MASTER

Magnetically orienting steel fibres in self-compacting concrete

Wijffels, M.J.H.

Award date:
2014

Link to publication
MAGNETICALLY ORIENTING STEEL FIBRES IN SELF-COMPACTING CONCRETE

M.J.H. WIJFFELS
MAGNETICALLY ORIENTING

STEEL FIBRES IN

SELF-COMPACTING CONCRETE

DATE: 22 DECEMBER 2013
REPORT NUMBER: A-2013.55
VERSION 2.0

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ACKNOWLEDGEMENTS

This graduating thesis is the result of a research at the Department of the Built Environment, Unit Structural Design at Eindhoven University of Technology. I would like to thank some people and instances by name for their contribution.

Roel Schipper for giving me the opportunity to perform my experimental research at Delft University of Technology and for helping me on the rheological experiments. Steffen Grünewald for helping me with the mixture design and performing the rheological experiments. Ton Blom for his assistance during the experiments. Barend van Arkel for spending his first days of holiday on wrapping the coil. Ivo de Visser, Sjaak Mangnus and Thomas Paus for helping me on carrying out the experimental program. Sven van de Bulck for performing the fibre pull-out tests.

The members of the Pieter van Musschenbroek laboratory for their kind help and advice during the entire study. The members of the group Transport in Permeable Media for their advice on the test set-up. Fontys Paramedic Academy Eindhoven for giving me the opportunity to take X-ray images. Tineke van Helvert for her expertise and help on taking the X-ray images. BASF Nederland B.V. for kindly offering me superplasticizer and stabilizer. Metalproducts B.V. for sponsoring the steel fibres. Math Pluis for participating in the committee. Finally, my family for their support and for repairing the car damage that was caused by the heavy load of the concrete.

Mark Wijffels
The construction industry is reticent in the use of Steel Fibre Reinforced Concrete (SFRC). After years of existence, the scope of application of SFRC is still mainly limited to elastic supported slabs. The industry remains cautious by the absence of proper regulation. This is mainly due to the relatively large spread in the material properties. The spread is mainly caused by the anisotropic fibre orientation and the inhomogeneous distribution of the fibres. Research on fibre distribution demonstrates that the amount of fibres in adjacent cross-sectional planes sometimes varies with a factor three. Keeping this in mind, it is important to optimally use the present fibres in a cross-section.

Experiments on pull-out load on single fibres indicate that optimal fibre inclinations angles may be within 10 to 30 degrees which results in a increase in peak load of 20 percent. Bending tests on SFRC beams with aligned fibres show a post-cracking behaviour which is significantly improved in comparison with beams that contain completely non aligned fibres. If it is possible to orient steel fibres in order to improve the bending moment capacity of the composite SCFRC at a constant volume fraction of steel fibres, it is indirectly possible to decrease the volume of steel fibres at a constant bending moment capacity. By increasing the efficiency of the present steel fibres, it might be possible to construct more durable and cost-efficient.

In this research, a method to magnetically orient fibres is presented. A magnetic field is generated by running a current through an electromagnetic coil. The fibres in a freshly casted beam tend to align to the magnetic field lines, which are directed in the span direction of the beam. The coil will be shifted over a freshly casted beam to orient all fibres in the beam. The method requires a conditioned environment and is therefore suitable for the prefab industry. Self-Compacting Concrete (SCC) is commonly used in the prefab industry and the method therefore focuses on Self-Compacting Fibre Reinforced Concrete (SCFRC).

By means of experimental research, the influence of a magnetic field on the behaviour a single fibre and the interaction between multiple fibres is studied. An electromagnetic coil was designed and built to generate a magnetic field. To enable observation on the behaviour, at first instance a translucent medium with similar rheological properties as SCC was used.
It appears that the orientation of a fibre is not blocked by gravel. The required time to orient a fibre decreases exponentially at increasing flux density. A magnetic flux density of \(2.3 \times 10^{-2} \, \text{T}\) makes it possible to orient a single fibre in a medium with a plastic viscosity of 60 Pa\cdot s in approximately 10 seconds.

The governing parameters for orientating fibres in SCFRC beams are the velocity of the specimen through the coil, and the flux density. The effect of both parameters on the orientation of the fibres was studied. A new electromagnetic coil was designed and twelve specimen were oriented using different combinations of velocity and flux density. The effect on the orientation of the fibres was evaluated by using X-ray imaging. The increase of the flux density enhances the alignment of the fibres to the field lines. However, it has negative consequences on the homogeneity of the fibre distribution. X-ray imaging revealed that the fibres have an increasing tendency to cluster. The optimal process parameters were used to investigate the effect of the orienting of fibres on the bending moment capacity. Six non-oriented, reference, beams, were compared with six oriented beams based upon a four point flexural test without notch. The orienting of the fibres did not lead to an increase in bending moment capacity.

Characteristic for the four point flexural test is that the specimen fails at the weakest cross-section. The weakest cross-section is however artificially created by exposing the specimen to a magnetic field which resulted in clustering. It is therefore explicable that the oriented specimen did not show an increasing bending moment capacity with respect to non-oriented specimen.

Additional research should be carried out to reveal the potential of the method. The bending moment capacity of normal casted beams should be compared with completely aligned beams to investigate to what extend improvement can be reached. Then, research should be carried out on the effect of the clustering of fibres on the bending moment capacity. If it appears that the clustering behaviour has a negative effect, the method should be improved to minimize the clustering effect. Possibilities are the design of a new fibre type or division of the mould during the orientation process.
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CHAPTER 1

1.1 SUBJECT

The construction industry is reticent in the use of Steel Fibre Reinforced Concrete (SFRC). After years of existence, the scope of application of SFRC is still mainly limited to elastic supported slabs. The industry remains cautious by the absence of proper regulation. This is mainly due to the relatively large spread in the material properties. The spread is caused by the anisotropic fibre orientation and the inhomogeneous distribution of the fibres. Research on fibre distribution [1] demonstrates that the amount of fibres in adjacent cross-sectional planes sometimes varies with a factor three. Keeping this in mind, it is important to optimally use the present fibres in a cross-section.

Experiments on pull-out load on single fibres indicate that the optimal fibre angle with respect to the main tensile stress is 10 to 30 degrees [2][3]. Bending tests on SFRC beams with aligned fibres show a post-cracking behaviour which is significantly improved in comparison with beams that contain completely non aligned fibres [4]. If it is possible to improve the bending moment capacity of SFRC at a constant volume fraction of steel fibres, it is indirectly possible to decrease the volume of steel fibres at a constant bending moment capacity. By increasing the efficiency of the present steel fibres, it might be possible to construct more durable and cost-efficient. If it appears that orienting steel fibres in SCFRC improves the mechanical properties of the composite, new research possibilities open up. Research on replacing stirrups by oriented steel fibres could be performed. Since stirrups are labour-intensive, a significant cost reduction could be achieved.

Steel fibres are ferromagnetic. That makes it possible to orient them by means of a magnetic field. The idea of orienting fibres by means of a magnetic field originates from 1977. Miller and Björklund proposed a method to orient fibres in slabs by moving a freshly casted slab through a rectangular coil [5]. The method was successfully tested on sample bodies of 40 mm. In 2001, Svedberg patented a method to align all fibres in a cross-section at a predefined height [6], see Figure 1.1. The goal of this method was to replace traditional reinforcement by steel fibres without negatively affecting the mechanical properties.
However, a literature survey points out that a combination of both traditional reinforcement and steel fibres could be much more effective [7].

![Image](image1)

**Figure 1.1** – A rotating magnet is shifted through a viscous medium with fibres. The fibres are attracted and released at a predefined height.

In this research, a new method to orient fibres is developed, see Figure 1.2. A magnetic field is generated by running a current through a electromagnetic coil. The fibres in a freshly casted beam tend to align to the magnetic field lines, which are directed in the span direction of the beam. The coil will be shifted over a freshly casted beam in order to orient all fibres in the beam. It is important that the field is homogeneous to prevent the fibres from clustering. The method requires a conditioned environment and is therefore suitable for the prefab industry. Self-Compacting Concrete (SCC) is commonly used in the prefab industry and the method therefore focuses on Self-Compacting Fibre Reinforced Concrete (SCFRC).

![Diagram](diagram1)

**Figure 1.2** – A method to align fibres to the span direction in a SCFRC beam. An electromagnetic coil can be shifted over a freshly casted beam. Left: fibres unaligned. Right: fibres aligned.
1.2 RESEARCH OBJECTIVE

The main purpose of this research is to orient steel fibres in such a way that the bending moment capacity of the composite SCFRC can be improved.

1.3 RESEARCH STRATEGY

The first step in this research is to design an electromagnetic coil to be able to generate a magnetic field. The coil will be used to investigate the behaviour of a single fibre in a magnetic field. To enable observation of the behaviour, a translucent medium with similar rheological properties as SCC will be used. Subsequently, the research will be extended to study the behaviour of multiple fibres in a magnetic field.

Then, the transition to orienting fibres in SCC will be made. By experimental research, the effect of the governing parameters on the fibre orientation in SCC will be studied. The fibre orientation will be evaluated by using X-ray imaging. Finally, the influence of orienting fibres using the new method that is presented in this research on the bending moment capacity will be studied.

The report can be divided into three main parts: Introduction, Main Study and Conclusions. The outline of the rapport is visualized in Figure 1.3. The content of the chapters will be briefly discussed.
Figure 1.3 – Outline of the report.
INTRODUCTION

Chapter 2. Theoretical background
Overview of previous work on related topics that provide the necessary background for the purpose of this research.

MAIN STUDY

Chapter 3. Design of an electromagnetic coil
The design process of an electromagnetic coil. Verification of the coil using finite element software.

Chapter 4. Orienting fibres
Design of an electromagnetic coil. Study of the behaviour of steel fibres in a viscous medium under the influence of a magnetic field.

Chapter 5. Orienting fibres in SCC
Design of a SCFRC mixture. Experimental research on rheological properties of the mixture. Experimental research on orienting fibres in a freshly casted SCFRC beam.

