Master thesis to obtain title of "Master Universitario en Ingenieria de Caminos, Canales y Puertos"

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Development of cold-forming technologies for the construction of concrete reef structures

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Summary

In this Master Thesis, the objective is to advance the mix design and technologies to produce thin shell concrete elements by cold forming criteria, based on Ultra High Performance Fiber Reinforced Concrete (UHPFRC). Therefore, a research is done containing three phases. In the first phase, a new type of setting test is used to define the influence of an accelerating admixture on the concrete hardening. In the second phase, specimens were compacted at different times relative to the start of the setting as defined in phase one. The influence of this delay on the strength of the concrete was tested. In the last phase the possibility to create thin shells by vibrating concrete externally was tested. This included trying different mixes and delays of vibration with the objective that the concrete kept its form in a negative, convex mold.

Keywords: UHPFRC, setting, shells, curved, accelerator, external vibration

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Emma Van Nuffel

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List of abbreviations

A/C	Accelerator/Cement ratio (*dimensionless*)
C_2S	Dicalcium Silicate
C_3A	Tricalcium Aluminate
C_3S	Tricalcium Silicate
CAD	Computer Aided Design
CO_2	Carbon Dioxide
FRC	Fiber Reinforced Concrete
HPC	High Performance Concrete
ICITECH	Instituto de Ciencia y Tecnología del Hormigón
ISO	International Organization of Standardization
MPa	MegaPascal (N/mm^2)
N	Newton
OC	Ordinary Concrete
RH	Relative Humidity
SCC	Self Compacting Concrete
SiO_2	Silicon Dioxide
SMF	Sulfonated Melamine Formaldehyde
SNF	Sulfonated Naphtalene Formaldehyde
SP/C	Superplasticizer/Cement ratio (*dimensionless*)
T1, T2, T3	Respectively $T_{ss}/2$, T_{ss}-5min and T_{ss}*1,5
T_{ss}	Start Setting Time
UHPC	Ultra High Performance Concrete
UHPFRC	Ultra High Performance Fiber Reinforced Concrete
UPV	Universitat Politècnica de València
w/b ratio	Water/Binder ratio (*dimensionless*)

1 Introduction

1.1 Justification

The keynote of this Master Thesis is to design a reef structure with a thin shell shape made in Ultra High Performance Fiber Reinforced Concrete (UHPFRC). This reef structure would be placed at the bottom of the sea in front of the Valencian coast to prevent the collapse of the thinning barrier of land in between the sea and the lake in Albufera National Park. To realize this large structure, more knowledge is necessary in the domain of Geotechnical Engineering (to know how much material is pulled back in the sea and what the external forces on the structure are), and Civil Engineering.

The domain of Civil Engineering will research many aspects about the reef structure, starting with an overall research about the cold forming technology used to create the thin shell shape of the structure.

The mix design of Ultra High Performance Fiber Reinforced Concrete (UHPFRC) will be adapted to the cold forming technology by incorporating admixtures. The technological complements to accelerate the concrete hardening without sensible strength reductions need to be researched. On the other hand, the design of the structure and the way of connecting the thin shell form elements must be developed.

The use of accelerator in UHPFRC is introduced to make the process of casting and demolding faster and thus more interesting from an economical point of view. Because of the complexity of the molds to create thin shell concrete elements, the accelerated process is desired so that only one or few molds could suffice to produce the structure.

Apart from the reef structure, the question for structural concrete thin shells in other applications is growing. For example in architecture, mainly to create special forms in walls. Until now curved concrete was not used in buildings unless they were iconic and there was a high budget. Some examples of curvatures in structures can be found in figure 1 and 2.

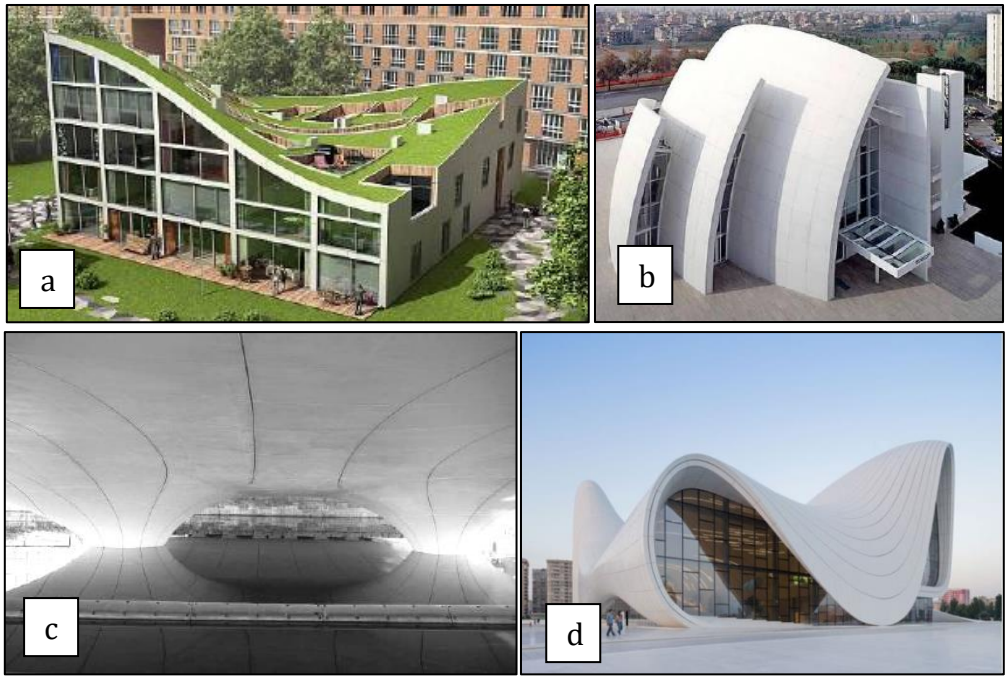

Figure 1. Examples of curvatures in structures.
Images a, b, c source: R. Schipper and B. Janssen, "Manufacturing Double-Curved Elements In Precast Concrete Using A Flexible Mould-First Experimental Results," Proc. fib Symp. (fédération Int. du béton), pp. 2, 2011. Image d: downloaded from https://www.homedit.com/12-curved-roof-buildings-that-will-blow-your-mind/ in June 2018

Figure 2. l'Oceanografic (Valencia).
Downloaded from https://shellbuckling.com/presentations/architecture/pages/page17.html in June 2018.

1.1.1 Cold forming

As stated, the cold forming technology for concrete will be researched as a possible way to create thin shells. When searching for the technology of cold forming on different information sources, most of the results are about cold forming of metals.

1.1.1.1 Cold forming of metals

Cold forming of metals is a well-known and commonly used technology to deform metals into different forms without heating them, using plastic properties of the metal. When a ductile material is stressed or strained past its elastic region (visualized in figure 3), the deformation stays and a new form is obtained. Some examples of cold-formed metal elements are shown in figure 4.

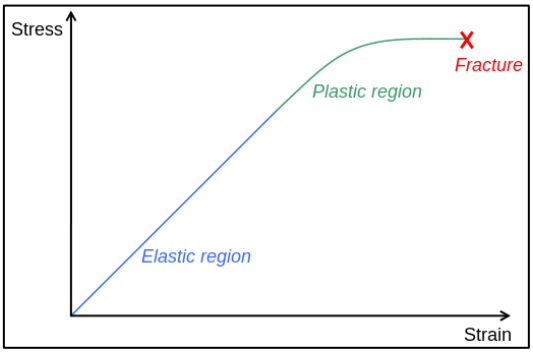

Figure 3. Stress-strain curve for steel.
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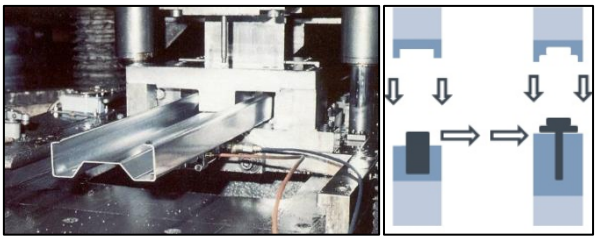


Figure 4. Cold rolling (left); cold heading (right).
Downloaded from https://www.steelconstruction.info/Steel_construction _products and http://www.nedschroefmachinery.com/cold-and-warm-forming-technology/138/151/152/ in June 2018

Cold forming of metals has advantages against hot forming like there is no spill of materials, tolerances are smaller, tensile and yield strengths are higher and production is faster. Some disadvantages are that less geometries are possible, small scale production is expensive, greater forces are required and that the material is less ductile after the process.

1.1.1.2 Cold forming of concrete

Cold forming of concrete, on the other hand, does not have a clear definition because it is a very new concept. We could say that cold-forming for concrete is the deformation of concrete after an undefined initial hardening. The difficulty with cold forming of concrete against metals is the timing. With metals it doesn't matter how long you wait to deform the material. If we cold form concrete in its hardened or almost hardened state, concrete will fracture because of the non-ductility and poor resistance to tension. This is what we can also see in figure 5: in the tension zone there is only a small elastic region which is not considered in theory, and in the compression zone only the elastic region is considered with a strain that is around $1/10^{th}$ of the strain of steel which means that a permanent deformation isn't possible for the material.

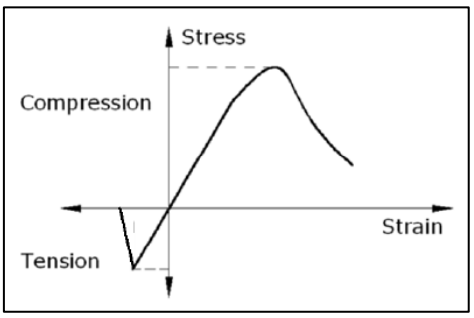


Figure 5. Sketch of a stress-strain curve for concrete.
Downloaded from https://www.researchgate.net/publication/ 277301966_CRITICAL_INVESTIGATION_OF_THE_FINITE_ELEMENT_MODELS_OF_STEEL_FIBER_REINFORCED_CONCRETE_SFRC_EVALUATION_OF_THE_GOVERNING_PARAMETERS_TO_PREDICT_THE_FLEXURAL_CAPACITIES?_sg=XzyD4xjsjFvuTauDp4KZXRTw8Eoe0Cy2Zi in June 2018.

Even with the use of UHPFRC, the non-ductility of the concrete is still a problem. It is possible to deform this concrete past its elastic region in the hardened state because of the ductility of the fibers but the appearance of cracks is an unsolvable problem up until today.

Therefore, in this work we take a closer look at the setting of the concrete and at what timing after mixing the concrete is in a suitable condition to deform. Because we use accelerator it could be that the setting is very quickly in a state where we should deform the element to its final shape.

Besides using accelerator, mixes with a low workability can be used to keep their shape very quickly after the mixing process. Furthermore, cold forming is also performed with materials that have similar properties than concrete, an example is the production of roof tiles in ceramics. Both are discussed in chapter 2.

1.2 Objectives

A concrete suitable to create the cold formed structural concrete thin shell, should have several specific properties concerning timing and strength. Overall, we will investigate towards a concrete that has a sufficient workability right after mixing, but that hardens within a certain timing so that the production of thin shells for the reef structure is possible with only one or very few molds. This means that we are looking for a concrete that is possible to be casted, compacted and demolded in a time that is as short as practically possible. The objective of this work is to advance the mix design and technologies to produce thin shell concrete elements by cold forming criteria, based on Ultra High Performance Fiber Reinforced Concrete (UHPFRC).

2 State of the art

2.1 Ultra High Performance Fiber Reinforced Concrete (UHPFRC)

Ultra High Performance Fiber Reinforced Concrete (UHPFRC) mainly contains the joint properties of High Performance Concrete (HPC), Fiber Reinforced Concrete (FRC) and Self Compacting Concrete (SCC).

Self Compacting Concrete (SCC) is a type of concrete that doesn't need any mechanical compaction during casting. This type of concrete is more fluid than a normal concrete because of the addition of powder components by adding fillers such as fly ash. This type of concrete has several advantages like the fact that it doesn't need to be vibrated and so reduces energy, labor and environmental costs. Also because of the fluidity, the concrete has a good surface quality. [1]

High Performance Concrete (HPC) is a concrete with special performance requirements against ordinary concrete (OC). This does not necessarily mean that HPC has a higher strength than OC. Possible performances from HPC against those from OC are a better workability and fluidity and a minimal permeability. These performances contribute to the property of long-term durability which is an important aspect of HPC. [2]

Fiber Reinforced Concrete (FRC) is a concrete with the addition of fiber elements randomly spaced in the matrix. The fibers that are added to the concrete give tensile strength and prevent microcracks from opening, which has a positive effect on the durability of the concrete. Fibers improve properties but are not a replacement for reinforcement bars. [2]

There is no limiting definition for UHPFRC but generally it has a compressive strength exceeding 150MPa and the tensile strength lays around 8-10MPa. The w/b ratio is very reduced against normal concrete and is lower than 0,25. The concrete has a very dense matrix containing no coarse aggregates and a specific distribution of particle sizes so that a maximum packing density is obtained. This in combination with the reduced water content (due to the dense matrix and admixtures) makes that the concrete is free of capillary pores and thus resistant to attacking gases or liquids. Further properties of UHPFRC were mentioned within the definitions of the concretes that contribute to UHPFRC. This means that UHPFRC is self-compacting and has the advantages of the fiber reinforcement.

UHPFRC is a lot more expensive than normal concrete because of the price of the composing materials, approximately 1800 euros/m^3[3]. Therefore, UHPFRC might seem too expensive as an alternative based on volumetric values. However, the higher material cost can be justified with less material use, high durability and other advantages. [4][5][3][6]

2.2 UHPFRC composition

2.2.1 Water

Water is an active agent in the hydration of the binder, in our case cement and silica fume. The relative dosage of water to binder w/b influences the strength, durability and workability. A lower w/b ratio makes a concrete stronger and more durable but less workable and possibly not mixable. With this lower workability comes the disability to self-compact. To solve this, often superplasticizers are added to reduce the water content, this is also the case for UHPFRC since the w/b ratio lays under 0,25.

2.2.2 Cement

Calcium silicate cements, also known as Portland cements, are most widely used in all concretes as well as in UHPFRC. UHPFRC contains 600-1000kg/m^3 of cement, which means around twice or more the cement content of ordinary concrete. As mentioned earlier, the matrix of UHPFRC is very dense, containing more fine particles than OC. Here, the cement fulfills an important role as fine particle. On the other hand, a cement type I 42,5 is sometimes preferred over a cement type I 52,5 because of the slightly bigger particle size and so a lower demand for water due to a lower specific surface. Secondly, a lower C_3A (which is highly soluble) content also means a lower demand for water, which is desired since UHPFRC has a w/b ratio under 0,25. Overall, to choose a cement it is important to consider the rest of the composing elements and have a look at particle size distribution and the total of chemical reactions taking place, which we will not discuss further in this case. [3] [5]

2.2.3 Aggregates

UHPFRC has an increased homogeneity against OC because coarse aggregates are replaced with sand. The aggregates are the largest particles of the concrete and should have a certain compression strength since it directly influences the compression strength of the concrete. Concerning water demand, a sand with a low absorption capacity and higher specific surface is desired, but on the other hand fine sand has positive effects on strength and durability. A suitable mix of aggregate sizes must be chosen.

Normally, a concrete contains aggregates up to 32 mm sieved and the smallest particles that are concerned in the granulometric curve are 0,125 mm, creating a continuous order of aggregate sizes. In the case of UHPFRC, the biggest aggregates in the granulometric curve are 2mm. Since the granulometry starts with only 2 mm as maximum aggregate size, the binders cement and silica fume are considered as fines in the granulometry. To have a continuous order of particle sizes, quartz flour is added to make the bridge between the size of the cement and fine sand.

2.2.4 Mineral additions

The past decades, the concept of sustainability has influenced a lot of processes, also in the concrete industry. The attention for the effects of concrete on the environment, society and economy has grown and consequently more and more mineral additives and chemical admixtures (see next chapter) are being added to the concrete mixture to improve defining characteristics for sustainability, for example CO_2-emission and durability.

Mineral additives can be found within the cement to slow down the hydration and so reduce the water demand. Other mineral additives are added to improve or achieve certain properties.

