Crack Evaluation in Double-Curved Concrete Elements

by

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A new architectural concept is being developed nowadays - free-form design, which allows the architects to add personality to a building through the shape itself. To sustain this development, the existing and available production techniques have to be combined with new technological innovations.

The flexible mould system uses the traditional technologies for pre-cast concrete fabrication to realize curved concrete elements. The flexible mould system relies on deformation of the concrete panels at very early age, when the tensile strength of the material has just started to develop and has not reached high values yet. Due to this physical deformation and the forced strains thus created in the material, a crack pattern can be formed on the surface of the element. The current research provides a quantitative and qualitative analysis of the cracks formed due to physical deformation. A range of influencing parameters were considered in the research: deformation time, radius of deformation, thickness of the elements and water/cement ratios. Also two alternative materials were analyzed and evaluated as potential replacements for the traditional concrete mixture.

The results of the current research showed that fabrication of double-curved elements by using a flexible mould system can be realized without affecting considerably the concrete's microscopic structure. A list of recommendations is provided as a result of the current thesis for the parties which in the future will be potentially involved in designing and manufacturing double-curved concrete elements.

The double-curved concrete elements promise to bring a significant amount of flexibility in the next generation of architectural entities.

Sergiu Troian
Delft, September 2014
Contents

Preface iii

Table of Contents vi

1 Introduction 1
  1.1 Free-Form Architecture ........................................... 1
  1.2 Double-curved concrete elements .................................. 2
  1.3 Potential Applications for Double-Curved Concrete Elements ........ 5
  1.4 Concrete Durability .................................................. 6
  1.5 Concrete Cracking .................................................... 9
  1.6 Current Research .................................................... 12

2 Methodology and Research 15
  2.1 Introduction ......................................................... 15
  2.2 Pilot Test ................................................................... 16
    2.2.1 Objectives .......................................................... 16
    2.2.2 Mould and Mixture ................................................. 16
    2.2.3 Investigation Parameters .......................................... 18
    2.2.4 Casting and Specimen preparation ............................... 19
    2.2.5 Results and observations ......................................... 22
  2.3 Conclusions ............................................................. 28

3 Investigations and results 31
  3.1 Investigation Parameters ............................................. 31
  3.2 Sample Nomenclature .................................................. 34
  3.3 Water-cement ratio .................................................... 34
  3.4 Results of the Investigations ......................................... 35
    3.4.1 Radius of deformation ............................................. 36
    3.4.2 Panel thickness .................................................... 38
    3.4.3 Deformation time .................................................. 40
    3.4.4 Water/Cement Ratio ................................................. 42
  3.5 Validation of results .................................................. 44
    3.5.1 Non-deformed elements ............................................ 44
    3.5.2 Slump tests ........................................................ 45
  3.6 Applying models of chloride penetration and carbonation ............. 47
    3.6.1 Carbonation ........................................................ 47
    3.6.2 Chloride penetration ............................................... 49

4 Alternative Materials 51
  4.1 Introduction ............................................................. 51
  4.2 Wood Fiber Reinforced Concrete .................................... 51
    4.2.1 Literature Review .................................................. 51
    4.2.2 Testing ............................................................... 52
    4.2.3 Results ............................................................... 53
    4.2.4 Conclusions ........................................................ 55
  4.3 Strain Hardening Cementitious Composite ................................ 55
    4.3.1 Literature Review .................................................. 55
    4.3.2 Testing ............................................................... 56
    4.3.3 Results ............................................................... 57
    4.3.4 Conclusions ........................................................ 58
4.4 General Conclusions ...................................................... 59

5 Conclusions and Recommendations .............................. 61
  5.1 Interpretation of results ............................................. 61
  5.2 Recommendations .................................................. 65
    5.2.1 Architecture ..................................................... 65
    5.2.2 Engineering ..................................................... 65
    5.2.3 Manufacturing .................................................. 66
    5.2.4 Alternative Materials ........................................ 67
  5.3 Further Research ................................................... 67
  5.4 General Conclusions ............................................... 68

A Results of the main investigations ................................ 69

B Results of the Pilot Test ............................................. 75

C Slump tests results ................................................... 77

D Images of the investigation procedure ............................ 81

Bibliography ............................................................... 83
1.1. Free-Form Architecture

The term of “free-form architecture” is becoming more popular nowadays and is firmly striking new trends in modern building design [6]. As an entire philosophy, the architecture becomes more expressive than ever before. For centuries every architect was trying to make his design a masterpiece, an embodiment of his typology and symbolism. The personification of the buildings was performed through the details, like facade sculptural elements, interior or exterior paintings, or even mosaic glazing, and it was practically the only way the architect could somehow reproduce his message through a building (see Figure 1.1). Other characteristics of an edifice were more or less driven by a trend or a style. Today, thanks to this new developed concept of free-form design, the architect adds personality to a building through the shape itself. The modern and non-conformist designs hide in their forms message, personality and uniqueness. The shape of the building defines the architect.

Digital modeling and innovations in production techniques had probably the largest contribution to the development of free-form concepts in architecture. Digital modeling, which basically represents a combination between geometry and computational mathematics, was mostly used in the design and production of automotive and aerospace industries, and later brought and adjusted to the construction world. Due to a large number of differences between these industries, like aesthetics, scale or manufacturing techniques, the adaptation seems to be a rather complex task [23]. An important difference between the industries is that in building industry generally the designs are only built once, whereas e.g. automotive or industrial designs are manufactured in large series.

Designing a high-complexity shape building is based on trustful collaboration, by bringing together the architects, engineers and clients from the early phases of the design process [30]. Sharing experience and knowledge through the entire production period will ensure a successful project implementation.

Developing a free-shaped surface is the first step in the design. The complex part is to make this surface realizable and feasible. In order to be produced, the shape has to be divided in panels or sections of rational sizes - a process called rationalization of the surfaces. A more complex surface will result in a more complex rationalization, a larger number of non-similar panels, complicated structural connections and details. All these combined will increase the complexity of the production and installation processes, which will come in the end to very high costs. That is why the collaboration between different specialists is very important.

Conceptually, free-form architecture developed considerably, especially with the implication of the students around the world in enhancing techniques of designing free-form buildings. This develop-
1.2. Double-curved concrete elements

Numerous materials were used along the centuries to create free-form architecture. Even the cupolas or arches used in medieval churches are examples of free-form architecture. Usually they were built from mud or wood, combined with bricks or stones. Nowadays, the architects use different materials for free-form designs, from the classical solutions such as wood, to modern plastic composites such as polyester.

Wood has always been considered a flexible material, and its limits were never fully discovered. Traditionally, laminated timber was used as the main scaffolding and formwork material for the early curved shell structures [12]. Later more innovative projects were designed, one of them being built on the Campus of the Saarland University by the School of Architecture. As result of a collaborative research project, a bionic inspired wooden shell was created (see Figure 1.2a).

Other material which was often used to create free-form buildings is glass. In most of the cases the secret was to place together planar elements within free-form structures, so that only the impression of a curved shape was created. However today already numerous designs have been performed were the glass panels themselves are designed in wavy or curvy shapes. One example would be the Emporia shopping pavilion in Malmo, Sweden (see Figure 1.2b). The Swedish architects from Whinardhs managed to find a perfect link between modernism and rectangular classic shapes of the existing buildings in the neighborhood. The design emphasizes the main entrance of the building with a curved glass roof, which besides its unique appearance has the role to bring light into the entrance courtyard. Another recent example of modern structure where glass was used in irregular shapes is the “Fondation Louis Vuitton pour la creation” exhibition center, which is currently under construction. The pavilion
1. Introduction

(a) Wooden Shell, Saarland University
(source: aasarchitecture.com)

(b) Emporia Shopping Centre, Malmo, Sweden
(source: fotoothing.com)

(c) Bus station - Amazing Whale Jaw
(source: e-architect.co.uk)

(d) Heydar Aliyev Cultural Centre, Baku, Azerbaijan
(source: archdaily.com)

Figure 1.2: Examples of free-form architecture

is a project signed by Gehry Projects and represents a multitude of functions as auditoriums and presentation galleries integrated within a complex-shaped envelope. The envelope is formed of different layers of glass double-curved elements [35].

Another example of free-form architecture is the bus station designed by Oscar Niemeyer - The Amazing Whale Jaw (see Figure 1.2c). The structure is entirely made of polyester and is considered to be the largest structure made of synthetic material. It is a perfect representation of the modern materials’ technology. Plastic materials are also often used as CNC-milled formwork for materials as concrete. An example is the Spencer Dock Bridge in Dublin.

Heydar Aliyev Cultural Center from Baku, Azerbaijan (see Figure 1.2d) is definitely considered to be a revolutionary design in modern architecture. With its uniquely fluid shape it became one of the most known symbols of free-form architecture. Zaha Hadid, the author of this masterpiece, is also the first woman to receive the Pritzker prize in Architecture. The building represents numerous glass reinforced concrete panels which shape undulated layers, embodying modernism and traditional Islamic architecture.

Considering the different materials in the projects mentioned above, it is hard to state which one of them is the most representative for the free-form architecture concept. Clearly the concrete has several benefits in comparison to wood, glass or polyester. By using concrete the architects can benefit from the material’s durability, smooth finishing, texture, color, slenderness and strength [27]. These
characteristics can be very important considering the complexity of the free-form structures. Also, by using concrete the architect can create customized appearances, by adding pigments or by changing the type of aggregate. Strong concrete structures can be created using the high performance mixtures available, e.g. UHPC (Ultra High Performance Concrete) or SCC (Self Consolidating Concrete).

Creating free-form architecture using concrete is not imminently simple, especially considering double-curved shapes. There are several technologies which can be used to create double-curved concrete elements. Among the most popular ones can be mentioned the timber formworks, steel formworks, CNC milling - which designs moulds from materials like foam, wood or soft metals, fabric formwork with air pressure. All these methods would result in high labour costs of formwork, mainly because each part (panel) of the free-form surface will have to be cast in a separate mould [28]. Mass production of customized double-curved free-form elements is generally possible only by using a flexible mould system, which represents an adjustable formwork of an elastic material that can be shaped in any curved surface by the use of pistons, actuators or the like [10]. The first mentioning of a flexible mould system dates from the 1960’s, when the famous architect Renzo Piano designed deformed plastic cladding elements, using a pneumatic formwork [22]. A similar installation was developed by Vollers, but much later, in 2004 [37]. The new flexible mould was already formed of a computer driven set of actuators, which by changing their position could form a curved surface on top.

The advantages of a flexible mould system are obvious. In some free-form architecture designs, after the rationalization of the curved surface, it is hard to find repetition in elements. That would assume that every element has to be produced using a different set of moulds. The flexible mould system however, can be fully reused and readjusted to a new different shape. The basic working principle of the deformation mould is presented in Figure 1.3.

The concrete mixture is poured into the mould while this is set to horizontal position. After a certain time span, the mould is deformed, together with the mixture on it. Then, after approximately 24 hrs the element can be demoulded and prepared for mounting. Deforming the concrete paste is strongly based on the rheological characteristics of the mixture. Knowing these characteristics will allow the manufacturer to:

✓ evaluate and approximate the correct deformation time;

✓ counteract the movement of the mixture under its slope, so that the mixture stays uniformly distributed on the deformed mould;

1Double-curved shape by definition represents a non-developable surface curved in two different directions
✓ prevent crack formation on the surface of the panel during the physical deformation.

The results of numerous investigations performed regarding the flexible mould system show that the system can be conceptually used for the production of double-curved concrete elements, even though the installation needs technical improvements and adjustments.

1.3. Potential Applications for Double-Curved Concrete Elements
The application of DCCE (double-curved concrete elements) is various. Koen Huyghe and Arnoud Schoofs presented the multitude of possible destinations where this construction technology can be applied [11].

In Figure 1.4 two main categories for potential destinations are presented: structurally performing elements and non-structurally performing elements.

Structurally performing elements are construction elements which are designed to carry loads others than the dead load (self load). Among the structurally performing elements are the building elements, as:

- **roof elements** - the case when the roof is designed to have a double-curved shape. Loads beside dead load have to be considered, as live load, snow load, temperature variation etc;

- **sandwich constructions** - when the DCCE is a part of a sandwich construction and has to interact with other layers to assure structural stability;

- **stay-in-place formwork** - part of the casting formwork, which will help in realizing complex double-curved shapes for floors or roof constructions. The double-curved elements in this case will play the role of stay-in-place form work and will have to sustain the load of a new concrete layer cast on top.

Another type of structurally performing elements are the infrastructural elements:

- **construction of bridges** - elements can be used as construction modules or parts of a lost formwork system;
→ *noise reduction barriers* - the double-curved concrete elements would replace the sound reflecting or absorbing barriers. These constructions are used to protect the living areas from the noise propagated by highways or railways.

The second basic type of DCCEs are the non-structurally performing elements, which include the facade cladding panels or interior cladding panels:

→ *facade panels* - panels which cover the exterior facade of a construction mostly as architectural elements; are carried by a secondary construction. In this case the double-curved concrete panels are exposed to exterior climate conditions and major durability issues of concrete have to be considered;

→ *interior panels* - the panels are placed in the interior of a building or structure, as part of the interior design. They generally are not load bearing and not exposed to damage mechanisms, thus easy to be designed, built and maintained.

### 1.4. Concrete Durability

Concrete durability represents the capacity of a concrete element to resist weather conditions and chemical attacks. Concrete durability is directly related to application, exposure conditions, quality of the material, quality of the construction and quality of the design [2]. That is why it is important to address the durability issue already in the design phase of any project. Considering the large variation of different applications for double-curved concrete elements, the durability is a primordial issue which has to be addressed if the technology is to be implemented.

An important characteristic for the durability of concrete structures is the exposure conditions, which basically reflect the position of the concrete element and its potential deterioration mechanisms. A classification of exposure conditions has been indexed in EN 206, and is presented in Figure 1.5.

Considering the classes presented in Figure 1.5 above, it can be concluded that the application of the double-curved elements for certain projects or designs is crucial in determining the durability issues of the future structure. Considering that DCCEs can be used for exterior facade cladding, even the most aggressive environmental conditions have to be considered as design conditions, where the panels could be exposed to airborne salts, freeze/thaw conditions or, in exceptional circumstances, even to chemical attacks.

**Damage mechanisms**

There are numerous damage mechanisms that have to be considered in the design phase of concrete structures. These mechanisms can affect not only the physical appearance of the structure, but they can also jeopardize the structural stability of an element or even the entire construction. Some of the most common deterioration mechanisms are presented below:

→ ASR - Alkali Silica Reaction

The ASR represents the chemical formation of a gel-like product in the structure of the concrete, as a result of the chemical reactions between reactive silica present in the aggregates of the concrete (stone, gravel or sand) and the alkaline solution present in the pores of the concrete (the pore water). The gel created has high affinity for moisture and tends to absorb any of the surrounding water. As a result, expansion of the gel occurs, which causes internal tension in the
1. Introduction

Concrete and results in cracking. The gel formation usually occurs in two phases:

1. **Alkali + reactive silica = alkali-silica gel;**
2. **Alkali-silica gel + moisture = expansion.**

Even if ASR is not a very common degradation mechanism, it is important to take appropriate precautions before the concrete is being placed on site, in order to avoid it. By precautions is meant that the materials of the mixture have to be investigated and evaluated in advance [9].

→ Freeze/Thaw

Another important and more common degradation mechanism is freezing and thawing. The basic principle of this mechanism relies on the fact that when physical water present within the pores of the concrete micro-structure freezes, it increases its volume by approximately 9%. As a result, internal tension is created and the hardened concrete mixture tends to crack. If the cracks appear close enough to the surface, they allow external moisture penetrate into the concrete mass again, this time in larger quantities, and repeat the same cycle. That is why an important characteristic of concrete in this particular case is the number of freezing cycles it is exposed to and material permeability. Another form of cracking which is formed due to freezing and thawing is D-Cracking. This type of deterioration is characteristic to pavements or to facade panels which have direct content with the ground soil. When the soil accumulates water, the aggregates within the concrete mass become quickly saturated. As a result, during freezing cycles expansion occurs. Since the pavements usually represent planar thin elements, the cracks can travel all the way up to the exterior surface and can be easily observed.