Chapter 6. The effect of oriented fibres on the mechanical behaviour of SCFRC
Experimental research on the mechanical behaviour of oriented fibres in beams.

Chapter 7. The effect of coupled fibres on the pull-out behaviour
Experimental research on the effect of the clustering of fibres on the pull-out behaviour of a steel fibre.

CONCLUSION

Chapter 8. Conclusions and recommendations
THEORETICAL BACKGROUND

CHAPTER 2

2.1 INTRODUCTION

This chapter presents an overview of previous work on related topics that provide the necessary background for the purpose of this research. In Table 2.1, an overview of the topics that will be discussed are listed. It is specified for which chapter the information is useful and which topics are recommended to understand this research.

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Table 2.1 – Overview of the discussed topics per chapter.
2.2 FIBRE IN A MAGNETIC FIELD

In this paragraph, a model is presented to describe the behaviour of a steel fibre in a magnetic field. It forms the basis to be able to interpret the results of the experimental research that will be conducted during this study.

2.2.1 HYSTERESIS CURVE

In Figure 2.1, the relation between the magnetization and the magnetising field is visualized in the hysteresis curve. A ferromagnetic material will be magnetized if it is exposed to an external magnetic field $H$. With an increasing field $H$, the magnetization of a substance approaches a saturation value. If $H$ decreases, the material remains magnetized at the remanence value $B_r$. The flux density of the material can be brought to zero by applying a negative coercive field $H_c$.

![Hysteresis curve](image)

**Figure 2.1** – Hysteresis curve for a ferromagnetic material.

The magnetization $M$ lies in between the borders of the hysteresis curve. For material equations, the magnetic polarisation can be derived from the magnetization.

\[ \mathbf{J} = \mu_0 \mathbf{M} \quad \text{(2.1)} \]

with:

- $\mathbf{J}$ = magnetic polarisation \([T]\)
- $\mu_0$ = vacuum permeability \([\text{Vs} / \text{Am}]\)
- $\mathbf{M}$ = magnetization \([\text{A} / \text{m}]\)
The magnetic flux density can be expressed as:

\[ \vec{B} = \mu_0 (\vec{H} + \vec{M}) = \mu_0 \vec{H} + \vec{J} \]  \hspace{1cm} (2.2)

with:
- \( B \) = magnetic flux density \([T]\)
- \( H \) = magnetic field strength \([A / m]\)

The initial magnetization curve is a function of the field strength \( H \). It can be expressed by the introduction of the relative permeability \( \mu_r \):

\[ \vec{B} = \mu_r (\vec{H}) \mu_0 \vec{H}_0 = \mu_r (\vec{H}) \vec{B}_0 \]  \hspace{1cm} (2.3)

with:
- \( H_0 \) = magnetic field strength in a vacuum \([A / m]\)
- \( B_0 \) = magnetic flux density in a vacuum \([T]\)
- \( \mu_r \) = relative permeability of the material \([-]\)

The permeability of the material can be expressed by the relative permeability of the material and the vacuum permeability:

\[ \mu = \mu_0 \cdot \mu_r \]  \hspace{1cm} (2.4)

with:
- \( \mu \) = permeability of the material \([-]\)

Because:

\[ \mu_0 = \frac{B_0}{H_0} \]  \hspace{1cm} (2.5)

The relative permeability of the material is the measure of the ability of a material to support the formation of a magnetic field within itself. The relative permeability can be noted as:

\[ \mu_r = \frac{B}{B_0} \]  \hspace{1cm} (2.6)

The magnetic susceptibility is a proportionality constant that indicates the degree of magnetization of a material in response to an applied magnetic field.

\[ M = \chi_m H \]  \hspace{1cm} (2.7)

with:
- \( \chi_m \) = magnetic susceptibility \([-]\)
The magnetic susceptibility can be noted as:

$$\mu = \mu_0 (1 + \chi_m) \quad (2.8)$$

with:

$$\mu_r = 1 + \chi_m$$

2.2.2 Hysteresis curve of a steel fibre

Linsel [8] stated that the demagnetizing field strength for a finite rod, e.g. steel fibre, is:

$$H_{\text{demag}} = - \frac{NJ}{H_0} \quad (2.9)$$

with:

- $H_{\text{demag}}$ = demagnetizing field strength [A / m]
- $N$ = demagnetizing factor [-]

For a steel fibre, with a ratio length to diameter $>> 1$ the demagnetizing factor is:

$$N \approx \frac{\ln(2p) - 1}{p^2} \quad (2.10)$$

with:

- $p = \frac{l_f}{d}$

with:

- $l_f$ = length of the fibre [mm]
- $d$ = diameter of the fibre [mm]

The magnetic field strength in a fibre is:

$$H_1 = H + H_{\text{demag}} = H - \frac{NJ}{\mu_0} \quad (2.11)$$

with:

- $H_1$ = magnetic field strength in a fibre [A / m]
In Figure 2.2, the hysteresis curve of a Dramix 3D fibre is shown.

**Figure 2.2** - Hysteresis curve of a Dramix 3D fibre. [8]

### 2.2.3 Rotational Behaviour of a Steel Fibre in a Viscous Medium

A steel fibre in a magnetic field can be described as a dipole with a positive and a negative charge, see Figure 2.3. The positive charge, the north pole, aligns with the direction of the magnetic field which is direct from north to south.

**Figure 2.3** – Dipole in a magnetic field.
The force that acts on the pole in a homogenous field is:

\[ \vec{F} = p \vec{B} \]

with:

- \( \vec{F} \) = force that acts on a pole \([\text{N}]\)
- \( p \) = charge at the pole \([\text{Am}]\)

The torque exceeded on a steel fibre is:

\[ M_{\text{mech}} = F l \sin \theta \]

with:

- \( M_{\text{mech}} \) = torsional moment \([\text{Nm}]\)

The product \( (p \vec{I}_f) \) is noted as the magnetic moment:

\[ \vec{m} = p \vec{I}_f \]

Thus:

\[ M_{\text{mech}} = \vec{m} \vec{B} \]

The polarisation \( J \) can be derived from the hysteresis curve, see Figure 2.2. By using Equation 2.2, the magnetization can be determined. The magnetic moment is the product of the magnetization and the volume of the fibre:

\[ m = M V \]

with:

- \( V \) = volume of the fibre \([\text{m}^3]\)
The fibre is schematized as an infinite small rod with two spheres, see Figure 2.4.

Figure 2.4 - A fibre is schematized as an infinite small rod with two spheres.

The equation that will be applied for determining the drag force depends on the Reynolds number:

\[
Re = \frac{v \cdot L \cdot \rho}{\eta}
\]

with:

- \(Re\) = Reynolds number
- \(v\) = velocity [m/s]
- \(L\) = characteristic length scale [m]
- \(\rho\) = density [kg/m³]
- \(\eta\) = dynamic viscosity [kg/m/s]

Linsel [8] found a Reynolds number of 0.02 for a fibre with length 50 mm and diameter 1 mm at a speed of 0.05 m/s. For a Reynolds number < 0.5, Stokes law for drag force may be applied:

\[
F_{\text{stokes}} = 6\pi\eta rv
\]

with:

- \(F_{\text{stokes}}\) = drag force [N]
- \(r\) = radius of the sphere [m]
The acceleration of the fibre can be determined by the following equilibrium equation, making use of Newton’s second law and Equation 2.14 and 2.16 and 2.19:

\[ -F_{\text{stokes}} + F_{\text{mag}} = F_{\text{Newton}} \]  
\[ -6\pi \eta r v + \frac{M \cdot V \cdot B}{l_f} = m a \]
\[ -6\pi \eta r v + \frac{M \cdot V \cdot B}{l_f} = m \frac{d^2 x}{t^2} \]

with:

\[ m = \text{mass of the fibre} \] [kg]

In Equation 2.20, it is assumed that the drag force is a constant force. In reality, this will not be the case. If the fibre is put in motion the drag force will decrease.
2.3 PREFERRED ORIENTATION IN A BEAM

In this section, the fibre orientation in a fresh casted beams is predicted. To understand the fibre orientation, the origins of fibre anisotropy will be briefly discussed. An example on the fibre orientation of a slab provides a better understanding in the role of the casting process.

2.3.1 ORIGINS OF ANISOTROPY

There are two main reasons why fibres in concrete adopt a preferred orientation. The first one finds its origin in the flow profile of a suspension. If a formwork is casted, the concrete will introduce a shear flow directed to the opposite side of the beam, as is schematically presented in Figure 2.5. The velocity of the flowing concrete is not uniformly divided over the width of the beam and increases towards the centre. Due to the non-uniform distribution of the velocity, the fibres can experience torque which leads to rotation of the fibre. Martinie and Roussel [9] stated that in a flow dominated by shear stresses, the torque exerted on the fibre reaches a minimum when the fibre is parallel to the flow direction.

The second reason is often referred to as wall effect. A fibre will not be able to orient itself perpendicular to a mould or wall if the distance between its midpoint and the mould or wall is less than half the fibre length, see Figure 2.6. Due to the wall effect, there exists a preferred orientation. This can be enhanced by the flow effect.

Figure 2.5 - Explanation for fibre alignment in flowing concrete. [11]

Figure 2.6 - Wall effect for a fiber of length $L_f$ at a distance of a wall $y \leq L_f/2$. [9]
2.3.2 Preferred orientation in a slab
Recently, research has been done to mimic the flow of self-compacting fibre reinforced concrete by creating a Computational Fluid Dynamics (CFD) model [10]. The fibre orientation in a square slab has been simulated and verified using computational tomography scans of a real concrete slab. Figure 2.7 shows the results of the simulation. The ellipses indicate the main direction of the fibres.