Two types of additions can be distinguished. Type I are the inert additions, with the only function to contribute to the particle distribution as smallest size particles to fill holes and create a denser matrix, not interacting with other components. They're also called fillers. Type II additions are pozzolan or latent hydraulic materials such as fly ash, silica fume, quartz flour, etc. [7] [5]

The mineral additions used for the UHPFRC in this thesis are silica fume and quartz flour, further described in the next two chapters.

2.2.4.1 Silica fume

Silica fume is a by-product in the production of silicon and ferrosilicon alloys. Silicon oxide vapors that come free during the heating process condense into spherical particles as the temperature decreases. These particles are pozzolanic and have a diameter of 0,1-0,12 µm and a surface of 15-25 m^2/g, up to a hundred times less than general Portland cement.

The fineness and spherical form of silica fume positively affects the particle distribution of a concrete since voids between the cement particles can be filled resulting in a denser matrix and so a less permeable concrete. Consequently because of the bigger surface the absorbing capacity of the mixture rises. As seen in the chapter about UHPFRC, a higher water content has negative effects on the performances of the concrete in hardened state. This is why water-reducing agents are necessary for UHPFRC, more specifically superplasticizers, discussed further in this document. [2]

The component is pozzolanic because of a high silica content (around 90%). This means it can react with the calcium hydroxide from the cement, increasing the chemical resistance. Pozzolanic reaction of the silica fume takes place in the hardened state and may be very little given that the pozzolanic activity is reduced with w/b ratio and that a significant amount of silica fume is required. For this reason often a part of the silica fume only serves as filler.[8]

2.2.4.2 Quartz flour

Quartz flour has the same composition as silica sand but the particle size is a lot smaller. The quartz flour is used to complete the granulometry of the concrete paste, with a size between the sand and cement size. Quartz flour doesn't cause any pozzolanic activity in normal circumstances and is therefore only used as filler, to dense the concrete matrix.

2.2.5 Chemical admixtures

In this chapter, important aspects about chemical admixtures for our case are discussed, most of them found in the book "Chemical Admixtures for Concrete" by Roger Rixom and Noel Mailvaganam, an easy to follow book with interesting references.

Chemical admixtures are used to modify the properties of a concrete by chemically influencing the hydration of the cement or its hydration products. Chemical admixtures can for example delay the start of the setting or accelerate it.

UHPFRC is a concrete with a high workability, strength and durability. To gain these properties, it is important to improve strength of the transition zone between paste and inert aggregate.

To improve, first a dense homogeneous matrix is preferred to prevent microcracking, which has a negative effect on the properties of the concrete. This matrix is obtained with mineral additives as mentioned before.

Secondly, a reduced water content is necessary to reduce the matrix porosity which directly affects the strength of the matrix. This porosity would in other cases occur due to high shrinkage stresses because of the high cement content. This is the reason that UHPFRC has a significant reduction in water content. To obtain this, most commonly and also in our case, large doses of superplasticizer are added. The improved workability is also required to avoid segregation and honeycombing.

Finally setting accelerators are discussed in this chapter because of their importance and application in this research that is focusing on the acceleration of the setting and the ability to form the concrete thin shells.

2.2.5.1 Superplasticizer

Superplasticizers are a specific type of water-reducers that can achieve a much greater workability with a certain w/b ratio or achieve a much lower w/b ratio while maintaining the workability. This without undesirable side-effects like air occlusions or a delay of the setting.

The decrease in water to binder ratio this admixture can provide is larger than any other water reducing agent (normally up to 30%), which results in significantly higher concrete strengths.

Basically, there's three materials that can be the main component of a superplasticizer. First and second, sulfonated naphthalene formaldehyde (SNF) and sulfonated melamine formaldehyde (SMF) were developed in the 80's but have now been overtaken by newer materials. Polyacrylate-based polymers are more recently developed. Problems with superplasticizers causing air occlusions or a delay of the setting can be easily solved by adding minor amounts of other materials.

Very straightforwardly explained, the admixture is absorbed by the initial hydration products of the cement, lowering the zeta potential of the cement, overcoming attraction forces and causing a dispersed system (electrostatic repulsion). Polyacrylates lower the zeta potential less but form a more physical barrier of polymer chains, as well causing dispersion. This meaning an initial retardation of the hydration, making the concrete more workable or making water reduction possible.

This effect is only of a short duration (30-40 minutes) for the overtaken SNF and SMF based superplasticizers, but of a rather longer duration (around 2 hours) for the newer polyacrylate-based admixture.[9]

Besides polyacrylates, today most superplasticizers are based on polycarboxylic ethers. These components work in the same way as polyacrylates. Polycarboxylic ethers are macromolecules just like polyacrylates. Most of the time further specifications of the molecules are kept by the producer for their product not to be copied.

2.2.5.2 Accelerator

Accelerators, as the name says itself, accelerate the concrete hardening. This admixture knows the most use in winter, so that precautions for freezing temperatures should only be taken over a reduced period of time. Furthermore, accelerators are used where an earlier finishing is required or where concrete has to be demolded faster for reusing the mold, as it is in this research.

In the scope of accelerators, calcium chloride is the main and most effective material used to accelerate the concrete hardening (initial and final setting time). Under the chloride accelerators we can also find the less used materials aluminum- and sodium chloride. Even though the way the salts operate is not clearly understood, it is sure that they accelerate the C_2S and C_3S hydration. In the first hours after mixing, a rapid setting occurs even though no specific reaction with the salt is observed.

After the accelerated setting, free calcium chloride is almost non- existing. Therefore, it is uncertain if the concerns about adding a salt to steel-containing concrete, which could cause corrosion, are justified. From several studies can be generally concluded that calcium chloride up to 1,5% of the cement weight is not dangerous. [9]

Besides chloride accelerators, other non-chloride accelerators are developed, from which calcium formate and triethanolamine are the most common ones with a similar action than calcium chloride. Triethanolamine tends to accelerate the hydration of C_3A but slows down the C_3S and C_2S hydration. Calcium formate is an organic compound that accelerates the C_3S hydration but is not as effective as calcium chloride, also this material is not sold in solutions, which is why it is often replaced by calcium nitrite. Non-chloride accelerators are developed to be non-corrosive accelerators or to undo retarding of the setting due to water-reducing admixtures.

Lots of other materials are used to accelerate the concrete hardening, like alkali hydroxides, silicates, nitrites, thiosulphates, thiocyanates, potassium, carbonates and organic compounds such as triethanolamine and formaldehyde. These are in this case not further highlighted. [10]

2.2.6 Fibers

Addition of fibers randomly spaced in the matrix of a concrete, prevent the micro- and macrocracks from developing and propagating, which is a property that reinforcement bars don't have. This has positive effects on durability, an important property of UHPFRC. There's several types of fibers available in the market, like those made from steel, glass, polypropylene or graphite, all improving properties of the concrete by adding tensile strength to the matrix of the brittle material. Steel fibers, the ones used in this research, can have several lengths from 10 to 60 mm and different cross sections. The fiber content usually varies from 20 to 165 kg/m^3.[8]

2.3 Production of curved elements

Curved concrete elements can be both structural and non-structural. To resist certain loads or impacts, often it is necessary to reinforce the element. To reinforce curved elements with bars is in most cases impossible, this is where fiber-reinforcement or textile-reinforcement [11] is introduced to make these elements structural. For concrete thin shells it is desired to use a concrete with high performances in strength and durability, since the elements are so thin.

2.3.1 Casting

The traditional way to give a certain shape to concrete elements is by pouring the concrete in a mold, where after hardening, the concrete keeps the shape of the mold. For non-curved elements, molds are made up by plate-form elements that are rigid enough to carry the weight of the concrete that will be poured in. The molds or materials that are composed to such a mold are reused many times for similar elements.

When on the other hand, unique elements that don't have a straight but free-form curved shape must be produced, the production of a mold is a lot more difficult, time consuming and expensive. A lot of curved concrete elements are thin shells, where an extra concern forms the compaction and complete filling of the mold. Besides, the delay between casting and demolding the element makes that the production of several elements is nearly non-achievable from an economical point of view. Producing several non-reusable molds, or the wait to reuse one mold are both time consuming.

2.3.2 Low-workability concrete

When it is preferred to demold elements rapidly, it is required for the concrete to keep its shape shortly after producing the element. There's two possible ways to achieve this: either the concrete should be a zero-slump concrete (see figure 6) or the hardening of the concrete should be accelerated. A combination of both is possible.

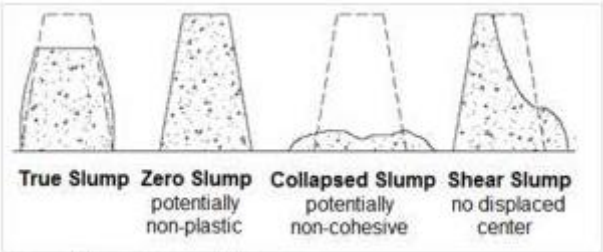


Figure 6. Concrete slump
Source: ACI 238 State of the art report.

Low-workability concretes are defined as concretes with a low water content and stiff consistency with a slump of 6 mm or less. These concretes are applied in the production of many elements for example sewage pipes, (hollow core) slabs, paving blocks, etc.

Zero-slump concretes are able to keep a shape before the setting of the cement. Main factors causing strength of the fresh concrete are liquid bridges between the fines and internal friction. Therefore, granulometric properties of the fines are an important factor. [12]

After filling and vibrating a mold with this concrete, it can be immediately demolded and carefully transported to a room with specific curing conditions. This process is called dry-casting because of the low water content of the concrete. Sometimes this is a continuous process where the concrete stays in place while the mold is vibrated and moved over the concrete. This process is known under the term extrusion or slip forming. Some products of a such process can be seen in figure 7. Other times elements are produced vertically (figure 8).

Figure 7. Extrusion products
Sources:https://www.unionprecast-qatar.com/pre-stressed-hollow-core-slabs and http://www.oldcastleprecastspokane.com/hollowcore

Figure 8. Vertical no-slump concrete products
http://www.kitomachine.com/product/automatic-vertical-pipe-machine/

2.3.3 Flexible mold method

When low-workability concrete won't meet required properties, and to avoid the time-consuming process of casting several concrete elements, the newest techniques first cast a plate-form concrete to deform after a certain initial hardening.

To make the production curved elements more efficient, isn't subject of many researches. When looking for research about production methods of curved concrete elements, the main outcomes are about the research in the Technical University of Delft.

In the TU Delft, mainly there is research about flexible molds, of which you can see the principle explained in figure 9.

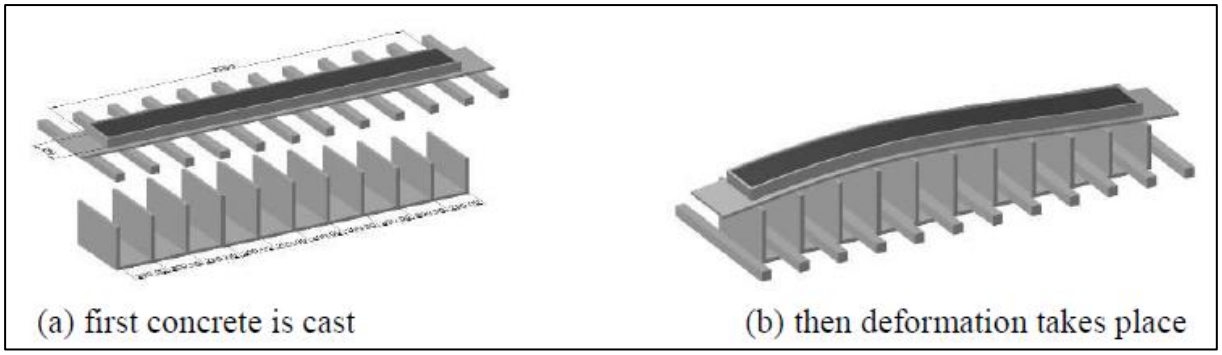


Figure 9. Patented mold of Daan Rietbergen and Karel Vollers (2010)

With the newest CAD-programs being able to design doubly curved surfaces, the use of these forms is getting more and more common in architecture. To answer the request for many customized doubly curved concrete elements, an adjustable formwork of an elastic material becomes a necessity in manufacturing the elements.

Such adjustable formwork for doubly curved surfaces was already introduced in the 1960's by Renzo Piano. Later Hans Jansen and Lars Spuybroeck came up with conceptual designs of the flexible mold (figure 10).

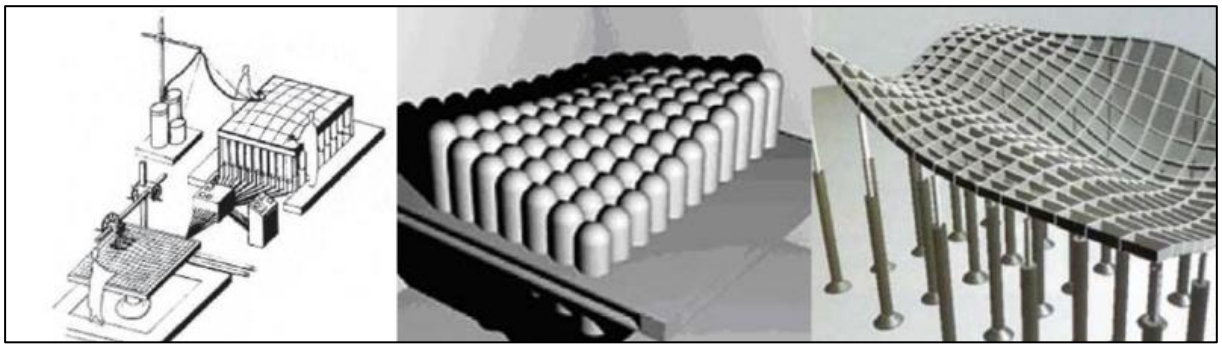


Figure 10. Flexible mold sketches by Renzo Piano (left), Hans Jansen (middle) and Lars Spuybroeck (right)

The first flexible mold prototypes were realized by Rietbergen, Schoofs and Huyghe (figure 11). Very soon it became clear that the stiffness (or on the other hand the flexibility) of the elastic material covering the adjustable supports, was a key factor influencing the final shape of the curved element. Also the distance between supports has a great influence on the element's final shape.

Figure 11. Flexible mold by Rietbergen, Schoofs and Huyghe (2009)

To lower in-plane stresses, which could cause buckling in the element edges, Hans Jansen designed a strip mold, where the first layer of strips is supported directly by the supports, and the second layer of strips is supported by the first one, as can be seen in figure 12.

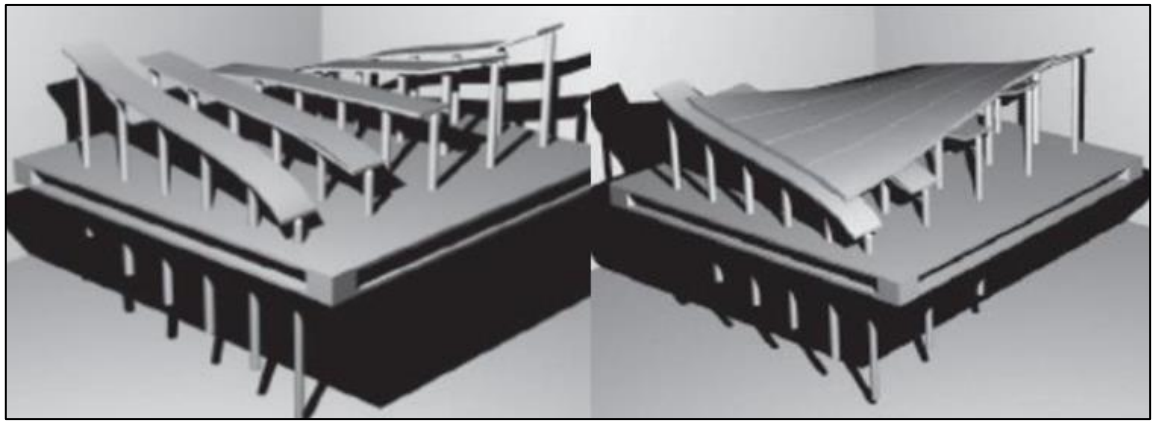


Figure 12. Strip mold sketched by Hans Jansen (2004)

The moment of deforming the flexible mold is very important so that the concrete doesn't flow to the lower parts of the curved mold, in that case a contra-mold is necessary or the deformation should be delayed (figure 13a). Secondly, depending on curvature and time of deformation, cracks can occur (figure 13b).

