fillers. This was due to the fact that the lower water demand for this combination resulted in a higher packing density and as a result a higher compressive strength was obtained. The second part of the graph comprising of all components mix describes the optimum content of filler/sand combination that will result in the maximum flow. From the results it is observed that the maximum flow would be observed when no filler is used at all and the optimum amount of filler/sand for maximum flow would be 0.2.

The results of mini flow test and compressive strength of reference mixes casted for evaluating the effect of filler ratio on the properties of the mix are shown in figure 20 and figure 21 respectively.

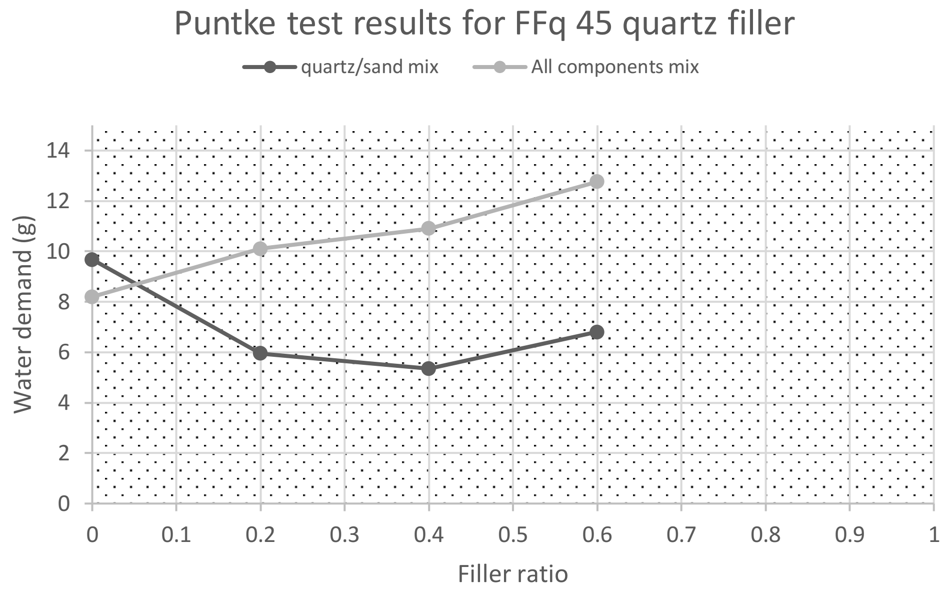


Figure 20 water demand of filler/sand mix and all components mix measured by Puntke test (FFq 45 quartz fillers).

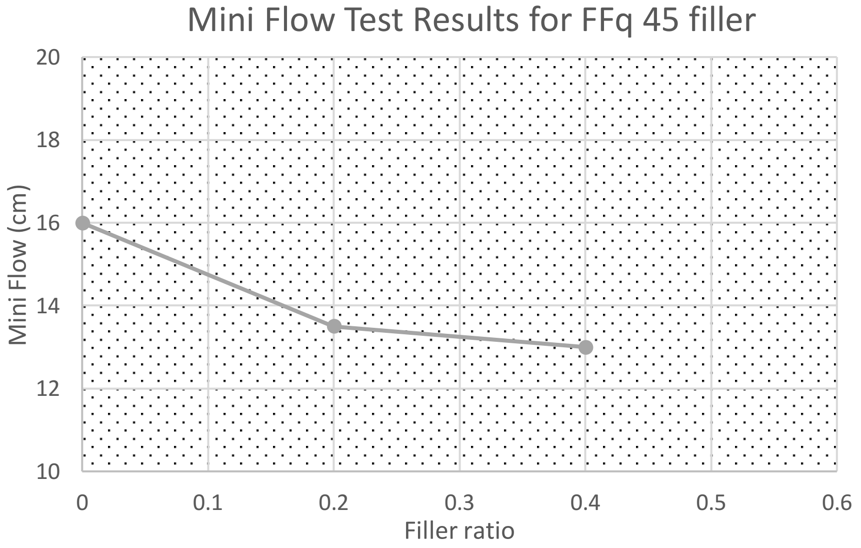


Figure 21 Mini Flow test results for UHPC mixes casted with FFq 45 fillers (w/c ratio 0.25).

The flow decreases as the filler amount increases. The optimum amount of filler amount obtained from Puntke tests for maximum flowability was validated, as with an increase in the filler amount beyond 0.2 the flow further decreased. The compressive strength results shows an increase in both 7-days and 28-days strength as the filler content increases. The highest 7-days and 28 days strength was observed for the mix containing 40% filler amount and 60 % sand. All the other constituents were kept constant in these reference mixtures and only the amount of filler varied.

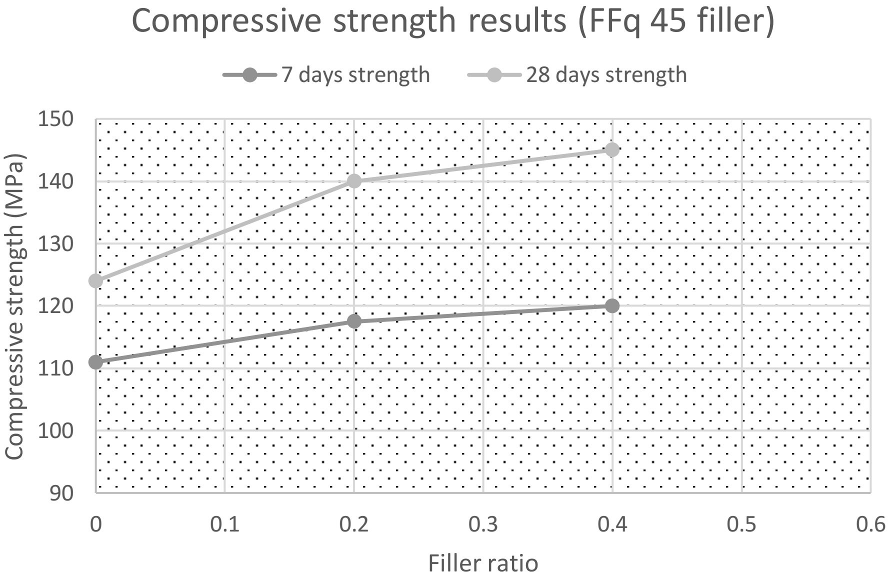


Figure 22 Compressive strength results for mixtures casted with FFq 45 quartz filler (w/c=0.25).

4.3.2 NFQ Nilsiä filler:

Figure 23 represents the Puntke test results for Nilsiä quartz. The quartz/sand mix results shows that the maximum packing density is obtained for a combination of 80 percent sand and 20 percent Nilsiä quartz fillers. This corresponds to the optimum amount of filler/sand for obtaining maximum compressive strength of the mix. The results of water demand for combination of all components mix indicates that with an increase in the Nilsiä filler content there is a reduction in the water demand corresponding to an increase in flow. Due to the higher water demand of Nilsiä filler as compared with Ffq 45 filler, binary mixtures of UHPC with Nilsiä fillers were not produced, and its effect on UHPC properties was evaluated by combining it with Ffq 45 fillers to produce ternary UHPC mixtures.

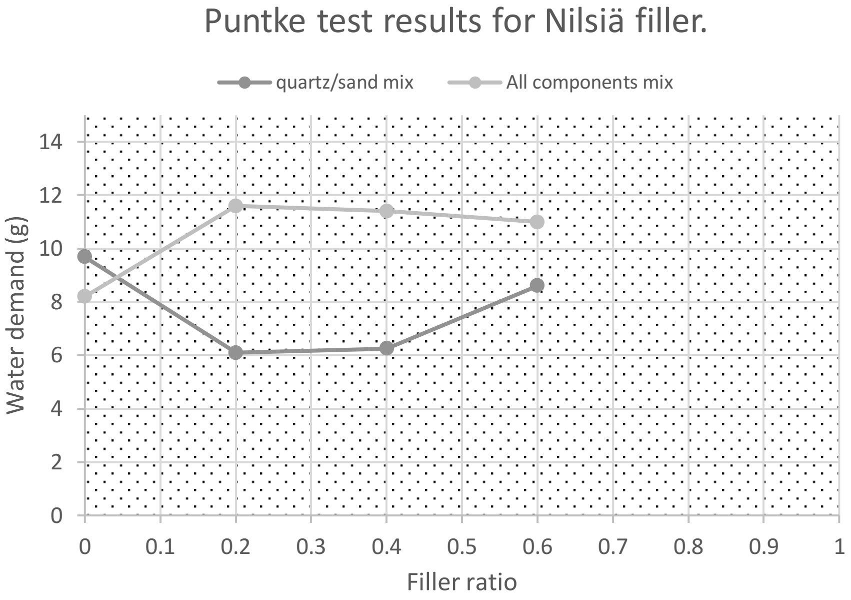


Figure 23 Water demand of filler/sand mix and all components mix measured by Puntke test method for Nilsiä filler.

4.4 Preliminary Test Results for Ternary mixes:

Puntke test was carried out in the same way for a combination of the two quartz fillers. The filler/aggregate ratio was kept at 0.2 for the ternary mixes. The results are described in figure 24. The results show that the water demand of different ternary mixes was almost equal. The water demand for all combinations of ternary mixes was lower than the water demand of the binary mixes. This is due to the fact that two different fillers of different sizes tends to fill the voids more often, than in the case when only one type of filler is used. The increase in packing density results in a lower water demand as verified by the water demand results. The lowest water demand corresponding to maximum compressive strength was observed for a combination of sand/Ffq45/Nilsiä in the proportion of 0.8/0.16/0.04. The minimum water demand corresponding to maximum flow given by the water demand tests of all components mix was observed for a combination of sand/Ffq45/Nilsiä in the proportion of 0.8/0.12/0.08.

The mini flow results are presented in figure 25, while the compression strength results for ternary mixes are shown in figure 26. The amount of silica fume used for ternary mixes was 15 % of the cement weight. The reduction in the amount of silica fume enhanced the flow properties of the mix quite significantly as shown in figure 25.

The highest flow was obtained for the mix comprising of 80 % sand, 12% Ffq 45 and 8 % Nilsiä quartz. The 7 days compressive strength showed a gradual increase as the Nilsiä amount was increased in the mix indicating the high early strength gain of Nilsiä filler with respect to Ffq 45 filler.

The highest 28 days compressive strength was observed for the mix combination with 80 % sand, 16 % ffq 45 and 4 % nilsiä filler indicating the much higher strength characteristics of ffq 45 filler with respect to nilsiä filler. It is obvious from the results of ternary mixes that a UHPC mix made of two different fillers can yield in a mix with excellent flowability and compressive strength properties.

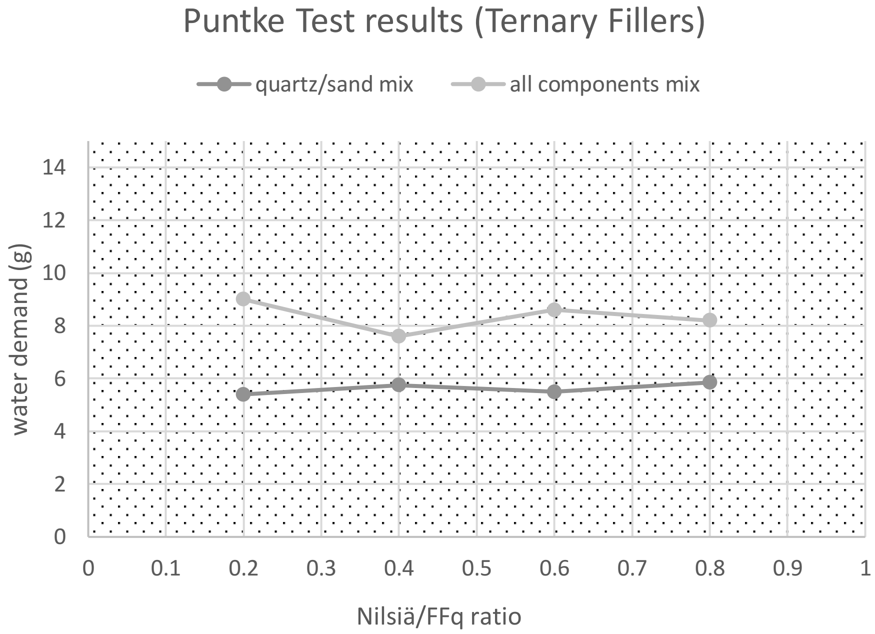


Figure 24 Water demand of Nilsiä/ffq 45 filler mix and all components mix measured by Puntke test (Filler/sand ratio=0.2).

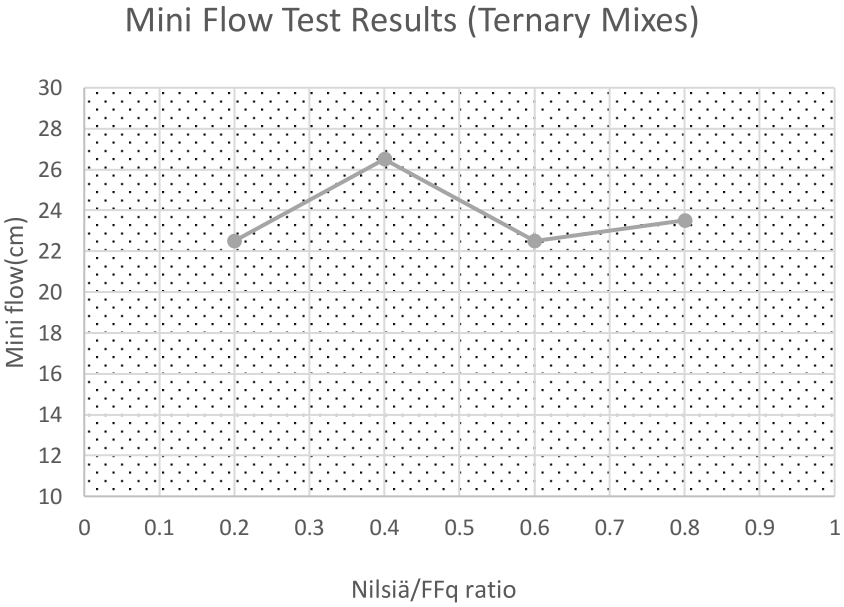


Figure 25 Mini Flow test results for ternary mixes cast with Nilsiä and FFq 45 fillers (w/c=0.25, filler/sand=0.2).

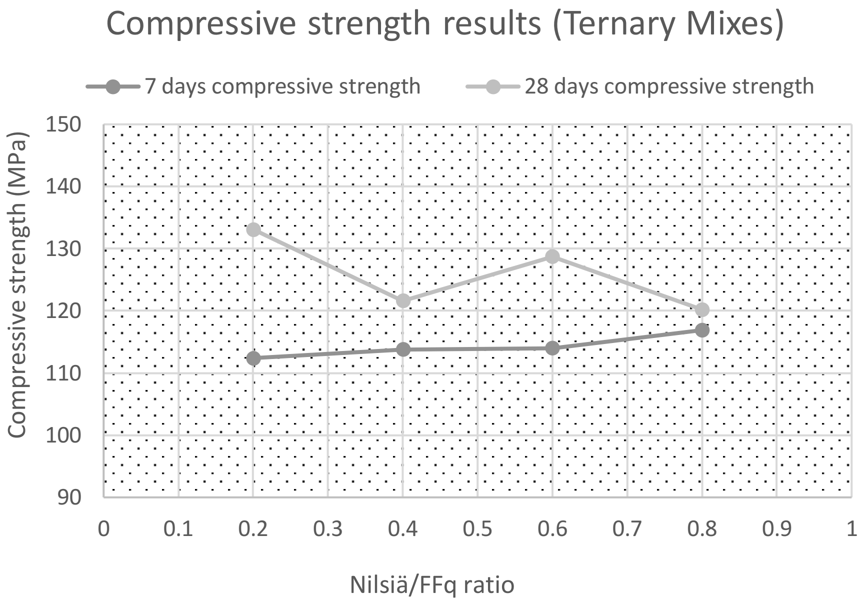


Figure 26 Compression test results for ternary mixes casted with Nilsiä and FFq 45 fillers (w/c=0.25, filler/sand=0.2).

4.5 Effect of different material constituents on the rheological and mechanical properties of the mix:

The effect of different material constituents was evaluated by examining the flowability and strength properties of the mix for different types of material compositions and varying the amount of the constituents in the mix. The materials used in the reference mix included pika cement, FFq 45 quartz fillers, sand with particle size (100-600 µm), Master Glenium 600 superplasticizer and Elkem 940 U silica fume.

Table 15 Mix proportions of material constituents of reference mixture by cement weight for preliminary tests.

Material	Cement	Sand	Silica fume	Quartz sand	Water	Superplasticizer
Composition	1	1	0.25	0.25	0.25	0.05

The detailed description of the tests and their results are presented below.

4.5.1 Effect of Silica Fume:

The effect of silica fume on the compressive strength properties and the flowability of the UHPC mix was observed by varying the silica fume proportion with respect to the cement weight. Three types of silica fume were used in this research study; Elkem Silica fume 920 ED, Elkem Silica fume 940 U and Elkem microwhite silica. The detailed physical and chemical properties are described in Chapter 3.