![Image of simulation results](image)

**Figure 2.7** - Top view of the lower (a.) and upper (b.) third of the slab at the end of the simulation. The grey scale indicates the density of the fibres. [10]

The slab is casted from out a corner and this results in a circular flow pattern. The fibres appear to align to the flow pattern. This is in agreement with the results found by Stähli et al. [11]. Furthermore, the simulation suggests that most fibres tend to settle at the bottom. Research on vertical fibre distribution supports this [1]. She found that sixty percent of the total amount of fibres in a cross-section were located in the bottom half.
2.4 EFFECT OF THE INCLINATION ANGLE ON THE PULL-OUT FORCE OF A FIBRE

This section will be concentrating on the maximum pull-out force of a single steel fibre with respect to the inclined angle and on the bending moment capacity of aligned fibres with respect to unaligned fibres. The inclination angle is defined as the angle the fibre makes with respect to complete alignment.

Tests on inclined fibres show that the maximum pull-out force is reached at increasing crack widths as the inclination angle increases [2][3][12][13][14]. The maximum pull-out force was independent on the fibre embedded length in between the hooked-ends, providing that the hook-ends were fully embedded [14].

These increments of crack width are most likely a combination of fibre straightening with crushing and spalling of the concrete that take place at the corner where fibre enters the matrix [2][3][13][14], see Figure 2.8. At large inclination angles the pullout response becomes progressively less influenced by the matrix strength and increasingly governed by the mechanical properties of the fibre as it attempts to straighten in line with the loading direction [14][15].

![Diagram of pull-out force](image)

**Figure 2.8** – Pull-out of an inclined fibre with matrix spalling at both sides of the cracked surface. [15]

Figure 2.9a presents different relations between the angle of fibre inclination and the normalized values of the maximum achieved “inclined” pullout force ($P_{\text{inclined}}$) in hooked-end...
steel fibres. The values of the forces are given relatively to the pullout force at the angle of fibre inclination = 0º ($P_{\text{aligned}}$). In most cases somewhat higher forces are required to pull out the inclined fibres, with a maximum for an angle of about 15º. Laranjeira de Olivia found for the maximum pull-out force an angle of 18º [15]. Even at a very large inclination angle of 60º, no significant differences comparing to the aligned fibre could be found, except in case of Bartos. The values of the fibre slips for which the maximum pullout force was reached, were always a number of couple of times higher for inclined fibres than for aligned fibres.

Such observations do not say much about the performance of fibres in real structures because crack widths far beyond 1 mm are not acceptable. Instead of observing only the maximum pullout force observe the values of the fibre pullout force for an appropriate constant fibre slip should be considered. Marković compared the pull-out force for different inclination angles for a fibre slip of 0.5 mm [16], see Figure 2.9b.

**Figure 2.9**  a. Relations between the angle of fibre inclination and the normalized maximum registered pullout force in hooked-end inclined steel fibres, for fibre slips at which this maximum force was achieved. b. Relations between the angle of fibre inclination and the normalized pullout force in inclined fibres, at an fibre slip (i.e. at crack width) of 0.5 mm. [16]

Figure 2.9b presents the relations between the angle of fibre inclination and the pullout force, registered at a fibre slip (i.e. at crack width) of 0.5 mm. The maximum values of the pullout forces (about 20 percent higher compared to aligned fibres), are achieved at inclination angles of about 10º - 15º. In most cases, the fibres with inclination angles larger than 30º, show drastically lower pullout forces than aligned fibres.
Another phenomenon that may occur during the pullout of inclined steel fibres, is the rupture of the fibres, due to stress concentrations. In e.g. van Gysel, all hooked-end steel fibres under inclination angles of 45° and 60°, ruptured in the first phase of their pullout. This is a consequence of the relatively high stress concentrations in the fibre at the bending point (i.e. near the crack surface). In some of these cases, rupture of the matrix around the fibre bending point, in the form of a splitting fracture, could be observed as well. Therefore, the optimum angles of fibre inclination lay in between 10° and 30°. Higher angles lead to a lower tensile capacity in the first phases of tensile loading, which is also the most important one, taking into account the role of fibres and their performance in the structure. In some cases, rupture of fibres at high inclination angles is possible as well, due to high stress concentrations.

2.5 EFFECT OF ALIGNING FIBRES ON THE BENDING MOMENT CAPACITY OF A BEAM

In Section 2.3, the direction of the fibres in a slab that was casted from out the corner has been discussed. Svec et al. also studied the bending moment capacity of beams that were cut out of the slab [4]. The fibre orientation of the slab was known. The beams were subjected to three point flexural tests. In Figure 2.10 the location of the specimen and the corresponding three point flexural test curves can be found.

![Figure 2.10 - Position of the specimen and the corresponding three point flexural test curves. [4]](image_url)
It appears that the post-cracking behaviour can be much improved if the fibres are approximately aligned to the span direction. Another study of Svec et al. on the effect of the mould surface lead to the same conclusion [4]. Experimental and numerical research on two mould types were carried out. In addition, beams were cut out of the slabs and subjected to four point flexural tests. In Figure 2.11, the location of the specimen and the corresponding four point flexural test curves can be found.

**Figure 2.11** - Position of the specimen and the corresponding three point flexural test curves. [4]
Chapter 3

Design of an electromagnetic coil

Figure 3.1 – Multiple electromagnetic coils placed a constant distance form a homogeneous field, based on the Helmholtz principle.
3.1 INTRODUCTION

An electromagnetic coil consists of a number of windings and layers on a coil body. The first step in the design process of the coil is to determine the flux density. The flux density determines the number of windings and layers of the coil. Geometrical and physical conditions are based on the purpose of the coil and the available resources.

The equation to determine the magnet field strength in an infinite long solenoid is:

\[ B = \mu_0 NI \]  

with:

- \( B \) = magnetic flux density [T]
- \( \mu_0 \) = permeability of free space = \( 4\pi \times 10^{-7} \) [-]
- \( N \) = number of windings [-]
- \( I \) = current [A]

A configuration was designed using Equation 2.1 together with the design flux density, the boundary conditions and the physical properties of copper wire. This is an iterative process for which a model is designed. The model allows to vary the diameter and length of the coil, as well as the current running through the coil. In Appendix C, the equations that were used in the model are noted. The output of the model consists of the magnetic flux density in the coil as well as the current the power supply has to deliver. The output is used as input in *Finite Element Method Magnetics*, short notation FEMM. In FEMM, the gradient of the magnetic flux density is plotted. The model calculation is verified using the FEMM model.

In Figure 3.2 the design process is schematically presented. The boundary conditions were verified by using the output of the FEMM model. If the boundary conditions were not met, adjustments concerning the length and number of windings were made. The configuration was then adjusted and again modelled in FEMM. The configuration that best matched the design criteria is produced. The flux density of the designed coil is verified with an electrostatic fieldmeter.
3.2 DESIGN

3.2.1 FIELD STRENGTH
Experiments were performed to determine the field strength that is needed to rotate a single fibre. Single fibres were oriented in paste composed of portland cement with a w/c ratio of 0.4 and 0.5 using an electrical horseshoe magnet. The magnetic flux density produced by the horseshoe magnet is 0.3 T at the poles and decreases to 0.1 T in between the poles. It was possible to orient the fibres in the mixture with a w/c ratio of 0.5, and partially in the mixture with a w/c ratio of 0.4. The average flux density of the horseshoe magnet, plus an overcapacity of 25 percent is chosen as the design magnetic flux density which amounts to 0.25 T.

3.2.2 BOUNDARY CONDITIONS
The power supply that will be used during the research has an output of 25 A at 120 V. Furthermore, 725 meters of 2.00 mm thick insulated copper wire was available (AWG12) and will be used. The field must be homogeneous over the length of one fibre, 60 mm. A 10 percent error is accepted. This makes it possible to determine the magnetic flux density necessary for orienting one fibre. The inner diameter of the coil was chosen to be 110 mm. This enables to research the behaviour of a single fibre in between grains of gravel. To guarantee homogeneity of the field, the radius of a solenoid must be at least equal to the radius [17].
The boundary conditions are summarized. The coil:

i. has to be homogeneous over a length of 60 mm (+/- 10 percent);
ii. should have diameter of 110 mm;
iii. will be used on a power supply of 25 A / 120 V;
iv. will be wrapped with AWG12 wire;
v. maximum wire length is 725 m;
vi. length should be at least the radius.

3.2.3 VERIFICATION

The FEMM model has been calibrated by modelling a test coil. The output of the FEMM model is used to verify if the coil is homogenous over 60 mm. In Figure 3.3, the designed coil is shown. The flanges, and indirectly the copper wire, are cooled with water to prevent overheating. In Appendix A, the drawings of the coil can be found.

![Figure 3.3 - The trial coil that will be used for experiments on fibre level.](image)
Figure 3.4 shows the output of the FEMM model. The current in the circuit is 25 A. The plot is a section of the coil in which the colors symbolize the field density. The black rectangles symbolises the copper area. The white dashed area fulfils the homogeneity design criteria. To meet this criteria, a small concession is done on the maximum field strength which is slightly lower than 0.25 T.

![Image](image.png)

**Figure 3.4** – Density plot of the magnetic flux lines of the coil in FEMM, at 25A.

The gradient of the flux density in the designed coil is compared with the FEMM model. The current was 25 A. A calibrated electrostatic fieldmeter is used. Figure 3.5 and 3.6 show the flux density in the middle of the coil, and 35 mm from the middle of the coil are plotted.
Figure 3.5 – Comparison of the flux density in the middle of the coil.

Figure 3.6 – Comparison of the flux density 35 mm from the middle of the coil.

The experimentally determined flux density in the middle of the coil is on average 2.1 percent lower than the calculated value in the FEMM model. For the flux density at 35 mm from the middle the FEMM model overestimates for 6.3 percent. It can be concluded that the FEMM model provides a good estimation on the field strength. The small difference is probably a result of the coating on the copper wire. It leads to a lower copper density than is assumed by the FEMM model. In Appendix D, the verification is listed in more detail.
4.1 **Introduction**

The behaviour of steel fibres in a viscous medium under the influence of a magnetic field will be studied in this chapter. A transparent fluid with similar properties as SCC will be used to enable visual observation on the experiments. The magnetic field is generated by an electromagnetic coil and the design process of the coil will be described. The experimental research in this chapter can be divided into three levels:

i. single fibre in a viscous medium;

ii. multiple fibres in a viscous medium;

iii. multiple fibres with gravel in a viscous medium.