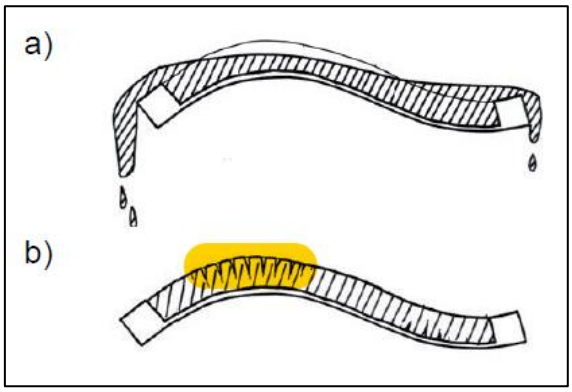


Figure 13. Fluidity and cracking of the curved element
Source: R. Schipper, S. Grünewald, T. Sergiu, P. Raghunath, S. Erik, and Ç. Oguzhan, "ASSESSMENT OF CONCRETE CHARACTERISTICS DURING THE DELIBERATE DEFORMATION OF A FLEXIBLE MOULD AFTER CASTING," no. April, pp. 19–21, 2017.

Further research about the flexible mold has been by Roel Schipper (2011), who only lowered the concrete on the flexible mold to deform, when it was previously casted in another mold. Other important researchers on the subject of flexible molds are Steffen Grünewald and Karel Jan Vollers, supported by several master students.[13]

Except from flexible molds as researched at the TU Delft, other techniques to keep the same mold to create different shapes are developed. For example the research on phase-changing materials from which semi-permanent molds can be created. [14]

2.3.4 Curved elements except from concrete

There's similar manufacturing processes than those discussed before, where a flat element is deformed to a curved element. This principle is also used in the production of ceramic roof tiles.

First, water and clay are mixed and put on a flat surface and then, after this mixture obtained a certain stiffness, it is deformed by pushing the clay onto a curved mold. Immediately after this, the mold is reused for the next element.

In figure 14 we can see the flat elements being transported to the mold (left), and the mold pressing the surfaces into their final shape (right), we can see some material flowing out of the mold on the right picture.

Figure 14. Production of ceramic roof tiles
Source: https://www.pond5.com/stock-footage/4172583/production-ceramic-roof-tile.html#

This concept is very important, since in this research part of the focus lays on forming concrete to a thin shell, where for we will press the material in between a positive and negative mold, and search for possibilities to reuse this mold as soon as possible.

3 Experimental program

3.1 Justification of the experiments

With the experimental program, we take a step aside from working towards the final goal of creating a cold formed reef structure. Instead we will attempt to gain knowledge about the behavior of an UHPFRC mixture in which an admixture is added to accelerate the concrete hardening.

Several variables will be tested with this concrete, such as the dosage of superplasticizer, the dosage of accelerator, the delay to compact and deform the material, etc. How the changes in these variables affect the concrete or the process, will be analyzed.

In every experiment, time is an important variable, because the behavior of the concrete in a short period after the mixing procedure is analyzed. Also, the influence of the moment when the concrete is treated on the final properties is analyzed.

The objective is to define a mixture where it is possible to create thin shells with. More specifically it is required that the mixture hardens to a state where it can carry its own weight, within a time that could be used in practice to create a lot of elements. Also, it is desired for the concrete to have a consistence that is possible to manipulate at the preferred timing.

To gain more knowledge on the aspects that were mentioned, three phases are foreseen in this experimental program.

3.2 Program

3.2.1 First phase

3.2.1.1 Objective

The objective of the first phase, is to test the influence of different amounts of superplasticizer and accelerator on the hardening of the concrete.

3.2.1.2 Concept

Setting time is the term that is used when it comes to gaining data on hardening of a concrete. Setting time tests define a time interval in which the concrete changes from fluid to solid. Existing standardized methods only evaluate the setting time of cement and water. These seem not very suitable for UHPC because the interaction with other components of the mixture (superplasticizer, accelerator, pozzolans) also has an influence on the setting time.

To keep into account the whole UHPC mixture, a method in the ISO 91.100.30: Concrete and concrete products "*ISO CD 1920-14 (E) 29-Jan-18 Testing of concrete – Part 14: Setting Time of Concrete Mixtures by Resistance to Penetration*" that is normally applied for dry spray concretes, is adapted to our application to define the start and ending of the setting.

This method defines the start- and end of the setting by measuring the resistance of the concrete to penetration at different times, creating a resistance curve in function of the time. The method defines the start- and end setting time as the time when the resistance is respectively 3,5MPa and 27,6MPa.

3.2.1.3 Program

A total of 12 setting tests is performed in this research, taking up to seven hours per test for the reference concretes without accelerator. Two different dosages of superplasticizer and several dosages of accelerator their influence on the setting times and duration of the setting is tested. Nine of the tests are with accelerator type AKF-63, the other three with accelerator type Nasil 3.35 (see material section). The dosages of the tests are listed in table 1. All tests were performed on mixes without the addition of fibers except one as a reference, which is why there's two mixes with the same dosage in this table.

Dosages of setting time tests

Superplasticizer		Accelerator		
kg/m³	SP/C	Type	kg/m³	A/C
25	3,1%	AKF-63	0	0,0%
			15	1,9%
			15	1,9%
			20	2,5%
			32	4,0%
30	3,8%		0	0,0%
			15	1,9%
			20	2,5%
			32	4,0%
25	3,1%	Nasil 3.35	11	1,4%
			20	2,5%
			32	4,0%

Table 1. Dosages of setting time tests

Accelerator type Nasil 3.35 was obtained in an advanced stadium of the research. Since there was no significant improvement in initial workability while setting times were similar to type AKF-63, this type was not applied in later phases. Although it should be mentioned that only few comparative tests were performed, and further research except from this thesis is desired.

3.2.2 Second phase

3.2.2.1 Objective

The general objective of the second phase is to see if the accelerated concrete is still workable at different times except from the first minutes after mixing, even past start setting time. Workability in this case, can be defined as the possibility of giving the concrete its final shape and compacting it.

3.2.2.2 Concept

Up until this moment there is no standard for testing the compaction of concrete at different times after the mixing process and possible strength reductions that go with this delay. Therefore, we introduce a new method, including a defined compaction of the mold at different times after the mixing process. To see if it was possible to compact the specimens at a certain timing, the compressive and flexural strength of specimens with the same dosages and a different compaction time, was compared.

3.2.2.3 Program

Three specimens with dimensions 40x40x160mm^3 were performed from each mix. One of the three was compacted before, one around and one after start setting time. The start setting time, a given property in this phase, was obtained in the previous phase.

The eight different mixes from the previous phase (table 1), where two dosages of superplasticizer and four dosages of accelerator were alternated, were also used in this phase. The eight mixes were performed with and without fibers, which makes 16 mixes.

As can be seen in table 2, three of 16 mixes were not performed. The mix with 30kg/m^3 superplasticizer and 32kg/m^3 plus fibers was left out because it was the least workable mix which would make it too complicated to perform the test. The mix with 30kg/m^3 superplasticizer and without accelerator was left out because one reference without accelerator was considered sufficient.

Dosages of compaction tests

Superplasticizer		Accelerator		Fibers	
kg/m³	SP/C	kg/m³	A/C	Without	With
25	3,1%	0	0,0%	✓	✓
		15	1,9%	✓	✓
		20	2,5%	✓	✓
		32	4,0%	✓	
30	3,8%	0	0,0%		
		15	1,9%	✓	✓
		20	2,5%	✓	✓
		32	4,0%	✓	✓

Table 2. Dosages of compaction tests

3.2.2.4 Unforeseen events

As in this phase a new test was performed that isn't based on any standard, the test is more vulnerable to unforeseen events that might affect the performance of the test and the test results. As will be described in the methodology section, during the preparation of the specimens some difficulties occurred, of which it is almost certainly possible to say they influenced the test results. The problems summarized, it was necessary to apply pressure on the concrete for it to take the shape of the mold, which could be considered as a previous compaction of the specimen.

3.2.3 Third phase

3.2.3.1 Objective

In the last phase, the objective is to see the practical possibilities of the accelerated concrete in the creation of thin shells. The goal is to simulate a sequence of actions of how real size thin shell elements could be produced with an accelerated UHPFRC.

3.2.3.2 Concept

This part of the research contains advances on the technologies to perform thin shell elements. The behavior of the concrete after an undefined initial hardening is researched by defining a time interval to create, partially demold (keeping the base support of the thin element) and totally demold the thin elements. A new production method of thin shells is introduced, with a positive (convex) and a negative (concave) mold, and a vibration on one of both (visualized in figure 15). It is desired that the positive mold can be lifted right after the vibration. Accelerator is an important component for the element to keep its shape in the negative mold a few moments after the mixing procedure, making the production more economically friendly.

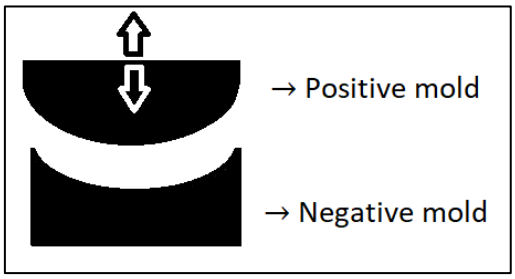


Figure 15. Sketch of thin shell production principle, where the positive mold vibrates.

3.2.3.3 Program

This phase can be divided in two parts.

a. Vibration technologies and concrete workability

With a process of trial and error, four mixes were made. Each mix was used to make four thin surface elements with a volume of one liter. The four specimens were vibrated one after another with more or less five minutes delay between each vibration. The consistency of the concrete during the acts was analyzed and changed for each following mix, to see what the maximum amount of accelerator was with the concrete still being fluid. From the last mix an analysis of the hardening of the concrete up to the moment where the specimen could carry its own weight was carried out.

b. Optimizing time interval to vibrate thin shell form

The vibrator in the previous part of this program was rejected and replaced by a vibrator that was possible to be perpendicularly lowered onto the concrete to assure the form of the specimen. The creation of thin shells was attempted by placing concrete in the negative mold, that was surrounded by wooden plates for the concrete not to escape on the sides, lowering the positive mold onto the concrete and then vibrating it.

3.2.3.4 Difficulties

Even though plates enclosed the negative mold, some concretes that kept the curvature when lifting the positive mold right after the vibration, could escape through small gaps. Maybe with a mold that encloses the concrete better during the vibration, it could be possible to use a more fluid concrete, or to vibrate the same concrete sooner.

3.3 Materials

3.3.1 Concrete

The influence of the materials and dosages has been previously studied in the UPV [15] and the current materials (as can be found in table 3) have been used for several years in different researches at the UPV so there's a lot of knowledge about their influences on different properties of the concrete. Materials are chosen because of a supplier, price and/or properties. To study all the components would be unnecessary extensive since our goals are not focusing on reaching specific properties, but they are about the influence of specific variables on the concrete properties. In all phases of this research, one standard combination of dosages is applied (table 3), only the dosages of superplasticizer and accelerator are not fixed as their influence on the flowability, strength and other properties of the concrete will be analyzed.

Component	Type	Producer	Dosage
Water	Tap water	/	150 kg/m^3
Cement	CEM I 42,5 R-SR5	Lafarge	800 kg/m^3
Silica fume	Non-combustible amorphous SiO_2	Elkem	175 kg/m^3
Fine quartz	Quarzfin U-S 500	Sibelco	225 kg/m^3
Fine sand	0/0,6 mm (AFA-60)	Caolines Lapiedra	302 kg/m^3
Medium sand	0/2 mm (AFA-45)	Caolines Lapiedra	565 kg/m^3
Superplasticizer	Viscocrete 20 HE	Sika	Variable
Accelerator	AKF - 325AT	IQE Group	Variable

Table 3. Mixture components

Pictures of the components can be found on the next page (figure 16 to 23).

Keeping in mind that other components than superplasticizer and accelerator always have the same dosage, often in this document the composition of the concrete is written as stated in the box below.

SXAY

With: S from superplasticizer and **X** = amount of superplasticizer (kg/m^3)

A from accelerator and **Y** = amount of accelerator (kg/m^3)

F = added when the mix includes fibers

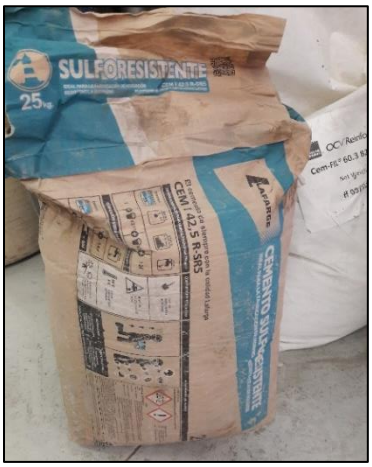


Figure16. Cement

Figure 17. Quartz flour

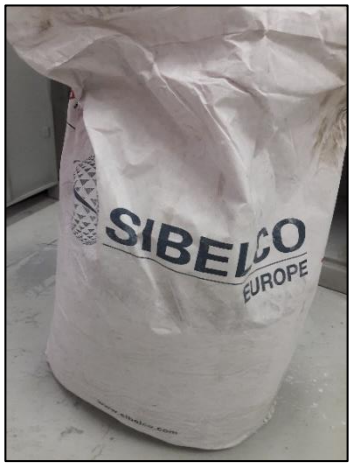


Figure 18. Silica fume

Figure 19. Fine sand

Figure 20. Medium sand

Figure 21. Superplasticizer

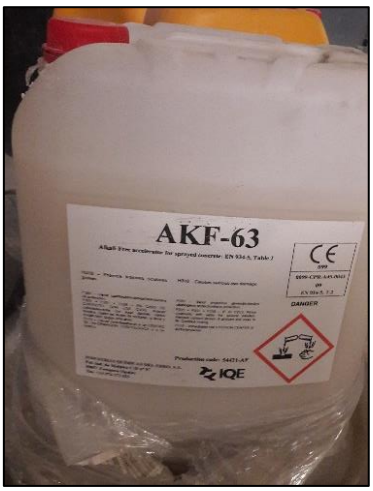


Figure 22. Accelerator AKF-63

Figure 23. Accelerator Nasil 3.35

Accelerator Nasil 3.35 (figure 23) was only available in the last weeks of the research. Setting tests to obtain a main idea of its behavior were done, but no further research was carried out with this product. If the accelerator is not further specified in this document, it means the type AKF-63 accelerator was used. Type AKF-63 is based on a complex aluminium salt, type Nasil 3.35 on sodium silicates.

3.3.2 Molds

Figure 24. Mold 40x40x160mm³

The steel mold to make 3 times a 40x40x160mm³ specimen is first used for the setting tests, where for the 2 plates in the middle are taken away to have a bigger surface. After for the compaction tests these molds are used to create one specimen of 40x40x160mm³ per mold.

Figure 25. Mold 200x200x200mm³

In the first part of phase three of the research, flat surfaces of around 15 mm thickness are made in the 200x200x200mm³ molds, with 15 mm in height and vibrated on the surface.

Figure 26. Mold to make negative concrete mold

The 200x200x200mm³ mold was used to create the positive and negative mold, later used to create a concrete shell. On this picture we can see a piece of PVC-pipe, which has an elevation of 50 mm in the middle, compared to both sides.

Figure 27. Positive and negative mold

In this picture we can see the cross section of the positive and negative mold, being continuous over the width of the mold.

To produce the mold the same UHPFRC mix as in the whole document was used, with 25kg/m^3 superplasticizer and no accelerator. The only difference is that less fibers were used, 80kg/m^3.