<table>
<thead>
<tr>
<th>Category Description</th>
<th>Class</th>
<th>Description of Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 No risk for corrosion or attack</td>
<td>XC0</td>
<td>No reinforcement or embedded metal; all types of exposure except freeze/thaw, abrasion or chemical attack</td>
</tr>
<tr>
<td>2 Corrosion induced by carbonation</td>
<td>XC1</td>
<td>Dry or permanently wet</td>
</tr>
<tr>
<td>2 Corrosion induced by carbonation</td>
<td>XC2</td>
<td>Wet, rarely dry</td>
</tr>
<tr>
<td>2 Corrosion induced by carbonation</td>
<td>XC3</td>
<td>Moderate humidity</td>
</tr>
<tr>
<td>2 Corrosion induced by carbonation</td>
<td>XC4</td>
<td>Cyclic, wet and dry</td>
</tr>
<tr>
<td>3 Corrosion induced by chlorides</td>
<td>XD1</td>
<td>Moderate humidity</td>
</tr>
<tr>
<td>3 Corrosion induced by chlorides</td>
<td>XD2</td>
<td>Wet, rarely dry</td>
</tr>
<tr>
<td>3 Corrosion induced by chlorides</td>
<td>XD3</td>
<td>Cyclic, wet and dry</td>
</tr>
<tr>
<td>4 Corrosion induced by chlorides</td>
<td>XF1</td>
<td>Moderate saturation, no de-icing agent</td>
</tr>
<tr>
<td>4 Corrosion induced by chlorides</td>
<td>XF2</td>
<td>Moderate saturation, with de-icing agent</td>
</tr>
<tr>
<td>4 Corrosion induced by chlorides</td>
<td>XF3</td>
<td>High saturation, no de-icing agent</td>
</tr>
<tr>
<td>4 Corrosion induced by chlorides</td>
<td>XF4</td>
<td>High saturation, with de-icing agent</td>
</tr>
<tr>
<td>5 Freeze/Thaw Attack</td>
<td>XA1</td>
<td>Slightly aggressive</td>
</tr>
<tr>
<td>5 Freeze/Thaw Attack</td>
<td>XA2</td>
<td>Moderately aggressive</td>
</tr>
<tr>
<td>5 Freeze/Thaw Attack</td>
<td>XA3</td>
<td>Highly aggressive</td>
</tr>
<tr>
<td>6 Chemical Attack</td>
<td>XA1</td>
<td>Slightly aggressive</td>
</tr>
<tr>
<td>6 Chemical Attack</td>
<td>XA2</td>
<td>Moderately aggressive</td>
</tr>
<tr>
<td>6 Chemical Attack</td>
<td>XA3</td>
<td>Highly aggressive</td>
</tr>
</tbody>
</table>

Figure 1.5: Exposure conditions of concrete (source: EN 206).
Another degradation mechanism which has to be considered regarding the application of double-curved concrete elements is frost salt scaling. The frost salt scaling process was extensively studied. Among the first mechanisms which were investigated and considered as an explanation for frost salt scaling was glue-spall, proposed by Valenza and Scherer [34]. The main idea behind this explanation is that the ice layer formed on the surface of the concrete, which is shrinking because of further cooling, will pass its tensile stresses to the concrete surface, due to the strong (glue) connection formed between the ice layer and the concrete porous structure. Different investigations were performed to evaluate the impact of salt concentration and concrete types. O. Copuroglu and E. Schlangen [3] developed a numerical model of deterioration in cement based materials, analyzing different parameters. The authors investigated how ice layer thickness, type of cement material or external salt concentration will influence the frost salt scaling and how this influence could be diagnosed and modeled.

**Reinforcement Corrosion**

Reinforcement corrosion is the most often occurring damage mechanism within existing concrete structures. As a result of corrosion processes, an oxidation layer is formed on the surface of the steel reinforcement elements. The oxidation layer constantly increases in volume, expands, and the concrete mass is cracked as a result of internal tensions. Since the corrosion is a continuous process, the oxidation layer constantly increases in size and can lead to large cracks or even spalling. Comparing to the previous deterioration mechanisms presented in the current chapter, reinforcement corrosion is the one with the highest risk to cause structural failure, in case that reinforcement elements become corroded enough to lose their strength characteristics. Permeability of the concrete is a major feature defining the risk to reinforcement corrosion. In normal conditions, the reinforcement steel is passivated with an oxide layer, which acts as a protective shield to corrosion. However, the passive layer can be destroyed when the alkalinity of the concrete is reduced or when chloride concentration is increased. Chlorides can come from sea-water salts (coastal regions) or de-icing salts. Thus, the presence of cracks and pores in concrete will have an important impact on the corrosion process. [21]
→ **Efflorescence**

Efflorescence is a white coating which is formed on the external face of the wall or other planar elements. The efflorescence is a result of soluble salt migration within the pore structure of the concrete or masonry elements. Salt migration is sustained by hydro-static movement, and deposits on the exterior side of the element. Most common product of efflorescence is the coating only, but if the deposit of crystals occurs within the concrete structure and not forthwith on the exterior surface, their expansion can cause the concrete to spall. [26]

![Examples of degradation mechanisms](#)

The current paragraph presents the most common degradation mechanisms. Degradation is almost inevitable in concrete materials, and that is why it is very important to consider and evaluate the risks of using certain materials or technologies.

### 1.5. Concrete Cracking

**Influence of cracks on deterioration mechanisms**

Cracking in concrete is a common reason for concerning. Appearance of cracks does not define only a structural issue, as it would be expected, but an integrity one as well. As mentioned above to the previous paragraph, it can be observed that cracks are strongly linked to damage mechanisms. Considering the most common deterioration mechanisms, it is a known fact that cracks would only amplify the degradation effect of these mechanisms.

Regarding Alkali Silica Reaction, the impact of the cracks and porosity can be high. A more porous
Concrete element (having frequent and large cracks) can absorb more water, which would lead to the expansion of ASR gel (the product of the alkali silica reactions). A denser concrete would limit the amount of water absorbed into the pores, this way limiting the expansion capacities of the gel. As a result no serious concrete damage would be created [38].

Similarities can be found between the impact of cracks on ASR and on freezing/thawing deterioration mechanisms. Larger cracks on the surface of concrete would allow the moisture penetrate the concrete mass, where it can freeze because of low temperatures. The absorbed water will tend to increase its volume during freezing, thus enlarging the cracks. As a result, after several cycles freezing could lead to spalling.

Considering corrosion of steel reinforcement, numerous researches have been performed evaluating the impact of cracks on durability of reinforced concrete. Otieno, Alexander and Beushausen concluded in their research article that the corrosion rate is sensitive to crack width, concrete quality (binder type, w/b ration, etc.) and crack reopening [20]. Also, they observed that the increase in corrosion rate was higher if the specimen was actively corroding prior to the crack reopening. This meaning that even if cracks are not the only reason for corrosion process to start, they can have a serious impact on an element’s physical and structural integrity.

Another similar research was performed by Jaffer and Hansson [13], where they evaluated how the cracks created by different loading conditions can affect the corrosion process. They observed that the corrosion process started mostly in the places where the cracks were situated. This means that cracks have the most important contribution to steel corrosion of reinforced concrete. Also, it was proven that there is a strong correlation between the sizes of the cracks and the diffusion rate of chloride in the concrete mass, in case of chloride exposure. The results of the research performed by Djerbi et al. [5] showed that the chloride diffusion coefficient increased with the increase of the crack width. The investigation was performed on ordinary concrete and two recipes of high performance concrete. The results also showed that if the cracks are larger in width than 80 μm, then the diffusion rate becomes constant.

Types of cracks. Classifications

Cracks in concrete can be formed as a result of a multitude of effects. These effects can be classified in two main groups: load cracks and non-load cracks. The load cracks represent the cracks formed in concrete as a result of excessive live-loading, structural miscalculations or unfortunate accidents (accidental loads). The non-load cracks can have different origins. Among the most common cracks found in concrete are the following:

- **shrinkage cracking** - formed as result of dehydration of the concrete mixture in the post-cast period, either through evaporation or through chemical binding of water, resulting in volume reduction;

- **rust cracking** - in reinforced concrete. They are formed as a result of the expansion of the oxide layer, the product of corrosion;

- **tension cracking** - cracks formed due to internal tension, a result of different chemical reactions (ASR, sulfate attack). The products of these chemical reactions tend to increase their volumes, thus creating excessive tension in the structure of the concrete, leading to cracking or even spalling;

- **freeze/thaw** - when the water found in concrete will increase in volume due to freezing, this leading to formation of cracks or spalling;
→ **thermally-induced cracking** - which is formed as a result of stresses produced by temperature changes.

Also, cracks can be classified according to their shape and orientation. Different types of cracks are known, such as pattern cracking, D-cracking, hairline cracking or checking. These different types of cracks are very important to be considered during evaluation of the cracking process and assuming the possible reasons of these cracks to be formed.

Cracks can be classified according to their sizes: depth and width. For the current research the following characterization was used:

Crack width:

→ micro cracks $< 0.01$ mm (negligible in size);
→ fine cracks $< 0.1$ mm (deterioration mechanisms);
→ coarse cracks $< 25$ mm (depending on frequency and position can have structural impact);
→ structural cracks $> 25$ mm (structural instability).

Crack depth:

For the current research three different levels of crack depth were considered.

→ level I $< 0.1$ mm;
→ level II $< 1$ mm;
→ level III $> 1$ mm;
→ level IV $> 5$ mm;

The crack classification presented in the current paragraph was elaborated by the author considering various sources ([7], [31] and others) and especially analyzing the results obtained during the Pilot Tests (see Section 2.2). This classification was also used in the evaluation process of the current research and in concluding the output results.

**Cracks in Double-curved concrete elements**

Analyzing the technology of production of double-curved concrete elements it is understandable that due to the elongation of the exterior surface of a DCCE in the deformation process, there is a possibility that a pattern of cracks will be formed. The crack formation depends on many factors as the degree of deformation (radius), material characteristics (mix design, w/c), time of deformation and other. Cracks in DCCEs have a technological origin and definitely have to be considered in service life evaluation. The quantitative and qualitative analysis of the cracks formed due to physical deformation using the flexible mould system is the subject of the current research. The analysis was performed considering various technological, structural and architectural parameters.
1.6. Current Research

Background

As presented in Figure 1.3 using the flexible mould system would result in an elongation of the external (top) surface of the concrete element. This elongation comes with a high probability that it will cause the appearance of cracks. As presented above, cracks can have a serious impact on the durability of the concrete elements and can enhance the effect of the deterioration mechanisms. That is why it is very important to evaluate and analyze the cracks formed due to physical deformation. Since the technology of casting double-curved concrete elements using the flexible mould system is a relatively new concept, no investigations were performed so far about the quantitative or qualitative analysis of the cracks formed during the deformation process. Also, the cracks are formed on the concrete surface at very early age, when the tensile strength is still in the raising phase, this limiting again the number of similar researches.

One detailed research was performed by Roel Schipper [28] as part of his PhD thesis. The main objective of his research was to develop and improve the flexible mould method for the manufacture of double-curved concrete elements. In order to support this development in modern architecture, Schipper focused on combining existing manufacturing techniques with a new simplified production process, which has a great industrial potential. In the experimental part of his research, the author tested numerous mix designs and investigated a large variety of parameters which, according to his assumptions, could influence the product of the flexible mould system. Among the variables which were investigated during his research were curvature, deformation time, deformation speed, thickness of the panels, concrete mix design and others. The aim of the experiments was to obtain a model for successful deformation varying the parameters mentioned. A successful deformation in author’s opinion meant no visible cracks after deformation, constant element thickness (height), high geometrical accuracy, smooth surfaces, homogeneous aggregate distribution and others. The cracking formed due to physical deformation during the production of double-curved concrete panels were not quantified. However, the author registered the results of every test and visually evaluated the cracking pattern formed, if there was one. The cracks sizes and patterns were considered as reference for quality of the final product and could give an impression of the viscosity or yield strength of the mixture in the moment of physical deformation. However, no numerical interpretation was performed and no correlation was made between the frequency or sizes of the cracks and the main parameters of the research.

Another important research was performed by Dao et al. [4], when the authors investigated the tensile properties of very early-age concrete. The investigations on fresh concrete mixture are not frequent, since there is more interest on the final product characteristics. However, for the flexible mould system, it is very important to know the tensile properties of fresh concrete and its development at very early age. The authors had the aim to investigate namely the very early age concrete and they developed an installation with the help of which they could test fresh concrete mixtures. Also, as parameters the authors considered different values for water/cement ratio and recipes in general. The recipes they considered were representing the commercial structural concretes used at the moment of publication. Analyzing their results, the authors were able to conclude that concrete mixtures behave similar to typical quasi-brittle materials. Also, they observed that the tensile strength and Young’s modulus have small values in the first 3 hours and increase very rapidly afterwards. For the current research and investigations the results offered by Dao and his colleagues are very relevant, since they represent the main characteristics of the fresh concrete mixtures and the development in time of this
These two researches described in the paragraph above represent the most relevant ones for the current investigation. The results and conclusions presented in the paper and the PhD report define the main characteristics of the concrete mixture at very early age and have major importance for preparing and planning the investigation process for the current research. Using these references, assumptions were made regarding the behavior of the concrete mixture under physical deformation and as a result the research parameters were defined, which will be explained in the Pilot Test section, at page 20.

**Research objectives**

Considering the fact that free-form architecture is striving new trends in modern building design, it is important to find feasible and real solutions to realize and sustain these trends. It is of utmost importance to build connecting bridges between the new revolutionary architectural concepts and the contemporary engineering and construction realities, to find real and feasible solutions for complex and innovative architectural challenges. The flexible mould system represents one of these solutions and it can firmly support modern challenging architecture. Using the flexible mould, new futuristic shapes can be created through the available production technologies of precast concrete elements. The current research comes as an addition to the technological solution. The main target of this research is to realize a list of technological and architectural recommendations for the production of double-curved concrete panels using the flexible mould system. The recommendations will indicate what are the technological, architectural and structural boundaries in designing double-curved concrete elements without any cracks which can affect the service life or the structural integrity of the elements.

Besides the designing recommendations the objectives of this research are:

- Investigate and quantify the cracking formed during the production of double-curved concrete elements;
- Evaluate the impact of various factors on the cracking size and pattern;
- Trace and estimate the impact of the cracks on the durability of the concrete elements;
- Explore and evaluate the performance of alternative concrete mixtures in terms of cracking (wooden reinforced concrete and strain hardening cementitious composite).

**Report Outline**

The objectives mentioned in the previous paragraph were achieved and are presented in the current report.

The report has been structured in five main chapters, as presented below:

**Chapter 1: Introduction**

It reflects the basic principles of the double-curved concrete elements and the flexible mould system. It also contains the literature review regarding cracking in concrete and deterioration mechanisms which can be influenced by cracking. Literature review represents the information background on which the research principles and targets were set. The introduction chapter also presents the main objectives and aimed results of the current research.

**Chapter 2: Methodology and Research**

This chapter describes the research strategy and investigation procedures. It also contains the results and conclusions of the pilot test, a phase of the research which was used as determinant ground.
for the main investigations. Based on the pilot test, the variables and factors for the main research investigations were selected.

**Chapter 3: Main Investigation and Results**

The chapter contains the description of the main investigation process. It describes the results and conclusions depicted form this research, and how they satisfy the presented objectives.

**Chapter 4: Alternative materials**

One of the aims of this research was to compare traditional concrete mixtures to the materials present on the market at the moment. This chapter explains the research conditions and parameters, and how the alternative materials perform in terms of cracking comparing to traditional concrete.

**Chapter 5: Conclusions and Discussions**

This chapter concludes the research and presents whether the objectives were fully accomplished or not. It also contains the list of designing recommendations which is considered as the main resultant product of the current research.
### Methodology and Research

#### 2.1. Introduction

As explained in the previous chapter, the aim of this research is to perform a quantitative and qualitative analysis of the cracking pattern formed due to physical deformation (bending) of double-curved concrete elements as part of the production process.

Considering that casting concrete elements using the flexible mould system is a relatively new production technology, similar researches have not been performed so far. That is why it was important to develop a research strategy before starting the investigation itself.

![Research Strategy](image)

**Literature Review**
- Flexible mould system;
- Double curved concrete elements;
- Degradation mechanisms;
- Cracking in concrete.

**Pilot Test**
- Design and build flexible mould;
- Casting and specimen preparation;
- Parameter evaluation;
- Increase practicability for the main research phase.

**Main Research**
- Design and build flexible mould;
- Casting and specimen preparation;
- Microscopic investigation;
- Quantitative and qualitative crack analysis;
- Data structuring.

**Alt. Materials**
- Research on WRC and SHCC;
- Perform similar casting sessions;
- Microscopic investigation;
- Quantitative and qualitative crack analysis;
- Data structuring.

**Conclusions and Recommendations**
- Interpretation of the results;
- Comments and discussions;
- List of recommendations;
- Further Research.

Figure 2.1: Research Strategy
2.2. Pilot Test

2.2.1. Objectives

The Pilot Test was named the investigation precursory to the main research phase and the primary objective of it would be to define and select the parameters and conditions for realization of the main investigation. The method of this first test was to analyze the crack pattern which theoretically would be formed on the concrete panel's surface due to physical deformation at very early age. Starting the main research immediately would result in hasty and erroneous conclusions, because the conditions and factors which would influence crack formation were only hypothetically assumed. Performing the pilot test at first would help in selecting the most important and relevant parameters which should be investigated. During the test, a series of concrete panels were cast and deformed into curved shapes, sectioned into small investigation samples and analyzed under the microscope. As a result a series of cracks was observed which could define the character of deformation and could be used as a foundation for further research study.