Silica fume amount was used in three different proportion: 15, 20 and 25 %. The test specimens were produced using Pika cement, FFq 45 quartz fillers, fine sand with a maximum dia. Of 0.6 mm and Master Glenium 600 superplasticizer. The influence of silica fume type and proportion on the mini flow test results is shown in figure 27. The results show that at any proportion of Silica fume dosage, Elkem SF 940 U has better flow properties than Elkem SF 920 ED. The flow of the mix was inversely related to the silica fume dosage amount. The best flow results were obtained when 15 % of silica fume by cement weight was used for both types of silica fume, and showed a gradual decrease in the flow as the silica fume amount was increased. This decrease of flow can be explained by the fact that silica fume is a much finer material than cement and requires a much higher amount of water to break the flocculation forces. The results agree with that carried out by Abu Shaban (2002) and Tasir (2013).

The mechanical properties of the mortars produced was evaluated by measuring the compressive strength of the cubes prepared. The effect of silica fume on the 7 days and 28 days strength of the mix was measured. The results are shown in figure 28 and 29.

An increase in the 28 days strength was observed with silica fume dosage rate. The highest 28-day compressive strength was obtained when 25 % of silica fume was used in the UHPC mix for both types of silica fume. Early strength gain of 920 ED silica fume was almost independent of the dosage amount for 920 ED silica. Maximum value of compressive strength and highest early age strength gain was observed when 25 % of 940 U silica was used in the mix indicating the strong dependency of compressive strength on the silica fume dosage amount. The results in literature about the silica fume dosage are quite varied. Some of the results indicates an increase in strength properties with increasing silica fume content up to 25 %. Some results indicate a decrease in strength properties by increasing silica fume dosage beyond 15 %.

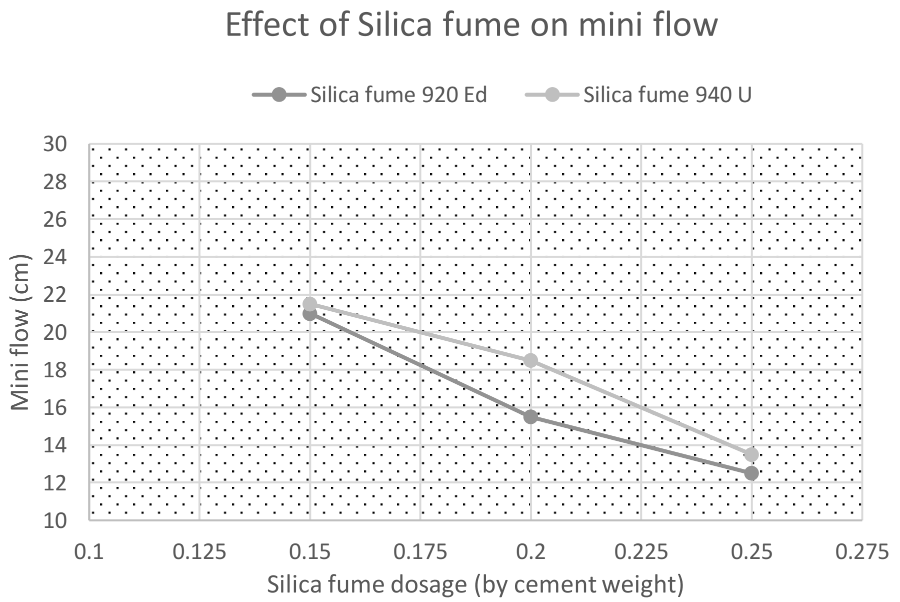


Figure 27 Effect of silica fume type and amount on mini flow test results of the UHPC mixes (w/c=0.25).

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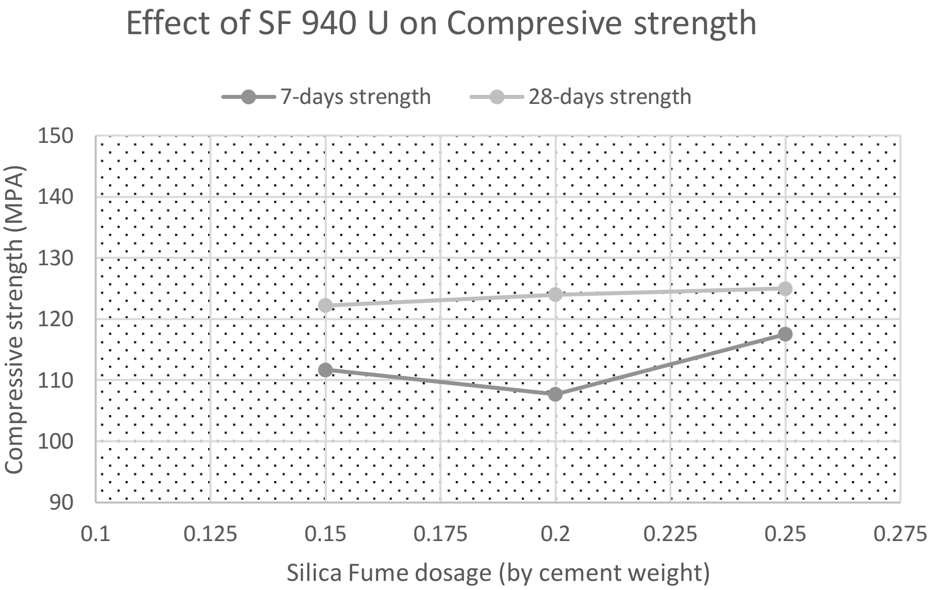


Figure 29 Effect of silica fume 940 U on compression test results of the UHPC mixes (w/c=0.25).

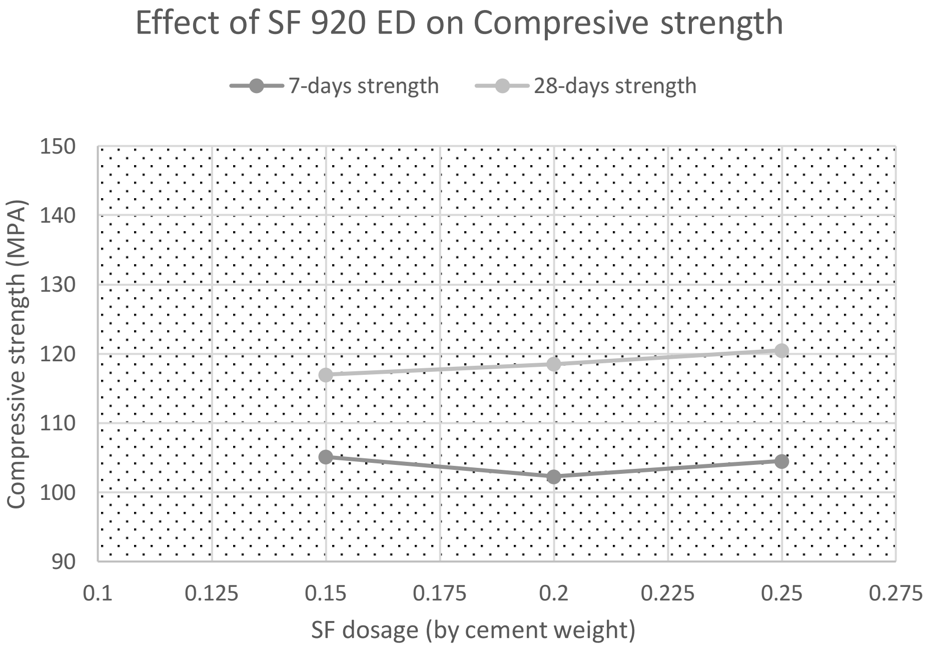


Figure 28 Effect of silica fume 920 ED on compression test results of the UHPC mixes (w/c=0.25).

4.5.2 Effect of Cement type:

The preliminary laboratory tests of grey UHPC were conducted with Pika cement which was the primary cement for this research study. The effect of Pika cement on the UHPC mix was compared with that of Plus and SR cement. The mix composition of other constituents was kept constant and two casts were made; one with plus cement and the other with SR cement for a w/c ratio of 0.25. The effect of different cement types on the flow of the mix measured through min flow test is shown in the figure 30.

The highest flow was observed for SR cement while the lowest flow was obtained for plus cement. There was a slight difference in the flow properties of Pika and Plus cement while SR cement had a considerably higher flow properties with respect to the other two. The lowest water demand of SR cement is attributed to the low fineness of SR cement as compared with the other two cement types which has slightly higher fineness. The water demand of cement type is related to the fineness and normally for ultra-high strength concrete which has a very low water to cement ratio, a cement with a lower fineness is preferred.

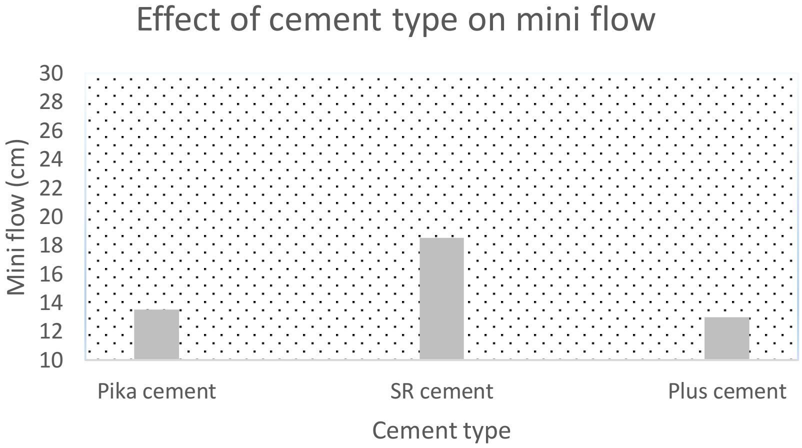


Figure 30 Effect of Cement type on the mini flow of the UHPC mixes (w/c=0.25).

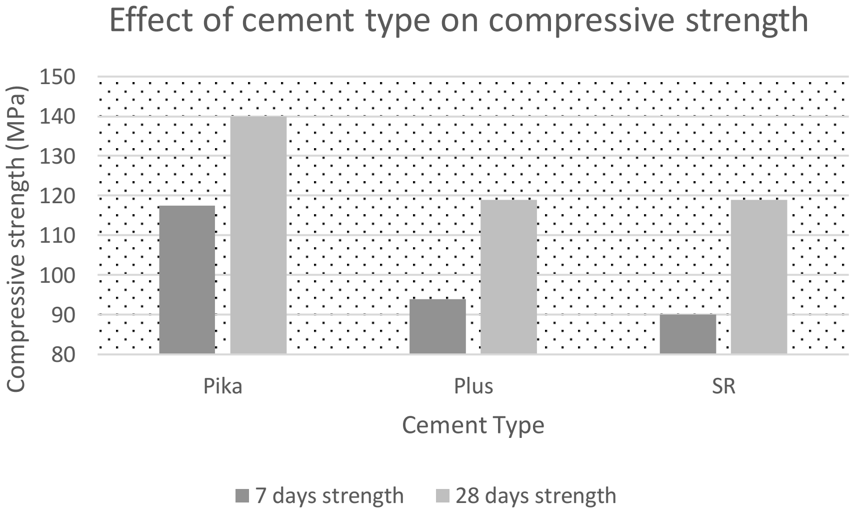


Figure 31Effect of Cement type on the compressive strength of the UHPC mixes (w/c=0.25).

Figure 31 shows the effect of cement type on the strength values of the mix. It can be noted that the 7 days and 28 days strength of plus and SR cement was almost similar with the latter showing a slightly slower increase in strength than the other. The compressive strength results of Pika cement has a much higher value than that of SR and plus cement. The 7 days strength of Pika cement is almost equal to that of 28 days strength of plus and SR cement. The 28 day strength of Pika cement is almost 20 MPa higher than the strength values of the other two types of cement. The strength test results shows that Pika cement is much more preferable for producing ultra-high performance concrete than plus and SR cement due to a higher compressive strength and faster strength gain values.

4.5.3 Effect of modified fly ash

Modified fly ash was used to replace cement in the UHPC mix. The effect of fly ash on the mechanical and rheological properties of the mix was evaluated for different proportions of cement replacement by fly ash. The results of mini flow test conducted to measure the rheological properties of the mix with varying cement replacement is presented in figure 32. It is observed that the flowability of the UHPC mix increases with an increase in the amount of fly ash. The maximum flowability was observed for the mix containing 30 % of modified fly ash by cement weight. There was a substantial increase in the flow of the mix with an increase of fly ash content from 10 to 20 % by cement weight. Further increase of cement replacement by fly ash showed a much slower increase in the flow of the UHPC mix.

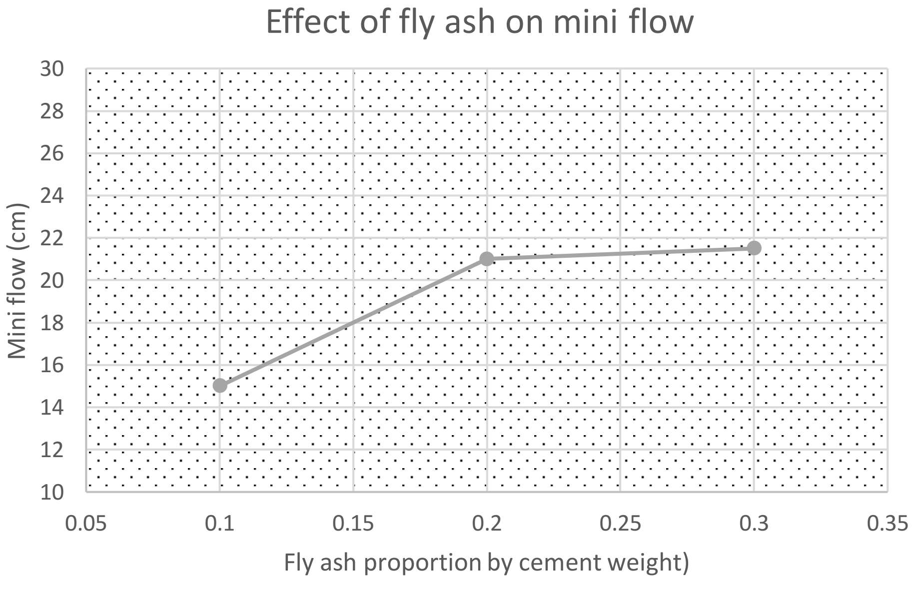


Figure 32 Effect of fly ash content on the mini flow of the UHPC mixes (w/c=0.25).

The compressive strength test results are described in figure 33. The 7-days strength results shows a decrease in the compressive strength of the mix as the amount of fly ash is increased. This can be described by the rapid early strength gain of Pika cement as compared to modified fly ash. The 28 days compressive strength results shows an increase in the strength, as the amount is increased from 10 to 20 % by cement weight, and a decrease in the strength value is observed with a further increase of the modified fly ash content.

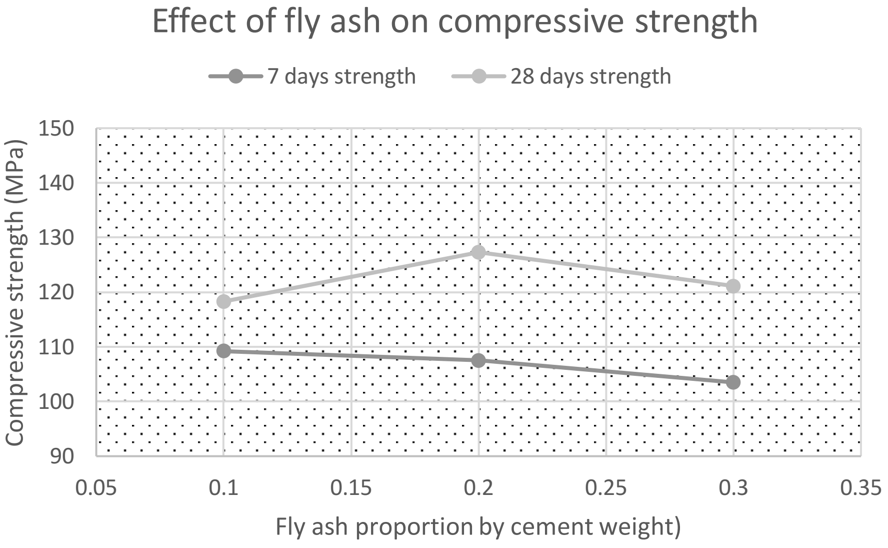


Figure 33 Effect of fly ash amount on the compressive strength of the UHPC mixes (w/c=0.25).

This gives the optimum amount of cement replacement by modified fly ash. The cement replacement by 20 % of modified fly ash by weight gives a UHPC mix with a mini flow value of 21 cm and a compressive strength of 127.3 MPa. Though the 28 days strength value as compared with the standard mix is reduced by 13 MPa, it is possible that at later ages this gap can be much smaller due to the slower strength gain of fly ash.

4.5.5 Effect of cement replacement by slag

The effect of cement replacement by slag was evaluated in a similar manner by casting three mixes with a 10, 20 and 30 % slag replacement by cement weight.