The first level will be treated both qualitatively and quantitatively. The second and latter level will only be treated qualitatively.
4.2 Behaviour of a single fibre in a viscous medium

Rheological measurements on SCC resulted in ranges of plastic viscosities of 7-160 Pa · s and yield values of 0-60 Pa [18]. Transparent silicon oil is used to simulate the SCC in order to observe the behaviour of the fibre in a magnetic field. The oil has a plastic viscosity of 60 Pa·s and a yield value of 0 Pa.

The behaviour of five fibres of two manufacturers in a magnetic field is examined. In Table 4.1 the properties of the fibres are listed.

<table>
<thead>
<tr>
<th>Type</th>
<th>Manufacturer</th>
<th>Length [mm]</th>
<th>Diameter [mm]</th>
<th>Tensile strength [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPZHT 50x1.0</td>
<td>Metalproducts</td>
<td>50.0</td>
<td>1.0</td>
<td>&gt;1400</td>
</tr>
<tr>
<td>MPZ 50x0.8</td>
<td>Metalproducts</td>
<td>50.0</td>
<td>0.8</td>
<td>&gt;1100</td>
</tr>
<tr>
<td>Dramix 3D</td>
<td>Bekaert</td>
<td>60.0</td>
<td>0.75</td>
<td>1225</td>
</tr>
<tr>
<td>Dramix 4D</td>
<td>Bekaert</td>
<td>60.0</td>
<td>0.90</td>
<td>1500</td>
</tr>
<tr>
<td>Dramix 5D</td>
<td>Bekaert</td>
<td>60.0</td>
<td>0.90</td>
<td>2300</td>
</tr>
</tbody>
</table>

Figure 4.2 – The fibres that were used during the experimental program. From top to bottom: 3D, 4D, 5D, 50x0.8, 50x1.0.
Each fibre is positioned perpendicular to the magnetic field lines andcentrically in the coil, in a transparent box filled with the silicone oil. The time it takes for the fibre to orient and to align to the magnetic field is measured.

The graph in Figure 4.3 shows the relation between the current output of the power supply and the time it takes to orient the fibres. It appears that the MPZHT and MPZ fibres rotate for 78°, while the Dramix fibres rotate for 84°. This difference is caused by the length, volume and alloy of the fibre.

![Graph showing the relation between current and time to orient fibres](image)

**Figure 4.3** – Relation between the current and the time it takes to orient a specific fibre.

The fibres of Metalproducts begin rotating at a current of 0.5A while the Dramix fibres start rotating at 1.0 A. The gradient of the graph is similar for all five fibres. The time needed to rotate a single fibre exponentially decreases to approximately 10 seconds. The measurement of the MPZ 50x0.8 fibre at 1.5 A seems disturbing and incorrect. The MPZHT 50x1.0 fibre is able to orient in the least time and will therefore be used during the rest of this study.
In Figure 4.4, the current in the coil is converted to the flux density generated in the coil based on experimental research. For 25 A, the mean value is 0.229 T. By means of extrapolation, the values for 0.5 up to 2.5 A are found.

![Graph](image)

**Figure 4.4** - Relation between the flux density and the time it takes to orient a specific fibre.

In Figure 4.4 the graph is plotted on a logarithmic scale. Approximately, an exponential function seems valid. Because only four points are available, the function will only be valid in between those points.
In Table 4.2, each graph is described by both an exponential and a power function, where \( x \) is the flux density and \( y \) is the time needed to orient a specific fibre.

**Table 4.2** – Description of the time it takes to orient a fibre under influence of a magnetic field.

<table>
<thead>
<tr>
<th>Type</th>
<th>Exponential function</th>
<th>( R^2 )</th>
<th>Power function</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPZHT 50x1.0</td>
<td>( y = 600.8 \ e^{-0.721x} )</td>
<td>0.965</td>
<td>( y = 1095.7 \ x^{-2.649} )</td>
<td>0.980</td>
</tr>
<tr>
<td>MPZ 50x0.8</td>
<td>( y = 407.5 \ e^{-0.520x} )</td>
<td>0.999</td>
<td>( y = 584.0 \ x^{-1.869} )</td>
<td>0.961</td>
</tr>
<tr>
<td>Dramix 3D</td>
<td>( y = 162.2 \ e^{-0.375x} )</td>
<td>0.923</td>
<td>( y = 344.5 \ x^{-1.658} )</td>
<td>0.968</td>
</tr>
<tr>
<td>Dramix 4D</td>
<td>( y = 299.7 \ e^{-0.490x} )</td>
<td>0.911</td>
<td>( y = 806.5 \ x^{-2.712} )</td>
<td>0.958</td>
</tr>
<tr>
<td>Dramix 5D</td>
<td>( y = 391.6 \ e^{-0.528x} )</td>
<td>0.906</td>
<td>( y = 1139.2 \ x^{-2.340} )</td>
<td>0.954</td>
</tr>
</tbody>
</table>

The behaviour of the Dramix fibres can be best described by a power function. The regression value for the power function is higher than the regression value for the exponential function. The exponential function can be best used for the Metalproducts fibres.
4.3 BEHAVIOUR OF MULTIPLE FIBRES IN A VISCOUS MEDIUM

The behaviour of a single fibre in a viscous medium has been investigated in Section 4.2. However, in fresh SCFRC many fibres will be exposed to the magnetic field. In this paragraph the behaviour and interaction of multiple fibres in a viscous medium under the influence of a magnetic field is researched. Because the coil diameter is too small for two fibres to lay side by side, the fibres were cut and placed in the container with silicone oil, see Figure 4.6. The container is placed in the middle of the coil.

To be able to orient the fibres in 30 seconds, the current running through the coil has been doubled to 5A. The maximum flux density doubles to \( 4.6 \cdot 10^{-2} \) T. All fibres are able to orient to the magnetic field lines. Groups of fibres start to rotate at intervals. A second phenomenon is observed, see Figure 4.7. The fibres act as small rod magnets. They attract and repel each other. Thereby, clusters of fibres are formed.

If the flux density is increased, the fibres tend to move to the edges of the box. The edge of the box is located near the edge of the coil body. The flux density near the coil body is higher than in the center of the coil.
Gravel (8 – 10 mm) is added to the silicone oil to see if the orienting process is blocked by large grains, see Figure 4.8.

It appears that the orientation is not blocked. The fibre tends to choose the path of the least resistance and uses its degrees of freedom when a grain is in its way. Again, clusters of
fibres are formed. If the flux density of the field is increased, the clusters are able to push the grains to the edge of the coil, see Figure 4.9. That is not desirable, since it can lead to inhomogenity of the SCFRC.

Figure 4.9 – Multiple fibres and gravel in a container with silicone oil.

Again, a clustering of the fibres is observed. Two full size fibres in a magnetic field are placed at a distance \( x \), see Figure 4.10.

Figure 4.10 – Scheme of two fibres in a magnetic field \( B \) at a distance \( x \).

In Figure 4.11, a schematic overview of two fibres aligning to the magnetic field is shown. The fibres both start rotating and aligning to the magnetic field. The rotational movement
almost comes to an end (1.). The red line indicates the interaction between both the negative and positive charge of the two fibres. Subsequently the fibres will rotate a little more, and translational movement will occur. Both translational and rotational movement have caused a collision between the fibres (2.). The electric charge moves to the outside of the combined fibre. From that point on, the two fibres together will act as one new rod magnet, with one positive and one negative pole.

Figure 4.11 – Schematic overview of two orienting fibres.

It depends on the distance $x$ between the fibres how they will connect. An overview of the patterns that were observed for two MPZHT 50x1.0 fibres is presented in Figure 4.12. The initial distance $x$ is expressed in fibre length.
Figure 4.12 – Overview of observed patterns for two clustering MPZHT 50x1.0 fibres. The initial distance $x$ is expressed in the fibre length.

4.4 CONCLUDING REMARKS

In this chapter the behaviour of a single fibre in a magnetic field was investigated. The required time to orient five fibre types has been measured, under varying magnetic flux density. The required time to orient a fibre decreases exponentially at increasing flux density. A magnetic flux density of $2.3 \cdot 10^{-2} \, \text{T}$ makes it possible to orient a single fibre in a medium with a plastic viscosity of $60 \, \text{Pa} \cdot \text{s}$ in 10 seconds. The spare capacity of the test coil is 90 percent. The fibres do not completely align with the magnetic field lines, at relative low flux intensities. Angles of 6 and 12 degrees with respect to the field lines where found, depending on the fibre length and alloy of the fibre.

To orient multiple fibres at once, an increase in flux density is desired. It depends on the amount of fibres per volume unit what flux density is desirable. Gravel does not block the orientation of a fibres. The fibre seeks the path of the least resistance. Multiple fibres in a magnetic field behave as small magnetic rods. They attract and repel eachother and thereby form clusters of fibres. The clusters tend to move to the edge of the coil if they were long exposed to the magnetic field. This was the result of the inhomogeneity of the test coil.
5.1 INTRODUCTION

This chapter concentrates on orienting fibres in SCC. A SCFRC mixture is designed and the rheological properties and compressive strength are tested. The set-up for orienting fibres in freshly casted SCC is described. Fibres are oriented in beams to study the influence of the governing parameters on the alignment. The results are evaluated using X-ray images. The experiments were carried out with a mixture which contains 0.75 percent by volume of steel fibres, an intermediate percentage.
5.2 MIXTURE

5.2.1 MIXTURE COMPOSITION

The mixture should fulfil some requirements:

- a viscosity similar to the differential oil used in the experiments conducted on the small coil, \( 60 \, \text{Pa} \cdot \text{s} \);
- a low yield value;
- strength conform prefab process. Minimum concrete class: B65;
- sufficiently coarse aggregate to minimize the thixotropic behaviour. Maximum particle size: 16mm;
- a constant workability during one hour, this leaves enough time to orientate the fibres.