2.2.2. Mould and Mixture

The first step in the Pilot Experiment was to prepare the flexible mold system. The mold designed for the Pilot Test consists of two main components: the casting mold and the deformation mold. The
The flexible surface was built from polyether mattress foam (SG25 with specific weight 25 kg/m³), glued to copolyester sheets (Vivak). The inner surfaces of the foam segments were treated in advance with bi-component silicone rubber P58510 (Poly-Service in Nieuwerkerk a/d ijssel), to prevent the absorption of the cement paste. The aforementioned materials were selected in order to assure proper flexibility. The mold was designed to cast elements of 15 cm in length and 9 cm in width. Size was limited due to technological reasons and was selected to fit the concrete elements in the vacuum machine used later in specimen preparation. The casting surface was built out of 4 mm thick MDF and cut using a laser cutter, meaning that the shape and sizes were of high accuracy and precision. The same technology and materials were used to construct the deformation mold. The flexible surfaces were fixed to the casting surfaces and prepared for the casting session (see Figure 2.3).

Deformation mold was the construction designed to deform the very early aged concrete. It consists of 4 arc-shaped ribs, which represent the radius of curvature. The process of deformation was planned to be simple, in order to minimize the deformation duration\(^1\). Considering this, the mold was designed in such a way that it would be easy to use. The casting mold could be easily placed on top of the deformation mold, which was leading to a deformed flexible surface and would result in the deformation of the concrete element in one smooth movement (quick and easy).

The concrete mix design was not considered a parameter and was constant for all 10 specimens realized. The composition and ratios presented in Table 2.1. 25 L of final mixture were prepared.

The presented mixture was used earlier for larger panels, as part of another project.

---

\(^1\)Deforation duration represents the time needed to perform the actual deformation process, changing the element from flat to curved shape). It is important to mention that “deformation duration” and “deformation time” are two different aspects.
Table 2.1: Concrete mixture composition - per m$^3$

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass, kg</th>
<th>Component</th>
<th>Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 52.5 R</td>
<td>400</td>
<td>Sand 0.25-0.5 mm</td>
<td>128.6</td>
</tr>
<tr>
<td>Fly ash</td>
<td>160</td>
<td>Sand 0.5-1 mm</td>
<td>209</td>
</tr>
<tr>
<td>Super plasticizer Chryso Premia 196 25% (0.7%)</td>
<td>3.92</td>
<td>Sand 1-2 mm</td>
<td>289.4</td>
</tr>
<tr>
<td>Water</td>
<td>172</td>
<td>Sand 2-4 mm</td>
<td>369.8</td>
</tr>
<tr>
<td>Sand 0.125-0.25 mm</td>
<td>48.2</td>
<td>Gravel 4-8 mm</td>
<td>562.7</td>
</tr>
</tbody>
</table>

2.2.3. Investigation Parameters

For the Pilot Test two parameters was considered, which theoretically would influence the crack formation on the surface of physically deformed concrete.

One parameter investigated was the thickness of the cast panel. According to Huyghe and Schoofs [11], they examined together with Roel Schipper the relation between the elongation under curvature and the thickness of the element.

![Figure 2.4: Possible height-strain relation (source: Schipper 2014 [28]).](image)

According to the authors there can be a certain relation between the height\(^2\) of the panel and the maximum strain value, as presented in Figure 2.4. If $h_2 > h_1$, it is possible that $\varepsilon_{\text{max},1} < \varepsilon_{\text{max},2}$.

Therefore, two values were considered for the trial test. Panels were cast in heights of 25 and 50 mm. Using two different values for the thickness could explain how this parameter would influence the distribution pattern and the sizes of the cracks on the surface of the deformed concrete.

The second parameter considered important to be investigated was the deformation time. By

\(^2\)The height is also used to define the thickness of the panel (height of the section).
“deformation time” is meant the time span between the moment when water is added to the concrete mixture and the moment when the concrete is started to be physically deformed in a curved shape. According to Roel Schipper [28] the deformation time has to be an important research variable, and not only because of the strength development of the mixture, but also because deformation time is a part of the fabrication process and it should not negatively affect the performance of the entire production technology. The deformation time should be considered in the evaluation of the economical feasibility of the production process. The results of the research performed by Grunewald et al. [10] imply that if the deformation time exceeds 50 min, the concrete yield stress is so high that the deformability of the mixture is reduced considerably and the quality of the panel becomes unacceptable due to large visible cracks formed. In an experiment meant to evaluate the tensile stresses in very early age concrete, Dao et al. [4] suggests that the tensile stress starts to develop mostly after 90 min, and after 5 hrs it already reaches values of 100 kPa. However, it is important to consider that the results of the mentioned experiments are directly influenced by the concrete mixture recipe or water-cement ratio. Therefore, these results can be accounted as referential only.

For the Pilot Test 5 different deformation times were considered. The concrete panels were deformed at 30, 60, 90, 120 and 150 min after water was added to the mixture. The large time span between the first and the last value would assure that the tensile strength could develop high enough to create cracks during physical deformation. Also, it is important to mention that no steel or fiber reinforcement was applied during the Pilot Test session.

As a result 10 different elements were cast, considering the two different parameters presented:

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Deformation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mm</td>
<td>30min SP1</td>
</tr>
<tr>
<td></td>
<td>60min SP2</td>
</tr>
<tr>
<td></td>
<td>90min SP3</td>
</tr>
<tr>
<td></td>
<td>120min SP4</td>
</tr>
<tr>
<td></td>
<td>150min SP5</td>
</tr>
<tr>
<td>50 mm</td>
<td>30min SP6</td>
</tr>
<tr>
<td></td>
<td>60min SP7</td>
</tr>
<tr>
<td></td>
<td>90min SP8</td>
</tr>
<tr>
<td></td>
<td>120min SP9</td>
</tr>
<tr>
<td></td>
<td>150min SP10</td>
</tr>
</tbody>
</table>

Table 2.2: Name of the specimens according to considered parameters

2.2.4. Casting and Specimen preparation

The mixture

All the mixing materials were prepared before the mixing process started. For this Pilot Test the mixture recipe was not considered a parameter of investigation, however it’s importance was not neglected and considered while analyzing the observations in Section 2.2.5. The mixing process itself was performed using an ordinary free-fall mixer and according to the following program:

<table>
<thead>
<tr>
<th>Action</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing Aggregates + Cement + Fly-ash</td>
<td>30</td>
</tr>
<tr>
<td>Adding water (90%), mixing</td>
<td>60</td>
</tr>
<tr>
<td>Adding water (10%) + Superplasticizer, mixing</td>
<td>90</td>
</tr>
<tr>
<td>Scraping the interior surface of the mixer, mixing</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>210</strong></td>
</tr>
</tbody>
</table>

Table 2.3: Mixing Process

After the mixture was prepared, it was poured into the casting molds. It is important to mention that the amount of plasticizer was increased from 0.7% (Table 2.1) to 0.9%, in order to obtain a workable mixture. After the mixture was poured, the concrete surface treatment was avoided as

3The workability of the mixture was lower than expected mostly because of its adherence to the interior surface of the mixer. In order to increase the workability the amount of plasticizer was increased from 0.7% to 0.9%
much as possible, in order to be sure that the surface was not physically damaged during the casting, which could finally lead to erroneous investigation results. The only surface treatment was to limit the evaporation using plastic foil, which was placed to cover the cast elements, but not touching the concrete surface.

The time of casting was recorded and every 30 min after that, each of the samples was deformed according to the parameters presented in Table 2.2. Meanwhile slump tests were performed as well, in order to analyze the workability of the mixture at different time periods.
### Specimen Preparation

After the casting was performed, the specimens were left to harden under normal room conditions. After 7 days two concrete elements were demolded and prepared for further investigations. The specimens selected were SP2 (25 mm thick, 60 min deformation time) and SP3 (25 mm thick, 90 min deformation time). After 20 days another 2 specimens were demoulded: SP7 (50 mm thick, 60 min deformation time) and SP8 (50 mm thick, 90 min deformation time). The 4 elements were selected because there was a visual difference between the crack patterns on each of them. Different crack patterns referring to different parameters could define a certain behavior in crack formation. As a result the elements were ready for the next step of sample preparation - epoxy impregnation.

The concrete specimens were placed one by one in a vacuum installation. Under vacuum conditions the elements were impregnated with a mix of liquid epoxy resin and hardener. In result the elements were fully impregnated with the chemical mixture. The aim of the impregnation process is to fill the micro cracks and micro pores of the element with the epoxy mixture, which has a high fluorescence under UV light. As the mixture hardens within the concrete element, it becomes easier to investigate the material’s micro structure. After the elements were impregnated, the characteristic sections of the elements were selected and collected by cutting. The surfaces of the sections which were to be investigated were grinded and polished for a higher quality of the collected images. Images with the characteristic steps of the impregnation process are presented in Figure 2.7.

![Specimen impregnation](image1)
![Sample extraction](image2)
![Micro investigation - UV](image3)

Figure 2.7: Specimen preparation

After the specimens were fully prepared, they were analyzed using a stereo microscope. This allowed to inspect visually the concrete samples and investigate the micro-cracking on the top surface of the concrete element. The images collected from the microscope were realized in two different magnifications - 6.3x and 12.5x, this helping to measure more accurately cracks of different sizes. Using the stereo microscope with a UV light filter helped in increasing the precision of the measurements collected, since under UV light the epoxy impregnated spots become fluorescent and clearly visible. The samples investigated were collected from the original concrete panels cast and demolded as explained before. A middle section was extracted from the concrete panels, which later was split in two parts, by using a diamond saw, with a thickness of 3 mm. The split surfaces were grinded, polished and put under microscope for further investigation. Figure 2.8 represents the sample extraction process.

It was expected that the samples which were extracted from the same specimen would have similar characteristics, and the images analyzed would have to be mirrored. However, in practice, that is not the case. Part of the concrete specimens was removed and lost during cutting, other part was lost during grinding and polishing. That is why the results presented later in the next section show that the
number of cracks collected from different samples of the same specimen are different.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Deformation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mm</td>
<td>30 min</td>
</tr>
<tr>
<td>SP1</td>
<td>SP2</td>
</tr>
<tr>
<td>SP1-1</td>
<td>SP2-1</td>
</tr>
<tr>
<td>SP1-2</td>
<td>SP2-2</td>
</tr>
<tr>
<td>50 mm</td>
<td>SP6</td>
</tr>
<tr>
<td>SP6-1</td>
<td>SP6-2</td>
</tr>
<tr>
<td>SP6-2</td>
<td>SP7-2</td>
</tr>
<tr>
<td>SP7-1</td>
<td>SP9-1</td>
</tr>
</tbody>
</table>

Table 2.4: Sample nomenclature

More types of information were gathered from the images collected through the stereo microscope. Each of the samples was investigated separately, during which the cracks were counted and each of them measured. It is important to mention that only the cracks formed on the exterior curved surface of the deformed concrete element were inspected, those being the ones most responsible for limiting concrete’s service life. The information collected was structured and is presented in the Appendix B1. The most important results collected are discussed in the next section.

2.2.5. Results and observations

Results

→ Frequency

Out of 8 samples prepared for investigations, all were analyzed under the microscope. The first characteristic evaluated was the frequency of the cracks (i.e. the number of cracks found per
unit of sample length - 1 cm). This theoretically reflects the influence of parameters like height of concrete panel or deformation time. The frequency of the cracks in all the samples is presented in the graph below.

The chart above shows that the frequency of cracks is higher on the samples SP3-1 and SP3-2 comparing to samples SP2-1 and SP2-2. This states that the number of the cracks depends on the deformation time. Also, a difference was observed between samples representing specimen SP2 and the ones representing specimen SP7. This indicates that the frequency depends on the thickness of the element as well.

Maximum Width

The maximum width of cracks in the analyzed samples is also important to consider as an effect of the physical deformation of concrete panels. Theoretically, having higher elements would result in larger cracks.

The width of the crack was measured at the top opening of the crack on the surface of the element. The width was determined as the maximum opening of the crack and was measured in the plane of the concrete sample, not the default horizontal plane. The measurement were performed using the image editing software - Adobe Illustrator. The size determined by the software was converted using the scale present in every microscopic image to determine the real size of the crack (see Figure 2.10).

The graph in Figure 2.11 represents the width of the largest crack found in each of the samples. Results reveal that there can be found a larger crack in the elements with longer deformation time, comparing specimens SP2 and SP3. The same can be stated about the panels with larger thickness, analyzing SP3 and SP8.

Average width

Maximum width of the cracks is an important characteristic, but statistically it is not acceptable, since it reflects the measure of one crack within the entire sample: the largest one. That is why the average width is important to be analyzed as well, where average width is meant the
The arithmetical average of the width among all the cracks observed within a sample. The results can be found in the Figure 2.12.

These results comply with the ones characterizing the maximum width, and same observations can be stated, that both height and deformation time will influence the crack size.

**→ Maximum Depth**

Depth of the cracks is also important to be analyzed, especially considering that the depth can affect the service life of the concrete if, for example, the element would be reinforced with steel reinforcement. If this proves to be the case then the concrete protective cover on top of the steel reinforcement has to be reconsidered for curved concrete panels.
The depth of the cracks was measured as the penetration distance, between the opening of the crack to the deepest visible point of the crack opening. The distance measured was determined perpendicular to the surface of the panel (default horizontal line), meaning that not the length of the crack was measured, but the distance each crack penetrates the concrete mass. The measurement were performed using the image editing software - Adobe Illustrator. The size determined by the software was converted using the scale present in every microscopic image to determine the real size of the crack (see Figure 2.13).

According to Figure 2.14 the thickness of the panel influences the maximum depth of the cracks, and so does the deformation time.

→ Average Depth
Considering the average depth, the influence of the height of the panel and deformation time is also considerable. Comparing specimens SP2 and SP3, it can be stated that a difference of 30 minutes in deformation time would increase the average depth of the cracks with about 10% (see Figure 2.15). The comparison between SP3 and SP8 shows that doubling the thickness of the concrete panel, the average depth of the crack is affected even more.

**Observations**

Besides the quantitative measurements performed during the microscopic investigation, other important observations were made.
2. Methodology and Research

Protective layer

It was observed in the collected microscopic images that all the panels have a paste layer placed above any aggregate with an approximate thickness of 1-2 mm, which is most probably formed due to segregation. From the large impregnated pores found during the investigations under the surface paste layer, it can be stated that it acts as a protective cover for the rest of the concrete mixture. This means that the layer is an important feature of the hardened concrete mixture, and if its characteristics can be influenced then different results can be obtained. Also, due to the homogeneous composition of the protective layer, it is probable that the cracks would self-heal during the hardening process and afterwards. This means that another important parameter which should be considered for further investigations would be the age of the concrete when it is impregnated with epoxy. It is reasonable to assume that if the investigated concrete panels would have an age of 1 year, then the number of cracks could be lower.

Self-entrapped air

During the investigations it was observed that a lot of pores could be found around the aggregates close to the surface. The reason for this can be the entrapped air which gathered there during the mixing process. Because the cracks found were acting as a connection bridge between the exterior and the pores of the self-entrapped air, they can have a strong impact on the durability of the material.

Multiple micro-cracks around aggregates

Analyzing the concrete micro-structure around the aggregate, a multitude of cracks can be found almost for every aggregate particle placed close to the panel’s surface. This phenomenon can
occur as a result of paste shrinkage during drying and hardening. That is why, a solution would be to assure high humidity environment for the age treatment of the deformed concrete panels, since the solution with placing the foil at certain distance may have resulted in RH<100%.

→ Outliers

During the quantitative analysis it has been observed that one of the specimens behaved not as expected in terms of cracking. It was unusual to see that the number of cracks in the specimen SP8 is lower than in any other specimen, especially considering that SP8 reflects the 50 mm height of the panel and the 90 minutes deformation time, those being the most unfavorable parameters investigated. This phenomenon reduces the value of the results of the Pilot Test and emphasizes that more attention has to be paid to statistical interpretation in the main research phase. A solution would be to investigate more panels with the same parameters of deformation in order to add statistical value to the results.

→ UV vs. Normal Light

The strategy used in collecting the images from the microscope was to analyze the specimens both under UV and Normal light. Both types of images were considered during the investigation and during quantitative analysis. This permitted not only to measure the cracks’ physical characteristics, but also to make observations regarding the concrete mixture and its components. It was important to use the same strategy during the main research phase as well (Figure 2.17).

Figure 2.17: Normal Light vs UV (Sample MT100-25.60[Sample2])

2.3. Conclusions

In the current chapter the Pilot Test was presented, together with its execution phase and results. The aim of the Pilot Test was to steer a direction for the main research investigation and to define the parameters which would be important to investigate during the main research. The need in executing the Pilot Test was irrefutable, since these types of investigations were not performed before, and it was difficult to assume which conditions will affect the cracking process in very early age concrete deformation and in what matters.