The increase in amount of slag increases the flowability of the mix (figure 34). The increase in amount of slag from 10 to 30 % by cement weight increases the mini flow from 15 to 27 cm. The increase is more prominent when the slag replacement is more than 20 % by cement weight.

The compressive strength results are represented in figure 35. The 7 days compressive strength decreases with an increase in the slag amount. This can be explained mainly due to a slower rate of hydration when the cement is replaced with supplementary cementitious materials. The highest strength value of 112 MPa was observed when only 10 % of slag was used to replace cement. The 28 days strength showed a decrease with the increase of slag amount from 10- 20 % by cement weight, but showed a slight increase as the amount was further increased to 30 %.

The maximum value of compressive strength (125.3 MPa) was observed for the mix with 10% cement replacement by slag. The optimum amount of slag replacement while considering just the compressive strength properties was found out to be 10 % while a 30 % cement replacement by slag can give a UHPC mix with excellent flowability and good compression strength properties. The long term strength of mixes in which SCMs are used to replace cement can gave much higher strength values due to very slow hydration of these materials as compared to cement. Ibrahim (2017) had shown that upto 20 % replacement of cement by SCMs enhanced the properties of UHPC mix after 90 days.

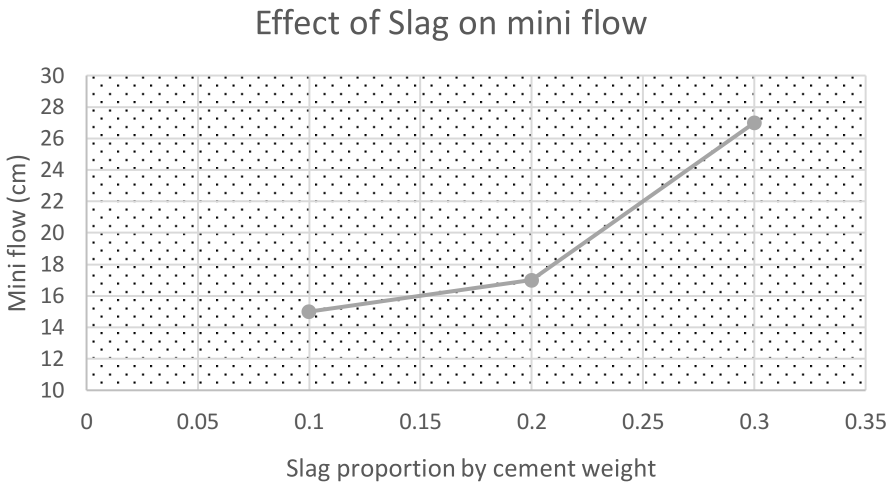


Figure 34 Effect of Slag content on the mini flow of the UHPC mixes (w/c=0.25).

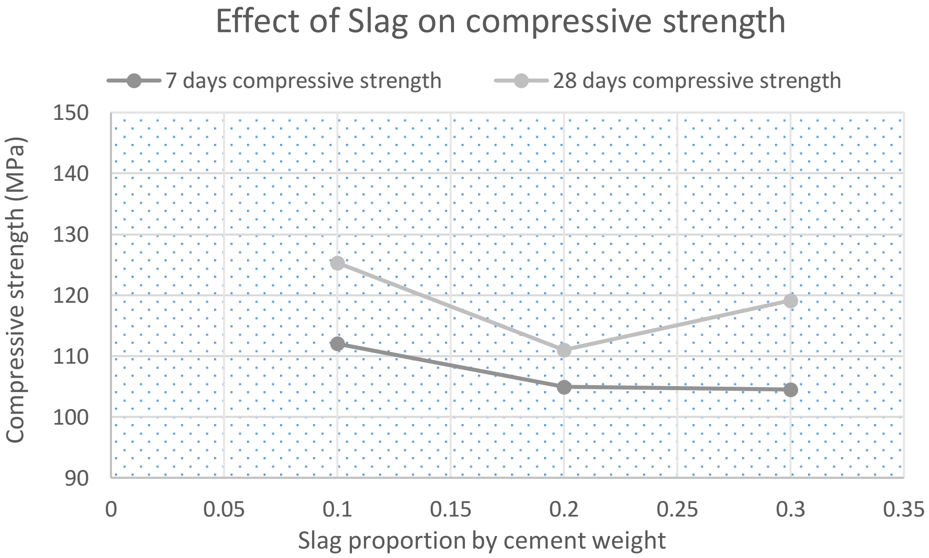


Figure 35 Effect of Slag content on the compressive strength of the UHPC mixes (w/c=0.25).

4.5.4 Effect of coarse aggregates:

The UHPC mixes analyzed in the preliminary tests so far were without any coarse aggregate inclusion. The maximum fine aggregate size was limited to 0.6 mm. The effect of granite coarse aggregates up to 2 mm was observed by casting mixes for UHPC with coarse aggregates. Two different sizes of coarse aggregates; 0.5-1.2 mm and 1-2 mm were included in the mix separately. The coarse aggregate /cement ratio used for these mixes was kept at one. The mix composition is described in table 16.

Table 16 Mix proportions of material compositions by cement weight for UHPC mixtures casted with coarse aggregates.

Material	Cement	Silica fume	Sand	Quartz filler	Coarse aggregate	Superplasticizer	w/c
Proportion/Cement weight	1	0.25	1	0.25	1	0.05	0.25

The inclusion of 0.5-1.2 mm sizes aggregates reduced the 28 days strength value from 140 MPa to 127 MPa (figure 36). Slightly higher value of 131.1 MPa was observed when coarse aggregates of 1-2 mm size were used. It can be noted that the inclusion of coarse aggregates causes a reduction in strength value but still is capable of producing concrete with good compressive strength properties.

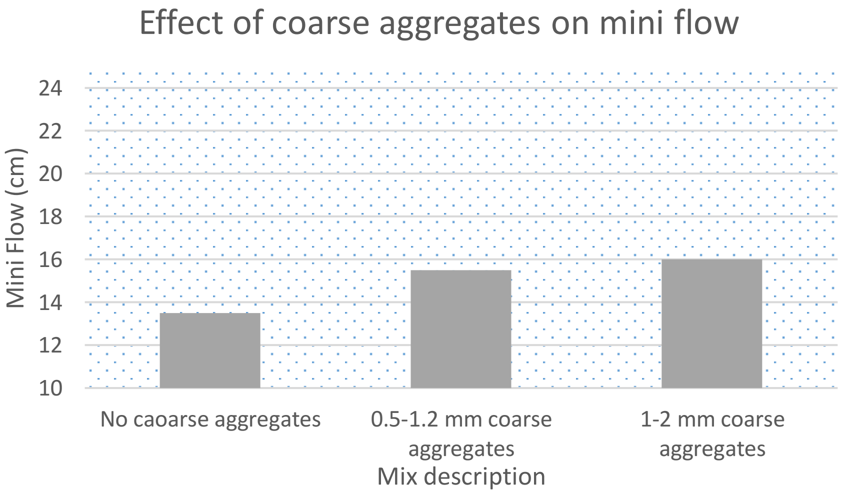


Figure 36 Comparison of mini flow test results of mixes with and without coarse aggregates (w/c=0.25).

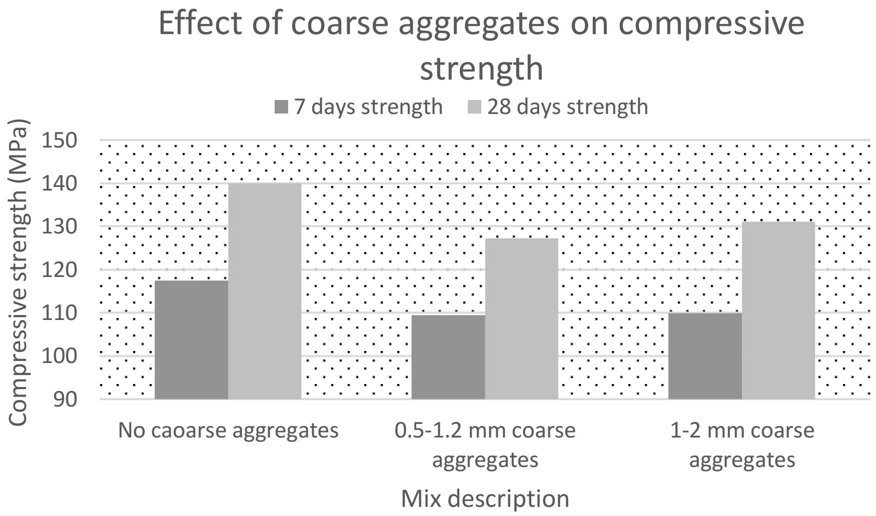


Figure 37 Compressive strength test results for mixes casted with coarse aggregates (w/c=0.25).

4.6 White UHPC

White UHPC was produced using white cement, micro white silica fume and limestone fillers. The main purpose behind the production of white UHPC was to develop concrete with exceptional strength properties that can also be used for applications requiring aesthetics. It can be of great use to cast irregular shapes for facades of different buildings. The preliminary tests for production of white UHPC included the following steps:

- Puntke Tests for fillers.
- Evaluating the compressive strength and flow for binary and ternary mixes casted with limestone fillers.
- Effect of water to cement ratio on the properties of the mix.
- Effect of silica fume content on the properties of mix.
- Effect of including coarse aggregates in the mix.

4.6.1 Puntke tests for fillers:

The following fillers were used for producing white UHPC; three different types of calcites; C2, C5 and C7, Parfill 80 and Parfill H80 fillers, Tytyri 63 and wolasanite. The first step was to find the content and type of the optimum filler for producing maximum packing density. This was done by finding the minimum water demand through Puntke tests. The results of Puntke tests are presented in the figure 38. The results show that the optimum ratio of fillers for producing the maximum compressive strength of the mix for Calcites, Parfill 80 and Tytyri 63 fillers was 20 % filler and 80 % sand. Wollastonite had the highest water demand for all ratios of filler content and was only used for producing ternary mixes where two different fillers would result in a much lower water demand of the mix resulting in higher packing density. The optimum filler content for Parfill H80 fillers was found out to be 40 % filler and 60 % sand content. The problem with an increasing filler content was reduction in flow and a much stickier mix. As the optimum filler content was similar for most of the fillers the same ratio of fillers was used for producing the ternary mixes.

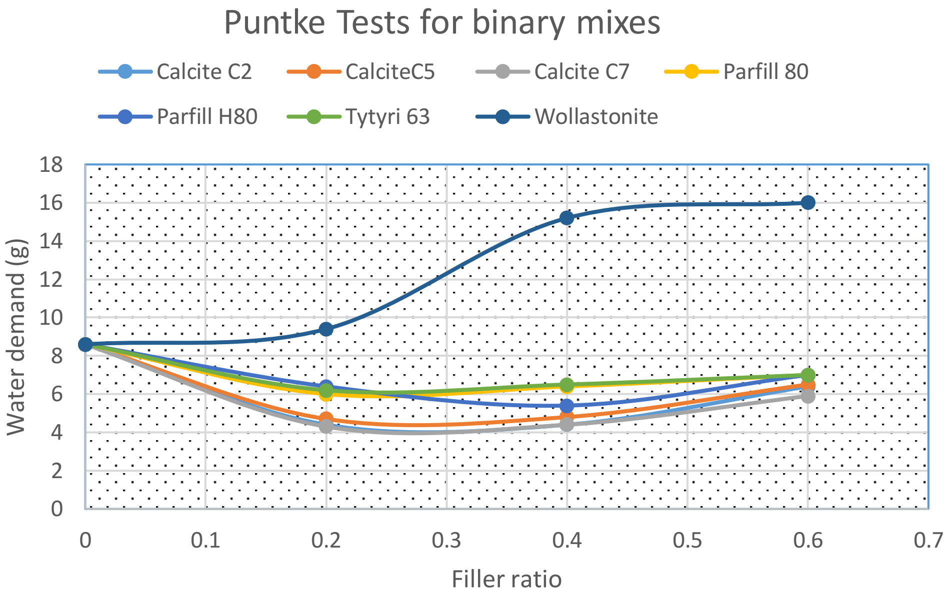


Figure 38 Water demand obtained through Puntke Test for binary combination of limestone fillers and sand.

4.6.2 Binary Mixes of white UHPC:

The mix composition of materials used for producing binary mixes of white UHPC is shown in table 17. The above mix composition was used to produce reference mixes for all the fillers that were described in the previous section except for Parfill H80 fillers where a filler/cement ratio of 0.5 was used instead of 0.25. A water to cement ratio of 0.22 was adopted after carrying out some zero tests with different w/c ratios. The mini flow test was conducted for evaluating the flowability of the mix and cubes were produced for finding out the compressive strength of the binary mixes. The results are described in figure 39 and 40.

Table 17 Mix proportions of material constituents used for producing white UHPC for preliminary tests (ingredient measured relative to cement weight).

Materials	Ingredient / cement content
Cement	1
Sand	1
White Silica fume	0.25
Limestone Filler	0.25
Water/cement ratio	0.22
Superplasticizer/cement ratio	0.05

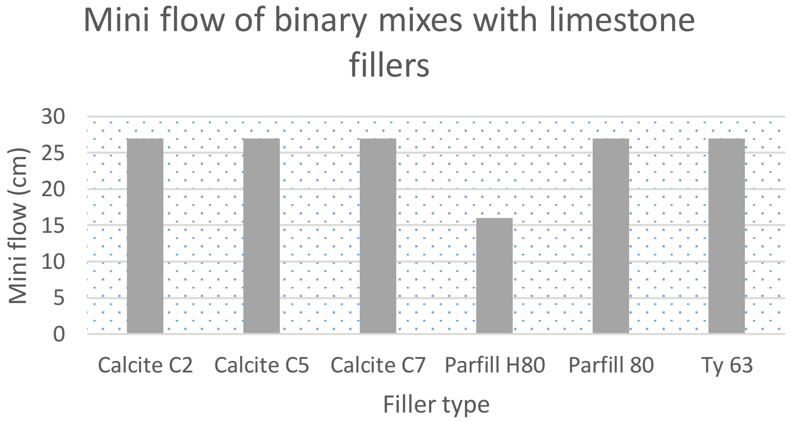


Figure 39 Mini flow test results for binary mixes made of white UHPC (w/c ratio =0.22).

Mini flow.

The mini flow was measured with a mini cone apparatus described in Chapter 3. The results are shown in figure 39.

The mini flow results indicates that the flow properties of white UHPC were quite good as compared with grey UHPC. The lowest flow was observed for Parfill H80 filler due to the greater filler content. For a combination of 20 % fillers and 80 % sand all fillers produced the maximum flow that could be measured with the mini cone apparatus. These results describes the self-compacting nature of white UHPC and no flow issues were associated with the use of these fillers.

Compressive strength.

The cubes prepared were covered with a plastic sheet for 24 hours after casting and were then kept in a water basin under standard conditions at room temperature till the test date. The 7-day and 28-day compressive strength was evaluated for the mixes produced. The results are shown in the figure 40. The results show a very high early strength gain of white UHPC for all types of fillers. This was due to the faster strength gain at early age of white cement as compared with other cements. The highest 7 day and 28 day compressive strength was observed for the mix casted with Tytyre 63 filler. All the limestone fillers used were capable of producing UHPC with strength greater than 120 MPa. The lowest compressive strength was observed for mixes casted with Parfill fillers. Calcite C2 had a slightly higher early strength gain as compared with the other two calcites. The strength values at 28 days for all the three calcites used was almost similar. The test results of binary mixes show that a white UHPC with a compressive strength of 140 MPa with self-compacting properties can be obtained by using 25 % silica fume content and Tytyri 63 fillers with a filler/sand ratio of 0.2.

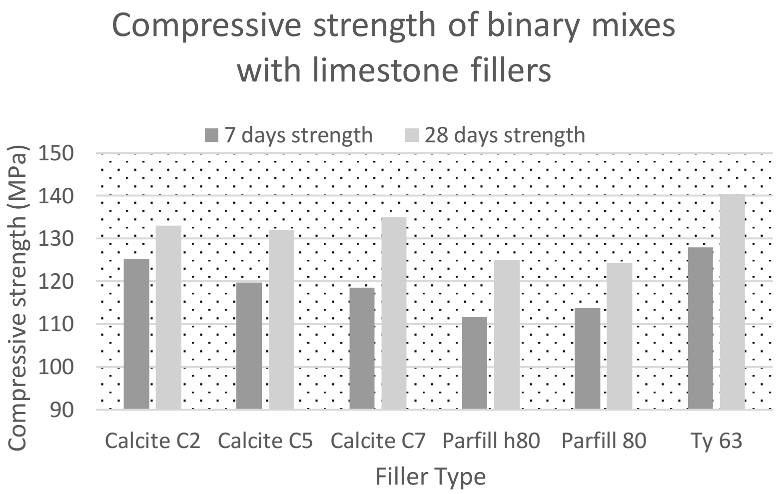


Figure 40 Compressive strength results for binary mixes of white UHPC (w/c ratio=0.22).