In his PhD-thesis [19], Grünewald concentrated on performance-based design of self-compacting fibre reinforced concrete. The PhD-thesis was the starting point for deciding which mixture to use. The first selection occurred on the concrete class and maximum particle size. That resulted in six mixtures left which all should be stable. The second selection was based on the rheological properties that have been measured. The mixture that best matched the plastic viscosity of \( 60 \, \text{Pa} \cdot \text{s} \) combined with a high slump flow was chosen. The mixture is presented in Table 5.1.

Some adjustments to the mixture were made. The superplasticizers CUGLA LR/HR are replaced by Glenium 27/51. A conversion factor of 1.0 is applied. In Grunewalds research, the coarse aggregates were stored on a sieve in a plastic container and had to remain under water for 24 hours. The sand fractions were premixed; water (2.2 percent by weight of the fine aggregate) was added during the mixing process. The prewetting of the fine aggregates was also necessary to avoid the segregation of especially the finest fractions of the bulk. Since all fractions in the mixing facility are clearly separated, they do not allow to be prewetted nor to be kept underwater. The fractions will therefore absorb water during the mixing process. To account for this capillary effect, extra water is added. The water absorbed by the coarse aggregate amounts 0.52 percent volume weight. For sand, 1.0 percent volume weight can be added. In total, an additional 10 litres of water is added.
To guarantee a constant workability during one hour, an adjustment to the superplasticizers is made. Lowering the ratio Glenium 51 / Glenium 27, and thus replacing Glenium 51 for Glenium 27 results in a more constant workability over a longer period. The ratio will be increased from 1:2 to 1:3. The conversion factor of replacing Glenium 51 to Glenium 27 is 3.

In the mixture presented in Table 5.1, the equivalent Glenium 51 quantity is the sum of half the Glenium 27 divided by the density and the Glenium 51 divided by the density. A ratio of 1:3 means 25 percent Glenium 51 and 75 percent Glenium 27. The latter one has to be tripled because of the conversion factor. The new mixture was tested and appeared to be too liquid. Therefore stabilizer was added, 1.4 kg/m³ Glenium Stream 2006. The adjusted mixture is presented in Table 5.2.

### Table 5.1 – Mixture composition and properties of Grünewalds mixture.

<table>
<thead>
<tr>
<th>Type</th>
<th>[kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 52,5 R</td>
<td>143</td>
</tr>
<tr>
<td>CEM III 42,5 N</td>
<td>269</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>173</td>
</tr>
<tr>
<td>Free Water</td>
<td>181</td>
</tr>
<tr>
<td>Coarse Aggregate (4-16mm)</td>
<td>487</td>
</tr>
<tr>
<td>Sand (0,125 - 4mm)</td>
<td>1045</td>
</tr>
<tr>
<td>Superplasticiser CUGLA LR</td>
<td>2.78</td>
</tr>
<tr>
<td>Superplasticiser CUGLA HR</td>
<td>1.85</td>
</tr>
<tr>
<td>Water/cement ratio</td>
<td>0.44</td>
</tr>
<tr>
<td>Water/binder ratio</td>
<td>0.39</td>
</tr>
<tr>
<td>Cube compression strength [N/mm²]</td>
<td></td>
</tr>
<tr>
<td>at 7 days</td>
<td>54.1</td>
</tr>
<tr>
<td>at 28 days</td>
<td>75.3</td>
</tr>
</tbody>
</table>

### Table 5.2 – Mixture composition and properties of the adjusted mixture.

<table>
<thead>
<tr>
<th>Type</th>
<th>[kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 52,5 R</td>
<td>143</td>
</tr>
<tr>
<td>CEM III 42,5 N</td>
<td>269</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>173</td>
</tr>
<tr>
<td>Free Water</td>
<td>191</td>
</tr>
<tr>
<td>Coarse Aggregate (4-16mm)</td>
<td>481</td>
</tr>
<tr>
<td>Sand (0,125 - 4mm)</td>
<td>1045</td>
</tr>
<tr>
<td>Superplasticiser Glenium 27</td>
<td>6.10</td>
</tr>
<tr>
<td>Superplasticiser Glenium 51</td>
<td>0.70</td>
</tr>
<tr>
<td>Stabilizer Glenium Stream 2006</td>
<td>1.40</td>
</tr>
<tr>
<td>Water/cement ratio</td>
<td>0.44</td>
</tr>
<tr>
<td>Water/binder ratio</td>
<td>0.39</td>
</tr>
<tr>
<td>MPZHT 50x1.0²</td>
<td>58.9</td>
</tr>
</tbody>
</table>

1 ratio

2 in case of SCFRC
The grain size distribution is adopted to obtain a similar plastic viscosity and yield value, see Table 5.3 and Figure 5.2. The distribution is based on commonly used crushed river sand originated from the Netherlands.

**Table 5.3 - Grain size distribution of the aggregate.**

<table>
<thead>
<tr>
<th>Fraction</th>
<th>0.125 -</th>
<th>.25 -</th>
<th>.5 -</th>
<th>1.0 -</th>
<th>2.0 -</th>
<th>4.0 -</th>
<th>8.0 -</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.25 mm</td>
<td>.5 mm</td>
<td>1.0 mm</td>
<td>2.0 mm</td>
<td>4.0 mm</td>
<td>8.0 mm</td>
<td>16.0 mm</td>
</tr>
<tr>
<td>Passing ability</td>
<td>6.34%</td>
<td>26.94%</td>
<td>47.55%</td>
<td>60.23%</td>
<td>68.21%</td>
<td>79.37%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

**Figure 5.2 – Grain size distribution of the aggregate.**
5.2.2 MIXING PROCEDURE

All concrete will be mixed using an Einrich mixer with a capacity of 150 liters. The mixing procedure is described in Figure 5.4. After adding and mixing the stabilizer a rest period of 10 minutes is taken into account. This enables the aggregate to absorb the free water in the mixture. Subsequently, fibres will be added and mixed. In case of SCC this step is skipped.

After the mixing procedure was completed, slump flow tests were performed according to the EN 12350-9 standard. The slump test was applied to determine the filling ability of the SCC or SCFRC. The slump test consists of filling an Abrams’ cone on a flat and oiled surface. After waiting for 30 s, the Abrams’ cone is lifted. The concrete forms a circle. The mean diameter of the circle is determined by measuring the greatest diameter and the diameter perpendicular on it, see Figure 5.3. The time of the flow front to reach a prescribed circle of 500 mm ($t_{50}$) after lifting the cone is measured.

Because of the small batches that will be mixed (maximum 70 litres), the spread in workability is high. If it appeared that the slump flow was higher than 620 mm, extra stabilizer was added and mixed. For a slump flow of less than 580 mm, extra superplasticizer was added and mixed. After mixing, the slump flow test is repeated again.

Figure 5.3 – After the Abrams’ cone is lifted, a concrete circle is formed. The largest diameter of the circle and the diameter perpendicular to it have to be measured, indicated by the white arrows.
Figure 5.4 – Mixing procedure for SCC and SCFRC.
5.2.3 **RHEOLOGICAL PROPERTIES**

5.2.3.1 **INTRODUCTION**

Rheology is the science of the deformation and flow of matter and it is concerned with the relationships between stress, strain, rate of strain and time. The rheological properties of the mixture with and without fibres will be investigated. In principal, there are four models to describe the behaviour of a fluid which are visualized in Figure 5.5.

![Figure 5.5 – Models to describe the behaviour of a fluid.](image)

**NEWTONIAN FLUID**

A Newtonian fluid is a fluid which behaves linear relative to stresses. In an Newtonian fluid the gradient of the flowrate is directly proportional to the shear stress in the shear plane. The following relationship applies:

\[ \tau = \mu \cdot \dot{\gamma} \tag{5.1} \]

where:

- \( \tau \) = shear stress (Pa)
- \( \mu \) = plastic viscosity (Pa·s)
- \( \dot{\gamma} \) = shear rate (1/s)
**NON-NEWTONIAN FLUID**

Two types of non-newtonian fluids exist, dilant fluids and pseudoplastic fluids. A dilant fluid is a fluid which viscosity increases with the shear rate. Such a behavior is also called shear thickening. A pseudoplastic fluids is a fluid which viscosity decreases with the shear rate, also called shear thinning.

**BINGHAM PLASTIC**

A bingham plastic starts to flow when a certain shear stress is reached. If an increasing shear stress is exerted on a liquid, the velocity gradient increases linearly. These liquids are referred to as Newtonian fluids. A bingham model is used to describe the flow behaviour of a suspension. The following equation applies:

\[ \tau = \tau_0 + \mu \cdot \dot{\gamma} \]

where:
- \( \tau_0 \) = yield value (Pa)

Traditional concrete is often described using the Bingham model. For self-compacting concrete, this model often leads to a negative yield value. To overcome this, a new model is introduced.

**HERSCHLEY-BULKLEY MODEL**

If a fluid starts to flow after a yield stress is being exerted, and the flow behaviour is either shear thickening or shear thinning, its behaviour can be described using the Herschley-Bulkley model:

\[ \tau = \tau_0 + \mu \cdot K \dot{\gamma}^e \]

where:
- \( K \) = consistentiecoëfficiënt (Pa·s^n)
- \( e \) = vloei-index (-)
5.2.3.2 Without fibres

A batch of 50 litres of SCC was mixed. The fresh concrete was subjected to four slump flow tests. In Table 5.4, the rheological properties of the mixture without fibres are listed. After each measurement, the SCC was returned into the mixer. The mixture has been mixed for 90 seconds before performing the next slump test to avoid internal bonds in the SCC.

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Slump flow [mm]</th>
<th>t50 [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>740-710</td>
<td>2.3</td>
</tr>
<tr>
<td>38</td>
<td>670-655</td>
<td>-</td>
</tr>
<tr>
<td>59</td>
<td>655-645</td>
<td>-</td>
</tr>
<tr>
<td>76</td>
<td>600-590</td>
<td>-</td>
</tr>
</tbody>
</table>

Seventy-five minutes after adding water, the mixture without fibres still fulfils the flow criteria of SCC with a slump flow of at least 600 mm. Therefore, it can be concluded that the workability of the SCC remains sufficient during one hour.