→ Test method
In the current chapter the test method was presented. It can be observed that the investigated test samples do not represent double-double curved shapes, but single-curved ones. This means that the method does not directly represent the Double-Curved Concrete technology. However, it can be assumed that the behavior of the concrete mass having two curves will result in similar performance in terms of cracking, only the cracks would have to be investigated in 3 different dimensions. For the purpose of this research the strategy of analyzing single-curved elements is enough to be considered valid and the results obtained can definitely explain the behavior of the concrete mass under physical deformation and the characteristics of the crack pattern formed due to this deformation.

→ **Height and deformation time**

The height and deformation time were the two parameters considered for the Pilot Test. According to the results presented in Section 2.2.5, these two parameters have a strong impact on the crack formation. Increasing the height of the panel and the deformation time will result in a higher number of cracks, larger in size and deeper penetrating the concrete mass. For the main research phase both of these parameters should be considered, however the deformation time could be readjusted, since there is no need in analyzing a time range of 2 hrs, as done in the Pilot Test. This range can be reduced, as well as the time steps.

Considering the height parameter, more values can be investigated in the main research. In that case, the results of the investigations could state whether it is possible to use the thicker double-curved concrete elements as durable structural constructions, or only as thin cladding elements (see Section 1.3).

→ **Recipe and curvature**

Other parameters which can be considered during the main research phase would be the water-cement ratio and the curvature of the deformation. As mentioned in the Observations of the Section 1.4, in the concrete micro structure a thin paste layer is noticed on the surface of the concrete mass, which is assumed to be formed because of segregation process. This process can be influenced by both the amount of plasticizer and the water-cement ratio. Thus, the water-cement ratio can be an important parameter to be analyzed and investigated, which could lead to important conclusions about the mixtures which can be used for very early age concrete physical deformation technology.

The curvature of the deformation is a geometrical condition which probably can affect the crack formation on the concrete surface. The importance of this parameter is reflected more by the architectural aspect of the technology, since the results of the investigation, if one will be done, will define what is the limit of bending deformation of the concrete mass. This limit will define a set of constraints for the architects in terms of possible applications of the deformed concrete technology.

→ **Self-Healing**

It is important to consider that cracks have the property to self-heal. The mechanism is called Autogenous Healing of cement-based materials. This phenomenon can occur because of two different reasons: (1) hydration of unhydrated particles and (2) dissolution and carbonation of Ca(OH)$_2$ (source: [24]).

Kim Van Tittelboom and Nele de Belie mentioned in their published research review [33] that the maximum opening of the self-healed cracks depends on various and can have values between
0.01 mm and 0.3 mm. A further research in this direction could determine whether self-healing can be addressed in double-curved concrete technology and what measures can be taken to sustain the autogenous healing mechanism.

→ Comparison to non-deformed concrete

Since similar investigations as the ones presented in this report were not performed before, it is important to understand whether the cracks measured and inspected are there only because of the physical deformation. That is why for the main research phase it is indicated to analyze a panel which is not deformed in curved shape, but keeps the same material characteristics and aging conditions as the panels which were deformed. This way a comparison of the crack pattern could be made between the elements and the impact of the physical deformation on the crack formation could be evaluated.

→ Comparison with alternative products

The technology presented in the current thesis is based on a common concrete recipe, the reason being that an important factor would be to assure that the entire production process of curved concrete elements will not have excessive investments costs. That is why it would be important to compare the performance in terms of cracking of the common recipe concrete to alternative materials present on the market at the moment. Strain Hardening Cementitious Composite is a material known on the market as “bendable concrete”, mostly because of its high strain capacity. Comparing it to the material used for the current research would underline the capacity of classic recipe concrete to compete with the new generation materials. Also, the classic recipe’s performance in terms of cracking could be compared to wood-reinforced concrete, a material relatively new on the market, which positions itself as a cheap and sustainable alternative solution to the classic concrete.
In the following chapter the results of the quantitative and qualitative analysis will be presented. The conditions of preparing the samples are similar to the ones used in the Pilot Test session (see Section 2.2.2). The concrete recipe for the main research investigations is the same used for the Pilot Test and is represented in Table 2.1. The mixing procedure can be found in Table 2.3. In conclusion, no changes were made to the procedure of preparing the concrete samples. The same methodology was used regarding the microscopic image analysis: after being impregnated, the samples were analyzed under the stereo microscope and images exported from every polished sample. The images were later analyzed, the observed cracks were quantified and measured in detail. The results were then analyzed and structured, in order to form reliable conclusions regarding the influence of various parameters on the crack formation and crack sizes.

3.1. Investigation Parameters

Using the results and observations concluded from the Pilot Test, a new set of investigation parameters was elaborated:

→ **Element Thickness**

Analyzing the results presented in section 2.2.5, it was observed the thickness of the element has a strong impact on the number (frequency) and sizes of the cracks formed due to deformation. Both depth and width values of cracks increased while increasing the thickness of the panel (see Figures 2.9, 2.12 and 2.15). For the Pilot Test two values for panel thickness were used: 25\(\text{mm}\) and 50\(\text{mm}\). The same two values were considered for the main research phase as well. It was assumed that the results from two different values would be enough to evaluate the impact of the thickness on crack formation.

Theoretically, the thickness of the panel will affect the width of the cracks. Analyzing the Figure 3.1, it can be stated that geometrically the cracks should be wider on a thicker concrete element.

We can consider that the length of the arc of the inferior surface of the deformed element \(L_{11}\) should be equal to the arc length of the deformed mould \(L_{\text{mould}}\) assuming that the mould will not become larger in size during physical bending and no slip will occur between mould surface
and concrete. In this case \( L_{11} \) and \( L_{12} \) represent two different arcs with the same center, but different radius. Therefore we can express these values by:

\[
L_{11} = \frac{n_{11}^i}{360^\circ} \times 2\pi r_{11}; \\
L_{12} = \frac{n_{12}^i}{360^\circ} \times 2\pi r_{12};
\]

(3.1)

where \( n_{11}^i \) and \( n_{12}^i \) are the angles which are formed by arcs relative to center.

In case the thickness of the panel is \( 25 mm \), than:

\[
r_{12} = r_{11} + 0.025 m
\]

(3.2)

Knowing that:

\[
n_{11}^i = n_{12}^i
\]

(3.3)

It can be concluded:

\[
L_{12} = L_{11} + \frac{n_{12}^i}{360^\circ} \times 2\pi \times 0.025;
\]

(3.4)

The numerical difference between the superior and inferior arc lengths of the surfaces of the panel with a thickness of \( 0.025 mm \) was calculated. Assuming that the material is completely brittle (high yield strength), than this difference in length represents the sum of widths of all the cracks which will be formed on the superior surface of the element.

If the value of the thickness is increased from \( 25 mm \) to \( 50 mm \), than the difference in lengths will be 2 times larger.

Definitely this will not be the case in the real situation, since the material is being deformed at very early age. However, the equations 3.1-3.4 explain the geometrical theory behind the assumption.
that the thickness of the panel will influence the crack width.

→ Deformation time

Deformation time is the second parameter which was considered for the main research phase. This parameter was used in the Pilot Test as well, and the results showed that there is a certain impact of the deformation time on the crack frequency and crack sizes. The impact was initially assumed and expected, since it was also mentioned by Grunewald et al. 2012 [10] and Schipper 2014 [28] in their own researches.

For the Pilot Test, 5 different values were used for deformation time: 30min, 60min, 90min, 120min and 150min. After performing a visual assessment of the elements cast in the Pilot Test, it was concluded that there is no need in analyzing panels deformed later than 90 min after adding water to the concrete mixture. The main reason was that the cracks formed on the surface of the concrete element were too wide and too deep and they could be classified as structural cracks, meaning that these panels could not be used in practice (see Figure 3.2).

![Figure 3.2: Panel deformed after 120 min - Pilot Test](image)

That is why a new range of values was selected for the main investigation: 45min, 60min, 75min and 90min. The investigated range was decreased, as well as the step between the values, this helping in a more accurate monitoring of the influence of the parameter on the crack propagation process.

→ Radius of deformation

The previous two parameters presented (deformation time and thickness) were both analyzed during the Pilot Test. Radius of deformation is a new parameter, which was considered to be analyzed in the main investigation phase. The radius of deformation represents a geometrical characteristic of the double-curved concrete panel. This characteristic will define the boundaries of the future shape of the concrete elements and it will help the architects to find the applicability limits of the double-curved concrete technology.

In the Pilot Test phase only one radius was considered - 0.5m. For the main research however another two values were added - 0.25m and 1m - making a total of three different variables. In order to perform the casting sessions considering this parameter, the existing moulds had to be adjusted. New deformation moulds were constructed, changing the radius of the stable ribs (see Figure 2.2), while the casting mould was each time reused.
The importance of the radius of deformation can as well be proved using the same theoretical geometrical model as for the panel thickness, expressed in Equations 3.1 - 3.4. Obviously changing the radius value will change the length of the superior surface (arc), that leads to crack formation.

3.2. Sample Nomenclature

Deformation time, panel thickness and radius of deformation are the three main parameters which were analyzed in the current research. For a more accurate evaluation of the impact these parameters have on the crack pattern and crack sizes, all three parameters were correlated, meaning that samples were cast considering all three parameter variations.

In order to simplify the result interpretation procedure a new nomenclature system was developed. The new system assures that the main characteristics of each sample is expressed in sample’s name, as explained in the next Figure 3.3.

![Sample nomenclature diagram](image)

Figure 3.3: Sample nomenclature

For example, if the analyzed sample has the name $MT50R - 25.60.1$, means that the concrete specimen from which the sample was extracted had a radius of deformation of 50 cm, a thickness of 25 mm and it was bent 60 min after water was added to the mixture (deformation time). The last digit in the name says that the sample is the first out of the two existing, with exactly the same characteristics.

The whole range of sample names is provided in the Appendix A1-A5.

3.3. Water-cement ratio

Besides the three main parameters presented in the current chapter, water/cement ratio was also considered as a research parameter.

First of all, the W/C affects the strength characteristics of the material. Numerous researches have been performed regarding the influence of water content on the strength of the concrete. Alawode et al. 2011 [1] evaluated the impact of water content variation on compressive strength of concrete. Their results showed that increasing the water content in the mixture will reduce the compressive strength of the material. Also, considering aging, the mixture with lower water content will increase in compressive strength at a higher rate than the concrete with a higher water content. Another important concrete characteristic determined by water/cement ratio is material’s permeability. Kim et al. 2014 [16] analyzed the impact of W/C on durability and porosity in cement mortar, and their results show that the porosity of the material increases together with the amount of water in the mixture. Another investigation they performed was the impact of water cement ratio on the chloride diffusion rate, which represents a durability issue and should be linked to the double-curved concrete technology. Their results show that chloride diffusion rate increases as the water content is increased.

The material characteristics influenced by water/cement ratio are very important for the current research. Besides that, the amount of water influences the workability of the mixture, which is important
as well for the flexible mould technology, considering that the concrete mass has to be cast preferably as self-compacting fluid, and then deformed at its very early age. In their research Mallikarjuna et al. 2013 [19] analyzed the impact of water cement ratio on slump flow, which represents the workability of the mixtures. They proved that there is a strong link between the amount of water in the mixture and the workability of the material. Increasing the water content will increase the slump flow as well, according to authors’ results and conclusions. Also, in the already mentioned paper of Dao et al. 2009 [4], there is a strong correlation between the water/cement ratio and the tensile strength of the concrete. The authors, with the help of their own designed installation, could evaluate the impact of water content on the tensile strength of very early age concrete. According to the results they obtained, the tensile strength of the fresh concrete is lower for the mixtures with a higher content of water. As well the tensile strength increasing rate for high water containing mixtures is low.

Considering the factors enumerated above in combination with the observations collected from the Pilot Test, it was decided to analyze the impact of water/cement ratio on crack propagation in double-curved concrete elements. The parameter was not used in full combination with the previous mentioned variables (deformation time, thickness and radius of curvature), mostly because of the high labor-intensity of the procedure. That is why, water/cement ratio was analyzed in combination with deformation time parameter, for elements having a curvature radius of 0.5m and 25mm thickness. The parameter of water/cement ratio had three different values for the research - 0.43 (representing the mixture used for the rest of the research as well - see Table 2.1), 0.38 and 0.5. The samples which were cast for this investigation were denominated as presented in Figure 3.4.

![Figure 3.4: Sample nomenclature](image)

In this section the main parameters were presented together with the reasons why they were selected. Also, besides the three main parameters, a secondary one was selected - the water/cement ratio. The quantitative and qualitative influence of these parameters on crack propagation and crack sizes is presented in the next section.

### 3.4. Results of the Investigations

As already explained in Section 2.2.5, the quantitative and qualitative analysis of the crack pattern was performed through microscopic image investigation. Every sample was analyzed under stereo microscope, using normal and UV light.

During the investigation:

- 10 different mould constructions were used;
- 30 different deformation moulds were built (considering three different deformation radii);
- approximately 45 L of concrete mixtures were cast;
- 40 different concrete samples were cast and impregnated;
80 different specimens were impregnated, polished and analyzed under the microscope;

over 2000 images were analyzed for crack counting and measuring.

### 3.4.1. Radius of deformation

In the current section the quantitative and qualitative impact of the radius of deformation will be analyzed. The results represent only one variable for thickness of the panels - 25mm. The rest of the results, which mostly reflect the same tendency, are attached to the Appendix A1-A3.

![Graphs showing number of cracks and frequency](image1)

According to the graphs in Figure 3.5, the radius of curvature has a definite impact on the number of cracks propagated on the surface of the bent concrete. The radii of 25mm and 50mm show very similar results, since the radius difference is small. Considering number of cracks or the frequency, the panels with a higher radius of deformation (1m) have fewer cracks, as it was expected, and also proven in the Pilot Test session.

It was considered important to investigate both the frequency and the number of the cracks, since the second would not directly reflect the amount of cracks on each sample. The main reason is that each sample had different lengths, as a result of the preparation procedure (low accuracy because the samples where cut with a 3 mm thick diamond disk). The frequency then represents the amount of cracks per 1 cm sample length. The crack number represents the total number of cracks observed in one sample.

Another defining characteristic of the crack pattern is the sizes of the cracks. The comparison of the sizes of the cracks considering a variation of deformation time and deformation radius are showed in Figures 3.6 and 3.7.

![Graphs showing average crack width and maximum crack width](image2)

In Figures 3.6 and 3.7 both average values and maximum values are represented, for crack width and crack depth respectively. Both characteristics, width and depth, are important to be analyzed, since
Investigations and results

they can be linked to resistance to degradation mechanisms of the double-curved concrete elements. Analyzing the graphs, it can be observed that a small radius of deformation of 25 cm will behave much worse than the other ranges of sample in terms of crack sizes. The only acceptable dimensions for this degree of bending are expressed by the panels deformed after 45 min. Increasing the deformation time can cause cracks wide as 4 mm and deep as 25 mm. Evaluating the other two values for deformation radii (50 cm and 100 cm) can be concluded that they behave similarly in terms of crack width. A more definite difference between these two can be observed at the values which represent the crack depth for 90 min deformation time, where the more bent panels (50 cm radius) showed cracks of 15 mm deep and an average of 0.4 mm per sample, comparing to an average of 0.1 mm in the panels deformed less (100 cm radius).

Besides the numerical values presented above, a statistical representation of the cracks was performed, considering the class classification of crack width and depth mentioned in Section 1.5.

From the Figure 3.8 it can be observed how the number of cracks larger than 0.1 mm increases while decreasing the radius of deformation. So it can be concluded that having a higher degree of bending of the DCCE will result in larger cracks. The same can be stated about the depth of the cracks. According to Figure 3.9, decreasing the radius of deformation will cause deeper cracks on the surface of the panel.

In conclusion, the results presented prove that the radius of deformation has a high impact on the crack pattern propagated on the surface of the DCCE after physical bending. As expected, a smaller radius will result in larger and deeper cracks than the bigger radii. The number of cracks however was not influenced a lot by this parameter, which means that bending more a concrete panel will not
necessarily cause more cracks, but will definitely increase their sizes. A possible reason could be the samples crack around the same strain value, and further deformation will be concentrated in the already existing cracks.

3.4.2. Panel thickness
The change in crack pattern and crack sizes was analyzed considering the thickness of the concrete panels. Two different values for thickness were investigated: 25mm and 50mm. The results are presented below.

From Figure 3.10 it can be concluded that the thickness of the panel does not affect considerably the frequency of cracks formed on the surface of the element. The results are similar for both 25mm and 50mm thick panels. Also, another observation is that the number of cracks for the 50mm thick panel deformed after 90min water was added to the concrete mixture, is lower than for the other specimens. Analyzing the type of cracks formed in Figure 3.14, it can be assumed that after 90min the tensile strength in the element is so high, that fewer cracks will be formed, but larger in size. This assumption can be supported by the geometrical model presented in Section 3.1.

In Figure 3.11 is represented the impact of panel thickness on crack width. Comparing these numbers to the crack frequency, a more obvious impact can be observed. Having a thicker panel will result in wider cracks, as it was expected. One large crack is observed for the element MT50R − 25.45, which was caused probably by a faulty deformation.