3.3.3 Mixers

Figure 28. Ibertest mixer 1L (left) and its details (right)

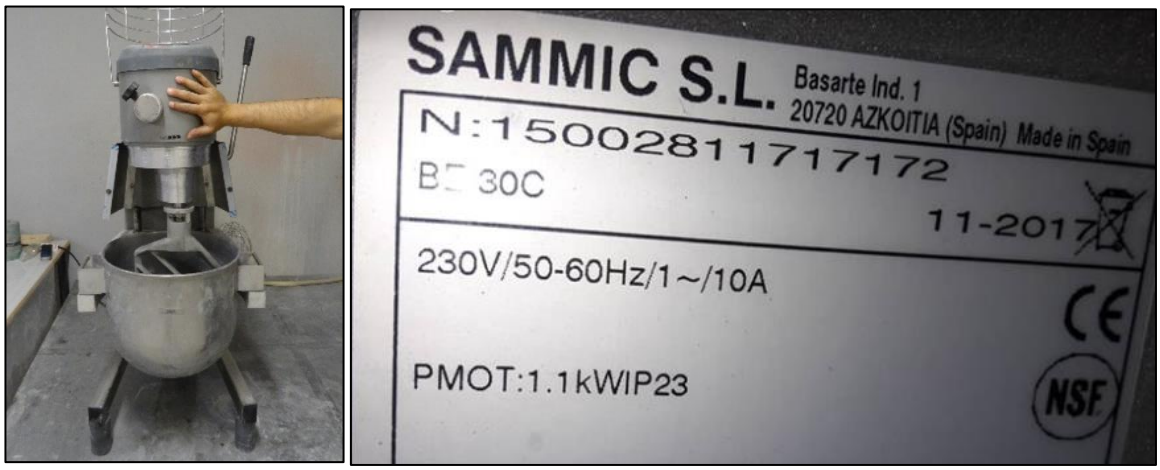


Figure 29. Planetary mixer BE 30C, producer: Sammic S.L. (left) and its details (right)

3.3.4 Compactor and vibrators

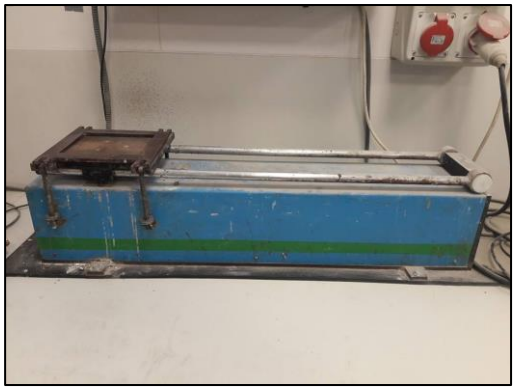


Figure 31. Compactador automático, producer: Proeti

Figure 30. External vibrator VE, producer: Enarco S.A.

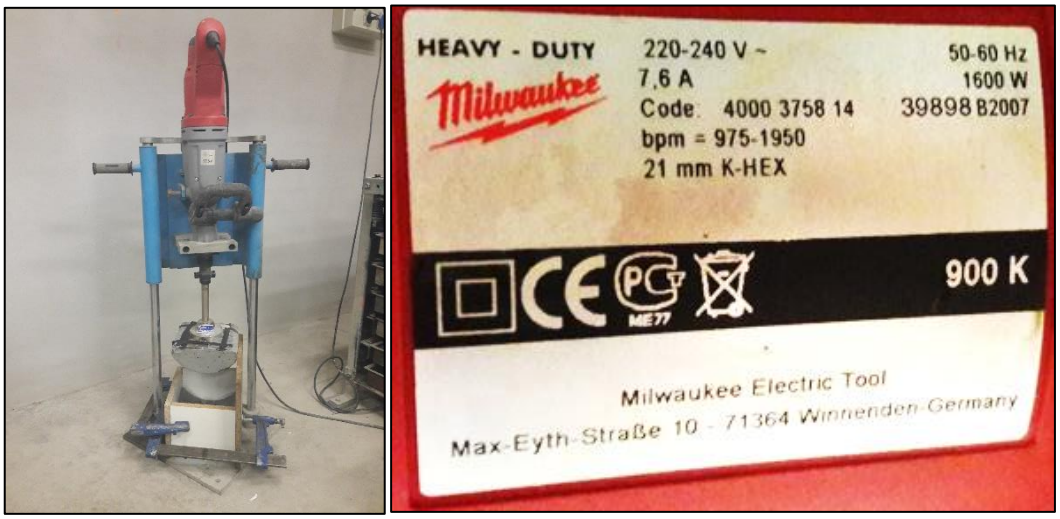


Figure 32. Vibrator, producer: Mecánica Científica S.A. (left), and details of the inserted device (right)

3.3.5 Other

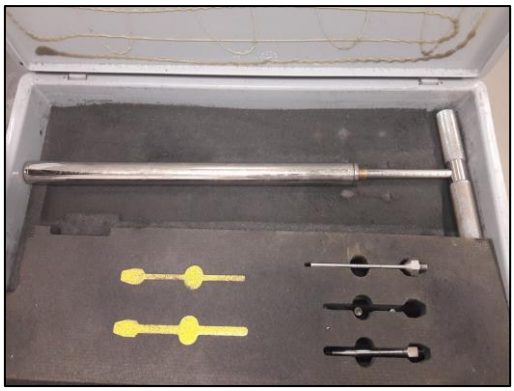


Figure 33. Penetration device for setting test, producer: Incotecnic lab-pre, s.l.

3.4 Methodology

3.4.1 First phase: setting time test

Applying the setting time test described in ISO CD 1920-14 (E), we obtain the start- and end setting time of different UHPC mixtures.

For each mix a 1-Liter Ibertest mixer is used in the slowest of two mixing modes. First dry components are added and mixed for 30 seconds, then the water is added and time is set 0'00", after 1 minute the superplasticizer is added. The addition of accelerator varies for every mixture but lies around 19 minutes after the addition of water, the end of the mixing procedure is always 1 minute later. The process is visualized in figure 34. The dosages of the concrete are the default ones for this thesis and fibers are not added for this test.

Figure 34. Mixing sequence setting time test

When the mix is ready, the mortar is put in a mold (see figure 35) with a depth of 40 mm and a surface of around 160x160mm^2, which is big enough for the penetration points to have enough distance as described in ISO CD 1920-14 (E). There was no formwork oil used for this test. Depending on how quickly the concrete is hardening, a time difference between the penetrations is chosen so that there are more than six test results at the end of the test, as requested in ISO CD 1920-14 (E). A needle with a surface of **16 mm^2** was used. This means that the measured resistance in Newton should be divided by 16 to obtain the penetration resistance in MPa.

Figure 35. Mold during setting test

Initially, some try-out penetrations without resistance are done, and from the time there is a resistance measured by the penetrating device, the test starts with measurements every 10 minutes. When the timing can be estimated from previous tests, the tries without resistance are reduced and the interval between measurements can be increased when it is expected that there will be six measurements done by the end setting time. Pressure is applied on the manual device until the concrete is penetrated for **20mm**. The pressure can be read as shown on figure 36, with a ring that stays up after the penetration.

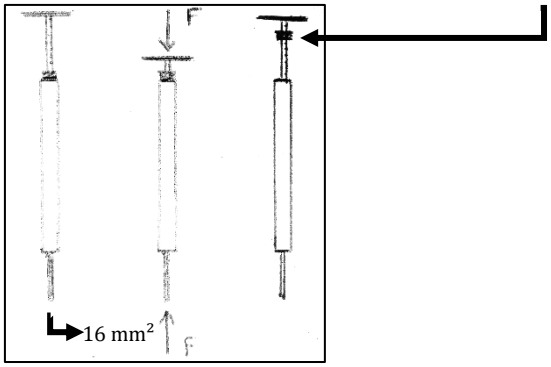


Figure 36. Read resistance of setting test (N)

As most of the mixes were not very fluid, there occurred some difficulties to put the concrete in the mold. In the mixes with no accelerator, this was no problem. For other mixes, a large spoon and the hands were used for putting the doughy substance of the concrete in the mold. With the least fluid mixes (the ones with less superplasticizer and more accelerator), it was even necessary to push on the concrete so that it would be divided over the whole mold (figure 37). This could have influenced the results, but not too much since it is other variables that have an influence on the setting.

Figure 37. Doughy substance of the concrete a few minutes after mixing (left), and after pushing and removing redundant concrete (right)

Following ISO CD 1920-14 (E), the start and end setting time are defined as the times when penetration resistance is respectively 3,5 MPa (lower horizontal line in graphs) and 27,6 MPa (upper horizontal line), intersected with a fitted power curve of the results. The graphs can be found in appendix A.

The ambient temperature during the test was between 20 and 25°C.

Normally the setting times should be the same for each mix with or without fibers because the steel fibers are inert for the chemical reactions. We did one test to state this and the results were similar for the same mix with and without fibers (see appendix A). This means the results of the mixes without fibers can be used for both cases.

The need for another type of accelerator, one which reaction starts later so that the workability doesn't change immediately and casting into the mold is possible, was made clear to the producing company of the used accelerator. They answered this need by sending another type of accelerator (Nasil 3.35). This was only later in the research process and so we could not do all the same tests with this new product. Three setting time tests were done with the new material (see appendix A).

3.4.2 Second phase: compaction test

The mixes we are testing are not self-compacting because of the accelerator that is added. To define how properties of the concrete change when the concrete is compacted at different times around the start setting time, three specimens of the same mix are compacted at three specific times T1, T2 and T3.

T1	T2	T3
Tss/2	Tss-5	Tss*1,5
Tss = start setting time (min)		

Table 4. Times T1, T2 and T3 in compaction test

The start setting time (Tss) is a result from the setting tests explained in section 3.4.1 (number of minutes after adding water). The mixing procedure is the same as in the previous test for each mixture, so that we can continue on the results obtained in that test.

From each 1-liter mix, 3 molds of 40x40x160mm^3 (smeared with formwork oil) are filled right after the mixing procedure. Then, at each specified time T1, T2 and T3 after the first contact with water, one of the specimens is compacted (60 cycles), and put in a conditioned room (20°C and RH 100%).

Here we bump into the same problem as in the setting test, because the concrete is not flowing. In this case the problem is more severe because the volume per specimen is smaller than the volume of the mold used for the setting test. To fill the mold for each specimen, we put some concrete in the mold (with hands or spoon), push it into the corners and maybe a second layer is needed to fill the mold. Even with pushing the concrete downwards into the mold, we can see that the form of the specimens is very textured and that there's no material in the corners, for one mix more than another. An example of this bad form of the specimens is shown in figure 38. In the mix without accelerator, this problem doesn't occur.

Figure 38. Bad form of specimen (example: S30A32, compacted at T1)

The problem lays also in the fact that the time of compacting is very important in this test. Because of the pushing and using hands when filling the molds, a certain undefined compaction is already performed, which has a big influence on the strength results of each specimen.

Another practical difficulty was wiping off the excessive amount of concrete from the mold after compaction. There was a lot of force needed to get the excessive amount of concrete from the surface of the specimen. At T3, this was the most difficult because the concrete was already partially hardened. At this time, it was necessary to kind of scratch over the surface to get rid of the excessive amount of concrete (figure 39b). When wiping the excessive amount off concrete that is not hardened yet, we should do it carefully in order to not push the doughy substance to one side of the mold (figure 39c). Fibers cause even more problems.

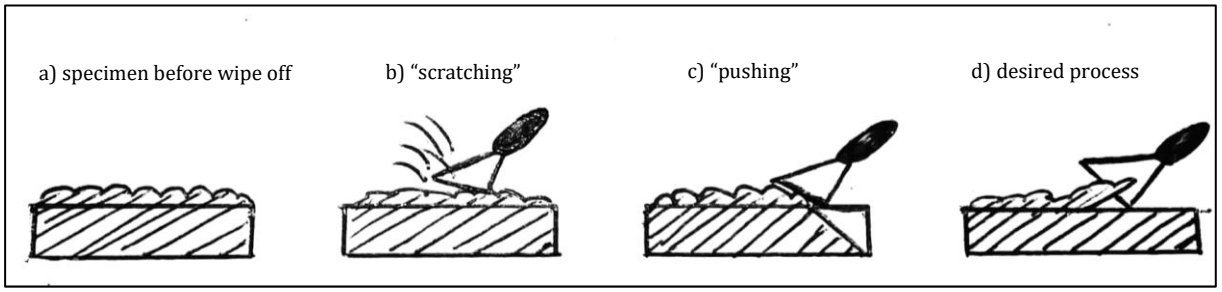


Figure 39. Clean specimen after compaction

After (around) seven days, the specimens are tested for flexural and compression strength. First, flexural strength is tested with a three-point flexure test with 100 mm distance between the supports. Then, both sides of the broken specimen are tested for compression between a 40mm*40mm surface.

For the first test, tensile strength of the concrete is calculated through the next equation:

$$\sigma = \frac{Mz}{I_y} = \frac{\frac{Pl^2}{8} * \frac{h}{2}}{\frac{bh^3}{12}} = \frac{3Pl}{2bh^2}$$

With:
σ = tensile strength (MPa)
P = measured maximum pressure (N)
l = length between supports = 100 mm
b = width of specimen = 40 mm
h = height of specimen = 40 mm

For the compression test, the next equation is used:

$$\sigma = \frac{P}{A}$$

With:
σ = compressive strength (MPa)
P = measured maximum pressure (N)
A = compression surface = 40*40 = 1600 mm

3.4.3 Third phase: practical procedure of cold forming

After researching the mix design, a process to cast, compact and demold the thin shell structure must be developed.

In this part, an amount of 25kg/m^3 of the superplasticizer was used.

3.4.3.1 Vibration technologies and concrete workability

Because of the poor workability of the concrete, a compaction by vibrating the surface of the concrete is preferred.

The first attempts include an external vibrator that is placed on a surface of wood of the same size as the surface of concrete we want to vibrate in the 200x200x200mm^3 mold (see material section). To vibrate, around 1 liter of concrete is placed in the mold that is smeared with formwork oil. Then the vibrator is introduced. All surfaces touching the concrete were smeared with formwork oil. Examples of the produced specimens can be seen in figure 40.

Figure 40. Examples of the specimens produced

The concrete was mixed in the Planetary mixer (see material section), with the same dosages as are default in the document, including fibers. Five liters were made, used to perform four specimens each mix. In this phase a different mixer is used, but the mixing sequence is similar to the previous two phases. Differences in mixing speed and timing are specified with each result.

The process of vibrating the thin surface of concrete was optimized:

- The vibration time and reaction of the concrete was analyzed
- The possible delay between end of mixing and vibration was stated
- The requirement to pour the concrete made us change the accelerator dosage
- The use of plastic for the device not to stick to the concrete was changed by placing a rubber slab on the device

After optimizing the mix and the process with this vibrator, the behavior of the concrete after vibration was analyzed by demolding only the side supports, leaving the base plate of the mold, then fully demolding and carefully transporting the concrete slab, and finally by testing if the plate can carry its own weight. The possibility to deform the slab to a thin shell was also tested.

A remaining problem was that the vibrator should be introduced perpendicularly, where for a new device is being used in the next stage of the research.

3.4.3.2 Optimizing time-interval to vibrate thin shell form

A concrete mold was casted to perform this part, as previously described. The positive mold was attached to the perpendicular vibrator and the negative mold was placed straight under it. The positive and negative part were covered with a PE plastic. Four wooden pieces were placed around the negative mold as can be seen in figure 41. Everything was smeared with formwork oil.

Figure 41. Perpendicular vibrator setup

With this setup, the objective was to create thin shells by lowering the positive mold onto the concrete that is placed in the negative mold, and vibrating the positive mold. After this action, it is desired to be able to immediately raise the positive mold and remove the wooden plates, with the concrete keeping its form. An example from a relative fluid concrete for this application being put in the mold can be seen in figure 42. After lifting the positive mold, the plates are removed with a spatula as can be seen in figure 43.

Figure 42. Putting concrete in negative mold

Figure 43. Partially demolding thin shell

Three thin shells were performed from each five liter mix with the Planetary mixer, each on another negative mold with the same shape. Keeping track of timing, the three specimens were performed each at a different timing after the mixing process. In between the production of each specimen, the negative mold was replaced with a new one and the wooden plates were placed around the new negative mold. To make sure the positive mold was placed straight above the negative one, the positive mold was lowered and fitted into the negative one, which is when placement of the wooden plates was done.