5.2.3.3 With fibres

The plastic viscosity and yield stress of the SCFRC mixture have been examined by using the BML Viscometer. Slump tests were performed to be able to verify the results of the BML Viscometer. A batch of 70 litres has been mixed and the slump cones and BML Viscometer were filled directly after mixing. The cones were lifted at the time indicated in the Table 5.5, just before executing the test script of the BML viscometer. The third cone appeared to leak. The measurement is therefore invalid and not included.

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Slump flow [mm]</th>
<th>t50 [sec]</th>
<th>Mini slump [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>740-710</td>
<td>2.6</td>
<td>200x200</td>
</tr>
<tr>
<td>42</td>
<td>570-540</td>
<td>4.3</td>
<td>140x125</td>
</tr>
<tr>
<td>53</td>
<td>-</td>
<td>-</td>
<td>115x115</td>
</tr>
</tbody>
</table>

The results indicate a high slump flow and workability in the beginning. Although fibres were added, the slump flow is of the same level as the mixture without fibres. This can be due to the higher volume of the batch. Absolutely, there is more free water in the mixture. The
water has to be absorbed by the aggregate and the absorption process was not yet completed. While emptying the mixture it became clear that the mixture had been segregated. The gravel and fibres had sunk to the bottom of the mixer. This effect also occurred in the container of the BML Viscometer and most likely in the cones as well. In Figure 5.6, the BML Viscometer is shown.

![Figure 5.6 – BML Viscometer for rheological measurements.](image)

In the BML Viscometer, the mixture was tested in three sessions of twice tests each. Between each session, the container is covered with plastic sheet in order to prevent evaporation. Each test begins with the execution of an automatic script. This script starts rotating the container with a speed of circa 0.39 round per second (rps), and then gradually starts lowering the measurement arm, the beater, into the mixture. After the beater has been lowered completely, the actual measurement starts. With time intervals of 5 seconds, the rotation speed is stepwise lowered to 0.03 rps, in 7 steps of 0.052 rps each. Meanwhile the torque value is continuously being registered. Figure 5.7 presents a brief overview of the registered torque. It contains of six peaks corresponding to the tests carried out. The two peaks in between the three sessions have been registered while cleaning the beater.
The torque measured during the second and third session is higher than the first session. It indicates that the resistance of the SCFRC to movement is increasing. However, there is only a minor difference in measured torque between the first and second session. A possible explanation could be that the fibres were partially sunk at t=0 and could deliver resistance to movement. Between the first and second session, they almost completely sank to the bottom while the concrete was bonding. These effects can more or less compensate one another which results in a minor improvement in the resistance to movement.

The first two peaks of Figure 5.7 are enlarged in Figure 5.8. The green line represents the torque while the red line indicates the velocity of the container. The first test is automatically performed without human interference. However, it became clear in a trial session and research performed by Schipper that the beater will not always reach zero after rotation stops [20]. Small aggregate particles and fibres stick between the measurement part and static part of the beater. This can be solved by manually returning the measurement part of the beater to zero torque position, for example with a steel rod. The second test of each session has been carried out so.

The peak of the second test of each session is lower than the peak of the first test. This is due to the fact that the first test destroys some of the bonding formed in the concrete. The resistance to movement will therefore decrease.
The plastic viscosity and the yield value can be determined based on the raw data of the BML Viscometer. In Figure 5.9, the graph indicates the first measurement at t=30 sec and sets the torque against the shear rate. Also, the relevant points are indicated. To determine the plastic viscosity and yield value, first a regression analysis has to be performed. The regression equation is notated in the figure.

**Figure 5.8** – Enlargement of the first two peaks of the rheological test.

**Figure 5.9** – Graph of the BML Viscometer test at t=0.
Using the Reiner-Rivling equations presented by Wallevik the plastic viscosity and yield value can be determined [21]. The first value of the regression equation corresponds to the H-value, while the second value in the equation corresponds to the G-value.

\[ \tau_0 = \frac{G}{4\pi h} \left( \frac{1}{r_f^2} - \frac{1}{r_0^2} \right) \frac{1}{\ln\left( \frac{r_0}{r_f} \right)} = -0.0529 \frac{1}{4\pi \cdot 0.200 \left( \frac{1}{0.120^2} - \frac{1}{0.175^2} \right) \ln\left( \frac{0.175}{0.120} \right)} = -0.0529 \cdot 38.8 = -2.1 \text{Pa} \] (5.4)

\[ \mu = \frac{H}{8\pi^2 h} \left( \frac{1}{r_f^2} - \frac{1}{r_0^2} \right) = \frac{8.7546}{8\pi^2 \cdot 0.200 \left( \frac{1}{0.120^2} - \frac{1}{0.175^2} \right) \ln\left( \frac{0.175}{0.120} \right)} = 8.7546 \cdot 2.33 = 20.4 \text{Pa} \cdot \text{s} \] (5.5)

The yield value is found to be negative, which is the result of the analysis using the Bingham model. Physically this is not possible. In Table 5.6 the regression equations of each test, as well as the plastic viscosity and the yield value are presented.

**Table 5.6** – Plastic viscosity and yield value of the mixture with fibres.

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Reg. equation</th>
<th>$R^2$</th>
<th>Plastic viscosity [Pa·s]</th>
<th>Yield value [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>$8.7546x - 0.0529$</td>
<td>0.972</td>
<td>20.4</td>
<td>-2.1</td>
</tr>
<tr>
<td>17</td>
<td>$7.9626x + 0.0238$</td>
<td>0.982</td>
<td>18.6</td>
<td>0.9</td>
</tr>
<tr>
<td>48</td>
<td>$12.656x - 0.3532$</td>
<td>0.980</td>
<td>29.5</td>
<td>-13.7</td>
</tr>
<tr>
<td>39</td>
<td>$9.5695x + 0.1994$</td>
<td>0.987</td>
<td>22.3</td>
<td>7.7</td>
</tr>
<tr>
<td>60</td>
<td>$12.751x + 0.1678$</td>
<td>0.968</td>
<td>29.7</td>
<td>6.5</td>
</tr>
<tr>
<td>61</td>
<td>$11.033x + 0.2816$</td>
<td>0.987</td>
<td>25.7</td>
<td>10.9</td>
</tr>
</tbody>
</table>

Grünewald found for the same mixture a plastic viscosity of 56.0 Pa·s and a yield value of -10 Pa. The difference might be the cause of the amount of free water, which appears to be too high. To compensate for this free water, an extra amount of stabilizer will be added. The new mixture composition is presented in Table 5.7. In Appendix E, the exact mixture composition can be found.
Table 5.7 – Composition of the adjusted mixture.

<table>
<thead>
<tr>
<th>Type</th>
<th>[kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 52,5 R</td>
<td>143</td>
</tr>
<tr>
<td>CEM III 42,5 N</td>
<td>269</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>173</td>
</tr>
<tr>
<td>Free Water</td>
<td>191</td>
</tr>
<tr>
<td>Coarse Aggregate (4-16mm)</td>
<td>481</td>
</tr>
<tr>
<td>Sand (0,125 - 4mm)</td>
<td>1045</td>
</tr>
<tr>
<td>Superplasticiser Glenium 27</td>
<td>6.10</td>
</tr>
<tr>
<td>Superplasticiser Glenium 51</td>
<td>0.83</td>
</tr>
<tr>
<td>Stabilizer Glenium Stream 2006</td>
<td>2.70</td>
</tr>
<tr>
<td>Water/cement ratio</td>
<td>0.44</td>
</tr>
<tr>
<td>Water/binder ratio</td>
<td>0.39</td>
</tr>
<tr>
<td>MPZHT 50x1.0(^2)</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) ratio \(^2\) in case of SCFRC

The target slump flow for the adjusted mixture is 600 mm. This will minimize the chance of segregation. The extra stabilizer lead to a slump flow which was slightly lower than aimed for, namely 580 mm. Therefore a small extra amount of superplasticizer was added. In Table 5.8 the results of the slump flow test are presented.

Table 5.8 – Slump flow tests of the adjusted mixture.

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Slump flow [mm]</th>
<th>t₅₀ [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>600-600</td>
<td>-</td>
</tr>
<tr>
<td>43</td>
<td>460-425</td>
<td>-</td>
</tr>
</tbody>
</table>

The slump flow is reduced by approximately 130 mm. The adjusted mixture is also tested using the BML Viscometer. In Table 5.9 the plastic viscosity and yield value of the adjusted mixture can be found.
Table 5.9 - Plastic viscosity and yield value of the adjusted mixture with fibres.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>$11.428x + 0.6461$</td>
<td>0.985</td>
<td>26.6</td>
<td>25.1</td>
</tr>
<tr>
<td>44</td>
<td>$14.977x + 1.0511$</td>
<td>0.987</td>
<td>34.9</td>
<td>40.3</td>
</tr>
<tr>
<td>45</td>
<td>$13.247x + 1.1380$</td>
<td>0.995</td>
<td>30.9</td>
<td>44.2</td>
</tr>
<tr>
<td>62</td>
<td>$16.753x + 1.3365$</td>
<td>0.995</td>
<td>39.0</td>
<td>51.9</td>
</tr>
<tr>
<td>63</td>
<td>$15.242x + 1.2960$</td>
<td>0.997</td>
<td>35.5</td>
<td>50.3</td>
</tr>
</tbody>
</table>

Stabilizing the mixture lead to an increase in plastic viscosity and yield value. Still, the plastic viscosity is lower than found by Grünewald. The yield stress derived in this research is however a lot higher. Therefore, it is likely that segregation will not occur anymore. Further experimental research on fibre orientation using the same mixture confirmed this.

Gram & Lagerblad derived a theoretical solution for relating yield stress to the diameter obtained from a slump flow test [22], see the graph in Figure 5.10. A slump flow of 600 mm correlates with a yield value of 23 Pa. The yield value found for the mixture directly after testing was 25 Pa and had a slump flow of 600 mm. It indicates that the yield value is plausible value. Of course, the slump flow depends on the relative humidity, the mixture, the way of testing and therefore no conclusions may be drawn from this figure.