Analyzing the depth of the cracks Figure 3.12, a difference can be observed in average crack depth,
3. Investigations and results

where the thicker panel performs worse, but considering the deepest cracks only, the results are similar.

Analyzing the crack pattern and crack sizes distribution, the following results were obtained.

From Figure 3.13 it can be concluded that the thicker panels will have more cracks larger than 0.1 mm in width. The difference expressed by the graphs impose that width of cracks is directly related to panel thickness. Consider the depth of cracks, the same tendency can be observed. Figure 3.14 shows that thicker panels will have deeper cracks, however the difference is not considerable. The probability is high that thicker panels deformed after 90 min will have several very large cracks, comparing to a thinner panel.
3.4. Results of the Investigations

3.4.3. Deformation time

Another investigated parameter was the deformation time. Even if in the previous two sections the results for panel thickness and deformation radius were directly correlated to deformation time, in the current section a separate investigation will be performed, in order to analyze the direct influence of the deformation time on the crack pattern and crack sizes formed on DCCEs.

The elements selected for this type of investigations were the ones having a radius of deformation of 50 cm and 25 mm thickness. According to the results presented in Figure 3.15 an overall increase in the number of cracks can be observed. Based on this it can be stated that the deformation time influences directly the number of cracks on the DCCEs.

Considering the cracks sizes, the same pattern can be observed regarding the average width of the cracks. The average width of cracks seems to be affected by deformation time. Similarly the largest cracks found in the elements are larger in size for the elements deformed at later deformation times. This meaning that the deformation time can be considered a boundary limit for crack sizes.

The crack depth graphs represent the same tendency as the previous one (see Figure 3.17). The only difference is that the element deformed after 75 min has a deeper crack than the element deformed later. For this type of outliers a more detailed statistical result would be needed, meaning that a larger amount of panels having the same characteristics should be cast. However, considering the overall results, the deformation time definitely affects the crack depth. The later the element is being
3. Investigations and results

![Graph](image)

Figure 3.16: Average crack width/Maximum crack width

![Graph](image)

Figure 3.17: Average crack depth/Maximum crack depth

Considering the type of cracks formed in these elements with respect to deformation time, the following results were obtained:

![Charts](image)

Figure 3.18: Number of cracks representing each class of width

It Figure 3.18 it is clearly visible how the number of wider cracks increases together with the deformation time value. For example at 45min and 60min deformation times no cracks wider than 1mm could be observed, however for the rest of the sample the number of cracks larger than 1mm increases considerably. The same observations can be concluded regarding the number of cracks classified by their depth. In Figure 3.19 it is shown how the number of cracks deeper than 0.01mm increases constantly together with the deformation time.

In conclusion it can be stated that the ‘deformation time’ parameter is an important factor for the crack formation in Double-Curved Concrete Elements and it should be carefully addressed during the manufacturing process.
3.4.4. Water/Cement Ratio

The water-cement ratio is another parameter which was analyzed during the main research phase. The importance of the parameter was proved by the results of the Pilot Test and the observations following that test (see "Protective layer" in Section 2.2.5). Its importance in crack propagation is irrefutable, mostly because the direct correlation between the water/cement ratio and material’s tensile strength (see Section 3.3).

Observations

The high water/cement ratio mixture was observed to be very fluid in the first 15 minutes, analyzing the results of the slump tests. After 45 min the mixture with 0.5 w/c hardened enough to be deformed with the flexible mould, since there was no deformations observed during the slump test, only minor surface bleeding. Deforming the element after 45 min of deformation time resulted in small cracks, which were quickly filled with paste. The same phenomenon was observed after 60 min of deformation time, however at a slower rate. After 75 min the cracks formed were more visible and only partially were filled with concrete paste, reducing their sizes. Similar behavior was observed after 90 min deformation time.

The 0.38 w/c ratio mixture behaved differently. It was observed during the mixing that the concrete mixture was not workable at all, especially comparing to the previous ones used. The low workability was observed during the casting as well. The mixture was not self-compacting at all. Also surface treatment was needed, to assure that the mixture filled entirely the flexible mould. During the deformation the mixture behaved normally. Cracks were visible already after 45 min of deformation time. After 75 min it was observed that the mixture was not following anymore the deformed mould, disconnecting from the edges of the mould. Larger cracks were observed. Similarities observed after 90 min deformation time.

The results of this investigation are presented below:
In Figure 3.20 it can be observed that the number of cracks is influenced by the water/cement ratios. Analyzing the curves of ratios equal to 0.38 (blue) and 0.5 (grey) a high difference can be spotted in number and frequency of the cracks. A strange pattern presents the mixture with the w/c equal to 0.43, having more cracks than the previous two elements mentioned. One of the reasons behind this values is that the mixture itself behaved slightly differently as expected in the slump tests, which are presented in the next section in Figure 3.28. The results there show that the tensile strength of the mixture was reached slightly faster than expected. This could influence the formation of more small cracks on the surface of the panel. According to Figures 3.23 and 3.24 the cracks which appeared on this element were relatively small (<0.1 mm).

Different results are presented by Figure 3.21, where the crack width is analyzed. Here the two mixtures with the higher w/c ratios behave similarly, while the mixture having the w/c equal to 0.38 shows the largest cracks. This results seem more realistic and where assumed before the testing.

Similar results show the investigations of crack depth, presented in Figure 3.22. The elements cast with a mixture of 0.43 and 0.5 w/c ratios behave similarly, while the 0.38 w/c mixture element shows deeper cracks. Also cracks tend to get deeper with increasing the deformation time.

Analyzing the distribution pattern of the crack sizes Figure 3.23, it can be observed the fact mentioned earlier, of the 0.43 w/c ratio element having a large number of very small cracks. Comparing the elements representing 0.43 and 0.5 w/c ratios, a difference is observed in the ratio of cracks <0.01 mm and <0.1. This also is a result of the numerous cracks found on the samples MTS0R. More realistic results shows Figure 3.24, where is showed the depth distribution pattern. Here the samples behave as expected, 0.43 w/c sample having deeper cracks than 0.5 w/c sample, but smaller in comparison to the 0.38 w/c sample.

In the end it can be concluded that the water/cement ratio is an important parameter to be further investigated which definitely affects the crack pattern and crack sizes in DCCEs. Since the water/cement
3.5. Validation of results

In order to validate the results of the current research, it was important to find testing models which would assure that the results are not erroneous, or at least to find ways of proving why some results are not equivalent to the ones expected.

3.5.1. Non-deformed elements

It is important to prove that all the cracks which were analyzed quantitatively and qualitatively were formed as a result of physical deformation and not any other reason. Possible causes for crack formation are numerous (see Section 1.5) and the purpose of the current research was to investigate the impact of physical deformation (bending) on double-curved concrete elements, so no other cracks were relevant for consideration. That is why it was considered to cast elements with the same concrete mixture and aging conditions, but which would not be deformed at all. This way the crack pattern (if there would be one) could be compared to the one present on bent elements, helping to sort out the origin of the
The casting session has been performed and the concrete elements were treated under the same conditions for the same period of time. The sample preparation was similar to the one presented in Section 2.2.4.

The results of this investigations showed that the concrete mixture characteristics and aging conditions do not cause any cracks on the surface of non-deformed elements. This means that the conditions were optimum for preserving crack propagation for the elements not deformed physically. In Figure 3.25 are presented two images realized using the stereo microscope under normal and UV light, where it can be observed that no cracks are created on the top surface of the concrete specimen.

![Figure 3.25: Non-deformed specimen - under Normal and UV light (no cracks observed)](image)

From these results it can be concluded that the cracks counted and measured in the previous section are created only as a result of the physical deformation and no other reason.

### 3.5.2. Slump tests

The current research was performed in different phases, using different concrete mixture batches. As explained in Section 2.2.2, the concrete mixture was cast in the fixed mould surface and then deformed at different time spans (deformation time parameter). Having all 80 samples cast at once, would make the deformation process totally inaccurate, since this process was performed manually. In order to
increase the accuracy of the results, the decision to divide the entire range of elements in several sessions was taken. Since more casting sessions were performed, the results of which had to be later compared, it was decided to monitor the characteristics of each mixture at each session.

The most relevant characteristic of the mixture which would make the comparison possible was based on the workability. According to Tattersal et al. 1983 [32] the term workability embraces all the necessary characteristic a fresh concrete mixture has to possess, related to mixing quality, flowing, less self-entrapped air, relatively good surface finishing. To diagnose the workability of each concrete batch used for different casting sessions, slump tests were performed during each session. The results of these slump tests would prove if the concrete mixtures had similar characteristics and could be compared in terms of cracking. It would help in validating the final results.

To measure the slump value, the small cone was used, also called Haegermann mini-cone, which is presented in Figure 3.27.

![Figure 3.27: Mini cone (Haegermann) source: Roussel and Coussot 2005 [25]](image)

Since a translation from the quantitative results presented by the slump tests to some qualitative characteristics defining the concrete mixtures was needed, the test results were directly correlated to the yield strength of the mixture. Numerous researches have been performed which would describe how the values of the slump test can be translated into yield stress characteristics. In Roussel and Coussot 2005 [25] the authors found an linear correlation between slump value and tensile strength of the material.

\[ \frac{\rho g (H - z_c)}{\sqrt{3}} = \tau \]  \hspace{1cm} (3.5)

where:
- \( \rho \) specific mass, \( kg/m^3 \)
- \( g \) acceleration of gravity, \( N/kg \)
- \( H \) height of cone, \( m \)
- \( z_c \) slump value, \( m \)
- \( \tau \) yield strength, \( Pa \)

The results of the research ([25]) state that generally the Formula 3.5 is overestimating the yield strength of the material. However, in the current research only a comparison between the mixtures is needed, and not a direct evaluation of the yield strength. That is why the Formula 3.5 satisfies the needs of the current research and permits the evaluation and comparison of different concrete mixtures. Using the Formula 3.5 the following results were obtained:

\footnote{This mixture was used in the casting of non-deformed concrete elements}
3. Investigations and results

Analyzing the results presented in Table 3.1 and in Figure 3.28 it can be stated that the difference between the mixtures was very small and that they behaved similarly during the slump tests. The two mixtures which behaved differently were the ones having W/C ratios of 0.38 and 0.50 respectively, which is normal and was expected. In conclusion, the results presented in Section 3.4 can be validated, even if different batches of concrete mixtures were used to perform the tests.

3.6. Applying models of chloride penetration and carbonation

One of the main purposes of the current research was to quantify and evaluate the crack pattern which can be formed as a result of physical deformation in the production of double-curved concrete elements. The results of crack pattern evaluation were presented in the current chapter. It is important however to predict the impact of the crack pattern in the development of the concrete damage mechanisms and to evaluate how the frequency or the sizes of the cracks can influence the penetration rates of the damage mechanisms.

3.6.1. Carbonation

Numerous studies and numerical models were developed regarding the prediction of carbonation in concrete structures. The aim of these studies in most cases is to determine the service life of a certain concrete structure in correlation to its exposure and technical characteristics. Among these studies is the research performed by Erkki Verikari [36], published in 2009. The objective of the author was to
develop a theoretical basis for practical service life models with respect to carbonation and chloride penetration in concrete structures. According to the author, the carbonation in cracked concrete surface can be directly correlated to the penetration rate of a normal concrete surface. He assumes that the $CO_2$ gas first diffuses into the crack, and then into the concrete mass via the walls of the crack [36].

Mathematically the author expresses the carbonation of cracked concrete using the following formula:

$$J_{Ry} = D_R \frac{\Delta c_a}{\gamma_{ca}} \frac{w}{z}$$

where $J_{Ry}$ is flux of carbon dioxide into concrete, $g/m^2 s$
$D_R$ the diffusion coefficient of concrete with respect to $CO_2$, $m^2 s$
$\gamma_{ca}$ depth of carbonation at the crack, $m$
$w$ width of the crack, $m$
$\Delta c_R = c_s - c_x, g(CO_2)/m^3$
$c_s$ $CO_2$ content of air at the surface of concrete, $g(CO_2)/m^3$
$c_x$ $CO_2$ content of air at the depth $\gamma_{ca}$, $g(CO_2)/m^3$.

Important to mention that this rate quantifies $CO_2$ flux through half of a crack only. The author’s model is described by the following figure:

![Figure 3.29: Carbonation at a crack of concrete (source: [36])](image)

Equation 5.1 describes the flux rate depending on $CO_2$ content and width of the crack. Analyzing the results obtained in the current research in combination with equation 5.1, it can be stated that the width of the crack will directly influence the $CO_2$ flux within a crack. A wider crack will have a higher $CO_2$ flux.

Considering only the average crack width, the following graphs were output, with the reference to different deformation parameters.

Reflecting on the graphs above it can be observed and defined how each deformation parameter will affect the carbonation rate, considering the direct relation between crack width and $CO_2$ flux. It is important to mention that the diffusion rate $D_R$ depends on humidity and degree of hydration meaning that the direct impact of the crack width on the $CO_2$ flux can vary from the graphs expressed in Figure 3.30.
Applying the above mathematical model to the crack pattern evaluation of the current research can give an overall impression of how different deformation parameters investigated in Chapter 3 can affect carbonation.

### 3.6.2. Chloride penetration

In the same research [36], another mathematical model was developed, to quantify the chloride penetration in cracked concrete. The author assumes that the chloride gradient will have a parabolic shape and is defined by the following equation:

\[
C_{RY} = C_{RS}(1 - \frac{y}{H_R})^2; \quad y \leq H_R
\]  

(3.7)

where 
- \(C_{RY}\) is chloride content at the crack at the distance of \(y\) from the surface, \(g/m^3\);
- \(C_{RS}\) chloride content at the mouth of the crack (at surface level of structure), \(g/m^3\);
- \(y\) distance from surface, \(m\);
- \(H_R\) the depth of chloride penetration at the crack, \(m\).

Using the same theory as in carbonation, the chloride ion flux into one wall of the crack is:

\[
J_{RY} = D_R \frac{2C_{RS}w}{H_R} \frac{y}{2}
\]  

(3.8)

where
- \(J_{RY}\) is flux of chloride ions into crack, \(g/m^2s\);
- \(D_R\) the diffusion coefficient of the crack with respect to chloride ions, \(m^2/s\);
- \(w\) width of the crack, \(m\).

The argumentation of this mathematical model can be found in Erkki Vesikari’s research [36].

Analyzing equation 5.3 it can be observed that again the width of the crack will have a major impact on the chloride penetration as well, similar to carbonation mechanism. The same graphs presented in Figure 3.30, which represent the impact of various parameters on the average crack width during the
production of Double-Curved Concrete Elements, can be investigated. The graphs can be directly linked to the influence of crack width on the chloride penetration mechanism. For example, Figure 3.30(a) represents the average crack width correlated to deformation time. The graph shows that delaying the deformation time will result in wider cracks on the surface of the deformed concrete, and this directly will result in a higher chloride penetration flux. The conditions to assure this correlation are that the elements are exposed to the same conditions and the concrete mix designs are similar.
4

Alternative Materials

4.1. Introduction
The current research has the aim to analyze the behavior of typical concrete mixtures under physical deformation, as part of the double-curved concrete panels manufacturing technology. One of the objectives of this new technology is to sustain the progress and development of modern free-form architecture in feasible and accessible ways. The flexible mould system has been developed to link the existing manufacturing techniques of building precast concrete elements with new architectural challenges.

The concrete material used for this research has a common recipe, which assures affordability and availability. At the same time it is important to identify potential alternative materials, which could be used in production of DCCEs. Two different materials were investigated, these being Wood Fiber Reinforced Concrete (WRC) and Strain Hardening Cementitious Composite (SHCC). In the following chapter these materials will be considered as replacement materials for the concrete mixture used in the main research. The objective is to compare the performance in terms of cracking of the alternative materials and to evaluate at what extent these materials could be used in Double-Curved Concrete Technology.

4.2. Wood Fiber Reinforced Concrete
4.2.1. Literature Review
Fibers were used as reinforcement material for centuries already. In her PhD Research Sierra-Beltran 2011 [29], the author analyzed the ductile properties of cement-based materials enforced with wood fibers. This research was used as the main informational background for the current investigations. The author mentions that a large number of types of fibers have been developed in time, mostly with the aim to increase material's strength characteristics and fatigue resistance. Among these types of fibers can be found the natural fibers, which have a certain number of advantages over the synthetic fibers. The natural fibers are easily available, making them affordable as well and friendlier to the environment since less energy is needed in production [29]. M.G. Sierra Beltran concluded in her research that there is a possibility of designing more sustainable fibre-reinforced composites with the use of natural fibers. She stated that “even though the bending strength and ductility is lower than
some other fiber-reinforced materials, the wood fiber reinforced composite presents advantages as low environmental-impact, low production costs and higher sustainability” [29].