4.6.3 Ternary mixes using Limestone fillers:

The water demand results of Puntke tests indicated an optimum amount of 20 % fillers in the mix for all the limestone fillers except Parfill H80. Ternary mixes were cast by using Calcite C2 as a reference filler and combining it with other fillers to evaluate its effect on the properties of the UHPC mix. The proportions of all the other material constituents was kept the same as described in table. The two different fillers were combined in a ratio of 0.16/0.04 (C2/filler) of the 20 % filler amount. The only exception was in case of Parfill H80 where C2/Parfill H80 ratio of 0.12/0.08 was used and a 40% filler content was combined with 60% sand content. The larger portion of C2 filler was used as it had the lowest water demand and the filler ratio was determined by using the optimum filler ratio of the second filler obtained through Puntke tests. This approach was adopted to evaluate the effect of combining different fillers in a similar way on the basis of water demand test results. The compressive strength and flow value was evaluated in a similar fashion. The results are shown in figures 41 and 42.

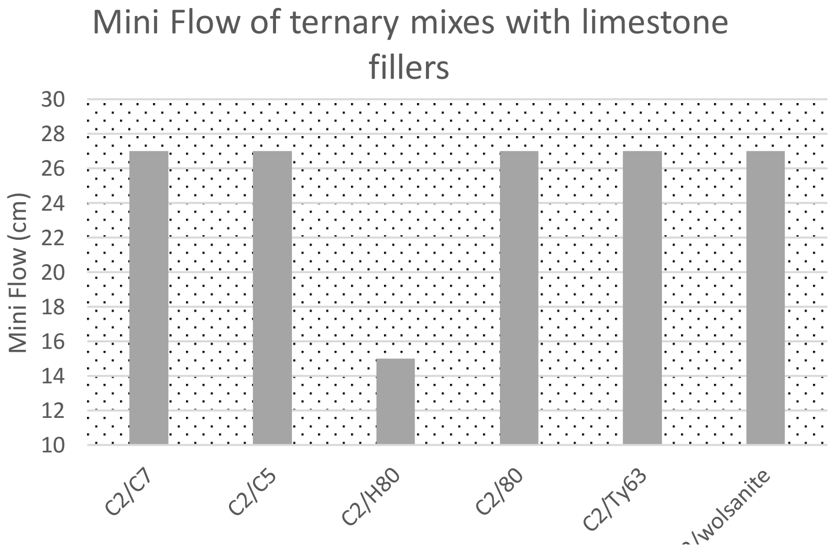


Figure 41Mini flow results for ternary mixes of white UHPC (w/c ratio=0.22).

Mini Flow:

All the ternary mixes produced had excellent flowability except the one with C2/Parfill H80 combination. The lowest flow of this mix was attributed to the greater filler content with respect to other mixes where only 20 % of fillers were used. All the mixes gave the maximum flow that could be measured with the mini cone setup. The mix combinations of other material constituents was kept same in the ternary mixes and so a combination of two fillers did not degrade the flow of the mix.

Compressive Strength:

The maximum compressive strength at 28 days of 141 MPa was obtained for the mix with a combination of C2/Tytyri 63 fillers. The calcites filler combination resulted in a slightly lesser strength than the mixes where only one type of calcite was used. The maximum enhancement of strength was observed with the Parfill 80 fillers. A binary mix of only Parfill 80 as a filler resulted in a compressive strength of 124.4 MPa while a combination of C2/Parfill 80 resulted in a compressive strength of 139.6 MPa after 28 days. A combination of C2/Wollastonite filler showed almost no difference in its strength gain at 7 and 28 days and produced a concrete with 133 MPa of compressive strength. No increase in strength was observed with Parfill H80 filler combined with calcite C2 and it resulted in the lowest strength indicating the degradation of both flow and compressive strength of the mix with an increase in filler content.

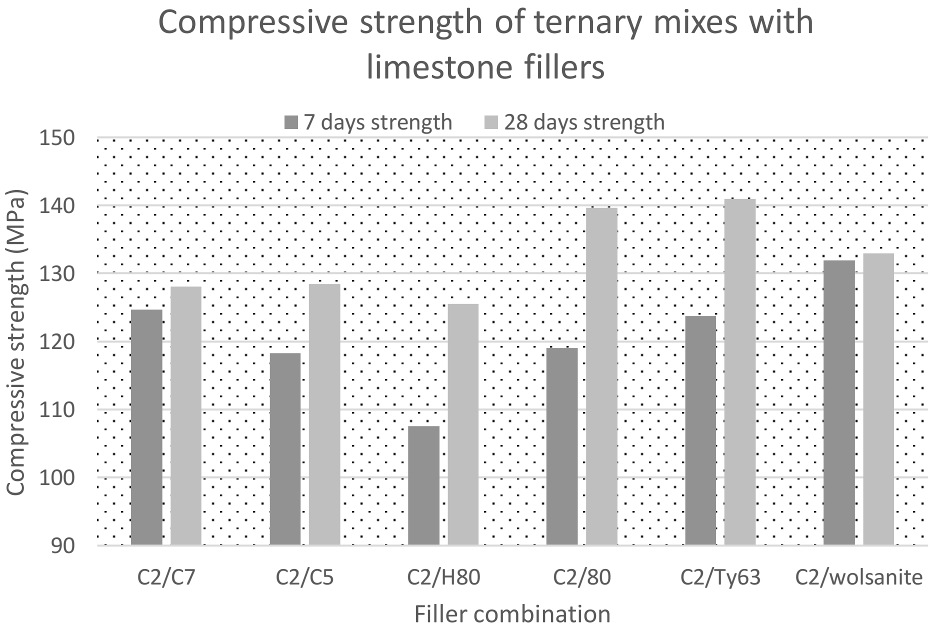


Figure 42 Compressive strength results for ternary mixes of white UHPC (w/c ratio=0.22)

4.6.4 Effect of water to cement ratio

In the case of grey UHPC the mixes produced were stickier and less flowable so it was not possible to reduce the water/cement ratio below 0.25. White concrete was quite flowable, therefore the effect of water to cement ratio on the mix properties was observed by varying the water/cement ratio of binary mixes cast with calcite C5 limestone fillers. The mix constituents of other materials was kept constant as shown above in table. Water to cement ratio of 0.25, 0.22 and 0.20 was used for casting three different mixes. The compressive strength test results of the mixes is presented in figures 43 and 44.

Mini Flow.

There was no degradation of flow properties of the mix with a decrease in w/c ratio from 0.25 to 0.22 and the maximum flow value that could be measured with the mini cone apparatus was observed. Substantial decrease was observed by further reducing the water to cement ratio to 0.20. The mini flow value decreased from 27 to 18.5 as the water to cement ratio was decreased from 0.22 to 0.2. Generally white cement has issues regarding optimum water content and a slight reduction beyond the optimum amount could have a much larger influence on the properties of the mix.

Compressive strength.

The compressive strength showed a similar trend. Normally no significant difference was observed in the 28 day strength values for mixes with w/c ratio of 0.22 and 0.25. The 28 day strength value of the mix with a w/c ratio of 0.2 was 125.2 MPa as compared with 132 MPa with a w/c ratio of 0.22. The highest early strength gain and final strength value was observed for the mix with w/c ratio of 0.25.

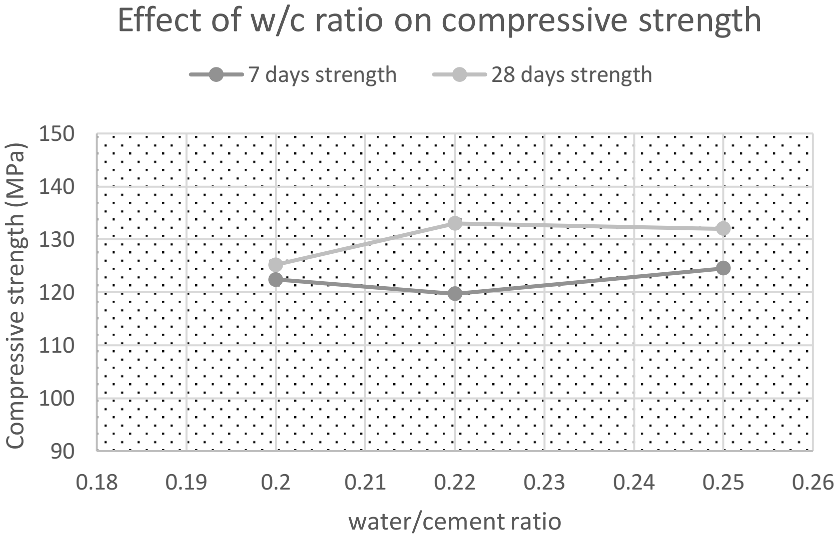


Figure 44 Effect of water to cement ratio on the compressive strength test results of white UHPC mix (Calcite C5 used as filler).

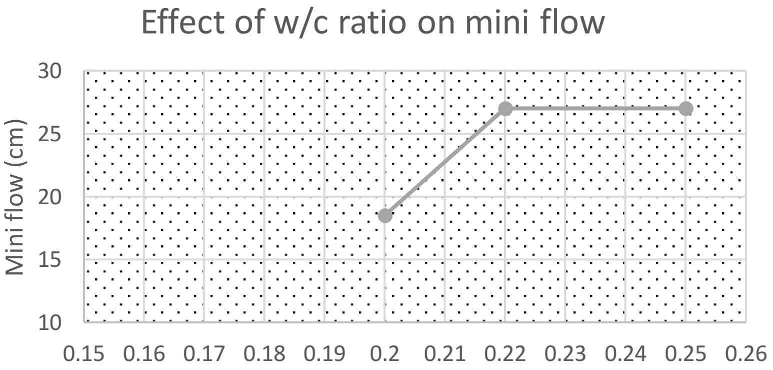


Figure 43 Effect of water to cement ratio on the mini flow of white UHPC mix (Calcite C5 used as filler).

4.6.5 Effect of Silica fume content

The selection of optimum amount of silica fume content was investigated by casting three different mixes with varying silica fume content. Calcite C5 filler was used as a limestone filler in the mix with all other material constituents kept constant. The mini flow table results showed the maximum value that could be measured with the mini cone apparatus for all the three mixes and so the only evaluating factor for the selection of optimum silica fume content was the compressive strength of the mixes. The results are described in figure 45.

The highest early strength gain was obtained when only 15 % of the silica was used in the mix. This was due to the fact that white cement gains strength quite rapidly so a reduction in silica fume meant a slight increase in cement content resulting in a slight higher early strength gain. Using a silica fume content of 15 % gave a 7 day strength of 123.3 MPa. The optimum amount of silica fume content is better presented by the 28 day strength values of the mix. An increase in the compressive strength was observed by increasing silica fume content upto 20 %. The strength increased from 136 MPa to 139.2 MPa as the silica fume amount was increased from 15 % to 20 %. Further increase in silica fume content reduced the strength value at 28 days, and with a silica fume content of 25 % the mix gave a compressive strength of 133 MPa.

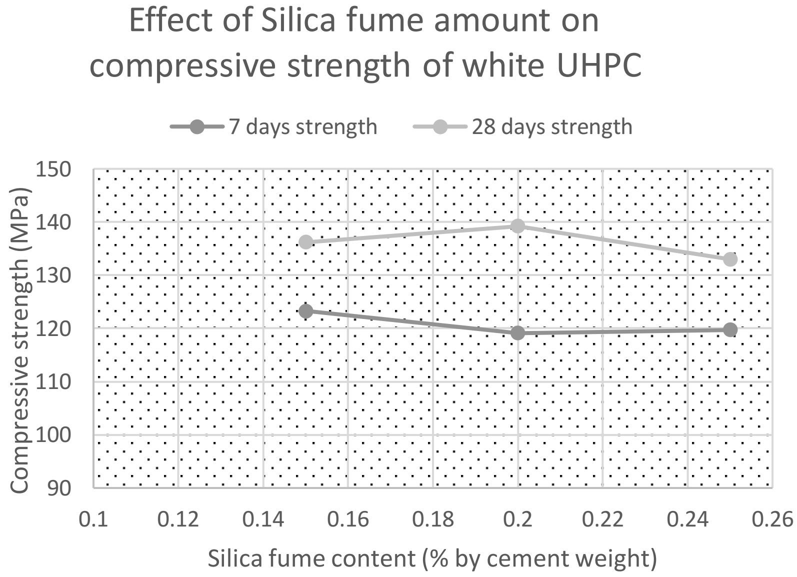


Figure 45 Effect of silica fume on the compressive strength test results of white UHPC mix (Calcite C5 used as filler).

4.6.5 Effect of coarse aggregates:

The UHPC mixes analyzed in the preliminary tests so far were without any coarse aggregate inclusion. The maximum fine aggregate size was limited to 0.6 mm. The effect of granite coarse aggregates up to 2 mm was observed by casting mixes for white UHPC with coarse aggregates. Two different sizes of coarse aggregates; 0.5-1.2 mm and 1-2 mm were included in the mix separately. The coarse aggregate /cement ratio used for these mixes was kept at 1. The mix composition is described in table 18.

Table 18 Mix proportions of material constituents by cement weight of white UHPC mixtures with coarse aggregates.

Material	Cement	Silica fume	Sand	Calcite C2 filler	Coarse aggregate	Super plasticizer	w/c
Proportion/Cement weight	1	0.25	1	0.25	1	0.05	0.22

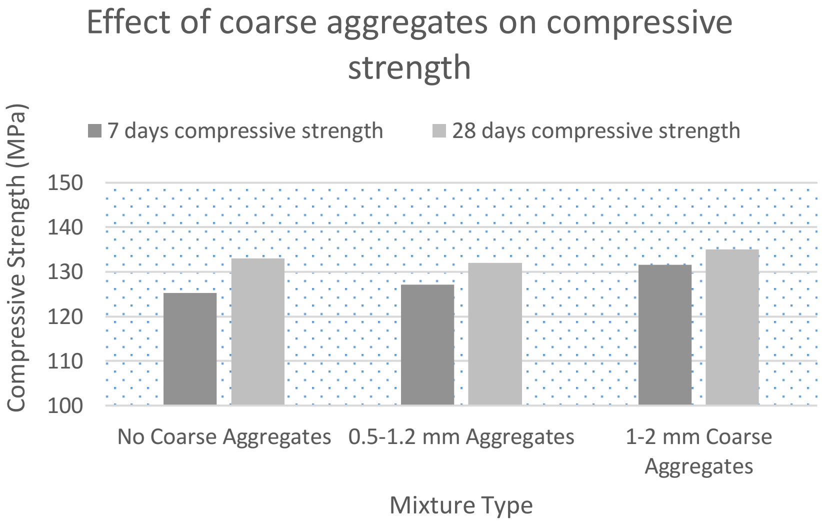


Figure 46 Effect of coarse aggregates on the compressive strength of white UHPC (w/c ratio=0.22)

The inclusion of coarse aggregates did not influence the flow of white UHPC. The compressive strength slightly increased with the inclusion of 1-2 mm coarse aggregates and a 28 days compressive strength of 135 MPa was recorded. The inclusion of coarse aggregates in the case of grey UHPC reduced the compressive strength with a slight increase in flow. The only problem with including coarse aggregates in white UHPC is the change in color, which might be a primary requirement for aesthetic purposes.

Chapter 5 Final Test Results and Discussions

The preliminary tests served a basis for analyzing the effect of different mix proportions and material variations on the properties of the UHPC mixes tested. On the basis of these tests, two different UHPC mix combinations were selected for both white and grey concrete for the production of UHFPRC. For each mixture, two mixes were cast with fibers and one mixture was cast without fibers. In total, four UHPC mixtures and eight UHFPRC mixtures were cast in the test program. The mixtures were cast with Eirich mixture having a maximum capacity of 75 liters. The fiber contents were based on cement weight and the UHFPRC mixtures were cast with 10 % and 20 % steel fibers by cement weight. The tests carried out included the flow table test, mini flow test, compressive strength testing of cubes and flexural strength testing of the UHPC mixtures. The results are described in detail below separately for grey and white concrete produced.

For each UHPC mixture, 30 litres batch was cast using Eirich mixer. A total of 12 test mixtures, six with grey materials and six with white materials were produced.

5.1 Grey UHFPRC

The mixture id, materials used and mix design of the mixtures are presented below.

1. G11 (UHPC produced with FFq 45 fillers and no steel fibers).
2. G12 (UHFPRC produced with FFq 45 fillers and 10 % steel fibers by cement weight).
3. G13 (UHFPRC produced with FFq 45 fillers and 20% steel fibers by cement weight).
4. G21 (UHPC produced with FFq 45 and Nilsiä fillers and no steel fibers).
5. G22 (UHFPRC produced with FFq 45 and Nilsiä fillers and 10% steel fibers by cement weight).
6. G23 (UHFPRC produced with FFq 45 and Nilsiä fillers and 20% steel fibers by cement weight).

Table 19 Mixture proportions of grey UHPFRC mixtures by cement weight.