Figure 5.10 – Theoretical solution and experimental results for relating the yield stress and spread length.
5.2.4 Compressive Strength

Cubes were casted using the mixture in Table 5.7. The cubes are loaded perpendicular to the casting plane. Table 5.10 shows the results of the compressive strength test.

Table 5.10 – Results of the cube compression tests.

<table>
<thead>
<tr>
<th>Cube</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Gem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate load</td>
<td>[kN]</td>
<td>1742.6</td>
<td>1729.8</td>
<td>1733.7</td>
<td>1746.9</td>
<td>1737.6</td>
<td>1755.3</td>
</tr>
<tr>
<td>Surface loading plane</td>
<td>[mm]</td>
<td>22,859.2</td>
<td>22,773.9</td>
<td>22,846.2</td>
<td>23,171.5</td>
<td>22,638.9</td>
<td>22,678.4</td>
</tr>
<tr>
<td>Comp. strength</td>
<td>[MPa]</td>
<td>76.23</td>
<td>75.96</td>
<td>75.89</td>
<td>75.39</td>
<td>76.75</td>
<td>77.40</td>
</tr>
<tr>
<td>Variance</td>
<td>[-]</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>St. deviation</td>
<td>[-]</td>
<td>0.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{ck;cube}$</td>
<td>[MPa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The found characteristic cube compressive strength ($f_{ck;cube}$) is 75.20 MPa. The mixture fulfils the strength criteria of class B65. The characteristic cube compressive strength found by Grünewald is 75.30 MPa. The results are in good agreement although the cubes of Grünewald did not contain any steel fibres. Research done by Maidl shows that the compressive strength of SFRC and plain concrete does not significantly differ [23].
5.3 Fibre orientation in SCFRC beams

5.3.1 Electromagnetic coil
A new coil will be designed to be able to orient fibres in SCC. The diameter of the trial coil that is designed for the experiments on fibre level is too small. The design of an electromagnetic coil is yet treated in Chapter 3. This paragraph only treats the design criteria. The density plot, the verification and the drawings can be found in Appendix B and D. The design flux density is determined by orienting multiple fibres in a viscous medium within 30 seconds. A fibre density of 0.75 percent by volume of steel fibres is mixed in the silicon oil. It was experimentally determined that it was possible to orient the fibres within 30 seconds at a flux density of $7.0 \cdot 10^{-2} \, T$. A 10 percent overcapacity is taken into account.

To be able to move a beam through the coil, the inner diameter of the coil should be at least 300 mm. The power supply that is used for the tests in Chapter 4 is also used for orienting the beams. From an economical point of view, the length of the coil will be limited to the length of the radius.

The design criteria are summarized. The coil:

i. should have a flux density of $7.7 \cdot 10^{-2} \, T$
ii. should have a diameter and length of 300 mm;
iii. will be used on a power supply of 25 A / 120 V.

5.3.2 Test set-up and procedure
The set-up consists of a power supply, a coil and a rail that enables a beam to be transported through the middle of the coil. The beams that will be oriented have a dimension of 600 x 150 x 150, a standardized size for bending tests.

5.3.2.1 Rail
A rail has been constructed to be able to move the freshly casted beam through the coil with a constant velocity. The rail consists of axles with wheels to minimize the friction while moving the beam. It is made of wood to not influenced the magnetic field lines in the coil. In Figure 5.11 the test set-up, consisting of the coil, rail and power supply is shown.
Figure 5.11 – Test set-up for orienting fibres in SCFRC beams.

The beam can be put in motion by winding up the rope that is connected to the mould. The distance per rotation is known, so by varying the rotation speed the velocity of the beam through the coil can be altered.

5.3.2.2 Test procedure

The concrete is mixed according to the mixture composition of Table 5.7. A batch of 60 litres is mixed to cast three beams. After the mixing is proceeded, the concrete is poured into a wheelbarrow. The mixture is then mixed with a trowel before the mould is filled. The mould is positioned on the outer right side of the rail. The beam is then filled from out the right side of the beam and levelled off with a wooden lath. Thereafter, the power supply will be activated and the beam will be moved over the rail at a constant velocity. The velocity is based upon the parameters that are selected, and will be treated in the next paragraph. The method is highly experimental, trial sessions demonstrated that the method of moving the specimen over the rails has an error of 10 percent.
5.3.3 Experimental Program

5.3.3.1 Introduction
Two series of trial beams were casted to find the effect of the parameters flux density and velocity. In the first series the velocity of the specimen was varied while the flux density remained constant. The flux density was chosen to be 40 percent of the flux density of the experiment that was performed in Paragraph 5.3.1. It is expected that the effect of the velocity can be better reviewed at a lower flux density. The lower limit of the velocity is determined by both rheological properties and the length of the beam. It is desirable that a beam of 20 m can be fully orientated in 45 minutes. This results in a velocity of 7.5 mm/s. The lowest limit is chosen as 5 mm. The effective time the beam is exposed to the magnetic field will then be 180 s. The effective time is five times lowered in steps of 30 s to determine all six configurations for the first series. The second series varies in flux density and velocity and is based upon the results of the first series.

5.3.3.2 Specimen
In Table 5.11 and 5.12 an overview of the parameters per specimen can be found. The flux density is expressed as the current output of the power supply.

**Table 5.11** – Configuration of the tests for the first series.

<table>
<thead>
<tr>
<th>Number [#]</th>
<th>Current [A]</th>
<th>Velocity [mm/s]</th>
<th>Effective time in coil [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>5.0</td>
<td>5</td>
<td>180</td>
</tr>
<tr>
<td>6.</td>
<td>5.0</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>2.</td>
<td>5.0</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>3.</td>
<td>5.0</td>
<td>6</td>
<td>150</td>
</tr>
<tr>
<td>4.</td>
<td>5.0</td>
<td>7.5</td>
<td>120</td>
</tr>
<tr>
<td>5.</td>
<td>5.0</td>
<td>15</td>
<td>60</td>
</tr>
</tbody>
</table>

**Table 5.12** - Configuration of the tests for the second series.

<table>
<thead>
<tr>
<th>Number [#]</th>
<th>Current [A]</th>
<th>Velocity [mm/s]</th>
<th>Effective time in coil [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.</td>
<td>7.5</td>
<td>5</td>
<td>180</td>
</tr>
<tr>
<td>8.</td>
<td>7.5</td>
<td>3.3</td>
<td>270</td>
</tr>
<tr>
<td>9.</td>
<td>10.0</td>
<td>5</td>
<td>180</td>
</tr>
<tr>
<td>10.</td>
<td>10.0</td>
<td>3.3</td>
<td>270</td>
</tr>
<tr>
<td>11.</td>
<td>12.5</td>
<td>5</td>
<td>180</td>
</tr>
<tr>
<td>12.</td>
<td>12.5</td>
<td>10</td>
<td>90</td>
</tr>
</tbody>
</table>
After casting and one week of hardening, the beams were cut into four cubes of 150 x 150 mm using a diamond saw. The numbering of every piece is based upon three digits. The first digit indicates the number of the beam. The second value correlates with the cube cut out of the beam. The third value indicates the vertical position of every slice. In Figure 5.12, the numbering of the first beam is presented. All beams were filled from the outside of the beam. The cube corresponding to that side is number 4.

Figure 5.12 – Numbering of the first beam.

The specimen were analyzed on segregation and fibre orientation using X-ray images. Finally, they were rated on segregation, homogeneity of the fibre distribution and fibre alignment based on a -- to ++ rate scale.

5.3.3.3 Analysis on Segregation
The beams were analyzed on segregation of both aggregate and fibres. The analysis was performed on the cross-section of cube 1 of each specimen, which is black-marked in Figure 5.12. Cube 1 is located on the opposite side of the casting position. The cube is more prone to segregation then the other cubes because of the longer distance to the inlet point.

The fibres and the coarse aggregate (>4 mm) of the top and bottom side of the cube were counted. They have been pointed out manually in separate layers in Adobe Photoshop. The layers were then analyzed using Nation Instruments Vision Builder. In Vision Builder the number of grains and fibres were counted based upon the separate layers.
In Figure 5.13 a cross-section of a beam and the Photoshop layer which was used for further inspection can be seen.

![Cross-section of a beam and the Photoshop layer](image)

**Figure 5.13** – Cross-section of a beam (left) and the corresponding Photoshop layer which was used for automatic inspection (right). The coarse aggregate has been marked by blue stripes, the fibres have been marked by red dots. The stripes and dots were counted in Vision Builder.

5.3.3.4 **Analysis on fibre orientation**

Every cube was cut into five slices of 150 x 150 x 30 mm excluding saw cut. Subsequently, X-ray images of the slices were made. The X-ray images were processed in Adobe Photoshop to images which highlight the fibres, see Figure 5.14.

![X-ray images and processed images](image)

**Figure 5.14** – Left: X-ray image of slice 635. Right: X-ray image processed into a black and white image which highlights the fibres.
The black and white images were used to determine the preferred orientation. The slices 1, 3 and 5 of cube 3 of every beam were analyzed. Every slice is divided into three regions, see Figure 5.15. For each region, the orientation with respect to the span direction was determined by applying the Fourier components analysis. The application *Directionality* of the open-source image processing program *ImageJ* offers an option for the analysis. The analysis is based on Fourier spectrum analysis. For a square image, structures with a preferred orientation generate a periodic pattern at $+90^\circ$ orientation in the Fourier transform of the image, compared to the direction of the objects in the input image. The application chops the image into square pieces, and computes their Fourier power spectra. The latter are analyzed in polar coordinates, and the power is measured for each angle using the spatial filters proposed by Liu [24].

![Diagram](Figure 5.15 – Division of the regions relative to the position of the beam.)
In Figure 5.16, an example of the output of the analysis of Region A of slice 635 is shown.

![Figure 5.16 – Output of the analysis on slice 635.](image)

A histogram indicates the amount of structures that were computed for each direction. Furthermore, the plug-in generates statistics on the highest peak found. The highest peak is fitted by a Gaussian function, taking into account the periodic nature of the histogram.