### 4.2.2. Testing

For the current research the same concrete mixture was used as the one in the Main Research phase, the only difference being the addition of wooden fibers. This way the direct impact of the fibers on the mixture was possible to evaluate. The recipe of the mixture is presented in the table below.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 52.5 R</td>
<td>400</td>
</tr>
<tr>
<td>Fly ash</td>
<td>160</td>
</tr>
<tr>
<td>Super plasticizer (0.7%)</td>
<td>3.92</td>
</tr>
<tr>
<td>Water</td>
<td>172</td>
</tr>
<tr>
<td>Sand 0.125-0.25 mm</td>
<td>48.2</td>
</tr>
<tr>
<td>Wooden Fibers</td>
<td>245.2 cm³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand 0.25-0.5 mm</td>
<td>128.6</td>
</tr>
<tr>
<td>Sand 0.5-1 mm</td>
<td>209</td>
</tr>
<tr>
<td>Sand 1-2 mm</td>
<td>289.4</td>
</tr>
<tr>
<td>Sand 2-4 mm</td>
<td>369.6</td>
</tr>
<tr>
<td>Gravel 4-8 mm</td>
<td>562.6</td>
</tr>
</tbody>
</table>

Table 4.1: Concrete mixture composition - per m³

5L of the mixture presented were prepared. The amount of wooden fibers used for the current research was 245.2 cm³, which represented 4.9% of the mixture. The wooden fibers were produced manually, using large spruce wooden beams. The fibers produced had sizes of 25 mm in length, 4 mm in width and a thickness of 0.12 mm. The small thickness was achieved by using the microtome installation, and the whole process was performed manually, that is why the sizes could result in not being so accurate. The production process is presented in Figure 4.1.

![Production of wooden fibers](image)

Figure 4.1: Production of wooden fibers

The produced wooden fibers were added to the mixture during the mixing process. It is important to mention that the wooden fibers were directly added in the mixing process, that is why the orientation of the fibers in concrete was random. If the fibers would be placed considering orientation, probably that would influence the final results.

**Observations**

After adding fibers to the mixture, it was observed that is was not representing a self-compacting
<table>
<thead>
<tr>
<th>Action</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing Aggregates + Cement + Fly-ash</td>
<td>30</td>
</tr>
<tr>
<td>Adding water (90%)</td>
<td>60</td>
</tr>
<tr>
<td>Addition of wooden fibers</td>
<td>60</td>
</tr>
<tr>
<td>Adding water (10%) + Superplasticizer</td>
<td>90</td>
</tr>
<tr>
<td>Scraping the interior surface of the mixer</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>270</strong></td>
</tr>
</tbody>
</table>

Table 4.2: Mixing Process

one anymore. However, it was workable enough to be poured in the flexible mould and it followed the shape with minor effort. A thin paste layer was observed on the surface of the concrete, which probably reduced the cracks’ sizes. Performing the slump test it was observed that after 7 min already the mixture was hardened enough to be deformed, the slump value being only 0.2 cm. After 15 min no deformations were observed during the slump test.

Not the entire range of parameters was investigated using the Wood Fiber Reinforced Concrete. The WRC panels were cast considering a thickness of 50 mm and a radius of deformation of 0.5 m. The results obtained were compared with the panels cast from traditional concrete, samples MT50R-50, presented in Chapter 3 of the current report. In conclusion, the alternative material of WRC was evaluated in terms of cracking considering only one variation parameter - deformation time. The results of this investigation are presented in the next section.

4.2.3. Results

The WRC samples were cast, deformed and treated as the procedure which was explained in Section 2.2.4. The specimen preparation was similar to the traditional concrete investigations. Comparing traditional concrete and WRC the following results were obtained:

Considering the number of cracks and crack frequency (Figure 4.2), it can be observed a slightly better behavior of WRC comparing to traditional concrete. The cracks seem to be less on the WRC, meaning that the wooden fibers improves the cracking propagation, however this improvement is not significant.

Considering the crack width, the WRC definitely performs better. The fibers perform the bridging between the cracks, and does not allow them to increase a lot in size. Even if the difference is not again significant, it can not be neglected.

Analyzing the crack depth, negligible difference can be observed in Figure 4.4. Even if the fibers help in controlling the crack width, apparently they do not help a lot with the depth. However, important to mention is the fact that the 90 min deformation time element is performing a lot better than the
4.2. Wood Fiber Reinforced Concrete

Figure 4.3: Average crack width/Maximum crack width

...traditional concrete, meaning that the fibers do manage to control the maximum depth. This can be better analyzed in Figure 4.6.

Figure 4.4: Average crack depth/Maximum crack depth

Analyzing Figure 4.5 and 4.6 it can be observed the impact of wooden fibers on controlling crack sizes. The wooden fibers do not behave as expected considering crack width, since from the figures it is notable that practically there is no difference in the number of cracks larger than 1mm comparing WRC and traditional concrete mixture. A difference however can be observed in crack depth. The WRC elements showed no cracks deeper than 5 mm, which could be observed in traditional concrete, and the number of cracks deeper than 1 mm is also smaller in WRC.

Figure 4.5: Number of cracks representing each class of width
4.2.4. Conclusions

Analyzing the results presented in the previous section, it can be concluded that there was spotted a positive impact of the wooden fibers added to the concrete mixture, however this impact was not as high as expected. A small improvement was performed related to the number of cracks and crack width. A more definite impact the wooden fibers had on the crack depth, which seemed to be controlled by the fibers. The small difference in crack width between WRC and traditional concrete could be caused by the random orientation of the fibers. For further research would be interesting to analyze the crack pattern in deformed WRC having the wooden fibers oriented in the direction of deformation. In this case a more definite impact is expected.

4.3. Strain Hardening Cementitious Composite

4.3.1. Literature Review

Strain Hardening Cementitious Composite represents a mortar-based material which is mixed with short and thin polypropylene or polyvinyl alcohol fibers. The main characteristic of SHCC is the high strain capacity, meaning that hardened material is very flexible compared to the typical concrete. One of the promoters of SHCC, Victor Li, published in 2003 a review of the material and its application [18], after 10 years since it was invented. The author evaluates the progress material has gained in research and examination, and mentions how the material entered the commercial market after years of investigations. Another research performed by Kamal et al. [15] mentions that probably one of the novel properties of the SHCC material is its exhibit of multiple fine cracks, which makes it very useful as a repair material. During the research the authors investigated the capacity of SHCC as repair material under tensile and flexural tests. Cracking in SHCC became a popular subject and numerous researches were performed considering this subject. Cracking was investigated by Fantilli et al. in their paper [8]. The authors elaborated an analytical model of micro-cracking formed in SHCC as a result of uniaxial tension. In conclusion, the general characteristics of the SHCC material make it very suitable for the current research. Since SHCC is very ductile because of its high strain capacity, it would be interesting to see its behavior under physical deformation in the production of curved concrete elements.
4.3.2. Testing

In comparison to WRC, the SHCC material is represented by a mortar mixture, that is why the traditional concrete mixture used for the main research phase could not be used for this investigation. A new recipe was used, which is considered to be more common for the SHCC, this way the traditional concrete mixture could be compared with a totally different alternative material existing on the market.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 52.5 R</td>
<td>440</td>
</tr>
<tr>
<td>Fly ash</td>
<td>558</td>
</tr>
<tr>
<td>Super plasticizer (GLENUM)</td>
<td>23</td>
</tr>
<tr>
<td>PVA Fibers</td>
<td>22</td>
</tr>
<tr>
<td>Sand 0.125-0.25 mm</td>
<td>440</td>
</tr>
<tr>
<td>Slag</td>
<td>114.4</td>
</tr>
<tr>
<td>Water</td>
<td>339</td>
</tr>
</tbody>
</table>

Table 4.3: Concrete mixture composition - per m³

As can be observed in Table 4.3 the maximum diameter of the used aggregate is 0.25mm, meaning that there is a difference between the SHCC and the traditional concrete mixture. However, the aim of this particular research was to compare the traditional concrete to alternative materials present on the market at the moment, in order to determine the most suitable one for the manufacturing of double-curved concrete elements. The PVA fibers mentioned in Table 4.3 represent polyvinyl alcohol fibers of 20 mm length. The main advantage of this product is its high elasticity and the good adherence the fiber forms with the cement matrix. The behavior of this material in terms of cracking will be analyzed in the following section. The comparison is again performed with the MT50R-50.XX.X samples from the Main Research phase.

![Figure 4.7: Deformation of Strain-Hardening Cementitious Composite](image)

**Observations**

During the casting the mixture behaved differently if compared to the traditional concrete used for the main research phase. The first slump test was performed after 7 min since water was added to the mixture during the mixing process. The resultant mortar was very adhesive with low workability. The slump value was 0.5 cm. Also important to mention that the mixture was far from being self-compacting. The second slump test proved that the mixture hardened extremely quickly, having a slump value of 0.2 cm. After 45 min no deformation during the slump test was observed.
4.3.3. Results

In Figure 4.8 the results considering crack number and crack frequency are presented. It can be observed that the number of the cracks in the SHCC material is considerably higher comparing to the traditional concrete mixture. Analyzing the results of the researches performed so far about the performance of SHCC (or ECC), they say that the use of PVA fibers helps in terms of cracking by reducing the sizes of the large cracks, splitting it in numerous microcracks. A similar tendency can be observed in the current investigation results. Analyzing the crack width, a positive trend is observed this time.

The results presented in Figure 4.9 show that the average width together with the maximum width values in case of the SHCC material are substantially lower than the same numbers related to traditional concrete. This proves that the PVA fibers perform good in terms of cracking, by limiting the width to much lower values. Considering crack depth, the same positive tendency can be observed. The SHCC materials performs considerably better than the traditional concrete, especially evaluating late deformation times.

Considering the crack size distribution, the tendency of the PVA fibers to limit the sizes (width and depth) can be observed.

In Figure 4.11 it can be seen that the SHCC material is having most of the cracks smaller than 1 mm, even after 90 min of deformation, while in the traditional concrete almost half of the cracks found were larger than 1 mm. The same happens with the crack depth. Analyzing the results presented in Figure 4.12, it can be observed that even if the traditional concrete after 90 min of deformation time can have cracks deeper than 5 mm, no cracks of this size were found in SHCC.
4.3. Strain Hardening Cementitious Composite

4.3.4. Conclusions

Referring to the results presented in the previous section, it can be concluded that the SHCC material used in the current research performed a lot better than the traditional concrete analyzed in the Main Research phase. The results show considerable differences regarding the crack sizes formed on both
materials, and prove that the PVA fibers definitely can limit the maximum depth and width of the cracks formed due to physical bending of the Double-Curved Concrete Elements.

4.4. General Conclusions

The objective of the current chapter was to analyze potential alternatives to the traditional concrete mixture used for the Main Research phase of the current investigation. Two alternatives were tested - the Wooden Fiber Reinforced Concrete (WRC) and Strain Hardening Cementitious Composites (SHCC). These materials were cast and treated following the procedure explained in Chapter 2. Elements similar to the ones cast in the main research investigation were created and deformed, considering deformation time as varying parameter. Analyzing the results obtained after the crack counting, the following conclusions could be drawn:

→ WRC - The material performed better than the traditional concrete mixture used in the current research, considering crack frequency or crack sizes. However, the difference between the two materials was very small. The wooden fibers did not perform that good in bridging and closing the large cracks as it was initially expected, so that the crack widths do not differ that much between the two materials. Only considering the maximum crack depth, the WRC performed considerably better than the traditional concrete. In conclusion the WRC, as an alternative material for the common concrete, performed better per total. However more detailed researches are needed in order to evaluate the production costs of the fibers; a life-cycle analysis to compare the materials in terms of sustainability; and an evaluation of the service life in order to understand the role of wooden fibers on the degradation mechanisms.

→ SHCC - Strain Hardening Cementitious Composite brought the expected results of a high engineered material. Comparing it to the traditional concrete mixture or the WRC, the SHCC performed considerably better. The theoretical assumption that the PVA fibers would split the large cracks in a multitude of microcracks was proven. However, it is important to state that the behavior in terms of cracking of the SHCC was influenced not only by the PVA fibers. An impact could have the mix design as well, especially the absence of large aggregates.

Even if the number of cracks in the SHCC samples was higher than in the other two materials (Figure 4.13), the sizes of the cracks, both width and depth, were substantially lower. Further research is needed in order to compare the performance of the different materials and the difference in costs. That research would result in proofs why certain materials are better to be used in the double-curved concrete technology. However - considering only the performance - SHCC is the best option.

Figure 4.13: Crack Frequency / Average crack depth
Conclusions and Recommendations

5.1. Interpretation of results
In order to evaluate any achievement, it is important to overview the accomplishment of the initially set goals. In the following section discussions about accomplishment of the research objectives will be presented.

- **Investigate and quantify the cracking formed during the production of double-curved concrete elements** - The double-curved concrete elements are one of the many representative details of the modern architecture, especially considering free-form structures. The current research investigated a technological method of manufacturing this type of elements through the use of existing methods and techniques of precast concrete fabrication. The innovative part of the technology is the flexible mould system, an installation concept which allows to deform the cast concrete element in its very early age. Since the deformation using the flexible mould system means solicitation of the concrete mass through tensile stresses, the deformation would result in a pattern of cracks in the concrete mass. Part of the current research was to cast a series of concrete elements and to deform them using the flexible mould system. By using the techniques of modern petrography and microscopic investigation, the crack pattern formed due to deformation was analyzed in qualitative and quantitative matters. Every crack produced during the curved bending was investigated, counted and measured manually. The results were statistically analyzed and structured, so that conclusions could be drawn about the factors which influence crack formation and to what extents.

- **Evaluate the impact of various factors on the cracking size and pattern** - The concrete panels were deformed considering a set of parameters. Since no similar research was performed so far, defining the parameters was considered an important phase of the current investigation. To define this set of parameters a Pilot Test session was performed in which several parameters were investigated. Concluding the results and observations obtained from the Pilot Test, a set of three main parameters was elaborated, which theoretically have the strongest impact on crack number and crack sizes formed during deformation.

1. **Radius of deformation** - Since the deformation of the panels was performed in a curved shape,
the extent of deformation was investigated, because it was considered an important factor in crack formation. It was initially assumed that smaller the deformation radius will produce higher tensile stresses and will result in larger cracks on the panel's surface. Three different values were investigated for deformation radius - 0.25, 0.5 and 1.0 m. Analyzing the results related to this investigations it was concluded that radius of deformation has a strong impact on the crack pattern. Some of the numerical results are presented below:

(a) The Frequency of the cracks will increase approximately by a factor of two if the deformation radius is decreased from 1.0 m to 0.5 m. If the radius is decreased from 0.5 to 0.25m the frequency of the cracks will increase with approximately 20%.

(b) The panels deformed with 1.0 m radius will generally have all the cracks smaller than 0.1 mm in width (with some exceptions). If the radius of deformation is 0.5 m, than approximately 10% of the cracks will be wider than 0.1 mm, and decreasing the radius to 0.25 m will cause cracks wider than 0.1 mm to consist 40% of the total number.

(c) Considering the depth of the cracks then again the panel with 1 m deformation radius performs the best, with no cracks deeper than 1 mm observed. For 0.5 m radius, even few cracks deeper than 5 mm could be spotted. 0.25 m radius results in noticeably more cracks deeper than 5 mm.

2. Deformation time - Represents the time span between the moment when water is added to the mixture in the manufacturing process and the moment when the panel was being deformed. During the Pilot Test it was observed that the current parameter has a high impact on the crack pattern formed. From the same observations, it was decided to avoid deformation times higher than 90 min, because those would result in cracks too wide to be used in practice. As a result 4 different values were selected as variables: 45 min, 60 min, 75 min and 90 min deformation time. The impact of this parameters is shortly described below:

(a) The Frequency of the cracks increases considerably if the deformation time is delayed. If at 45 mins the frequency of the cracks usually less than 1 unit per cm length, than at 90 min deformation time this value exceeds 3 units in some of the cases.

(b) The same impact deformation time has on the cracks sizes. For example in most of the cases no cracks larger than 0.1 in width will be observed if the deformation time is 45 min. For 90 min deformation time, the number of cracks larger than 0.1 mm increases considerably, and can form a rate of 40% of the total number.

(c) Crack depth is also affected by the deformation time rate. In some of the investigated samples deformed after 45 min, most of the cracks were not going deeper than 0.01 mm into the mixture, while being deformed after 90 min half of the cracks were deeper than 0.1 mm.

3. Panel Thickness - Assuming the thickness of the panel will vary, than geometrically speaking, the cracks on the deformed surface should change in size as well. Because of this theoretical assumption it was decided to consider the thickness a parameter. Two different values were investigated in the research, these being - 25 mm and 50 mm. The impact of this parameter was evaluated and shortly presented below:
(a) The impact of the thickness of the panel on crack pattern was evaluated, and interesting facts were observed. Having a thicker panel will not directly result in more cracks on the deformed surface. There was a small difference spotted in all the examined samples, but being so small this difference could be neglected.

(b) Different results however were obtained considering the sizes of the cracks. Most of the results showed that having a thicker panel definitely will result in wider cracks. Increasing the thickness from 25 mm to 50 mm in some of the cases increased the number of cracks larger than 0.1 mm from a rate of 10% to a rate of 50% of the total crack number.