Material/C	Mixture Id					
	G11	G12	G13	G21	G22	G23
Cement	1	1	1	1	1	1
Water	0.25	0.25	0.25	0.25	0.25	0.25
Silica Fume	0.20	0.20	0.20	0.15	0.15	0.15
Sand	0.875	0.875	0.875	1	1	1
FFq 45 filler	0.375	0.375	0.375	0.2	0.2	0.2
Nilsia Filler	-	-	-	0.05	0.05	0.05
Superplasticizer	0.05	0.05	0.05	0.05	0.05	0.05
Steel Fibers	0	0.1	0.2	0	0.1	0.2

5.1.2 Fresh Concrete Properties

Fresh concrete properties for the final test mixes were evaluated by the mini cone test and the flow table test. The test apparatus and procedure have been described earlier. As observed from the figures 48 and 49 below, the flow results of the G2 mixtures has a much higher value than the G1 mixtures. The reduced flowability of the G1 mixtures is due to an increased silica fume and filler content. The increase in packing density of the mixture due to two different types of fillers also increases the flow slightly for the G2 mixtures. The results comply with the preliminary test results as the G2 mixture was selected by compromising the compressive strength in favor of flowability. The G1 mixture gave the maximum strength value recorded in the preliminary tests along with minimum flow properties.

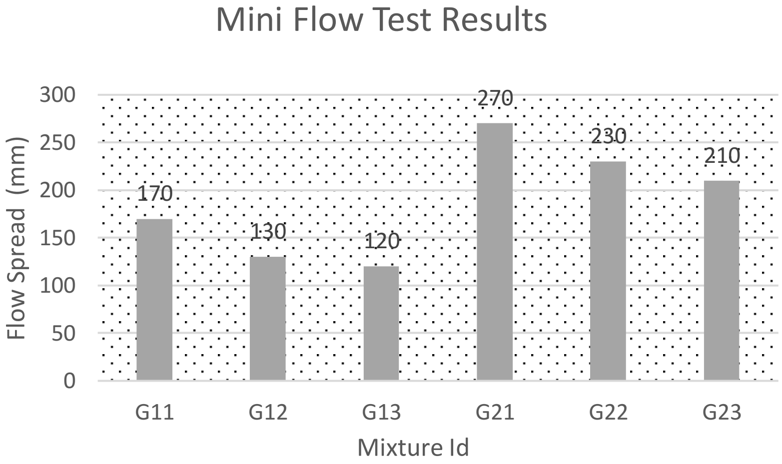


Figure 48 Mini Flow test results for grey UHPFRC mixtures (w/c ratio=0.25).

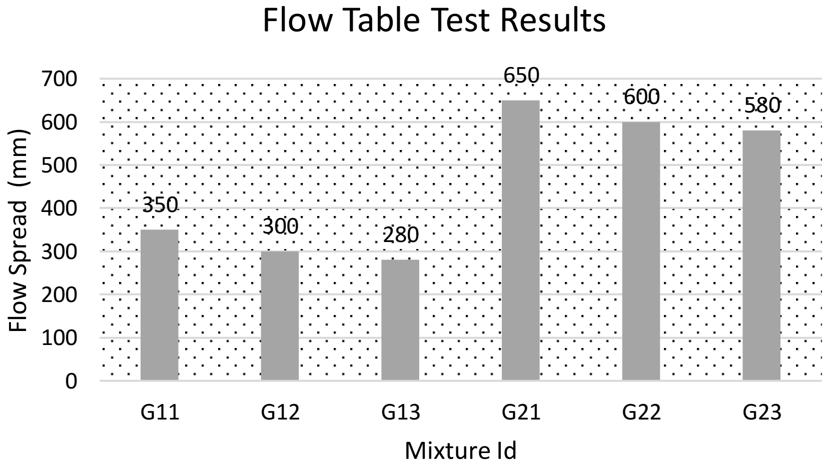


Figure 47 Flow table test results for grey UHPFRC mixtures (w/c ratio=0.25).

There is a decrease in the flow value with the incorporation of fibers into the mix as shown in the results above when the fiber content is increased from 0 to 10 %.The maximum flow for the G2 mixes was 650 mm recorded from the flow table test when no fibers were used in the mix. The flow decreased to 580 mm when 20 % of fibers by cement weight were included in the mixture. The maximum flow for the G1 mixes was 350 mm recorded from the flow table test when no fibers were used and the value decreased to 280 mm with the incorporation of 20% steel fibers in the mix. A more accurate presentation of the flowability of the UHPC mix is presented by the mini cone test. The mini flow result of G2 mixes decreased from 270 mm to 210 mm when fiber content increased from 0 to 20 % by cement weight. G1 mixes had a much lower mini flow value, 170 mm when no fibers were used and 120 mm when 20 % of the steel fibers were incorporated in the mix.

5.1.3 Compressive Strength:

The compressive strength test results for the grey UHPC and UHFPRC mixes are presented in figure 49. The G1 mixes had slightly higher compressive strength values than the G2 mixes. The maximum 7-day compressive strength of 129 MPa was recorded for the G13 UHFPRC mixture. A slightly lower strength gain and strength value was noted for the G2 mixes. A maximum 7-day compressive strength of 123 MPa was recorded for the G23 mix with 20% steel fibers. The overall maximum compressive strength value of 148 MPa for the grey UHPC mixes was obtained for the G13 mixture. The maximum compressive strength for the G2 mixes was 140 MPa obtained for the G23 mixture.

The slower strength gain rate of G2 mixtures as compared with G1 mixtures can be explained by the slightly larger amount of silica fume content present in the G1 mixes, 20 % Silica fume in the G1 mixes as compared to 15 % in the G2 mixes. The higher strength value of G1 mixes is explained by the greater amount of filler present. The G2 mixes were casted with ternary fillers resulting in better flow properties but slightly compromising the mechanical properties due to the presence of Nilsiä filler. As shown in the preliminary test results, mixes casted with Nilsiä filler had lower compressive strength values than FFq 45 fillers due to the lower packing density and higher water demand of Nilsiä fillers. The influence of steel fibers on compressive strength is almost negligible. An increase of only 8 MPa has been observed with mix incorporating no steel fibers compared with the mix including 20 % steel fibers for the G1 mixes. A similar increase is noted with the G2 mixes. The increase is almost same for both the 7 days compressive strength and 28 days compressive strength values.

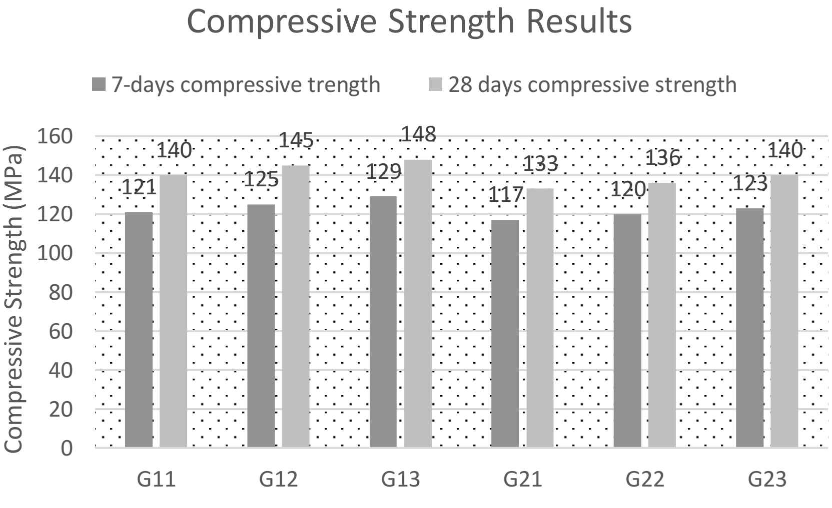


Figure 49 Compressive strength test results for grey UHPFRC mixture (w/c ratio=0.25).

5.1.4 Flexural Strength:

The flexural strength of the UHPC mixes was measured by two methods, described earlier in Chapter 3. The average test results of the specimen tested for each mixture is presented below.

Table 20 Flexural strength test results for grey UHPFRC mixtures (EN 1015-11).

Mixture ID	Description	Maximum Load (N)	Flexural Strength (MPa)
G11	No Steel Fibers	8327	18.8
G12	10 % Steel Fibers	9544	24.1
G13	20 % Steel Fibers	11900	29.8
G21	No Steel Fibers	8460	20.1
G22	10 % Steel Fibers	8073	20.2
G23	20 % Steel Fibers	11400	28.5

Table 21 Flexural strength test results for grey UHPFRC mixtures (EN 12390-5).

Mixture ID	Description	Maximum Load (kN)	Flexural Strength (MPa)
G11	No Steel Fibers	36.6	17
G12	10 % Steel Fibers	48	22
G13	20 % Steel Fibers	57.1	27
G21	No Steel Fibers	40.8	18.3
G22	10 % Steel Fibers	46.6	21.1
G23	20 % Steel Fibers	57.1	27

The ultimate flexural strength results for all the grey concrete mixtures varied from 18.8 to 29.8 MPa. There was a significant increase in the maximum load and ultimate flexural strength with the inclusion of steel fibers. The flexural strength increased from 18.8 MPa to 29.8 MPa with increasing the fiber content from 0 to 20 % for the G1 mixtures. The increase in flexural strength for the G2 mixtures was less significant up to 10 % addition of steel fibers but showed a greater increase with further increasing the fiber content to 20 %. The cracking pattern of the concrete was also significantly affected by the addition of steel fibers. A brittle failure occurred when no fibers were included in the mix while the addition of fibers led to ductile failure of the UHFPRC samples. The failure behavior of the samples can be observed from the force-deflection curves given in Appendix 2. The beam samples prepared from the UHPC and UHFPRC mixtures was also tested using the standard three point bending test method (EN 12390-5). The results are described in the table 21. As it can be seen, the maximum load varied between 36 kN to 57 kN with the increasing fiber content. This shows a strong dependence of steel fibers on the toughness and flexural strength of the sample and agrees with the literature described in Section 2.7. The comparison between both test methods is shown in the figure 50.

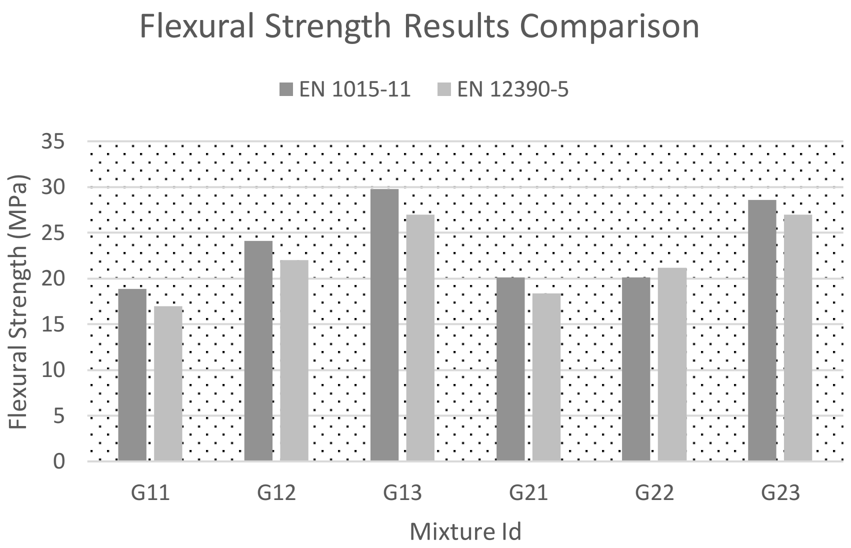


Figure 50 Flexural strength test results comparison of grey UHPFRC mixtures (EN 1015-11 & EN12390-5).

5.2 White UHFPRC:

The mixture id's and mixture proprtions are described below:

1. W11 (UHPC produced with TY63 fillers and no steel fibers).
2. W12 (UHFPRC produced with TY63 fillers and 10% steel fibers by cement weight).
3. W13 (UHFPRC produced with TY63 fillers and 20% steel fibers by cement weight).
4. W21 (UHPC produced with Calcite C2 and Parfill 80 fillers excluding steel fibers).
5. W22 (UHFPRC produced with Calcite C2 and Parfill 80 fillers including 10 % steel fibers).
6. W23 (UHFPRC produced with Calcite C2 and Parfill 80 fillers including 20 % steel fibers).

Table 22 Mixture proportions of material constituents by cement weight of white UHPFRC mixtures.

Material/C	Mixture Id					
	W11	W12	W13	W21	W22	W23
Cement	1	1	1	1	1	1
Water	0.22	0.22	0.22	0.22	0.22	0.22
Silica Fume	0.20	0.20	0.20	0.2	0.2	0.2
Sand	1	1	1	1	1	1
Tytyri 63 filler	0.25	0.25	0.25	-	-	-
Parfill 80 Filler	-	-	-	0.05	0.05	0.05
Calcite C2 filler	-	-	-	0.20	0.20	0.20
Superplasticizer	0.05	0.05	0.05	0.05	0.05	0.05
Steel Fibers	0	0.1	0.2	0	0.1	0.2

5.2.1 Fresh Concrete Properties:

Mini Flow test and flow table test was conducted to find out the flowability of the mixtures described above. The test results are described below in figures 51 and 52.

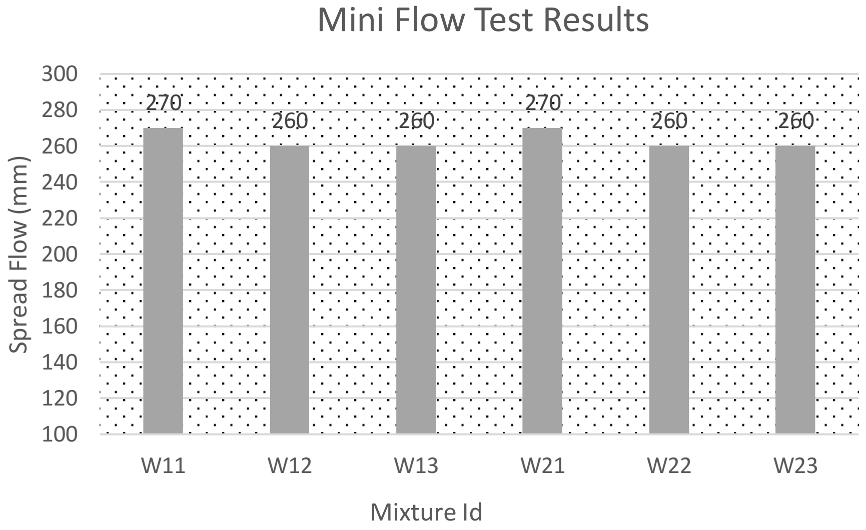


Figure 51 Mini Flow test results for white UHPFRC mixtures (w/c ratio=0.22).