To not create confusion, it must be mentioned that the mixing process ends one minute after adding the accelerator and that the concrete is resting the remaining time until it is put in the mold to vibrate. This is also to approach the real conditions in which the larger thin shells will be created: some delay between the end of mixing and casting is necessary to be able to perform the production process: transport the concrete, etc.

In the previous part, the mix containing as much accelerator as possible, but was still pourable, was preferred. For this application, a higher dosage of accelerator was used since tests showed that it would take too much time for the concrete to be in a state where the vibration could be carried out without problems of concrete escaping between the wooden plates and the concrete mold, and without the concrete to fall off the sides when removing the plates after vibrating.

After the mixing process, before performing the first specimens, the concrete was conserved in the mixing bowl. For later specimens, the concrete was first taken out this bowl and put to rest in units of one liter. Like this it was possible to clean the bowl sooner. Besides, it was easier to take the units from the freshly mixed concrete instead of waiting to take the unit before each vibration (figure 44).

Figure 44. Conservation of three times one liter, as done in the last tests

When concrete was rising on the sides between the concrete mold and the wooden plates, it was considered too fluid for this application. Although some of these 'rising' concretes were quite stiff already, keeping the curvature, and could maybe be used if the mold would be improved.

For future researches in this case, it is desired to optimize the mold to one with smaller tolerances, where maybe the negative mold has a permanent case around it without having to put wooden plates on all four sides while preparing for each vibration.

The results of these tests will contain:

- Time of vibration
- Duration of the vibration
- If there was concrete escaping
- Time from when demolding is possible

The time from when demolding is possible is defined as a timing where it is possible to take the concrete out of the negative mold without deformation of the specimen, and with the specimen keeping its form when supported on the convex side, carrying its own weight.

The performed tests lead to an optimal accelerator dosage, timing when to vibrate and time to demold for the thin shell in our application.

4 Results

All time data mentioned in the following part, is related to the time of adding water, which is 00'00", unless if stated otherwise.

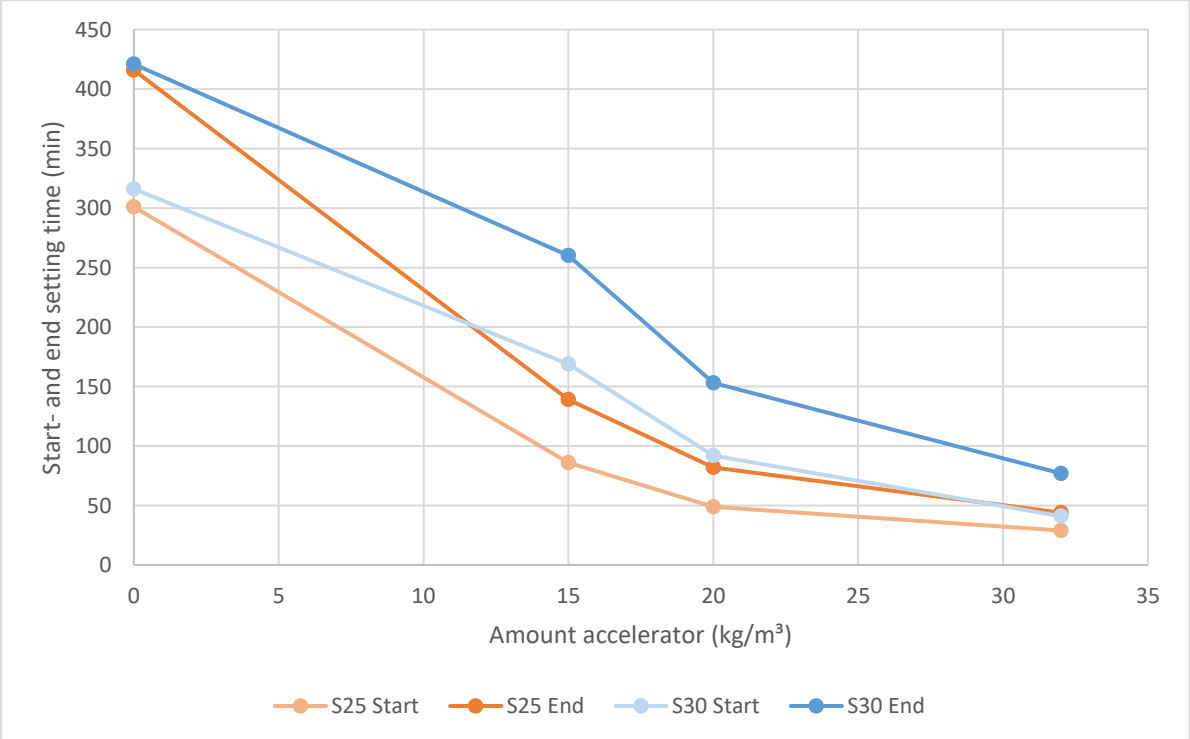
4.1 First phase: setting time test

4.1.1 With accelerator AKF-325AT

In table 5 we have an overview of the start- and end setting time from every tested mix. The graphs with measurements of each test can be found in annex 1. We notice that the margin of error is much bigger for start than for end setting times, because a small difference in resistance can mean a big difference in time when you look at the left side of the power curve, and the opposite counts for the right side of the curve. This means the end setting time is expected to be approaching the real value more than the start setting time.

Mix	Superplasticizer (kg/m^3)	SP/C	Accelerator (kg/m^3)	A/C	Start setting time (min)	End setting time (min)
A	25	3,1%	0	0,0%	301	416
B	25	3,1%	15	1,9%	86	139
C	25	3,1%	20	2,5%	49	82
D	25	3,1%	32	4,0%	29	44
E	30	3,8%	0	0,0%	316	421
F	30	3,8%	15	1,9%	169	260
G	30	3,8%	20	2,5%	92	153
H	30	3,8%	32	4,0%	41	77

Table 5. Overview setting times



4.1.2 With accelerator Nasil 3.35

Mix	Superplasticizer (kg/m^3)	SP/C	Accelerator (kg/m^3)	A/C	Start setting time (min)	End setting time (min)
N1	25	3,1%	11	1,4%	194	245
N2	25	3,1%	20	2,5%	151	197
N3	25	3,1%	32	4,0%	92	138

4.1.3 Analysis

At first, it can be said that the setting test worked out as expected. This means that the measurements created a curve of the expected form, where from the start and end setting time could be extracted (appendix A).

Secondly, with the increase of superplasticizer the setting started later except in the mixture without accelerator. Since we are working with accelerated mixes, and in this research we desire a rapid hardening of the concrete, the amount of $30kg/m^3$ accelerator was left out in the next two phases.

There is a big influence of the accelerator on the setting time, and in the graph of accelerator type AKF-63 we can see that with increasing the accelerator dosage more and more, the effect on the setting times gets less.

Finally, we have chosen not to continue with the accelerator type Nasil 3.35. This because only very little knowledge was obtained from this accelerator since it was introduced in a later stadium of the research.

Although there is not further focused on type Nasil 3.35 accelerator, a few intermediate conclusions can be drawn from the setting test results.

1. Generally, the duration of the setting relative to the start setting time, is lower with the Nasil 3.35 accelerator.
2. Almost the same results (start setting time and duration of setting) are obtained with an amount of $32kg/m^3$ Nasil 3.35 accelerator and $15kg/m^3$ AKF-63 accelerator.
3. For the three tests performed with accelerator Nasil 3.35, the duration of the setting remains more or less constant.

4.2 Second phase: compaction test

	Without fibres		Theoretical	Practical	Tensile strength (MPa)	Compressive strength mean value (MPa)
A	S25A00 (7 days)	T1	150,5	150,5	18,16	120,31
		T2	296,0	296,0	18,75	116,41
		T3	451,5	451,5	12,89	116,41
B	S25A15 (7 days)	T1	43,0	43,0	14,77	116,09
		T2	81,0	81,0	12,19	97,03
		T3	139,0	129,0	11,72	98,13
C	S25A20 (8 days)	T1	24,5	25,0	20,39	97,50
		T2	44,0	45,0	21,09	102,97
		T3	73,5	75,0	17,58	101,25
D	S25A32 (8 days)	T2	24,0	23,0	17,34	76,41
		T2	24,0	23,0	17,34	76,41
		T3	43,5	37,5	10,55	44,69
F	S30A15 (7 days)	T1	84,5	84,5	15,23	106,09
		T2	164,0	164,0	15,47	91,41
		T3	253,5	253,5	15,23	104,06
G	S30A20 (7 days)	T1	46,0	46,0	17,58	90,70
		T2	87,0	87,0	15,23	78,75
		T3	138,0	147,0	16,99	88,28
H	S30A32 (7 days)	T1	20,5	22,0	17,58	87,19
		T2	36,0	36,0	12,89	80,31
		T3	61,5	61,5	13,48	85,94

Table 6. Results of compaction test for specimens without fibers

	With fibres		Theoretical	Practical	Tensile strength (MPa)	Compressive strength mean value (MPa)
A	S25A00F (7 days)	T1	150,5	150,5	32,81	150,63
		T2	296,0	296,0	32,34	154,69
		T3	451,5	451,5	29,30	144,22
B	S25A15F (10 days)	T1	43,0	43,0	25,78	158,44
		T2	81,0	81,0	21,56	136,09
		T3	139,0	129,0	31,41	134,84
C	S25A20F (8 days)	T1	24,5	25,0	33,75	113,44
		T2	44,0	45,0	17,11	130,47
		T3	73,5	75,0	34,22	118,28
F	S30A15F (10 days)	T1	84,5	84,5	33,75	151,41
		T2	164,0	164,0	39,14	153,75
		T3	253,5	253,5	37,73	141,88
G	S30A20F (7 days)	T1	46,0	46,0	26,95	113,28
		T2	87,0	87,0	17,11	79,06
		T3	138,0	138,0	23,32	59,84
H	S30A32F (9 days)	T1	20,5	24,0	29,30	103,13
		T2	36,0	36,0	22,03	93,75
		T3	61,5	61,5	12,66	108,44

Table 7. Results of compaction test for specimens with fibers

4.2.1 Analysis

The difficulties discussed in the methodology, have a clear effect on the test results. Results are very poor, not showing a lot of tendencies. Something can be concluded from the compression strength results, but not from the tensile strength results. Improvements of the methodology are required.

4.3 First and second phase results analysis

When we disregard fluidity problems and look only at timing, we can make two main conclusions.

1. *Compacting at T3 = T_{ss}*1,5 is not logical*

Analyzing the results from the compacting test (table 6 and 7), the results from the compression test seem the most useful because we can see some pattern.

Four colours were added in table 6 and 7 (results of compacting tests):

1	This result is quite good, minding the testing time.
2	This result is not quite good, minding the testing time.
3	This strength is clearly less than the strength from the same concrete that is earlier compacted.
4	This result is very illogical.

In the third column it is made visible that quite a few times, there's a strength reduction when compacting at T3 and even T2. If T2 and T3 are in red, we see that for every case, compacting at T3 is worse for the compression strength than at T2. We can conclude that at least T3 is not a useful compaction time, and maybe T2 too. More of these tests should be done for better statistics of the strength reduction, but for this more time is necessary.

What can as well be seen in table 6 and 7 when noticing colour 2, is that an amount of 32 kg/m^3accelerator is either way too much if we don't want a significant strength reduction relative to non-accelerator concrete. We can see that every mix with accelerator is less strong than the reference mixes without accelerator, and it makes sense that the mix with the most accelerator has the largest strength reduction.

2. *Some T_{ss} are not useful in practice*

Not forgetting the key purpose of this work, which is realizing a reef structure, we must take a look at the practical casting procedure and its timing. A few square meters thin surface will be casted one after another. This means that first, casting right after the mixing process will be difficult because of the amount of concrete, transportation time etc. And secondly the start of the setting cannot be too late after the mixing procedure because this is not interesting and will slow down the production of the structure.

For this, we set two boundaries for the start setting time:

$$40 \text{ min} \leq T_{ss} \leq 100 \text{ min}$$

To see the mixes that have a start setting time within these boundaries, we retake table 5. A coloured letter means a mixture that has a start setting time within the boundaries.

Overview setting times for conclusion

Mix	Superplasticizer (kg/m³)	SP/C	Accelerator (kg/m³)	A/C	Start setting time (min)	End setting time (min)
A	25	3,1%	0	0,0%	301	416
B	25	3,1%	15	1,9%	86	139
C	25	3,1%	20	2,5%	49	82
D	25	3,1%	32	4,0%	29	44
E	30	3,8%	0	0,0%	316	421
F	30	3,8%	15	1,9%	169	260
G	30	3,8%	20	2,5%	92	153
H	30	3,8%	32	4,0%	41	77

⇒ ***Overall conclusion***

Second part of conclusion - practical	First part of conclusion - strength	
Possible mixes	Without fibers	With fibers
B – S25A15	Good	Strength reduction T2 & T3
C – S25A20	OK	Strength reduction T3
G – S30A20	OK	Strength reduction T2 & T3
H – S30A32	Not good (32kg/m³ accelerator)	

Table 8. Conclusion of phase 1 and 2

We can conclude that B, C and G are the most useful mixes for our case. We might even leave out G (S30A20) because the start setting time is not very different from mix C (S25A20) and it takes longer for the concrete to harden, as described earlier.

Most useful for this application:	B – S25A15
	C – S25A20

Of course, time objectives can change depending on the applied technologies or the possibility to add more energy during compaction, in that case it could be possible that T2 and T3 are in fact useful.

4.4 Third phase: practical procedure of cold forming

4.4.1 Vibration technologies and concrete workability

General information about the results:

- 'Vibration' means: time that passed between the addition of accelerator and the vibration.
- Information about the time of adding fibers and accelerator, is relative to the time of adding water: 0''00''.
- Initially, the dry components were mixed for 30" on a speed of '2', one minute later superplasticizer was added.
- The end of the mixing procedure is always one minute after the addition of accelerator.

Mix	Vibration	Condition of concrete	Remarks
S30A20	03'00'' 08'00'' 13'00'' 18'00''	Very dry, not pourable.	The concrete for this test was taken from a 60L mix with same dosages, mixing process unknown. Plastic was put between vibrator and concrete.
Lower accelerator dosage,			
No plastic on the concrete surface but a rubber slab attatched to the vibrator			
S25A10	02'30'' 09'30'' 17'00'' 22'15''	Pourable if inclined over 45°, vibration still possible for the fourth specimen.	Speed of the mixer was kept on '2' the whole mixing process. Fibers at 19', accelerator at 20'
Raise accelerator dosage			
S25A12	01'00'' 07'00'' 10'30'' 16'30''	Concrete significantly dryer than previous, scooping got more difficult when preparing the last specimens.	Speed of the mixer was '2' until the change from dry to wet (around 8'), from then the speed was '5'. Fibers at 11', accelerator at 14'.
Optimize accelerator dosage			
S25A11 ✓	05' à 10' 05' à 10' 05' à 10' 05' à 10'	Could be poured from 5-liter bowl if inclined over 45°, and pushed towards border with a large spoon. Good enough for the application and since we desire a rapid hardening.	Same process than previous. All specimens performed in 5 minutes. **These specimens were further tested.**

Table 9. Results of phase 3, part 1

Conclusion: it was possible to vibrate in all cases.

The mix was optimized concerning workability in the first minutes after mixing.

The S25A11 mix was further analyzed.
Time that passed after the addition of accelerator + possibilities of the specimens:

- **45'** Partially demolding, carefully (keeping base plate)
- **1h15'** Moving specimen horizontally over the base plate by pushing one side
- **1h30'** Placing specimen over a PVC tube to deform.
  ⇒ State = **too fluid**. Cracks appear from the concrete flowing down on both sides.

Figure 45. Cracks due to deformation (1)

- **3h00'** Placing specimen over a PVC tube to deform.
  ⇒ State = **too rigid**. Cracks appear because the concrete needs to be pushed to take the form.

Figure 46. Cracks due to deformation (2)

- **3h45'** Placing two supports under two opposite flanks of the specimen with each 10 mm overlap.