(c) Similar behavior was spotted regarding the crack depth. Significant increase of the average depth of the cracks was spotted in the thicker element.

Besides the three main parameters mentioned and discussed above, one more technological parameter was investigated.

4. Water/cement ratio - This parameter is directly affecting the tensile strength of the material, meaning that it should affect the crack pattern on the deformed element as well. Three different values were investigated for water/cement ratio, these being - 0.38, 0.43 and 0.5. A short discussion about the results is presented below:

(a) Analyzing the three different ratios presented above showed close results for the mixtures representing 0.43 and 0.5 water/cement ratios, if considering the crack frequency. A lot worse performed the lowest water/cement ratio samples, in some of the cases increasing the number of cracks by a factor of 3.

(b) Same tendency was observed regarding the crack sizes. The panels representing the highest two values of water/cement ratios behaved similarly, having most of the cracks smaller than 0.1 mm in width. Also very few cracks deeper than 5 mm were spotted in the samples with W/C=0.43, none in the samples where W/C=0.5 w/c and significantly more in the samples with the W/C=0.38.

✓ Trace and estimate the impact of the cracks on the durability of the concrete elements - In the Introduction Chapter of the current report a lot of information was gathered about the degradation mechanisms in concrete and the correlation between this mechanisms and cracking. Just analyzing the crack pattern and performing quantitative analysis is not enough, if no link is formed with the degradation mechanisms. The gathered information allowed to create a classification of crack sizes, related to their impact on the degradation process. The list was a result of literature review, and not a predefined one. An adjustment of this list can always be performed, as well as re-categorization of the cracks counted in the current research. The categorization lists helped in evaluating the direct impact of every parameter on the crack pattern, and estimating the influence of these parameters on the service life of the concrete panels.

✓ Explore and evaluate the performance of the alternative concrete mixtures in terms of cracking - The whole research was based on analyzing only one concrete mixture, which would describe a common used recipe on construction market nowadays. This makes the results helpful directly to the technologists and there is no need in result interpretation. However, beside the common mixture investigated, numerous cement-based alternatives are present on the market, which theoretically would perform better than the traditional concrete mixture. Two alternative materials
considered as potential alternatives, as Wood Fiber Reinforced Concrete and Strain Hardening Cementitious Composites.

1. Wood Fiber Reinforced Concrete - The mixture investigated in the current research was similar to the traditional mixtures used for the previous investigations, with the difference of adding wooden fibers into it. Numerous studies were realized regarding the ductility of the wooden reinforced concrete. Also, using wooden fibers makes the whole material more sustainable and affordable (in comparison to other fibrous cement mixtures). These were the main reasons why this material was selected for the investigations. The research was performed under the same conditions as with the traditional concrete mixture, and resulted in the following:

(a) Analyzing the frequency in WRC and comparing the results to the traditional concrete mixture, it was observed that the WRC material performs better. In most of the cases the number of cracks is diminished by the wooden fibers.

(b) Considering the sizes of the cracks, the same pattern was observed. The width of the cracks is smaller, the difference being very small though. A larger difference is observed in the crack depth evaluation, where the WRC performs considerably better. If in the traditional concrete mixtures cracks deeper than 5 mm could be spotted, no such were observed in the WRC elements.

2. Strain Hardening Cementitious Composite - This time the recipe of the mixture was chosen to be one common for SHCC materials. A mortar mixture (0.25 mm aggregate max size) was produced and PVA (polyvinyl alcohol) fibers were added. The results are listed below:

(a) Crack frequency was evaluated and it was observed that more cracks are formed in SHCC than in traditional concrete as a result of the physical deformation. The difference was considerable, since the number of cracks in SHCC was higher with about 70% on average.

(b) The width of the cracks though was substantially smaller in SHCC comparing to traditional concrete. If in common concrete cracks could reach 2 mm in width, in SHCC the largest crack spotted was smaller than 1 mm.

(c) The same results showed the crack depth values. SHCC performed considerably better in this case, especially analyzing 90 min deformation time samples, where in traditional concrete cracks were reaching values of 14 mm, in SHCC the deepest was approximately 1 mm. Only several cracks deeper than 1 mm could be observed

To generalize, both of the alternative materials performed better in terms of cracking compared to the traditional concrete mixture, especially SHCC. However, in order to fully consider them as replacement products more investigations should be performed, regarding production costs, affordability, availability and sustainability. Only evaluating these factors an overall determination of the best product can be realized. Considering only parameters investigated in the current research, the best results were provided by the Strain Hardening Cementitious Composite.

The section above presented the accomplished objectives of the current research and an overall description of the results obtained from the research investigations.
5.2. Recommendations
In the following chapter a list of recommendations will be provided to the specialist parties, which will be potentially involved in the design, manufacturing and installation of double-curved concrete elements. The recommendations are based on the results, observations and conclusions of the current research. It is important to mention that the recommendations presented in sections 5.2.1, 5.2.2 and 5.2.3 refer to the mixture described in Table 2.1, which was investigated during the current research.

5.2.1. Architecture
The part which is mostly related to architecture and was investigated in the current research was the deformation radius. The deformation radius allows the architects to understand the possibilities of the technology and to what extent of deformation curved concrete elements could be used. Knowing the limits of the material, the potential destinations of the material can be defined as well.

![Figure 5.1: Recommended values - Radius of deformation](image)

Considering the radius of deformation, from the values investigated, the 1.0 m radius performed the best. Analyzing the results of the investigations almost no cracks larger than 0.1 mm and deeper than 1 mm were found. The 0.5 m deformation radius can also be implemented, but only with technical limitations as deformation time. If the architect is in need in more deformed shapes, the elements should be deformed not later than 45 min after water was added to the mixture. 0.5 m radius represents the limit of deformation, according to the results of the research. 0.25 m radius, which was also analyzed in the current research, performed good in terms of crack depth, but significantly worse considering crack width. This basically means that for highly deformed elements as corner elements or column cladding elements, which would have a radius smaller than 0.5 m, additional techniques should be considered in the production process, such as surface treatment or reinforcement which would limit the cracking.

5.2.2. Engineering
In the first chapter of the current report the potential applications of double-curved concrete elements was discussed. Among the possible implementation destinations was the concept of lost formwork system. In case these type of elements would be designed, the engineers who will calculate them will look for thicker panels, since these panels will work as structural elements. The thickness of the panels was a parameter investigated in the current research.

![Figure 5.2: Recommended values - Thickness of the panel](image)

Two different thicknesses were investigated: 50 and 25 mm. The results showed that both values
can be used in practice, with some limitations though. A difference was observed in crack width. Generally, the 25 mm thick panel will not contain cracks wider than 0.5mm, which is not characteristic for the 50 mm panel. Thus, for thicker elements surface treatment should be considered as a solution to avoid propagation of large cracks.

In both of the cases it is strongly recommended to not deform the elements later than 60 min after water is added to the concrete mixture. That would limit the maximum crack width values. The results show that after 60 min the deformation will result in deep cracks, which can negatively affect the durability of the concrete material. Referring to the numbers, if the panels are deformed within the first 60 min, no cracks deeper than 2 mm will be formed as a result of deformation.

Reinforcement in Double-Curved Concrete Elements can be an important addition to the technology. One potential application of the elements which was discussed in the first chapter of the current report is the facade cladding elements. Since the concrete elements would have to be attached to a secondary structure of the facade, it is important to design a system of anchorages. The reinforcement in this case would assure that the anchorage system is properly installed and will not disconnect from the concrete mass. The reinforcement can as well reduce the cracking. Probably the frequency will not be influenced, but the crack maximum depths and widths can surely be reduced using reinforcement.

Since the production of DCCEs uses a flexible mould system, the reinforcement applied should also be flexible. The types of reinforcements that can be used were analyzed by Marijn Kok in his master thesis project [17].

5.2.3. Manufacturing
For the future manufacturers of this type of construction elements it is important to realize an economically feasible product, which can be produced in any shape and form is asked on the market. There are numerous technology-related issues which have to be considered before producing double-curved concrete elements. Some of them have been investigated in the current research.

*Deformation time* - Represents the time span between the moment when water is being added to the concrete mixture and the moment when the concrete panel is being deformed. The deformation time is not important only because of technological reasons, but also for organizational ones. Since the flexible mould is planned to be used, the impact of the deformation time on the production operations process is very high. Considering only deformation time, the recommended value is 60 min. Later deformation times investigated were resulting in wider or deeper cracks in some of the cases and can be used with certain limitations and additional techniques. The 60 min deformation time would assure that no wide nor deep cracks are formed on the surface of the deformed concrete, meaning that the damage mechanisms would not affect the concrete significantly.

*Water/cement Ratio* - Three different values for water cement ratio were investigated during the current research - 0.38, 0.43 and 0.5. The results of the investigations showed that the highest two values performed similarly in terms of cracking, and both can be used in the later mass production process. Both of the mixtures are flexible enough to deform to sufficient extents, the only decisive factor would be the desired strength of the material. It is not recommended to use the 0.38 water/cement ratio mixture, since the results showed that this type of mixture can result in cracks up to 19 mm deep and 3 mm wide.

Procedure recommendations
The procedure of fabrication of the investigation specimens was explained in detail in Chapter 2. One complex issue observed during the production process is that mixing the same concrete recipe two consecutive times is almost impossible. The same mix-design was re-used several times in the current research, and it never resulted in the same characteristics. A recommendation for the potential producers would be to use more flexible moulds, so that larger amounts of the same concrete mixture could be used at a time. Varying too often the mix design within the same range of products could result in aesthetic differences.

Another technical recommendation related to the production of the double curved elements is the surface treatment. The surface of the panels which can crack as a result of deformation usually is not the exposed one. Since it will not be visible when mounted as a structure, the surface can be physically treated to limit the crack formation, by using additives or regular hydration (self-healing).

5.2.4. Alternative Materials

Two alternative materials were investigated and compared to the traditional concrete mixture - Wood Fiber Reinforced Concrete and Strain Hardening Cementitious Composite. Both these materials performed better than the traditional concrete and definitely can be used in the production process.

The WRC overall performed better in terms of cracking, comparing to the traditional concrete. Both the frequency and crack sizes were smaller for the material containing the wooden fibers. The difference between the two mixtures is very small, almost negligible. The wooden fibers managed mostly to bridge and to limit the max crack width and almost did not succeed in limiting the crack depth.

The SHCC material performed significantly better than the traditional concrete. Even if the frequency of the cracks was higher in SHCC, the sizes of the cracks, both width and depth were substantially lower.

Further calculations have to be performed regarding material feasibility in order to determine which material is better to be used in double-curved concrete technology.

5.3. Further Research

There are numerous potential studies which would complete the current research. Few of them are listed below:

- **Influence of cracks on degradation mechanisms** - An important study would be to investigate at what extent the crack sizes and crack pattern in general contribute to degradation mechanisms. The researches performed so far are mostly related to reinforcement corrosion and chloride penetration. More mechanisms could be investigated and as a result a certain range of crack size limits would be determined, crucial for every degradation mechanism.

- **Various surface treatment procedures** - For the current research no surface treatment procedures were considered during the aging of concrete panels, besides the limiting of evaporation process using plastic foils. The technology permits already today to use numerous techniques in order to avoid crack formation or other damages. A potential research subject would be to evaluate the impact of these techniques on the cracking pattern and to determine the best techniques which should be applied, and most important when - before or after hardening.

- **Materials’ Study** - In the current research two alternative materials were evaluated in comparison with the traditional concrete mix design. In order to determine the most suitable one for the double-curved concrete technology, a more detailed evaluation has to be performed, and
5.4. General Conclusions

The current research represents a qualitative and quantitative analysis of the crack pattern formed in double-curved concrete elements. The technology analyzed represents a combination of existing and available techniques of precast concrete fabrication with a flexible mould system, which allows the casting of free-form concrete elements. This combination comes to sustain the entire development process of free-form modern architecture. The flexible mould system relies on deformation of the concrete panel at very early age, when the tensile strength of the material had not reached too high values. Due to this physical deformation and the tensile stresses created in the material a crack pattern can be formed on the surface of the material. In this research an evaluation of this pattern has been performed, by analyzing the quantitative and qualitative characteristics of it. Numerous parameters were considered in the investigations: deformation time, water/cement ratio, radius of deformation, thickness of the element. These parameters were considered crucial in crack formation that is why the impact of each of them was determined through the current research. Besides the parameter investigations, two alternative materials were studied, which were considered potential replacements for the traditional concrete - Wood Fiber Reinforced Concrete and Strain Hardening Cementitious Composite. The results of the current research showed that fabrication of double-curved concrete elements by using flexible mould system can be realized without bringing considerable changes in the concrete micro structure. In result, a list of recommendations was produced with the aim to help the main parties involved in design, construction and installation of double-curved concrete elements - a list for architects, engineers and manufacturers.

The modern architecture becomes more complicated and challenging each day. In order to sustain this development, it is important to develop production techniques and materials which will assure proper implementation of modern designs. Certainly double-curved concrete panels produced by the use of the flexible mould system integrate in these techniques and can bring significant amount of flexibility in the future architectural entities.
Results of the main investigations
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<th>Frequency of the cracks</th>
<th>Average Frequency</th>
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Appendix A1: Results Non-deformed elements and Elements with 1.0 m R
### Specimen Name

| MT50R-25.45.1 | MT50R-25.45.2 | MT50R-25.50.1 | MT50R-25.50.2 | MT50R-25.75.1 | MT50R-25.75.2 | MT50R-25.90.1 | MT50R-25.90.2 | MT50R-50.45.1 | MT50R-50.45.2 | MT50R-50.75.1 | MT50R-50.75.2 | MT50R-50.90.1 | MT50R-50.90.2 |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Number of Cracks | 26.00 | 26.00 | 39.00 | 16.00 | 34.00 | 36.00 | 34.00 | 40.00 | 28.00 | 23.00 | 23.00 | 26.00 | 28.00 | 36.00 | 28.00 | 23.00 |
| Average number of cracks | 26.00 | 27.50 | 35.00 | 37.00 | 25.00 | 24.50 | 32.00 | 25.00 |
| Width of the Specimen | 5.55 | 5.55 | 5.60 | 5.65 | 5.70 | 5.60 | 5.60 | 5.60 | 5.60 | 5.60 | 5.60 | 5.60 | 5.60 | 5.60 | 5.60 | 5.60 |
| Frequency of the cracks | 3.48 | 3.48 | 6.96 | 2.83 | 5.96 | 5.54 | 5.57 | 6.45 | 4.83 | 3.97 | 4.11 | 4.68 | 4.87 | 6.26 | 5.00 | 4.11 |
| Average Frequency | 4.68 | 4.90 | 5.75 | 6.01 | 4.40 | 4.40 | 5.57 | 4.55 |
| Average Crack Width (Sample) | 0.09 | 0.06 | 0.09 | 0.10 | 0.08 | 0.12 | 0.15 | 0.17 | 0.15 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 |
| Maximum Crack Width (Sample) | 1.17 | 0.20 | 0.22 | 0.28 | 0.26 | 0.28 | 0.40 | 0.16 | 1.00 | 0.45 | 1.80 | 0.45 | 0.90 | 0.65 | 2.10 | 1.80 |
| Average Crack Depth (Sample) | 0.08 | 0.08 | 0.14 | 0.16 | 0.67 | 0.20 | 0.35 | 0.23 | 0.26 | 0.17 | 0.17 | 0.71 | 0.75 |
| Maximum Crack Depth (Sample) | 0.60 | 0.20 | 0.40 | 0.20 | 0.44 | 0.62 | 15.00 | 1.00 | 1.25 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 0.75 | 14.44 | 13.40 |
| Maximum Crack/Depth (Sample) | 0.60 | 0.40 | 0.62 | 15.00 | 1.25 | 1.10 | 1.10 | 1.10 | 14.44 |
| Cracks Width <0.01 mm | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cracks Width >0.01 mm (AVG) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cracks Width >0.1 mm | 24.0 | 25.0 | 35.0 | 16.0 | 26.0 | 25.0 | 25.0 | 33.0 | 14.0 | 14.0 | 14.0 | 14.0 | 14.0 | 16.0 | 16.0 | 14.0 |
| Cracks Width <25 mm (AVG) | 24.5 | 25.5 | 25.5 | 23.5 | 29.0 | 11.5 | 14.5 | 17.0 | 15.0 |
| Cracks Width >25 mm (AVG) | 2.0 | 4.0 | 0.0 | 8.0 | 11.9 | 7.4 | 14.0 | 10.0 | 16.0 | 14.0 |
| Cracks Depth >0.1 mm | 24.0 | 22.0 | 31.0 | 11.1 | 16.0 | 16.0 | 16.1 | 9.8 | 11.8 | 15.0 | 10.7 | 3.0 |
| Cracks Depth <0.1 mm (AVG) | 23.0 | 21.0 | 16.0 | 12.0 | 10.0 | 9.5 | 11.5 | 8.5 |
| Cracks Depth <1 mm | 2 | 4 | 8 | 5 | 18 | 23 | 20 | 14 | 14 | 14 | 19 | 21 | 17 | 15 |
| Cracks Depth <1 mm (AVG) | 3 | 6.5 | 19 | 23.5 | 13.5 | 14 | 20 | 16 |
| Cracks Depth >1 mm | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 3 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Cracks Depth >1 mm (AVG) | 0 | 0 | 0 | 0.5 | 2 | 1 | 0.5 | 0 |
| Cracks Depth >5 mm | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| Cracks Depth >5 mm (AVG) | 0 | 0 | 0 | 0.5 | 0 | 0 | 0 | 1 |