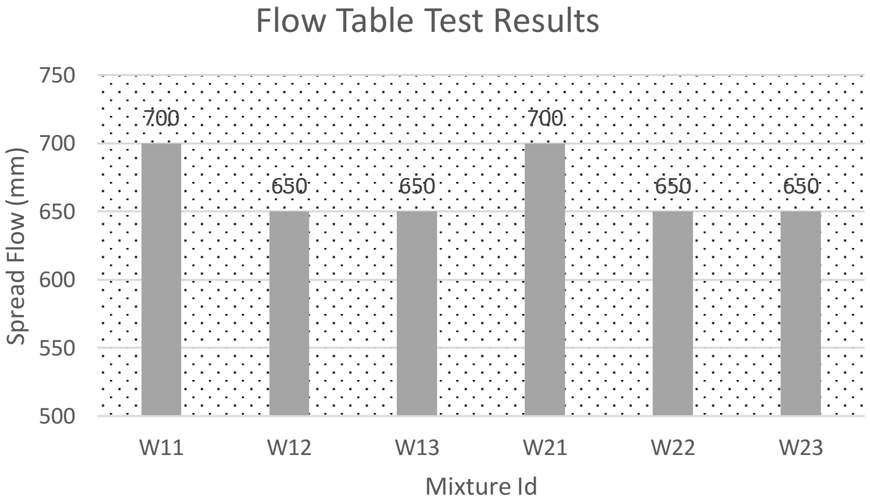
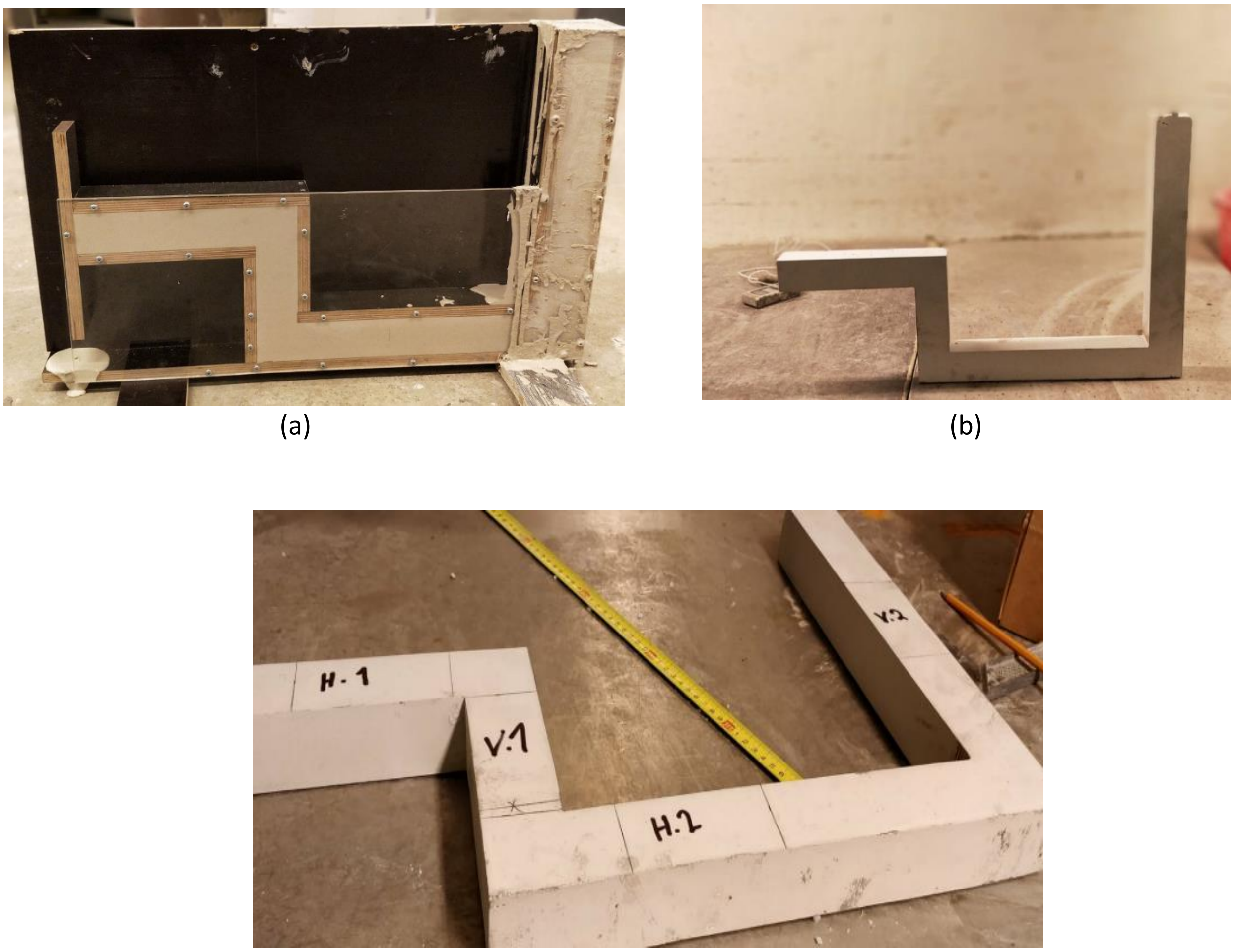


Figure 52 Flow table test results for white UHPFRC mixtures (w/c ratio=0.22).

The preliminary tests for white UHPC showed excellent flowability for all the mixture types. The final tests showed a similar trend and quite flowable concrete was produced with white cement and fillers. The test results showed that without any fiber addition the maximum flow value was obtained for both the mini flow test and flow table test. The introduction of fiber reduced the flow slightly but still managed to produce self-compacting concrete. The flow reduced from 270 mm to 260 mm by addition of 10 % fibers into the mix. Further increase of fiber amount did not produce any effect on the flow of the mix. The flow properties were further observed by pouring the white UHPC mixtures into a special U-shaped mould which will be described later.

A special U-shaped plexi mould was prepared to validate the self-compacting nature of the white UHPFRC produced. The plexi mould is presented in figure 52 (a). The basic idea was to pour concrete through the vertical end and check whether it can rise through the other shorter vertical end. Two UHPFRC casts were tested through the special mould, W13 and W23. The fresh concrete flow through the mould is shown in figure 52 (a) and the hardened sample obtained after the removal of the plexi mould is shown in figure 52 (b). It was visually analyzed from the plexi mould test, that the white UHPFRC produced flows smoothly through the mould validating the self-compacting nature of white UHPFRC. The basic idea about the flow test through the special U-shaped plexi mould was that the white UHPFRC produced should have sufficient flowability to be cast into irregular shapes such as facades of a structure. This type of test can be carried out, if the UHPFRC produced is intended for special applications where the concrete is cast into irregular shapes.



(a)

(b)

(c)

Figure 53 (a) U-shaped plexi mould with fresh UHPFRC. (b) Hardened UHPFRC sample obtained after the opening of the plexi mould. (c) Cutting of samples from the specimen for measuring density of concrete at various locations.

The hardened UHPFRC specimen was cut into smaller samples at various locations as presented in figure 52 (c). The density of the cutted samples was calculated by measuring the weight of the specimen in air and then under water. The difference in density indicates a difference in the fiber content at various locations as shown in table.

Table 23 Density of UHPFRC specimens obtained from the special mould.

Sample Id	Density (kg/m^3)
H1	2424
H2	2424
V1	2435
V2	2434

As it can be seen that the difference in density at various locations is not much, thus indicating an approximately equal distribution of fibers along the sample.

5.2.2 Compressive Strength:

The compressive strength results are presented in figure 48. The W1 and W2 mixes showed a maximum 7 and 28 days compressive strength for the mixes with 20 % steel fibers by cement weight as described by the W13 and W23 mixtures in the figure below. There was a slight increase in the early strength gain for all the UHPC mixes irrespective of steel fiber addition. The increase in strength gain after 7 days was much pronounced with the addition of fibers into the mix. This can be observed by comparing the 28 days compressive strength of the mixes. The compressive strength of the mixture increased from 121 to 131 MPa when no fibers were included. An addition of 10% steel fibers by cement weight significantly increased the strength gain rate with time, the compressive strength increased from 124.5 MPa to 150.9 MPa. Further increasing the fiber content to 20 % by cement weight, resulted in an increase in compressive strength but the strength gain was less pronounced. The 28 days compressive strength was noted to be 155 MPa for the W13 mix. The strength gain was much lesser with the increase in fiber content, a 5 MPa increase in compressive strength was observed by increasing the amount of fibers from 10 to 20 %, while 20 MPa increase in compressive strength was observed by increasing fiber amount from 0 to 10 %. The compressive strength gain with time showed an increase with increasing fiber content from 0 to 20 %. The W2 UHPC mixes showed similar results. The early age strength increased slightly with addition of steel fibers, the 7-day compressive strength increased from 123 MPa to 130 MPa with increasing the fiber amount from 0 to 20 %. The 28 days compressive strength showed much higher increase in strength gain with the increase in amount of fibers. The 28 days compressive strength increased from 135 to 148 MPa with an increase in fiber content from 0 to 10 %, and further increased to 155.5 MPa when 20 % fibers were added in the UHPC mix. This shows an increase in strength gain rate with fiber addition at the beginning, but there is a reduction in the strength gain rate once the fiber amount is increased beyond 10 %. The strength gain rate with time increased linearly for increase in fiber content irrespective of the fiber amount.

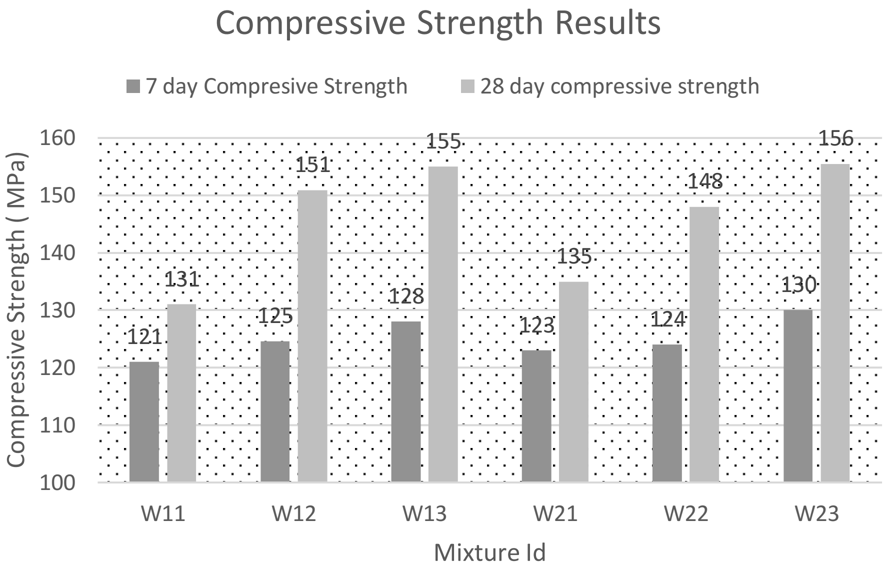


Figure 54 Compressive strength test results for white UHPFRC mixtures (w/c ratio=0.22).

5.2.3 Flexural Strength:

The 28 days flexural test results obtained from white UHPC and UHFPRC samples are presented below:

Table 24 Flexural strength test results for white UHPFRC mixtures (EN 1015-11).

Mixture ID	Description	Maximum Load (N)	Flexural Strength (MPa)
W11	No Steel Fibers	6827	15.74
W12	10 % Steel Fibers	7320	17.44
W13	20 % Steel Fibers	7777	18.85
W21	No Steel Fibers	7050	16
W22	10 % Steel Fibers	8073	19.94
W23	20 % Steel Fibers	8264	24.5

Table 25 Flexural strength test results for white UHPFRC mixtures (EN 12390-5).

Mixture ID	Description	Maximum Load (kN)	Flexural Strength (MPa)
W11	No Steel Fibers	37	17
W12	10 % Steel Fibers	37.2	17.7
W13	20 % Steel Fibers	41.5	19.3
W21	No Steel Fibers	37.7	17.2
W22	10 % Steel Fibers	40.1	19
W23	20 % Steel Fibers	44.3	20.5

As it can be seen from table 24 and 25, an increase in flexural strength occurs with an increase in fiber content from 0 to 20 % for the W1 mixtures. The increase in flexural strength is more prominent in the W2 mixtures with a 34% increase in strength as the fiber content is increased by 20 %.

The failure pattern of the UHPC and UHFPRC samples also varied as was the case with the grey concrete. A sudden brittle failure occurred with no fibers in the mixture of the UHPC samples W11 and W21. The UHFPRC mixtures showed a ductile failure and were able to withstand a further increase in the load after the cracking load was exceeded. The increase in flexural strength and change of failure behavior occurs due to the bridging of gaps in the element due to fibers, decreasing the crack length and enhancing the ductility of the material. The inclusion of steel fibers in the mix results in strain hardening behavior of the mixture. This leads to multiple crack formation leading to high ductility of the mixture. The force-deformation curves presented in the Appendix 2 shows the behavior of the samples with variation of fiber contents. The results obtained for the flexural strength through three point bending test described in EN 12390-5 are also presented in table. The results follow the same trend and showed an increase in the maximum load and flexural strength with the increase in fiber content. The maximum load varied between 37kN and 44kN with the fiber content. The flexural strength values found out through both methods are compared in figure. The results obtained by both methods are almost identical with a slightly higher values are obtained through EN 1015-11 three point bending test method.

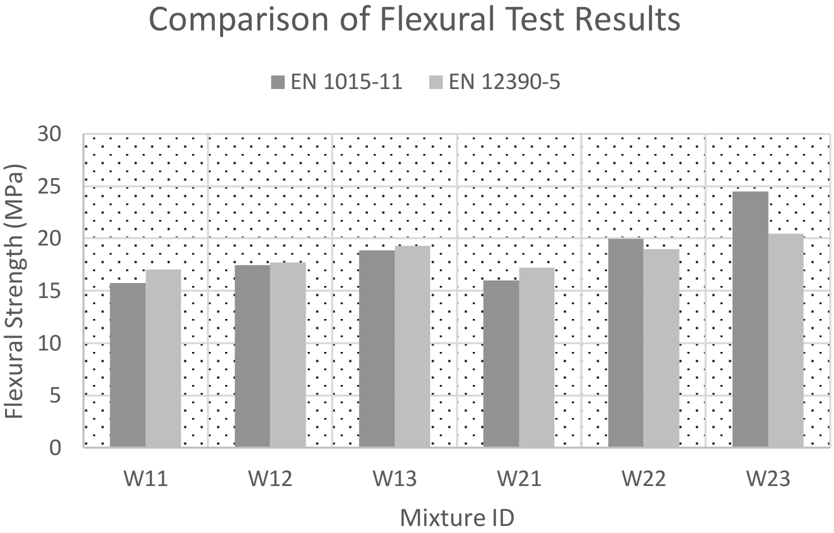


Figure 55 Flexural strength test results comparison of white UHPFRC mixtures (EN 1015-11 & EN 12390-5).

5.3 Conclusions

UHPFRC is concrete characterized with high compressive strength, flexural strength and excellent flowability. The advantages over normal concrete are considerably higher mechanical and rheological properties.

The objective of this research was development of white and grey UHPFRC using locally available materials. The experimental phase was carried out in two parts; preliminary laboratory tests aimed at water demand tests for optimization of filler composition and the effect of various material constituents and proportions on the compressive strength and flow of the mixture. In the preliminary tests, UHPC was produced without fibers. The preliminary tests resulted in obtaining two best mixtures for white and grey UHPFRC, which were then tested with varied fiber content in the final testing phase. The tests carried out in the final phase were compressive and flexural strength tests, mini flow and flow table tests. The conclusions drawn out from the experimental testing for development of UHPFRC are discussed in the section below.

Results of the research study shows that it is possible to obtain UHPFRC with a high compressive strength of over 140 MPa and flexural strength of over 20 MPa by the selection of appropriate content and type of filler, silica fume, cement and incorporation of thin steel fibers into the mixture. The UHPFRC produced is also characterized with excellent flowability. The test program was quite extensive with various types of quartz and limestone fillers, silica fume and cements were tested to obtain the best mixture combination. The conclusions drawn from preliminary tests and final tests are presented below.

5.3.1 Preliminary Laboratory Tests

Grey UHPC

- The optimum amount of sand/cement was found out to be 1/1 for two different water to cement ratio combinations (0.25, 0.28).

- Puntke test gave a good correlation for achieving the maximum packing density of different filler combinations resulting in maximum compressive strength. The water demand of polydisperse mixes resulted in finding the appropriate amount required for achieving maximum flowability. The water demand results were in agreement with the strength and flowability values observed for reference mixes based on water demand results.
- Silica fume 940 U resulted in achieving better flow results and higher compressive strength values than the densified silica fume 920 ED. The optimum amount of silica fume for maximum compressive strength was found out to be 25 % of the cement weight. Reducing the silica fume amount increases the flow but decreases the strength values.
- It was found out that appropriate amount of SCMs can be used to replace cement. The replacement of cement by SCMs provides excellent flow results and the strength values though are reduced, but still above the limit set for a concrete to be defined as ultra high performance concrete. A maximum compressive strength of 127 MPa was observed when 20 % of the cement was replaced by modified fly ash. The optimum amount of slag replacement turned out to be 10 % resulting in a compressive strength of 125.3 MPa. The actual strength value of UHPC with SCMs can show an increase in strength after 28 days and usually the 90 days strength is slightly higher than that at 28 days.
- Pika cement gave better strength results than plus and SR cement and is the preferred cement for production of UHPC. The higher fineness of pika cement can result in a higher water demand, but can be replaced with SCMs still managing more strength than plus and SR cement.
- FFq 45 quartz filler had the lowest water demand and was preferred for producing UHPC. The maximum compression strength of 145 MPa was observed for a UHPC mix containg 40 % of the fine aggregate content as ffq45 filler and 60 % as sand. The highest 7 days strength (120.2 MPa) was also observed for the same mix.
- Using a combination of different types of fillers and by reducing the silica fume amount it is possible to produce UHPC without fibers having excellent flowability and strength values in excess of 130 MPa.
- One binary filler combination mix with the maximum compressive strength and one ternary filler combination mix with optimized flow and compressive strength value were selected for final testing for the production of UHPFRC.

White UHPC

- The optimum proportion of filler/sand ratio for majority of the limestone fillers used was equal to 0.2.
- The optimum amount of cement/sand was found out to be 1/1.
- All the UHPC mixtures showed excellent flow properties as compared with grey UHPC mixtures.
- The optimum amount of w/c ratio was found to be 0.22 for white UHPC. Increasing the w/c ratio above 0.22 did not caused significant difference in the flow and compressive strength values. Decreasing the water to cement ratio below 0.22 caused a significant decrease in the mini flow value of the mixture and a slight reduction in the compressive strength was also noticed.

- The optimum amount of silica fume was found out through experimentation. The optimum amount was measured to be 20 % of the cement weight. Increasing silica fume amount beyond this caused a reduction in 28 days strength.
- UHPC mixes were cast with binary and ternary filler combinations. The binary combinations showed that maximum compressive strength value of 140 MPa was measured when Tytyri 63 was used as a filler. All the limestone fillers used were capable of producing concrete with compressive strength of over 120 MPa. Parfill fillers gave the least compressive strength value.
- The ternary filler combinations were cast by using Calcite C2 as a reference filler and combining other fillers with it. It was found out that maximum compressive strength of 141.3 MPa was obtained for C2/Tytyri 63 filler combination. The combination of two calcite fillers reduced the compressive strength of the mix in comparison with the mix where only one type of calcite filler was used. The most significant improvement was observed by combining Calcite C2 filler with Parfill 80 filler. An increase of 15 MPa was observed by casting a ternary mix of C2/Parfill 80 filler as compared with the mix where only Parfill 80 filler was used.
- One binary and one ternary filler combination mix was selected for final testing for production of white UHPFRC.