4.4.2 Optimizing time-interval to vibrate thin shell form

General information about the results:

- 'Timing' means: time that passed after the addition of accelerator.
- Mixing process is fixed:
    - speed: mode '2'
    - previously mix dry components for 30"
    - 0'00'': put water
    - 1'00": put superplasticizer
    - when concrete changes from dry to wet (around 8'): put speed mode '5' until the end
    - 13'00'': put fibers
    - 15'00": put accelerator.
    - Mixing procedure ends at 16'00"

Mix	Timing	Action	Condition of concrete
S25A11	3'	Vibrate a few sec	When lifting positive mold, concrete flows to the middle until surface is horizontal.
	15'	Vibrate a few sec	Curved form stays but removing the wooden plates is not possible since the concrete flows off the edges of the negative
	35'	Vibrate a few sec	
Raise accelerator dosage			
S25A13	10'	Vibrate for 5"	When lifting positive mold, concrete flows to the middle, curved form stays visible.
	22'	Vibrate for 10"	Curved form stays but removing the wooden plates is not possible since the concrete flows off the edges of the negative
	35'	Vibrate for 10"	
Raise accelerator dosage			
From here, an additional plastic that stays on the concrete surface after vibration was introduced.			
S25A17	8'	Vibrate for 10"	Concrete escapes between positive mold and wooden plates
	21'	Vibrate for 10"	Concrete escapes between positive mold and wooden plates
	38'	Vibrate for 10"	Concrete didn't escape.
	2h15'	Fully demold	At 2 hours the concrete still deformed when supporting it on one half, 15 minutes later it could carry its own weight.
Adjust time to vibrate			
S25A17	20'	Vibrate for 15"	Concrete escapes between positive mold and wooden plates
	25'	Vibrate for 15"	Concrete escapes between positive mold and wooden plates
✓ ⇒	30'	Vibrate for 15"	The concrete doesn't escape and realizing shell is possible
	2h15'	Fully demold	At 2 hours the concrete still deformed when supporting it on one half, 15 minutes later it could carry its own weight.

Table 10. Results of phase 3, part 2

Photos of the specimens created in this phase can be found on the next pages.

4.4.3 Analysis

Even though there is sometimes a waiting period before vibration of the concrete, still the timing of vibration is nowhere near the start setting time. For this, in the future it is desired to research a test other than the setting time test, that analyses the behavior of the concrete in the time before the 'start setting time' as defined previously.

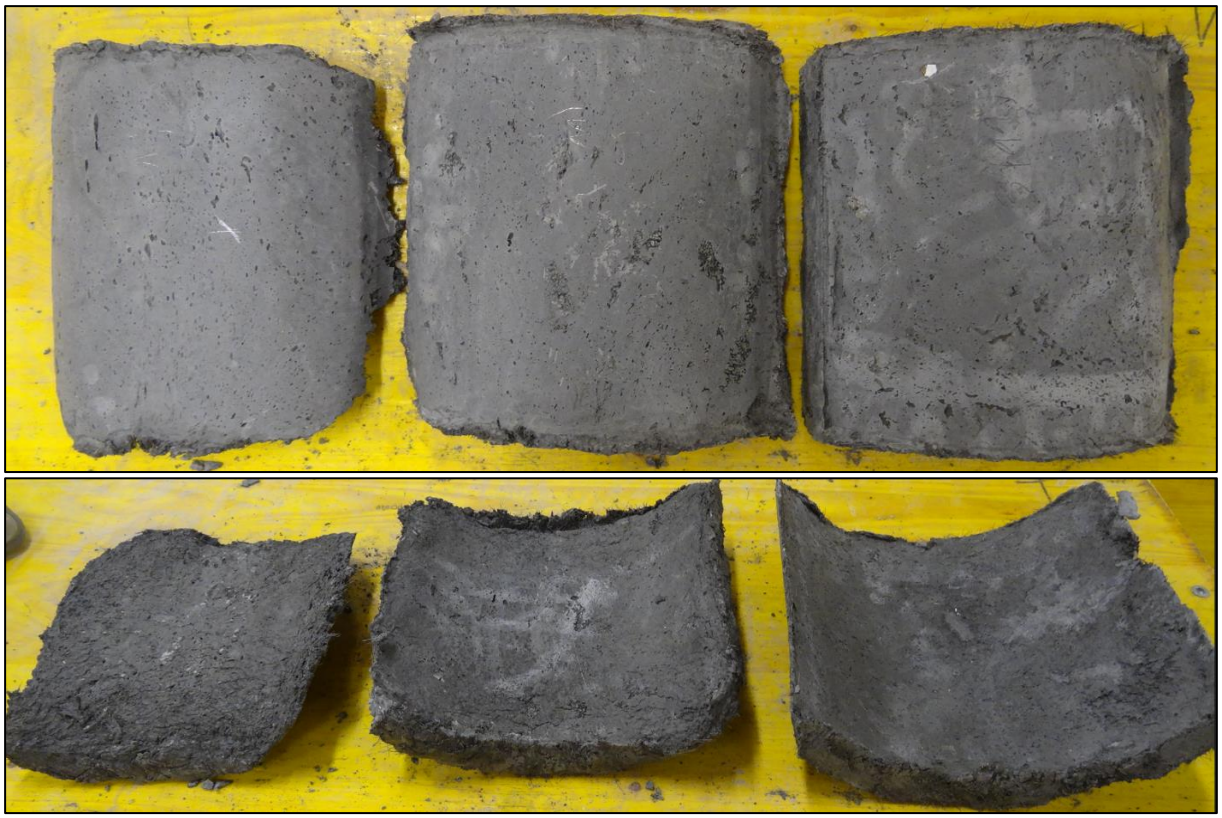


Figure 47. Pictures of the shells created with the mix S25A11

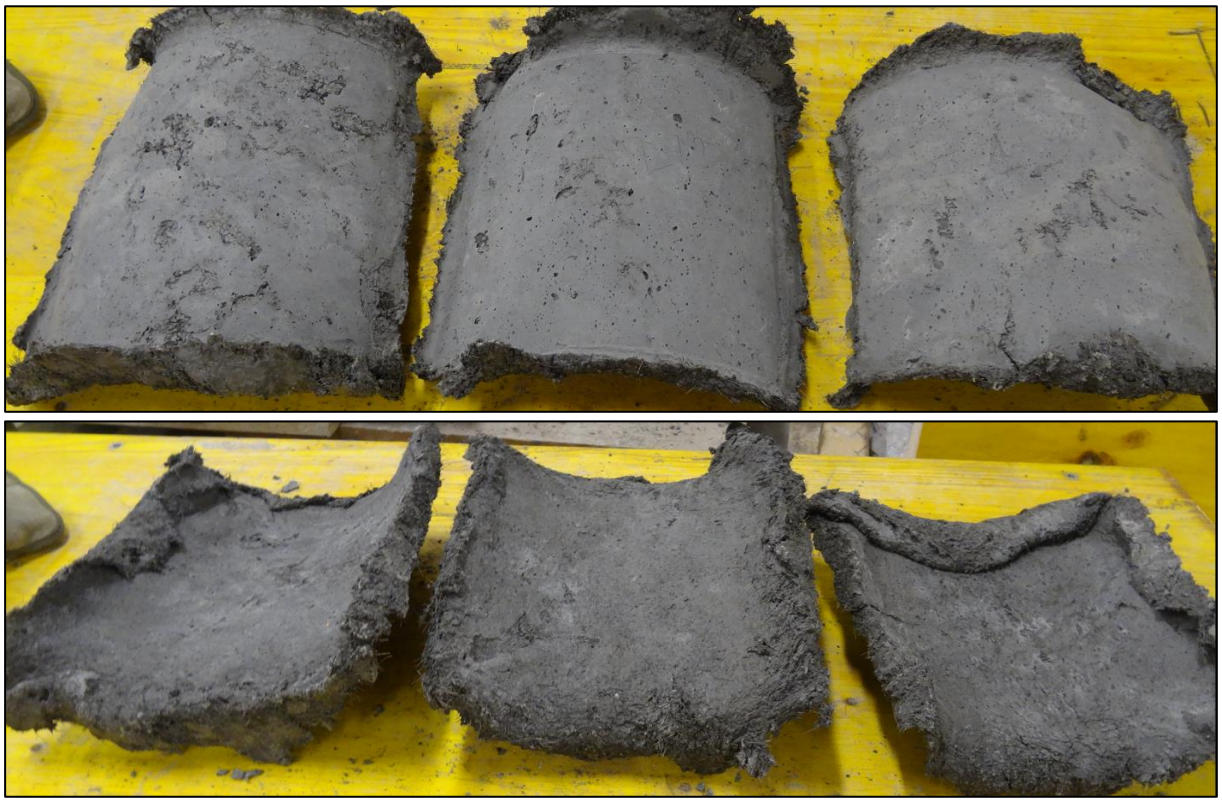


Figure 48. Pictures of the shells created with the mix S25A11

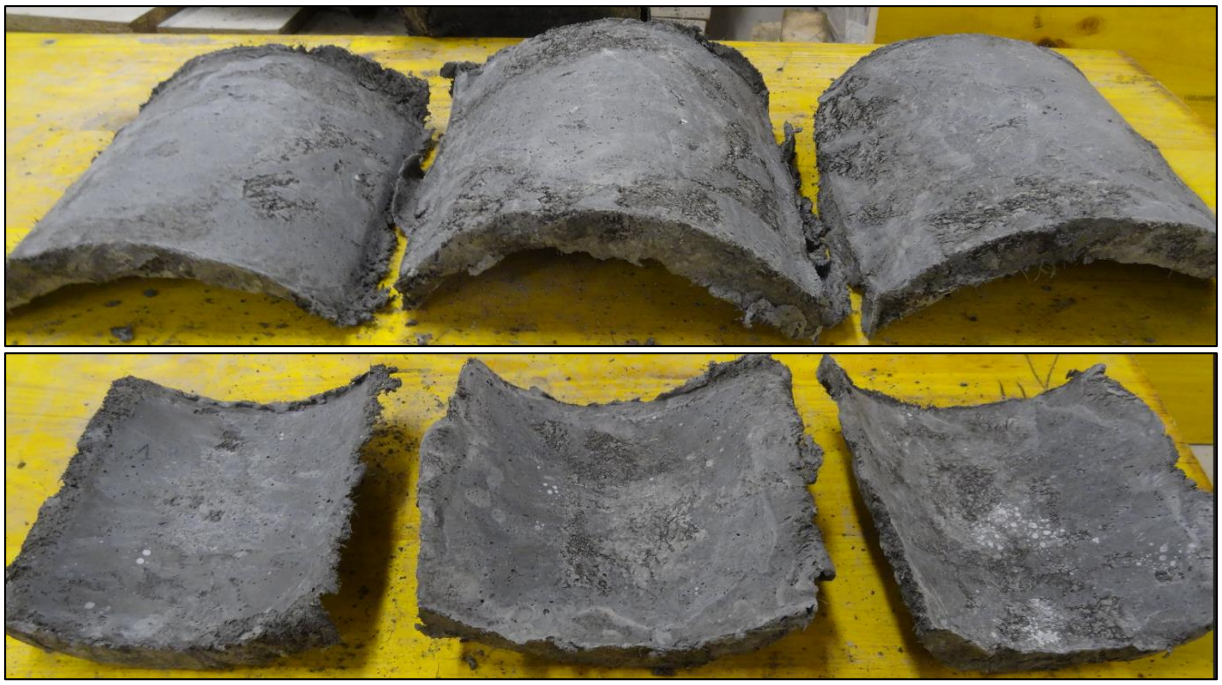


Figure 49. Pictures of the shells created with the first S25A17 mix

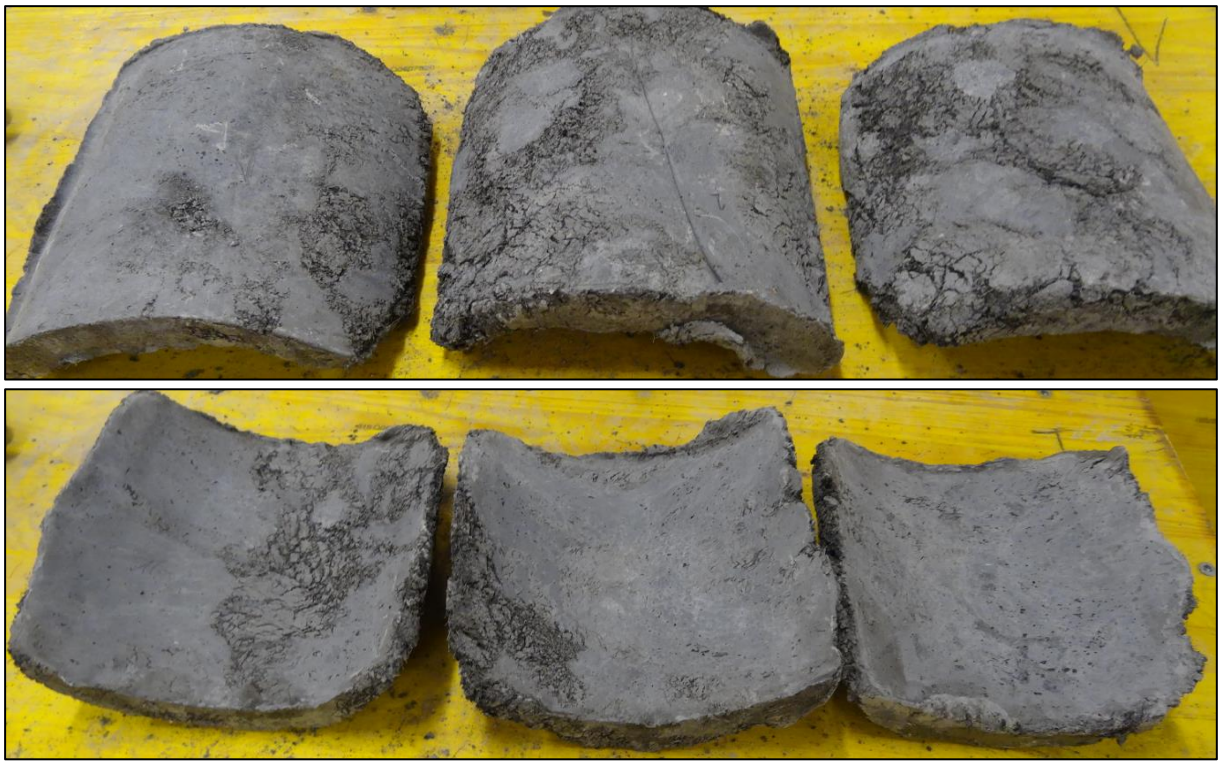


Figure 50. Pictures of the shells created with the second S25A17 mix

We can see that there is some more honeycombing in the specimens of the S25A17 mix than the mixes before. To avoid this problem the first two mixes and an optimized mold could be used, vibration energy could be increased, or some changes in the mix design to reduce the honeycombing can be researched.

5 Conclusions

In this research, a new concept to try answering the need for an economically possible production of curved thin shell elements is proposed. The influence of accelerating admixtures on the possibilities of shaping the elements and giving them the ability to carry their own weight within a short period following the mixing procedure, is researched.

Generally, the objective of this work, which was creating curved elements with an accelerated mixture for the concrete to keep its form more rapidly (as in rapid enough for an industrial process to be applicable), was achieved.

Further conclusions drawn from this work are:

- As more accelerator is added, the effect of this admixture reduces.
- UHPFRC can keep its form in the time before the start setting time as defined with the test described in ISO CD 1920-14 (E).
- Compacting and thus also forming an element after the start setting time as defined with the test described in ISO CD 1920-14 (E), is impossible; at least using the same compactor as the one in this research.
- Within the fixed variables and materials in this research, it wasn't possible to create an accelerated concrete which had a high fluidity right after admixing accelerator, and at the same time an accelerated setting.
- For our prototype of creating thin shells with a positive and negative mold, a mix containing 25kg/m^3 of the superplasticizer in this research, and an amount of 17kg/m^3 accelerator type AKF-63 was considered. This mixture showed the best balance between initial workability and ability to produce thin shells within an economically interesting timing. The time to vibrate this concrete between our molds was most efficient 30 minutes after the addition of accelerator. Demolding of the element from the negative mold was possible starting from 2 hours and 15 minutes after the addition of accelerator.

6 Improvements and future research

A basic concept for creating thin shell concrete elements, which could be applied in an industrial process, was developed in this work. Thin shells were possible to be produced, although some advances on several aspects of the work can be made in the future.