Appendix A2: Results Elements with 0.5 m R
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Appendix A3: Results Elements with 0.25 m R
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Appendix A4: Results SHCC and WRC
| Specimen Name | W/C-0.38-45.2 | W/C-0.38-75.1 | W/C-0.38-60.2 | W/C-0.50-45.2 | W/C-0.50-90.2 | W/C-0.50-75.2 | W/C-0.50-90.2 | W/C-0.50-60.2 | W/C-0.38-45.2 | W/C-0.38-75.1 | W/C-0.38-60.2 | W/C-0.50-45.2 | W/C-0.50-90.2 | W/C-0.50-75.2 | W/C-0.50-90.2 |  
|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Number of Cracks | 11.00 | 18.00 | 28.00 | 22.00 | 24.00 | 26.00 | 29.00 | 25.00 | 8.00 | 12.00 | 16.00 | 19.00 | 21.00 | 23.00 | 19.00 |  
| Average number of cracks | 14.50 | 25.00 | 25.00 | 27.00 | 10.00 | 17.50 | 22.00 | 20.00 |  
| Width of the Specimen | 5.55 | 5.55 | 5.60 | 5.60 | 5.75 | 5.75 | 5.50 | 5.55 | 5.90 | 5.95 | 5.75 | 5.70 | 5.60 | 5.60 | 5.60 |  
| Frequency of the cracks | 1.98 | 3.24 | 5.00 | 3.93 | 4.17 | 4.52 | 5.27 | 4.50 | 1.36 | 2.02 | 2.78 | 3.33 | 3.75 | 3.75 | 4.11 | 3.39 | 3.75 |  
| Average Frequency | 2.61 | 4.46 | 4.35 | 4.89 | 1.69 | 4.06 | 3.93 | 3.57 |  
| Average Crack Width (Specimen) | 0.28 | 0.26 | 0.17 | 0.27 | 0.34 | 0.27 | 0.14 | 0.18 | 0.07 | 0.05 | 0.10 | 0.09 | 0.24 | 0.29 | 0.22 | 0.18 |  
| Average Crack Width (Sample) | 0.27 | 0.21 | 0.30 | 0.16 | 0.06 | 0.16 | 0.27 | 0.20 |  
| Maximum Crack Width (Specimen) | 0.65 | 0.84 | 0.85 | 1.23 | 2.58 | 1.27 | 1.32 | 1.43 | 0.28 | 0.15 | 0.40 | 0.35 | 2.78 | 3.69 | 1.43 | 1.46 |  
| Maximum Crack Width (Sample) | 0.84 | 1.23 | 2.58 | 1.43 | 0.28 | 0.40 | 3.69 | 1.46 |  
| Average Crack Depth (Specimen) | 0.76 | 0.46 | 0.45 | 0.67 | 0.84 | 0.79 | 0.96 | 0.98 | 0.17 | 0.16 | 0.24 | 0.17 | 0.60 | 0.22 | 0.29 | 0.30 |  
| Average Crack Depth (Sample) | 0.58 | 0.55 | 0.82 | 0.97 | 0.16 | 0.20 | 0.22 | 0.29 |  
| Maximum Crack Depth (Specimen) | 4.11 | 3.31 | 4.77 | 6.10 | 7.83 | 6.81 | 18.13 | 14.47 | 0.30 | 0.38 | 0.41 | 0.32 | 10.21 | 2.36 | 2.79 |  
| Maximum Crack Depth (Sample) | 4.11 | 6.10 | 7.83 | 18.13 | 0.30 | 0.41 | 10.21 | 4.10 |  
| Cracks Width <0.01 mm | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  
| Cracks Width <0.1 mm (AVG) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  
| Cracks Width <0.1 mm | 3 | 5 | 12 | 6 | 6 | 7 | 21 | 14 | 7 | 11 | 12 | 14 | 15 | 13 | 5 | 11 |  
| Cracks Width <0.1 mm (AVG) | 4 | 9 | 6.5 | 17.5 | 9 | 13 | 14 | 8 |  
| Cracks Width <25 mm | 8 | 13 | 16 | 16 | 18 | 18 | 8 | 11 | 1 | 1 | 4 | 5 | 6 | 10 | 14 | 10 |  
| Cracks Width <25 mm (AVG) | 10.5 | 16 | 18.1 | 18.1 | 9.5 | 15 | 13.5 | 13 |  
| Cracks Width <25 mm | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  
| Cracks Width >25 mm (AVG) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  
| Crack Depth <0.1 mm | 0 | 2 | 8 | 2 | 3 | 3 | 4 | 7 | 3 | 5 | 0 | 1 | 8 | 11 | 9 | 11 |  
| Crack Depth <0.1 mm (AVG) | 1 | 5 | 3 | 5.5 | 4 | 0.5 | 9.5 | 10 |  
| Crack Depth <1 mm | 9 | 15 | 18 | 18 | 18 | 19 | 23 | 15 | 5 | 7 | 16 | 18 | 12 | 11 | 9 | 9 |  
| Crack Depth <1 mm (AVG) | 12 | 18 | 18.1 | 19 | 6 | 17 | 13.5 | 9 |  
| Crack Depth >1 mm | 2 | 1 | 2 | 1 | 2 | 3 | 1 | 2 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |  
| Crack Depth >1 mm (AVG) | 1.5 | 1.5 | 2.5 | 1.5 | 0 | 0 | 0.5 | 1 |  
| Crack Depth >5 mm | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |  
| Crack Depth >5 mm (AVG) | 0 | 0.5 | 1 | 1 | 0 | 0 | 0.5 | 0 |  

Appendix A5: Results variation of W/C ratios
Results of the Pilot Test
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<tr>
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<th>TT60</th>
<th>TT90</th>
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<tbody>
<tr>
<td><strong>T60-Sample 1</strong></td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td><strong>T60-Sample 2</strong></td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td><strong>T90-Sample 1</strong></td>
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<td>15</td>
</tr>
<tr>
<td><strong>T90-Sample 2</strong></td>
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</tr>
<tr>
<td><strong>Total Number of cracks</strong></td>
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<tr>
<td><strong>Length of the Sample</strong></td>
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<td>6.68</td>
<td>6.58</td>
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<td><strong>Frequency cracks per cm</strong></td>
<td>2.11</td>
<td>2.27</td>
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<td>2.02</td>
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<tr>
<td><strong>Maximum Thickness crack</strong></td>
<td>0.7</td>
<td>2.5</td>
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<td></td>
<td>0.70</td>
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<td><strong>Minimum Thickness crack</strong></td>
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<td>0.10</td>
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<td><strong>Maximum Depth crack</strong></td>
<td>2.3</td>
<td>4.3</td>
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<td>4.30</td>
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<td><strong>Minimum Depth crack</strong></td>
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<td>0.05</td>
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<td><strong>Average Thickness crack</strong></td>
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<td>0.17</td>
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<td><strong>Average Depth crack</strong></td>
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<td>1.62</td>
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<td>1.06</td>
<td>1.43</td>
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<td><strong>Nr cracks thicker &gt; 1mm</strong></td>
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<td>12</td>
</tr>
<tr>
<td><strong>Nr cracks deeper &gt; 1mm</strong></td>
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<td>9</td>
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<tr>
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<td>7.50</td>
<td>8.50</td>
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<td><strong>Nr cracks deeper &gt; 2mm</strong></td>
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Appendix B1: Results Pilot Test
Slump tests results
Appendix C1: Results Slump Tests ND and R50

### Session #1 MT50R and ND

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<thead>
<tr>
<th>Date</th>
<th>1-May-14</th>
<th>Sand 0.125-0.25 mm</th>
<th>0.34 kg</th>
<th>Sand 0.25-0.5 mm</th>
<th>0.90 kg</th>
<th>Sand 0.5-1.0 mm</th>
<th>1.46 kg</th>
<th>Gravel 1-2 mm</th>
<th>2.03 kg</th>
<th>Gravel 2-4 mm</th>
<th>2.59 kg</th>
<th>Gravel 4-8 mm</th>
<th>3.94 kg</th>
<th>CEM I 52.5 R</th>
<th>2.8 kg</th>
<th>Fly-ash</th>
<th>1.12 kg</th>
<th>Specific Mass</th>
<th>2343.53 kg/m³</th>
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<tr>
<td></td>
<td></td>
<td>Superplast Chryso Premia 196</td>
<td>0.027 kg</td>
<td>(0.70% of pwd)</td>
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<tr>
<td>Aggregates + Cement + Fly-ash</td>
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<tr>
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<tr>
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<td>90 sec</td>
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### Session #2 MT25R

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<th>Date</th>
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<th>Sand 0.125-0.25 mm</th>
<th>0.24 kg</th>
<th>Sand 0.25-0.5 mm</th>
<th>0.64 kg</th>
<th>Sand 0.5-1.0 mm</th>
<th>1.04 kg</th>
<th>Gravel 1-2 mm</th>
<th>1.45 kg</th>
<th>Gravel 2-4 mm</th>
<th>1.85 kg</th>
<th>Gravel 4-8 mm</th>
<th>2.81 kg</th>
<th>CEM I 52.5 R</th>
<th>2.0 kg</th>
<th>Fly-ash</th>
<th>0.8 kg</th>
<th>Specific Mass</th>
<th>2343.53 kg/m³</th>
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</thead>
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<tr>
<td></td>
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<td>Water</td>
<td>0.86 kg</td>
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<td>Superplast Chryso Premia 196</td>
<td>0.0196 kg</td>
<td>(0.70% of pwd)</td>
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<tr>
<td>Aggregates + Cement + Fly-ash</td>
<td></td>
<td>30 sec</td>
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<tr>
<td>Add 10% of Water + Premia</td>
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<td>90 sec</td>
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### Appendix C2: Results Slump Tests R25

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<tr>
<th>Slump</th>
<th>Height (mm)</th>
<th>Slump (mm)</th>
<th>c_o (Pa)</th>
<th>at t =</th>
<th>min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump #1</td>
<td>0.42</td>
<td>0.08</td>
<td>399.16</td>
<td>at t =</td>
<td>6</td>
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<td>Slump #2</td>
<td>0.48</td>
<td>0.02</td>
<td>398.16</td>
<td>at t =</td>
<td>15</td>
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<tr>
<td>Slump #3</td>
<td>0.50</td>
<td>0.00</td>
<td>465.80</td>
<td>at t =</td>
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### Appendix C3: Results Slump Tests R100

#### Session #3 MT100R

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<th>Date</th>
<th>Aggregate Size</th>
<th>Quantity (kg)</th>
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<tr>
<td>1-May-14</td>
<td>sand 0.125-0.25 mm</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>sand 0.25-0.5 mm</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>sand 0.5-1.0 mm</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>gravel 1-2 mm</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>gravel 2-4 mm</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>gravel 4-8 mm</td>
<td>2.81</td>
</tr>
<tr>
<td></td>
<td>CEM I 52.5 R</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>Fly-ash</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Superplast Chryso Premia 196</td>
<td>0.0196 (0.70% of pwd)</td>
</tr>
<tr>
<td></td>
<td>water</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>specific mass</td>
<td>2343.53 kg/m³</td>
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<tr>
<td></td>
<td>wcf</td>
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<tr>
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<td>wpf</td>
<td>0.307</td>
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- **Batch Volume**: 5.00 ltr
- **Slump Results**:
  - Slump #1: 0.40 mm, τ₀ = 532.60 Pa at t = 5 min
  - Slump #2: 0.48 mm, τ₀ = 639.10 Pa at t = 15 min
  - Slump #3: 0.50 mm, τ₀ = 667.80 Pa at t = 45 min

#### Session #4 W/C 0.38

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<th>Aggregate Size</th>
<th>Quantity (kg)</th>
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<td>1-May-14</td>
<td>sand 0.125-0.25 mm</td>
<td>0.25</td>
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<tr>
<td></td>
<td>sand 0.25-0.5 mm</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>sand 0.5-1.0 mm</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>gravel 1-2 mm</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>gravel 2-4 mm</td>
<td>1.91</td>
</tr>
<tr>
<td></td>
<td>gravel 4-8 mm</td>
<td>2.91</td>
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<tr>
<td></td>
<td>CEM I 52.5 R</td>
<td>2.00</td>
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<tr>
<td></td>
<td>Fly-ash</td>
<td>0.80</td>
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<tr>
<td></td>
<td>Superplast Chryso Premia 196</td>
<td>0.0196 (0.70% of pwd)</td>
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<td>water</td>
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<td>wpf</td>
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</table>

- **Batch Volume**: 5.00 ltr
- **Slump Results**:
  - Slump #1: 0.48 mm, τ₀ = 671.10 Pa at t = 8 min
  - Slump #2: 0.48 mm, τ₀ = 648.10 Pa at t = 15 min
  - Slump #3: 0.50 mm, τ₀ = 667.80 Pa at t = 45 min

---

Appendix C4: Results Slump Tests W/C 0.38
Appendix C5: Results Slump Tests W/C 0.50

Session #5  W/C 0.50

<table>
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<tbody>
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<td>sand 0.125-0.25 mm</td>
</tr>
<tr>
<td>sand 0.25-0.5 mm</td>
</tr>
<tr>
<td>sand 0.5-1.0 mm</td>
</tr>
<tr>
<td>gravel 1-2 mm</td>
</tr>
<tr>
<td>gravel 2-4 mm</td>
</tr>
<tr>
<td>gravel 4-8 mm</td>
</tr>
<tr>
<td>CEM I 52,5 R</td>
</tr>
<tr>
<td>Fly-ash</td>
</tr>
<tr>
<td>Superplast Chryso Premia 196</td>
</tr>
<tr>
<td>water</td>
</tr>
<tr>
<td>specific mass</td>
</tr>
<tr>
<td>wcf</td>
</tr>
<tr>
<td>wpf</td>
</tr>
<tr>
<td>batch volume</td>
</tr>
</tbody>
</table>

|                                                                 |          |
| aggregates + cement + fly-ash                                        | 30 sec   |
| add 90% of water                                                     | 60       |
| add 10% of water + Premia                                            | 90       |
| scraping of mixer                                                    | 30       |
|                                                                           | 210 sec  |

Hobart Mixer

<table>
<thead>
<tr>
<th>Height [mm]</th>
<th>Slump [mm]</th>
<th>$\tau_c$ [Pa]</th>
<th>$t$ [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>slump #1</td>
<td>flow</td>
<td>212.45</td>
<td>7</td>
</tr>
<tr>
<td>slump #2</td>
<td>0.28</td>
<td>0.22</td>
<td>369.50</td>
</tr>
<tr>
<td>slump #3</td>
<td>0.50</td>
<td>0.00</td>
<td>651.30</td>
</tr>
</tbody>
</table>
Images of the investigation procedure
Appendix D1: Mould Construction

Appendix D2: Mould Construction and Casting Preparation

Appendix D3: Casting and Specimen Preparation

Appendix D4: Casting and Specimen Preparation
Bibliography


[7] EUROCODE2-Design of Concrete Structures. (EN-206)


[12] Isler H. “Concrete Shells Derived from Experimental Shapes Concrete shells derived from experimental shapes” Structural Engineering International, 1994


[18] Li V.C. "On Engineered Cementitious Composites On engineered cementitious composites” Journal of Advanced Concrete Technology, 2003


[26] Russel P. "Efflorescence and the Discoloration of Concrete” Taylor and Francis, 2005

[27] Schipper H.R., Janssen B. "Manufacturing double-curved concrete elements in precast concrete using a flexible mould - First Experimental Results" 2011

[28] Schipper R. "Manufacturing Double-curved Concrete Elements” (to be published) Technical University of Delft

[29] Sierra-Beltran M. "Ductile Cement-based Composites with Wood Fibres” Delft Technical University of Technology, 2011


[33] Tittelboom K.V., Belie N.D. "Self-Healing in Cementitious Materials A Review" Magnel Laboratory for Concrete Research, Department of Structural Engineering, Faculty of Engineering, Ghent University, 2013

[34] Valenza J., Scherer G.W., "Mechanism for salt scaling of a cementitious surface" RILEM Spring Meeting, 2004


[36] Vesikari E. "Carbonation and Chloride Penetration in Concrete Carbonation and chloride penetration in concrete" 2009


[38] Winter N.B. "Understanding Cement" WHDMicroanalysis Consultants Ltd. 2012