5.3.2 Final Tests

Grey UHPFRC

- Grey UHPFRC with a compressive strength of 148 MPa and flexural strength of 29 MPa can be produced by using Pika cement, Ffq 45 filler/sand ratio of 0.3, 25 % silica fume by cement weight, 5 % superplasticizer by cement weight and a w/c ratio of 0.25. The flowability of the mix was quite low, a mini flow value of 120 mm and a flow table value of 280 mm was recorded.
- The flowability of the mixture is reduced with increasing fiber content of the UHPFRC mix composition. The flow however is not entirely dependent on fiber content. As it was observed from the preliminary studies, an increase in filler proportion and silica fume proportion causes a reduction in the flow.
- A compressive strength of 140 MPa, flexural strength of 28 MPa can be achieved by combining pika cement, 15 % Elkem 940 U silica fume, combination of ffq 45 fand Nilsiä filler with filler/sand ratio of 0.2 with Nilsiä/Ffq 45 filler ratio of 0.2, 20 % steel fibers by cement weight, 5 % superplasticizer by cement weight and a w/c ratio of 0.25. The mini flow value was recorded to be 210 mm and the flow table value was 580 mm. The flow increased due to reduction in filler and silica fume content and the use of a ternary filler combination. The compressive strength decreased due to the inclusion of weaker Nilsiä filler, reduced silica fume and filler content.
- The impact of steel fiber addition on the compressive strength of the grey UHPFRC mixtures was not quite significant; an increase of only 8 MPa was observed for the G1 mixture while an increase of 7 MPa was noted for the G2 mixture for a 20 % increase in fiber content by cement weight.
- The impact of steel fiber addition on the flexural capacity of the UHPFRC mixture was quite notable. An increase of almost 10 MPa was observed for the G1 mixture while the flexural

strength of the G2 mixture increased from 20 to 28 MPa with a 20 % steel fiber incorporation into the mixture.

- The failure pattern of the test specimens were also affected by the inclusion of fibers. Sudden brittle failure was observed with no steel fibers while a ductile failure was observed for samples incorporated with steel fibers.

White UHPFRC

- White UHPFRC with a compressive strength of 155 MPa, flexural strength of over 20 MPa with self-compacting properties can be produced by using white cement, 20 % Elkem microwhite Silica fume, filler/sand ratio of 0.2 with Calcite C2/Parfill 80 filler ratio of 0.8, 5 % superplasticizer by cement weight, 20 % steel fibers by cement weight and a water/cement ratio of 0.22.
- White UHPFRC with similar compressive strength and flow properties as above but slightly lower flexural strength can be produced by using only one filler, Tytyri 63 with a filler/sand ratio of 0.2.
- Slight reduction in flow value is noted by incorporation of fibers into the mixture. The value however did not show any reduction with increasing fiber content from 10 % to 20 % and quite flowable concrete was produced even with a higher steel fiber content.
- The effect of steel fiber addition on the compressive strength in case of producing white UHPFRC was much more significant than grey UHPFRC. The W1 mixture showed an increase of 24 MPa, the compressive strength increased from 131 MPa with no steel fibers to 155 MPa with 20 % steel fibers. A similar increase was observed with the W2 mixture, the compressive strength increased from 135 MPa to 155.5 MPa.
- The effect of steel fiber addition on the flexural strength of the white UHPFRC was almost negligible for the W1 mixture. The W2 mixture showed a significant increase, the flexural strength increasing by almost 33 % with a 20 % steel fiber addition.
- The failure pattern of the test specimens were also affected by the inclusion of fibers. Sudden brittle failure was observed with no steel fibers while a ductile failure was observed for samples incorporated with steel fibers.

5.4 Recommendations for future research

The research study was mainly focused on development of UHPFRC. The following recommendations are given for future purposes.

- Further study can be carried out on evaluation of mechanical properties of UHPFRC such as the stress-strain behavior in compression and tension, static and dynamic modulus, drying and autogenous shrinkage and creep etc.

- The effect of orientation of steel fibers on the properties of UHPFRC and the type of steel fibers can be studied in detail.

- Different types of fibers can be studied such as propylene fibers, plastic fibers and other metallic fibers. The use of plastic fibers can be effective in not only reducing the cost of the material but can also be effective for aesthetic applications where steel fibers can have a negative impact on the aesthetics.

- The effect of superplasticizer content and the comparison of different types of superplasticizers on the properties of UHPFRC can be studied.

- The behavior of UHPFRC under severe conditions can be also studied, the effect of freezing and thawing cycles on the properties of UHPFRC can be analyzed.

- The long term strength development of UHPFRC can be studied especially for UHPFRC with supplementary cementitious materials.

Appendix 1 Mix proportions and test results of preliminary UHPC mixtures.

Mix proportions of material constituents by cement weight for preliminary tests. (Grey UHPC).

Mixture Id	Parameter under investigation	Description	Mixture proportions (ratios with respect to cement weight)								
			Cement	Silica fume	Sand	Quartz filler	HRWRA	w/c	Coarse aggregates	Slag	Fly Ash
S0.75	Sand/Cement ratio	C/S=0.75	1	0.25	0.75	0.25	0.05	0.25	-	-	-
S1		C/S=1	1	0.25	1	0.25	0.05	0.25	-	-	-
S1.25		C/S=1.25	1	0.25	1.25	0.25	0.05	0.25	-	-	-
S0.75/0.28	Water/Cement ratio for different Sand amounts	C/S=0.75	1	0.25	0.75	0.25	0.05	0.28	-	-	-
S1/0.28		C/S=1	1	0.25	1	0.25	0.05	0.28	-	-	-
S1.25/0.28		C/S=1.25	1	0.25	1.25	0.25	0.05	0.28	-	-	-
Pi	Cement type	Pika cement	1	0.25	1	0.25	0.05	0.25	-	-	-
Pl		Plus cement	1	0.25	1	0.25	0.05	0.25	-	-	-
SR		Sulphate resistant cement	1	0.25	1	0.25	0.05	0.25	-	-	-
SFU15	Silica fume 940U	15 % SF	1	0.15	1	0.25	0.05	0.25	-	-	-
SFU20		20% SF	1	0.2	1	0.25	0.05	0.25	-	-	-
SFU25		25% SF	1	0.25	1	0.25	0.05	0.25	-	-	-
SFE15	Silica fume 920 ED	15% SF	1	0.15	1	0.25	0.05	0.25	-	-	-
SFE20		20%SF	1	0.2	1	0.25	0.05	0.25	-	-	-
SFE25		25% SF	1	0.25	1	0.25	0.05	0.25	-	-	-
FF0	Filler/fine aggregate proportion	No filler	1	0.25	1.25	0	0.05		-	-	-
FF0.2		20 % FFq 45 filler	1	0.25	1	0.25	0.05	0.25	-	-	-
FF0.4		40 % FFq 45 filler	1	0.25	0.75	0.5	0.05	0.25	-	-	-
FA0.1	Modified Fly Ash	10% fly ash	0.9	0.25	1	0.25	0.05	0.25	-	-	0.1
FA0.2		20 % fly ash	0.8	0.25	1	0.25	0.05	0.25	-	-	0.2
FA0.3		30% fly ash	0.7	0.25	1	0.25	0.05	0.25	-	-	0.3
SL0.1	Slag	10% slag	0.9	0.25	1	0.25	0.05	0.25	-	0.1	-
SL0.2		20% slag	0.8	0.25	1	0.25	0.05	0.25	-	0.2	-
SL0.3		30 % slag	0.7	0.25	1	0.25	0.05	0.25	-	0.3	-
T1	Ternary mixes (Sand/ffq45/ nilsiä)	0.8/0.16/0.04	1	0.15	1	0.25	0.05	0.25	-	-	-
T2		0.8/0.12/0.08	1	0.15	1	0.25	0.05	0.25	-	-	-
T3		0.8/0.08/0.12	1	0.15	1	0.25	0.05	0.25	-	-	-
T4		0.8/0.04/0.16	1	0.15	1	0.25	0.05	0.25	-	-	-
C0.5-1.2	Coarse aggregates	0.5-1.2mm aggregates	1	0.25	1	0.25	0.05	0.25	1	-	-
C1-2		1-2mm aggregates	1	0.25	1	0.25	0.05	0.25	1	-	-

Fresh properties, mixing time and compressive strength of preliminary grey UHPC mixtures.

Mixture Id	7 days compressive strength (MPa)	28 days compressive strength (MPa)	Mini flow (mm)	Mixing Time (min)	Unit Weight (kg/m3)
S0.75	110.7	>125	140	10	2250
S1	117.5	140	135	10	2280
S1.25	107.4	123	150	10	2255
S0.75/0.28	98.1	>125	165	10	2250
S1/0.28	114.5	>125	190	10	2280
S1.25/0.28	109.1	117.1	180	10	2210
Pi	117.5	140	135	10	2280
Pl	94	119	130	10	2236
SR	94	119	185	10	2292
SFU15	111.7	122.2	215	10	2260
SFU20	107.7	124	185	10	2270
SFU25	117.5	140	130	10	2280
SFE15	105.1	117	210	11	2250
SFE20	102.3	118.5	155	13	2220
SFE25	104.5	120.5	125	17	2310
FF0	Nil	124.6	160	10	2274
FF0.2	117.5	140	130	10	2280
FF0.4	120.2	145	135	13	2280
FA0.1	109.2	118.3	150	10	2240
FA0.2	107.5	127.3	210	10	2270
FA0.3	103.5	121.1	215	10	2250
SL0.1	112	125.3	150	10	2235
SL0.2	104.9	111	170	10	2230
SL0.3	104.5	119.1	270	10	2285
T1	112.4	133.1	235	10	2270
T2	113.8	121.6	225	10	2283
T3	114	128.7	265	10	2292
T4	116.9	120.2	225	10	2262
C0.5-1.2	109.4	127.3	155	8	2310
C1-2	109.9	131.1	160	8	2347

Mix proportions of material constituents by cement weight for preliminary tests. (White UHPC).

Mixture Id	Parameter under investigation	Description	Mixture proportions (ratios with respect to cement weight)						
			Cement	Silica fume	Sand	Limestone Filler	HRWRA	w/c	Coarse aggregates
WC2	Binary Filler Combinations	Calcite C2	1	0.25	1	0.25	0.05	0.22	-
WC5		Calcite C5	1	0.25	1	0.25	0.05	0.22	-
WC7		Calcite C7	1	0.25	1	0.25	0.05	0.22	-
WPH80		Parfill H80	1	0.25	0.75	0.5	0.05	0.22	-
WP80		Parfill 80	1	0.25	1	0.25	0.05	0.22	-
WTy63		Tytyre 63	1	0.25	1	0.25	0.05	0.22	-
WC2C7	Ternary Filler combinations	C2/C7	1	0.25	1	0.25	0.05	0.22	-
WC2C5		C2/C5	1	0.25	1	0.25	0.05	0.22	-
WC2/80		C2/80	1	0.25	1	0.25	0.05	0.22	-
WC2/H80		C2/H80	1	0.25	0.75	0.5	0.05	0.22	-
WC2/TY63		C2/TY63	1	0.25	1	0.25	0.05	0.22	-
WC2/ WOLS		C2/WOLS	1	0.25	1	0.25	0.05	0.22	-
W0.2	Water/cement ratio		1	0.25	1	0.25	0.05	0.2	-
W0.22			1	0.25	1	0.25	0.05	0.22	-
W0.25			1	0.25	1	0.25	0.05	0.25	-
WS0.15	Silica fume content		1	0.15	1	0.25	0.05	0.22	-
WS0.2			1	0.20	1	0.25	0.05	0.22	-
WS0.25			1	0.25	0.75	0.5	0.05	0.22	-
WCA0.5-1.2	Coarse aggregates		1	0.25	1	0.25	0.05	0.22	-
WCA1-2			1	0.25	1	0.25	0.05	0.22	1

Fresh properties, mixing time and compressive strength of preliminary grey UHPC mixtures.

Mixture Id	7 days compressive strength results (MPa)	28 days compressive strength results (MPa)	Mini Flow (mm)	Mixing time (mins)
WC2	125.3	133	270	16
WC5	119.7	132	270	16
WC7	118.6	135	270	16
WPH80	111.6	125	160	25
WP80	113.7	124.4	270	16
WTy63	128	140.3	270	16
WC2C7	124.7	128.1	270	16
WC2C5	118.3	128.4	270	16
WC2/80	119	125.5	270	16
WC2/H80	107.6	139.6	150	33
WC2/TY63	123.7	141	270	16
WC2/ WOLS	131.9	133	270	16
W0.2	122.4	125.2	185	18
W0.22	119.7	133	270	16
W0.25	124.5	132	270	16
WS0.15	123.3	136.2	270	16
WS0.2	119.1	139.2	270	16
WS0.25	119.7	133	270	16
WCA0.5-1.2	127.1	132	270	15
WCA1-2	131.6	135	270	15

Appendix 2. Mixture proportions and test results of final UHPFRC mixtures.

Mix proportions of material constituents by cement weight for final tests. (Grey UFPFRC).

Material/C	**Mixture Id**					
	G11	G12	G13	G21	G22	G23
Cement	1	1	1	1	1	1
Water	0.25	0.25	0.25	0.25	0.25	0.25
Silica Fume	0.20	0.20	0.20	0.15	0.15	0.15
Sand	0.875	0.875	0.875	1	1	1
FFq 45 filler	0.375	0.375	0.375	0.2	0.2	0.2
Nilsia Filler	-	-	-	0.05	0.05	0.05
Superplasticizer	0.05	0.05	0.05	0.05	0.05	0.05
Steel Fibers	0	0.1	0.2	0	0.1	0.2

Mix proportions of material constituents in kg/m^3 for final tests. (Grey UFPFRC)

Material (kg/m^3)	**Mixture Id**					
	G11	G12	G13	G21	G22	G23
Cement	833	825	816	848	839	830
Water	208	206	204	212	209.5	207.5
Silica Fume	167	165	163.2	127	125.7	124.5
Sand	726	716	708	848	839	830
FFq 45 filler	313	309	306	170	169	168
Nilsia Filler	-	-	-	42	41	40
Superplasticizer	42	41	41	42	42	41.5
Steel Fibers	0	82.5	163	0	82.5	163
Steel Fibers (% concrete volume)	0	3.5	7	0	3.5	7

Mix proportions of material constituents by cement weight for final tests. (White UFPFRC).