- A new test to research concrete hardening before the start setting time is desired, since the forming process of the elements is performed in an earlier stadium, before the start setting time.
- Compaction tests at a time before the by us specified T1 could be more useful since in the end it came out that elements were vibrated way before the specified time T1. When to compact could be concluded from the test specified in the previous bullet point.
- Lower tolerances on the mold used in phase three to create thin shells are desired to prevent the concrete from escaping.
- A higher number of tests is desired so that statistics could be done to optimize the test outcomes.
- The time interval to vibrate the thin shells could be fine-tuned more by analyzing more tests.

In the future, other concepts except from those in this research, could be researched.

- The mix design could be adjusted, based on the zero-slump principle as discussed in the state of the art section. The possibility of reducing the amount of accelerator and replacing the effect of the accelerator by reducing superplasticizer, can be tested.

  When reducing the superplasticizer dosage, a higher mixing energy will be necessary to make the concrete change from its dry to fluid state. Extending the mixing process is also an option but a long mixing time is not desired. It should be noted that the concrete cannot be too dry for the process of performing thin shells.

  Furthermore, for dry concrete a higher vibration energy and a very strong and rigid mold is necessary.

  The limits of reducing accelerator and superplasticizer should be researched.

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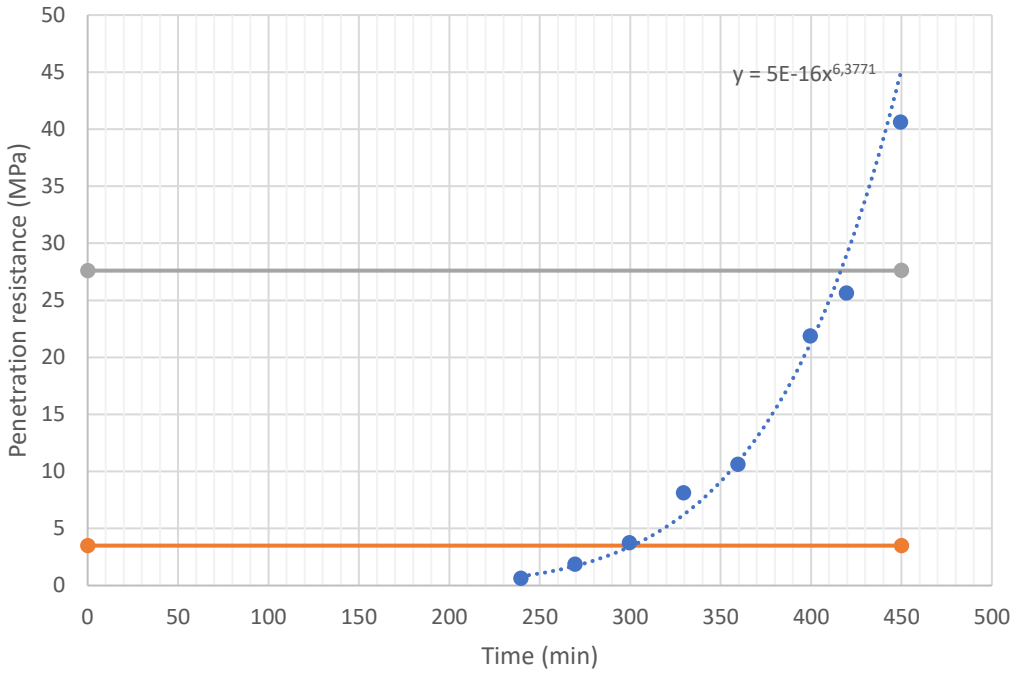
Appendix A: Intermediate results of the setting time tests

All time data mentioned in the following part, is related to the time of adding water, which is 00'00", unless if stated otherwise.

Mix A

Superplasticizer: 25 g	Accelerator: 0 g

Graph



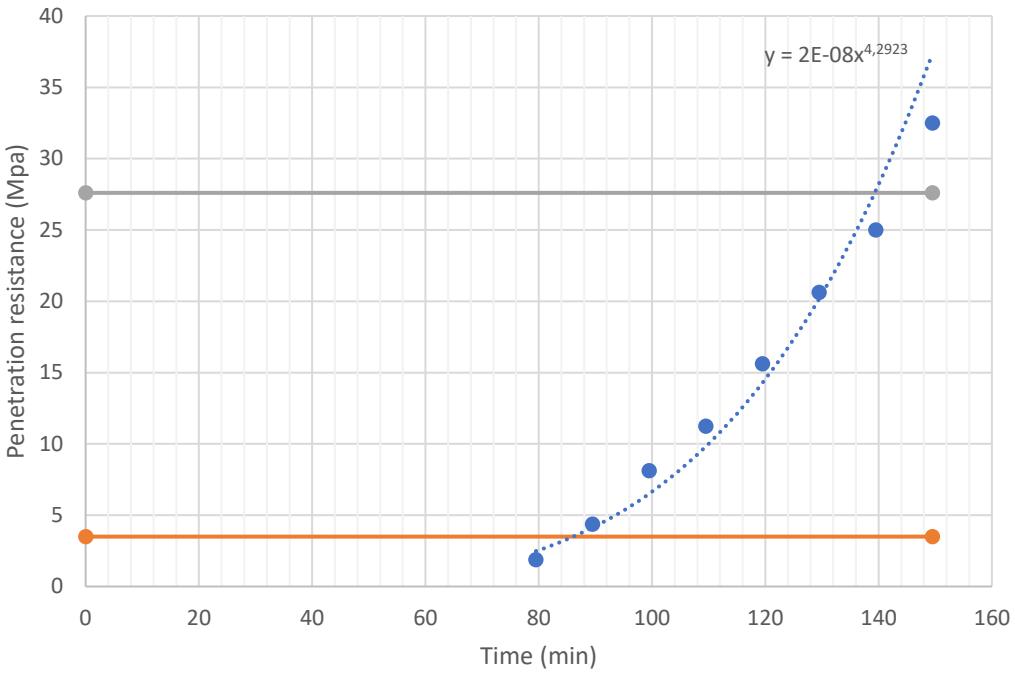
addition accelerator: 19'00"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
239,5	0,625	301	416
269,5	1,875		
299,5	3,75		
329,5	8,125		
359,5	10,625		
399,5	21,875		
419,5	25,625		
449,5	40,625		

Mix B

Superplasticizer: 25 g	Accelerator: 15 g

Graph



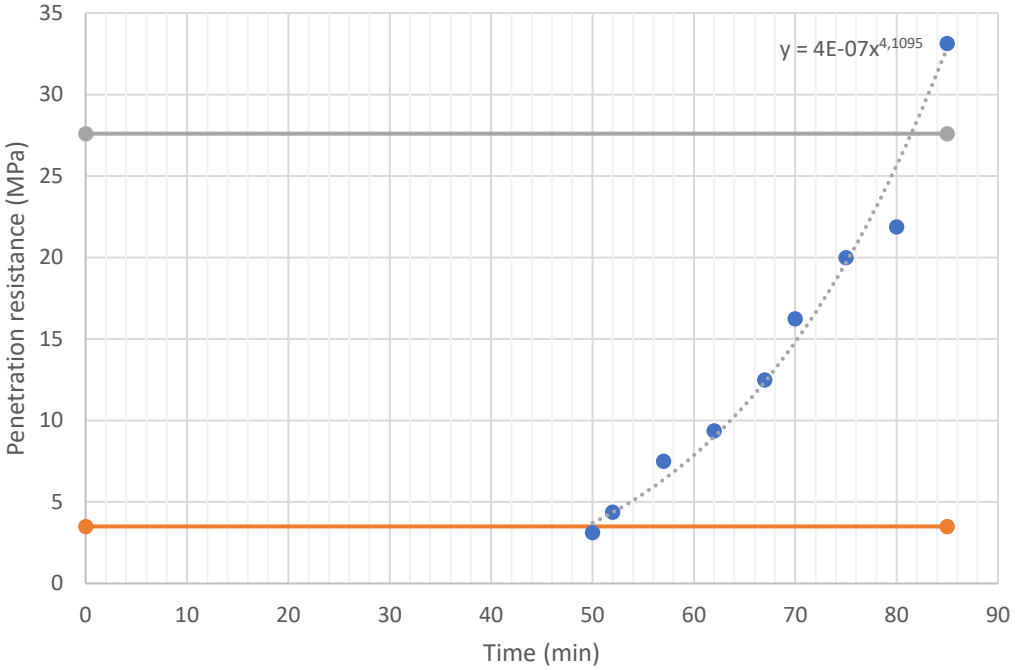
addition accelerator: 18'30"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
79,5	1,875	86	139
89,5	4,375		
99,5	8,125		
109,5	11,25		
119,5	15,625		
129,5	20,625		
139,5	25		
149,5	32,5		

Mix C

Superplasticizer: 25 g	Accelerator: 20 g

Graph



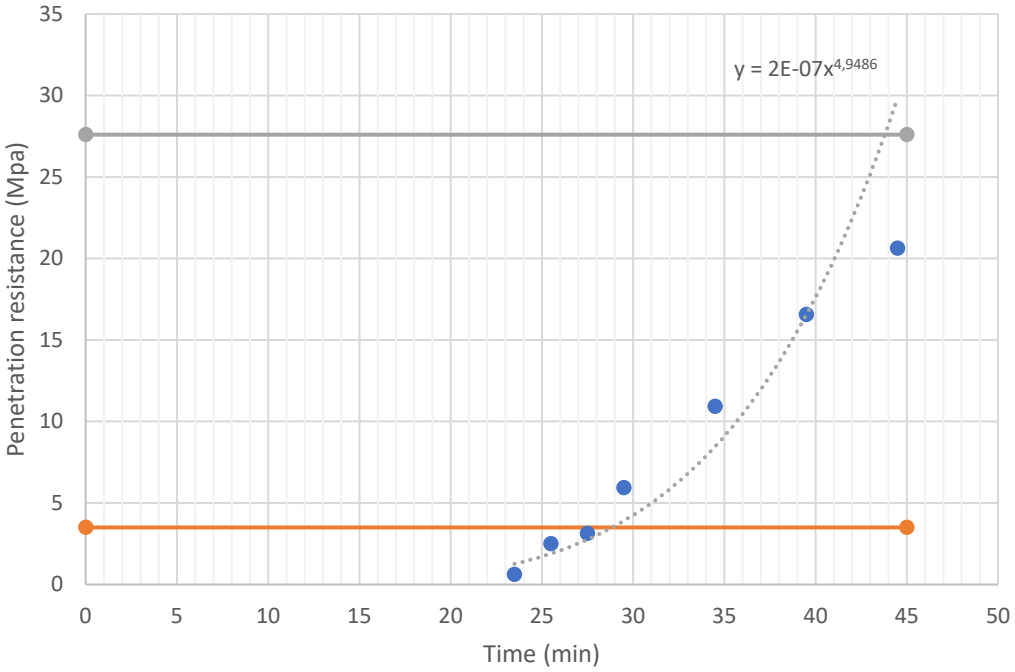
addition accelerator: 20'00"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
50	3,125	49	82
52	4,375		
57	7,5		
62	9,375		
67	12,5		
70	16,25		
75	20		
80	21,875		
85	33,125		

Mix D

Superplasticizer: 25 g	Accelerator: 32 g

Graph



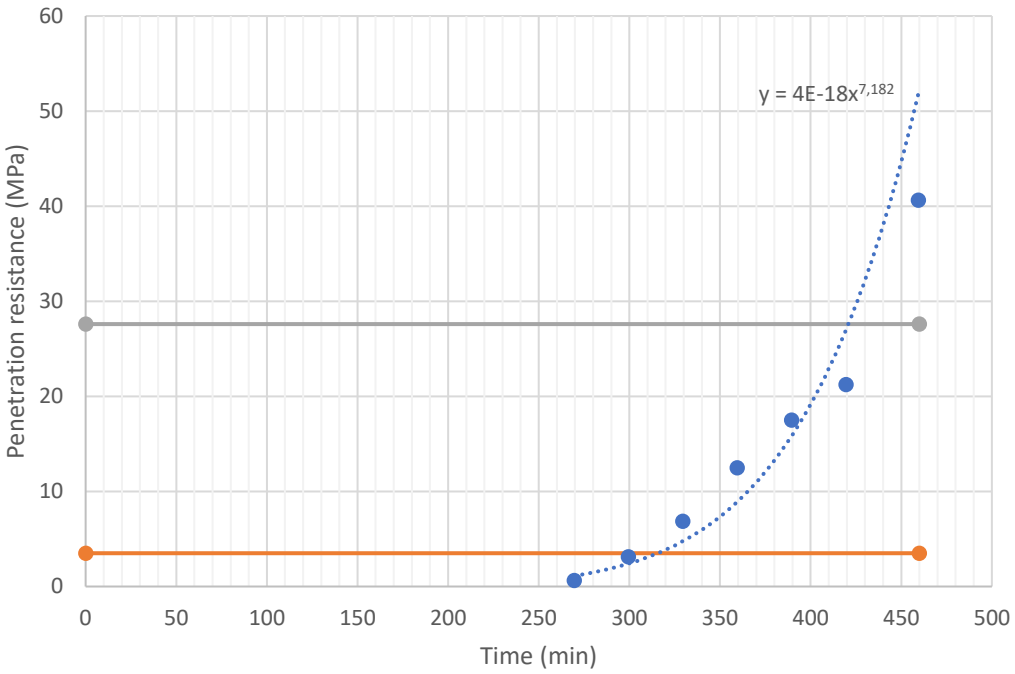
addition accelerator: 19'30"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
23,5	0,63	29	44
25,5	2,50		
27,5	3,13		
29,5	5,94		
34,5	10,94		
39,5	16,56		
44,5	20,63		

Mix E

Superplasticizer: 30 g	Accelerator: 0 g

Graph



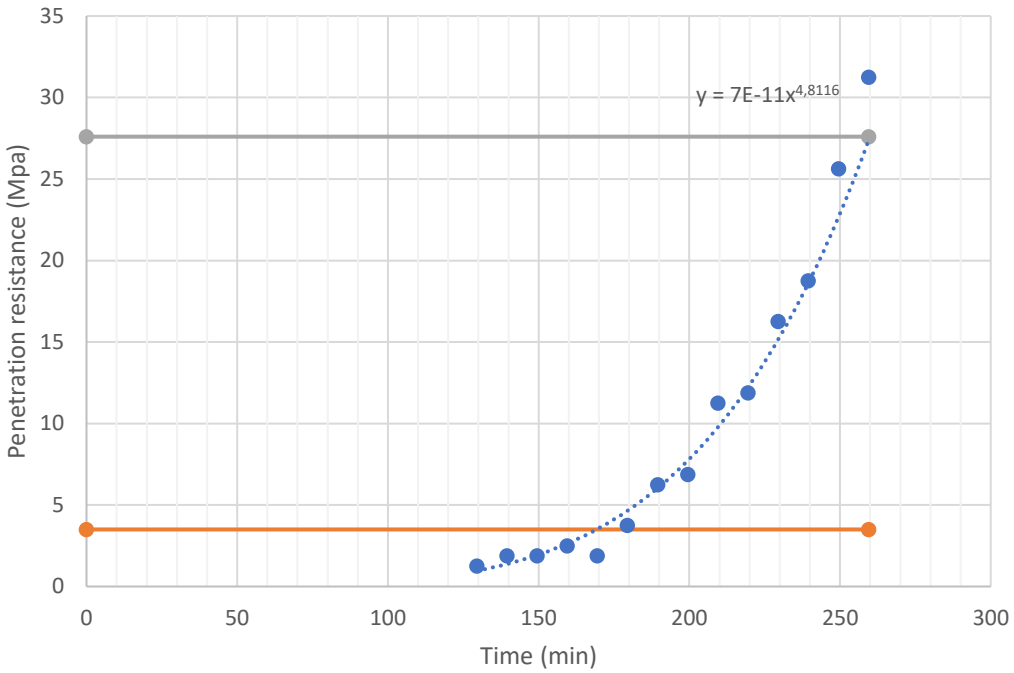
End of mixing: 19'30"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
269,5	0,625	316	421
299,5	3,125		
329,5	6,875		
359,5	12,5		
389,5	17,5		
419,5	21,25		
459,5	40,625		

Mix F

Superplasticizer: 30 g	Accelerator: 15 g

Graph



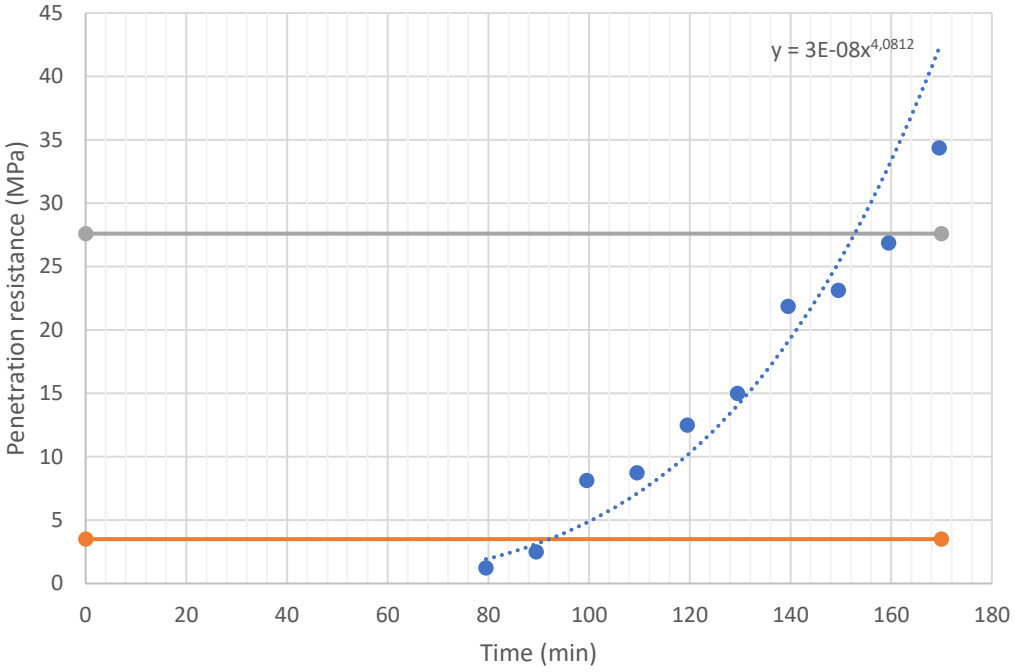
addition accelerator: 19'00"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
129,5	1,25	169	260
139,5	1,875		
149,5	1,875		
159,5	2,5		
169,5	1,875		
179,5	3,75		
189,5	6,25		
199,5	6,875		
209,5	11,25		
219,5	11,875		
229,5	16,25		
239,5	18,75		
249,5	25,625		
259,5	31,25		

Mix G

Superplasticizer: 30 g	Accelerator: 20 g

Graph



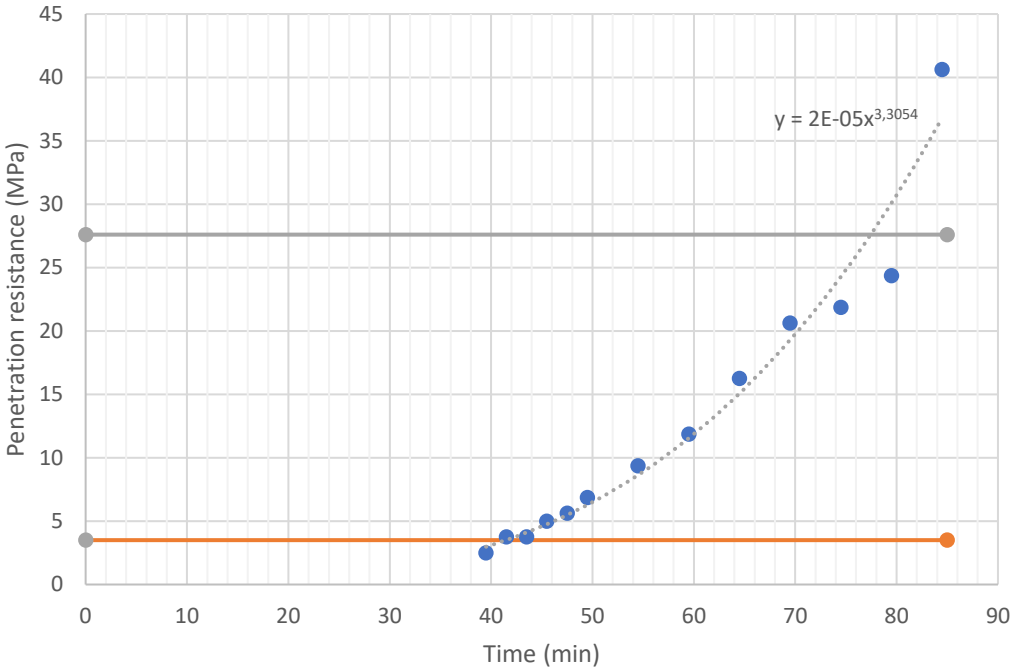
addition accelerator: 19'00"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
79,5	1,25	92	153
89,5	2,5		
99,5	8,125		
109,5	8,75		
119,5	12,5		
129,5	15		
139,5	21,875		
149,5	23,125		
159,5	26,875		
169,5	34,375		

Mix H

Superplasticizer: 30 g	Accelerator: 32 g

Graph



addition accelerator: 19'00"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
39,5	2,5	41	77
41,5	3,75		
43,5	3,75		
45,5	5		
47,5	5,625		
49,5	6,875		
54,5	9,375		
59,5	11,875		
64,5	16,25		
69,5	20,625		
74,5	21,875		
79,5	24,375		
84,5	40,625		

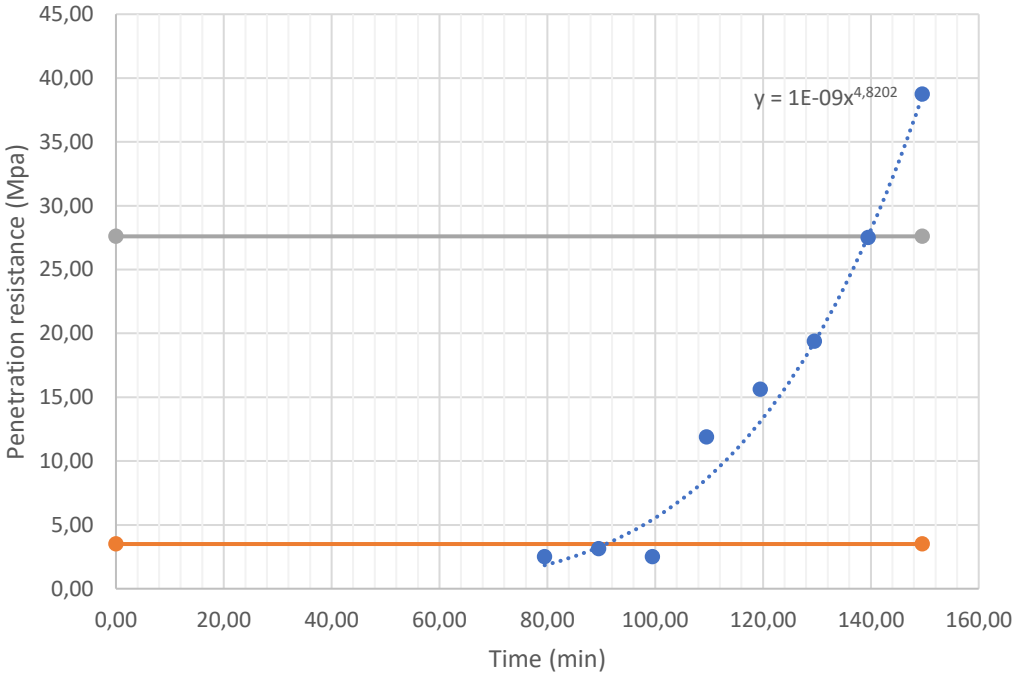
Reference – with fibers.

We obtain almost the same curve so we assume the results from setting tests without fibers to continue.

Setting test with fibers

Superplasticizer: 25 g	Accelerator: 15 g

Graph



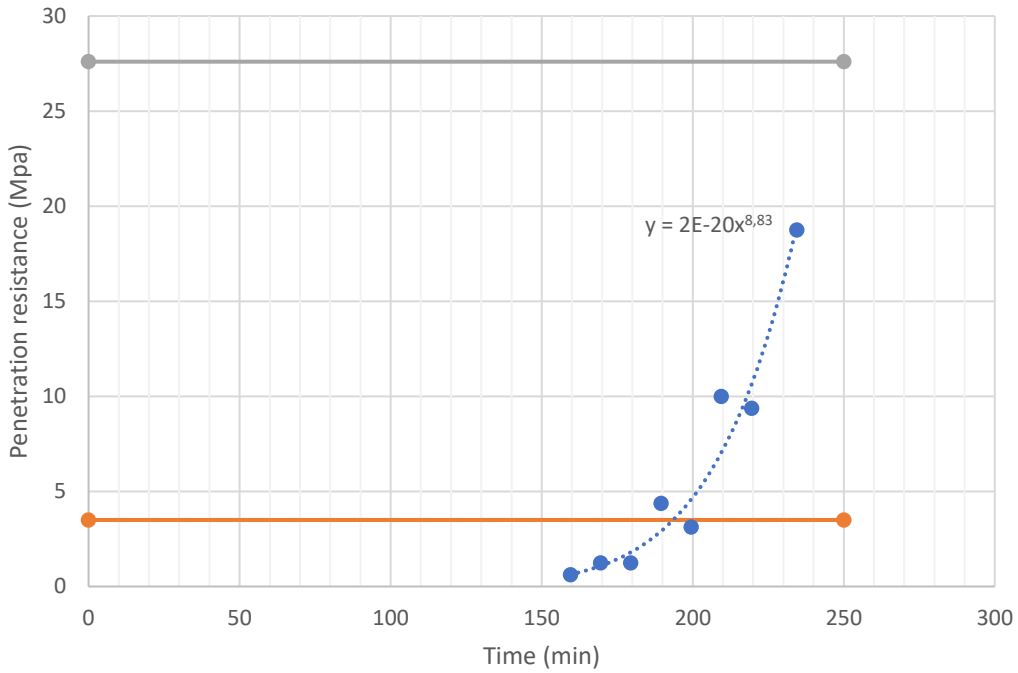
addition accelerator: 18'30"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
79,5	2,5	91	139
89,5	3,125		
99,5	2,5		
109,5	11,875		
119,5	15,625		
129,5	19,375		
139,5	27,5		
149,5	38,75		

Accelerator Nasil

Superplasticizer: 25 g	Accelerator: 11 g

Graph



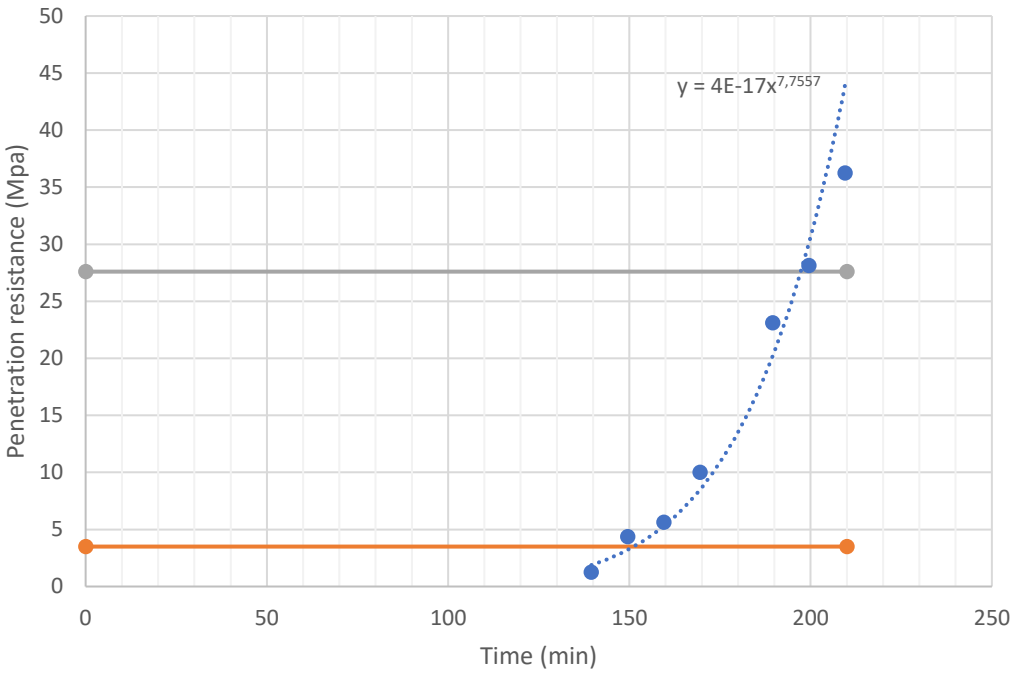
addition accelerator: 18'30"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
159,5	0,625	194	245
169,5	1,250		
179,5	1,250		
189,5	4,375		
199,5	3,125		
209,5	10,000		
219,5	9,375		
234,5	18,750		
239,5	25,000		
249,5	31,875		

Accelerator Nasil

Superplasticizer: 25 g	Accelerator: 20 g

Graph



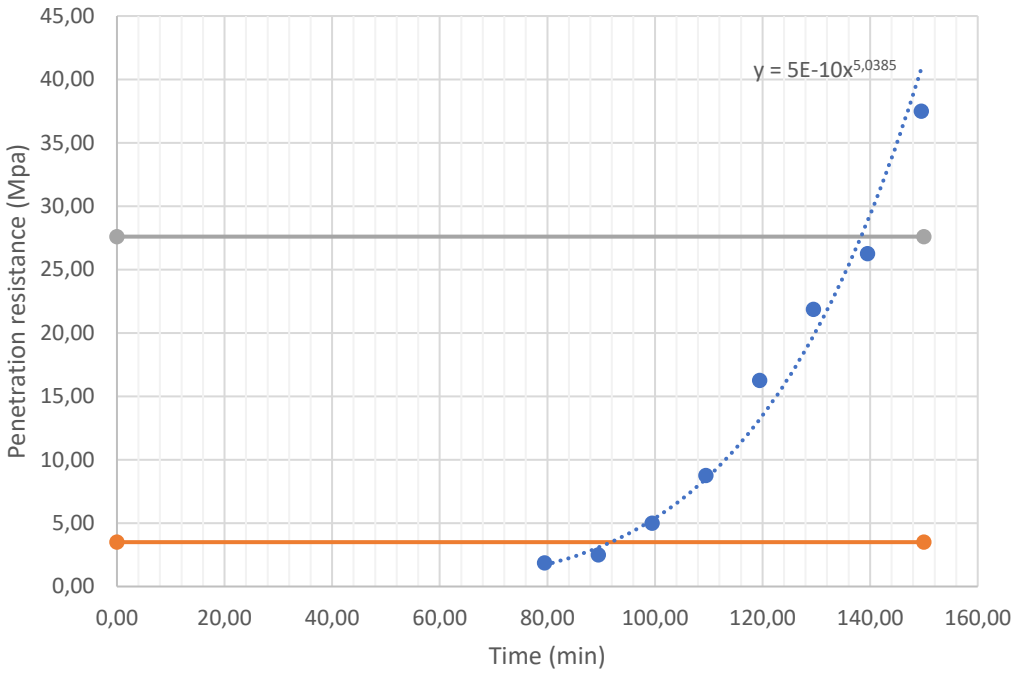
addition accelerator: 18'30"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
139,5	1,250	151	197
149,5	4,375		
159,5	5,625		
169,5	10,000		
189,5	23,125		
199,5	28,125		
209,5	36,250		

Accelerator Nasil

Superplasticizer: 25 g	Accelerator: 32 g

Graph



addition accelerator: 18'30"

Dot properties		Calculated result	
Time (min) After adding water	Penetration resistance (MPa)	Start setting time (min)	End setting time (min)
79,5	1,875	92	138
89,5	2,5		
99,5	5		
109,5	8,75		
119,5	16,25		
129,5	21,875		
139,5	26,25		
149,5	37,5		