Material/C	**Mixture Id**					
	W11	W12	W13	W21	W22	W23
Cement	1	1	1	1	1	1
Water	0.22	0.22	0.22	0.22	0.22	0.22
Silica Fume	0.20	0.20	0.20	0.2	0.2	0.2
Sand	1	1	1	1	1	1
Tytyri 63 filler	0.25	0.25	0.25	-	-	-
Parfill 80 Filler	-	-	-	0.05	0.05	0.05
Calcite C2 filler	-	-	-	0.20	0.20	0.20
Superplasticizer	0.05	0.05	0.05	0.05	0.05	0.05
Steel Fibers	0	0.1	0.2	0	0.1	0.2

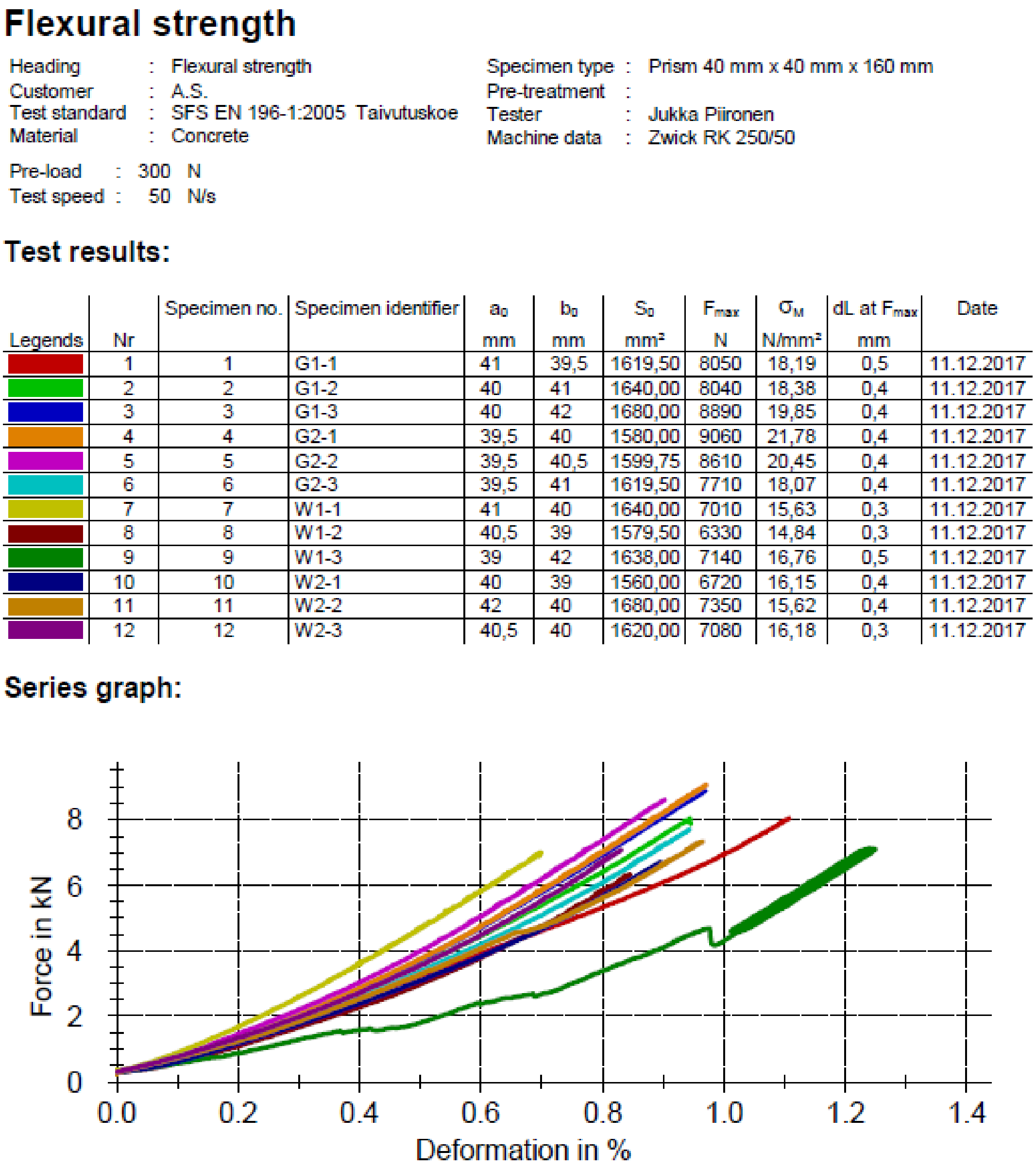
Mix proportions of material constituents in kg/m^3 for final tests. (White UFPFRC).

Material (kg/m^3)	**Mixture Id**					
	W11	W12	W13	W21	W22	W23
Cement	854	844	835	854	844	835
Water	188	185.6	183.7	188	185.6	183.7
Silica Fume	171	168.8	167	171	168.8	167
Sand	854	844	835	854	854	835
Tytyri 63 filler	213.5	211	208.75	-	-	-
Parfill 80 Filler	-	-	-	42.7	42.2	167
Calcite C2 filler	-	-	-	170.8	168.8	41.75
Superplasticizer	42.7	42.2	41.75	42.7	42.2	41.75
Steel Fibers	0	84.4	167	0	84.4	167
Steel Fibers (% concrete volume)	0	3.5	7	0	3.5	7

Compressive strength, Mini Flow, Flexural strength properties of final test UHPFRC mixtures.

Mixture Id	7 days compressive strength (MPa)	28 days compressive strength (MPa)	Mini flow (mm)	Flexural Strength (MPa)	Unit Weight (kg/m3)
G11	121	140	170	18.83	2295
G12	125	145	130	24.1	2335
G13	129	148	120	29.76	2444
G21	117	133	270	20.1	2221
G22	120	136	230	20.15	2400
G23	123	140	210	28.56	2420
W11	121	131	270	15.74	2374
W12	124.6	150.9	260	17.44	2451
W13	128	155	260	18.85	2461
W21	123	135	270	16	2354
W22	124	148	260	19.94	2392
W23	130	155.5	260	24.5	2457

Force-Deformation data obtained through flexural Strength Test (EN 1015-11).



Flexural strength

Heading : Flexural strength
Customer : A.S.
Test standard : SFS EN 196-1:2005 Taivutuskoe
Material : Concrete
Specimen type : Prism 40 mm x 40 mm x 160 mm
Pre-treatment :
Tester : Jukka Piironen
Machine data : Zwick RK 250/50

Pre-load : 300 N
Test speed : 50 N/s

Test results:

Legends	Nr	Specimen no.	Specimen identifier	a_0 mm	b_0 mm	S_0 mm²	F_{max} N	σ_M N/mm²	dL at F_{max} mm	Date
🟥	1	1	G1-1	41	39,5	1619,50	8050	18,19	0,5	11.12.2017
🟩	2	2	G1-2	40	41	1640,00	8040	18,38	0,4	11.12.2017
🟦	3	3	G1-3	40	42	1680,00	8890	19,85	0,4	11.12.2017
🟧	4	4	G2-1	39,5	40	1580,00	9060	21,78	0,4	11.12.2017
🟪	5	5	G2-2	39,5	40,5	1599,75	8610	20,45	0,4	11.12.2017
🟦	6	6	G2-3	39,5	41	1619,50	7710	18,07	0,4	11.12.2017
🟨	7	7	W1-1	41	40	1640,00	7010	15,63	0,3	11.12.2017
🟥	8	8	W1-2	40,5	39	1579,50	6330	14,84	0,3	11.12.2017
🟩	9	9	W1-3	39	42	1638,00	7140	16,76	0,5	11.12.2017
🟦	10	10	W2-1	40	39	1560,00	6720	16,15	0,4	11.12.2017
🟫	11	11	W2-2	42	40	1680,00	7350	15,62	0,4	11.12.2017
🟪	12	12	W2-3	40,5	40	1620,00	7080	16,18	0,3	11.12.2017

Series graph:

Force deformation curves for G11, G21, W11 and W21 mixtures.

Flexural strength

Heading : Flexural strength
Customer : A.C.
Test standard : SFS EN 196-1:2005 Taivutuskoe
Material : concrete

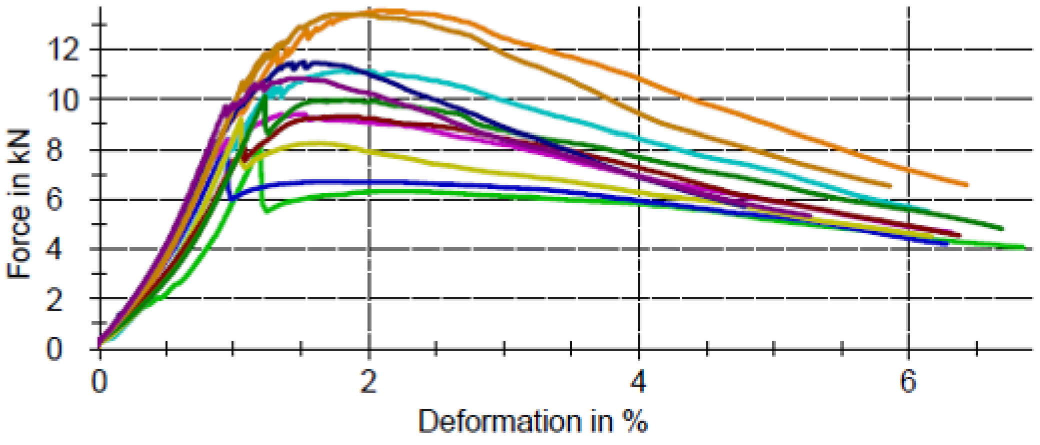
Specimen type : Prisma 40 mm x 40 mm x 160 mm
Pre-treatment :
Tester : Pertti Alho
Machine data : Zwick RK 250/50

Pre-load : 300 N
Test speed : 50 N/s

Test results:

Legends	Nr	Specimen no.	Specimen identifier	a_0 mm	b_0 mm	S_0 mm²	F_{max} N	σ_M N/mm²	dL at F_{max} mm	Date
🟥	1	1	0.1-G2-1	38,5	39,5	1520,75	7570	19,38	0,4	12.12.2017
🟩	2	2	0.1-G2-2	40	38	1520,00	8230	20,31	0,5	12.12.2017
🟦	3	3	0.1-G2-3	39	40	1560,00	8420	20,76	0,4	12.12.2017
🟧	4	4	0.2-G2-1	39,5	39,5	1560,25	13600	33,03	0,9	12.12.2017
🟪	5	5	0.2-G2-2	38	40	1520,00	9400	24,42	0,6	12.12.2017
🟦	6	6	0.2-G2-3	39	39	1521,00	11200	28,23	0,8	12.12.2017
🟨	7	7	0.1-G1-1	39	40	1560,00	9210	22,71	0,4	12.12.2017
🟥	8	8	0.1-G1-2	38	40	1520,00	9320	24,20	0,8	12.12.2017
🟩	9	9	0.1-G1-3	39	39	1521,00	10100	25,59	0,5	12.12.2017
🟦	10	10	0.2-G1-1	39,5	39,5	1560,25	11500	28,02	0,6	12.12.2017
🟧	11	11	0.2-G1-2	39	40	1560,00	13400	33,13	0,8	12.12.2017
🟪	12	12	0.2-G1-3	38,5	39	1501,50	10800	28,15	0,6	12.12.2017

Series graph:



Force deformation curves for G12, G13, G22 and G23 mixtures

Flexural strength

Heading : Flexural strength
Customer : A.C.
Test standard : SFS EN 196-1:2005 Taivutuskoe
Material : concrete

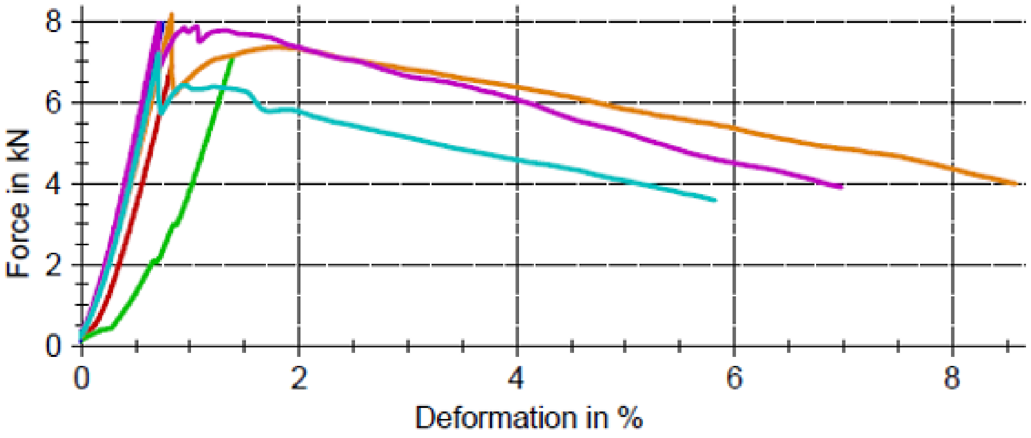
Specimen type : Prisma 40 mm x 40 mm x 160 mm
Pre-treatment :
Tester : Pertti Alho
Machine data : Zwick RK 250/50

Pre-load : 300 N
Test speed : 50 N/s

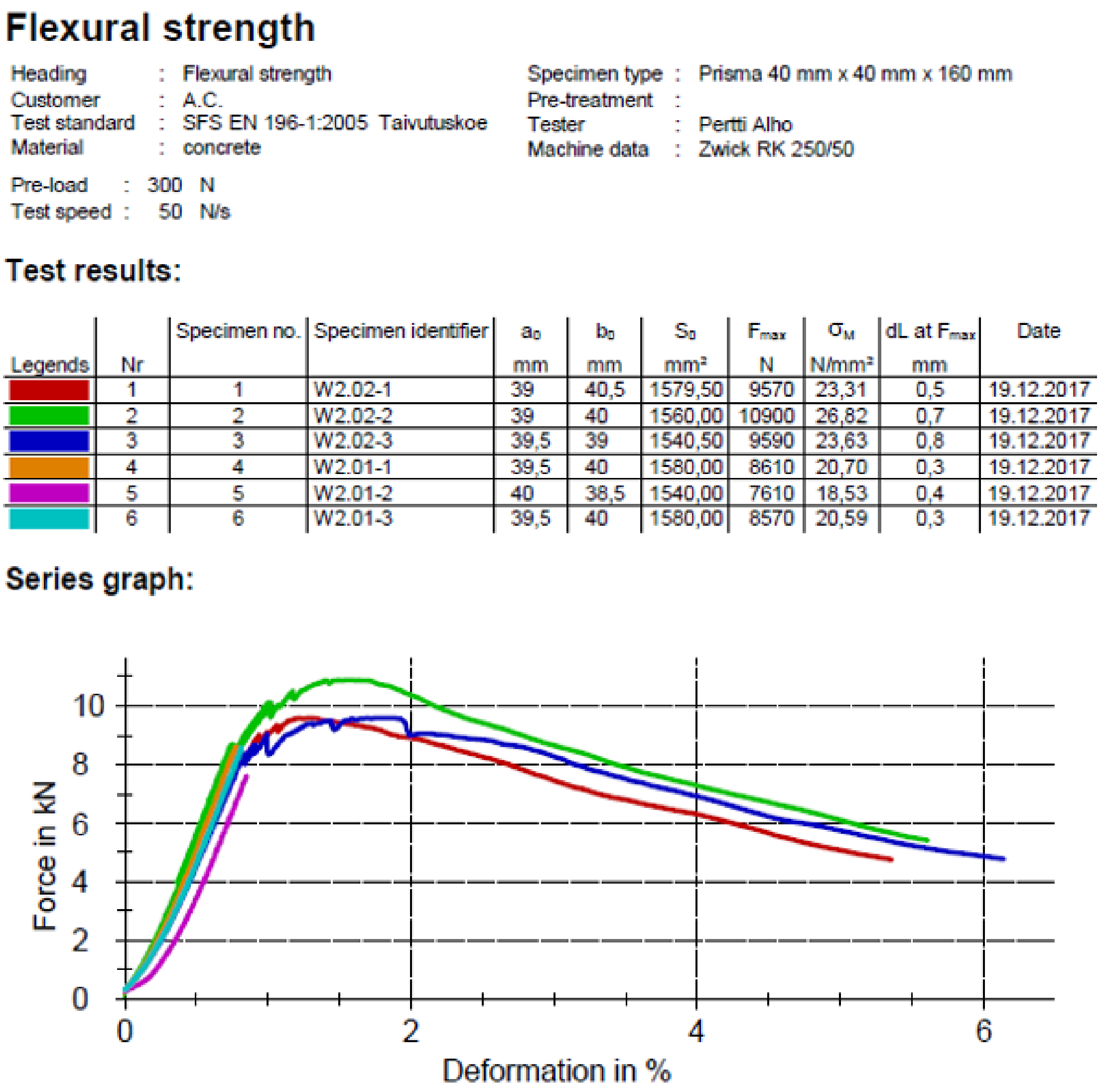
Test results:

Legends	Nr	Specimen no.	Specimen identifier	a_0 mm	b_0 mm	S_0 mm²	F_{max} N	σ_M N/mm²	dL at F_{max} mm	Date
🟥	1	1	W1.01-1	39,5	39	1540,50	6900	17,00	0,3	18.12.2017
🟩	2	2	W1.01-2	39,5	41	1619,50	7110	16,67	0,6	18.12.2017
🟦	3	3	W1.01-3	39,5	41	1619,50	7950	18,65	0,3	18.12.2017
🟧	4	4	W1.02-1	40	39	1560,00	8170	19,65	0,3	18.12.2017
🟪	5	5	W1.02-2	39,5	39,5	1560,25	7960	19,38	0,3	18.12.2017
🟦	6	6	W1.02-3	40	38,5	1540,00	7200	17,53	0,3	18.12.2017

Series graph:



Force deformation curves for W12 and W13 mixtures



Flexural strength

Heading : Flexural strength
Customer : A.C.
Test standard : SFS EN 196-1:2005 Taivutuskoe
Material : concrete

Specimen type : Prisma 40 mm x 40 mm x 160 mm
Pre-treatment :
Tester : Pertti Alho
Machine data : Zwick RK 250/50

Pre-load : 300 N
Test speed : 50 N/s

Test results:

Legends	Nr	Specimen no.	Specimen identifier	a_0 mm	b_0 mm	S_0 mm²	F_{max} N	σ_M N/mm²	dL at F_{max} mm	Date
🟥	1	1	W2.02-1	39	40,5	1579,50	9570	23,31	0,5	19.12.2017
🟩	2	2	W2.02-2	39	40	1560,00	10900	26,82	0,7	19.12.2017
🟦	3	3	W2.02-3	39,5	39	1540,50	9590	23,63	0,8	19.12.2017
🟧	4	4	W2.01-1	39,5	40	1580,00	8610	20,70	0,3	19.12.2017
🟪	5	5	W2.01-2	40	38,5	1540,00	7610	18,53	0,4	19.12.2017
🟦	6	6	W2.01-3	39,5	40	1580,00	8570	20,59	0,3	19.12.2017

Series graph:

Force deformation curves for W22 and W23 mixtures

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