- The 'Direction' column reports the centre of the Gaussian. Zero is total alignment with the span direction. The angle is computed from left to right and can therefore be negative.
- The 'Dispersion' column reports the standard deviation of the Gaussian function.
- The 'Amount' column is the sum of the histogram from centre - standard deviation to centre + standard deviation, divided by the total sum of the histogram.
- The 'Goodness' column reports the goodness of the fit, the higher the better.

5.3.4 Test results

5.3.4.1 Varying velocity mixture

Two batches of each 60 litres were mixed to cast three beams each. The mixture that is used is presented in Table 5.2. The first batch was used to cast the beams 1, 2 and 6. The second batch was used to cast beam 3, 4 and 5.
SEGREGATION

The result of the segregation analysis on fibres is presented in Table 5.13.

**Table 5.13 – Results of the segregation analysis on fibres.**

<table>
<thead>
<tr>
<th>Batch [#]</th>
<th>Cube [#]</th>
<th>Top half [#]</th>
<th>%</th>
<th>Bottom half [#]</th>
<th>%</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>8</td>
<td>20.5</td>
<td>31</td>
<td>79.5</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>61</td>
<td>3</td>
<td>6.5</td>
<td>43</td>
<td>93.5</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>36</td>
<td>16.5</td>
<td>182</td>
<td>83.5</td>
<td>218</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>16</td>
<td>14.5</td>
<td>85</td>
<td>85.5</td>
<td>101</td>
</tr>
<tr>
<td>2</td>
<td>31</td>
<td>16</td>
<td>22.9</td>
<td>54</td>
<td>77.1</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>41</td>
<td>20</td>
<td>20.6</td>
<td>77</td>
<td>79.4</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>91</td>
<td>46.2</td>
<td>106</td>
<td>53.8</td>
<td>197</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>42</td>
<td>29.9</td>
<td>79</td>
<td>70.1</td>
<td>121</td>
</tr>
</tbody>
</table>

The fibres tended to segregate in the wheelbarrow, after mixing. Beam 2 and 5 were the last to be casted and therefore contain significantly more fibres.

The fibre distribution is inhomogeneous for both the first and the second batch. The top half of the cross-section of the first batch contains on average 14.5 percent of the total amount of fibres. The top half of the second batch contains 29.9 percent of fibres. In absolute terms, the top half of the specimen of the first batch contains approximately one third of the fibres that were found in the top half of the specimen of the second batch.

The results of the segregation analysis on aggregate are presented in Table 5.14.

**Table 5.14 – Results of the segregation analysis on aggregate.**

<table>
<thead>
<tr>
<th>Batch [#]</th>
<th>Cube [#]</th>
<th>Top half [#]</th>
<th>%</th>
<th>Bottom half [#]</th>
<th>%</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>23</td>
<td>29.5</td>
<td>55</td>
<td>70.5</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>61</td>
<td>25</td>
<td>39.7</td>
<td>38</td>
<td>60.3</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>42</td>
<td>43.8</td>
<td>54</td>
<td>56.3</td>
<td>96</td>
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<tr>
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<td></td>
<td>30</td>
<td>37.6</td>
<td>49</td>
<td>62.4</td>
<td>79</td>
</tr>
<tr>
<td>2</td>
<td>31</td>
<td>42</td>
<td>46.2</td>
<td>49</td>
<td>53.8</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>41</td>
<td>36</td>
<td>46.8</td>
<td>41</td>
<td>53.2</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>42</td>
<td>47.7</td>
<td>46</td>
<td>52.3</td>
<td>88</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>40</td>
<td>46.9</td>
<td>45</td>
<td>53.1</td>
<td>85</td>
</tr>
</tbody>
</table>
The aggregate ratio top to bottom is on average almost 40 to 60. The aggregate distribution of the second batch can be considered homogeneous.

**Fibre orientation**

In Table 5.15 the result of the analysis on fibre orientation is presented. In Appendix F, the columns “Amount” and “Goodness” can be found. The minus sign in the table indicates that no fibres were present in the region.

**Table 5.15** – Results of the analysis on fibre orientation.

<table>
<thead>
<tr>
<th>Effective time of beam in coil [s]</th>
<th>Location</th>
<th>Region A</th>
<th>Region B</th>
<th>Region C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slice</td>
<td>Direction</td>
<td>Goodness</td>
<td>Direction</td>
</tr>
<tr>
<td>180</td>
<td>131</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>133</td>
<td>3.0</td>
<td>0.61</td>
<td>25.2</td>
</tr>
<tr>
<td></td>
<td>135</td>
<td>0.2</td>
<td>0.81</td>
<td>7.0</td>
</tr>
<tr>
<td>90</td>
<td>631</td>
<td>-</td>
<td>-</td>
<td>-10.9</td>
</tr>
<tr>
<td></td>
<td>633</td>
<td>1.7</td>
<td>0.85</td>
<td>-13.5</td>
</tr>
<tr>
<td></td>
<td>635</td>
<td>14.0</td>
<td>0.63</td>
<td>6.0</td>
</tr>
<tr>
<td>30</td>
<td>231</td>
<td>0.4</td>
<td>0.85</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>233</td>
<td>8.6</td>
<td>0.85</td>
<td>-57.2</td>
</tr>
<tr>
<td></td>
<td>235</td>
<td>5.2</td>
<td>0.89</td>
<td>-3.5</td>
</tr>
<tr>
<td>150</td>
<td>331</td>
<td>12.5</td>
<td>0.84</td>
<td>47.5</td>
</tr>
<tr>
<td></td>
<td>333</td>
<td>11.8</td>
<td>0.77</td>
<td>68.7</td>
</tr>
<tr>
<td></td>
<td>335</td>
<td>3.2</td>
<td>0.85</td>
<td>1.5</td>
</tr>
<tr>
<td>120</td>
<td>431</td>
<td>1.1</td>
<td>0.71</td>
<td>-7.9</td>
</tr>
<tr>
<td></td>
<td>433</td>
<td>24.7</td>
<td>0.70</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td>435</td>
<td>10.2</td>
<td>0.81</td>
<td>1.8</td>
</tr>
<tr>
<td>60</td>
<td>531</td>
<td>-43.6</td>
<td>0.42</td>
<td>40.3</td>
</tr>
<tr>
<td></td>
<td>533</td>
<td>17.4</td>
<td>0.59</td>
<td>34.4</td>
</tr>
<tr>
<td></td>
<td>535</td>
<td>2.9</td>
<td>0.86</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

The bottom slices of all cubes appear to be better aligned than the middle and top slices.
EVALUATION

The specimen are rated on segregation, homogeneity of the fibre distribution and fibre alignment in Table 5.16. The homogeneity of the fibre distribution is rated based upon both the X-ray images and the segregation analysis. Inhomogeneity of the X-ray images expresses itself by regions where little fibres can be observed. This might be the result of the fibres which tend to form clusters. It could indicate that the effective time the beam was exposed to the magnetic field could be decreased, if the fibres are aligned well.

**Table 5.16 – Rating of the specimen.**

<table>
<thead>
<tr>
<th>Beam [#]</th>
<th>Segregation Fibres</th>
<th>Aggregate</th>
<th>Fibre distribution</th>
<th>Fibre alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fibres</td>
<td>Aggregate</td>
<td>Horizontal</td>
<td>Vertical</td>
</tr>
<tr>
<td>1</td>
<td>--</td>
<td>- / 0</td>
<td>+</td>
<td>--</td>
</tr>
<tr>
<td>6</td>
<td>--</td>
<td>- / 0</td>
<td>0</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>--</td>
<td>- / 0</td>
<td>++</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>++</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>++</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>++</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The segregation analysis demonstrates that fibre segregation does not necessarily imply aggregate segregation. It can be concluded that the fibres are more prone to segregation than the aggregate. This is the result of the density of steel (7850 kg/m³) and aggregate (2640 kg/m³) in comparison with the total density of SCC (2330 kg/m³ in this research). The density of the steel fibres is almost three times as high as the density of the SCC and the fibres will therefore tend to settle at the bottom half.

The bottom slices of all cubes appear to be better aligned than the middle and top slices. The cause of this difference can be found in the inhomogeneous flux density gradient in the coil. The flux density is higher near the edges, the coil body. If the length of the coil with respect to the radius would be increased, the magnetic field would become more homogenous. It is expected that the fibres in the middle and top slice would then better align to the span direction.

In Figure 5.17, an X-ray image of slice 432 is shown. Slice 432 is located just above the vertical center of the cube. The fibres did not orient to the span direction and can be considered as unaffected by the magnetic field. It can be clearly observed that the fibres
follow a circular pattern, which is indicated by the blue line. This pattern is in line with the flow front as was discussed in Section 2.3.

![Image of a circular pattern with blue line indicating flow direction]

**Figure 5.17** – X-ray image of slice 432. Fibres tend to align to the flow pattern. Blue: the main direction of the fibres.

The specimen casted from the first batch score good on fibre alignment but the mixture was not representative. It appears that accidentally 7 percent or 1.14 kg of Portland cement was not mixed in the first batch. The mixture was therefore too fluid and prone to segregation. The fibres were able to orient due to the high workability, but the mixture is not representative.

The fibre alignment of the second batch is not find to be optimal. A second series will be casted with increased flux density.
5.3.4.2 Varying flux density and velocity

Segregation

The second series was casted with the mixture of Table 5.7. The results of the segregation analysis on fibres are presented in Table 5.17.

<table>
<thead>
<tr>
<th>Batch [#]</th>
<th>Cube [#]</th>
<th>Top half [#]</th>
<th>%</th>
<th>Bottom half [#]</th>
<th>%</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>71</td>
<td>45</td>
<td>35.7</td>
<td>81</td>
<td>64.3</td>
<td>126</td>
</tr>
<tr>
<td>81</td>
<td>62</td>
<td>44.6</td>
<td>77</td>
<td>55.4</td>
<td></td>
<td>139</td>
</tr>
<tr>
<td>91</td>
<td>65</td>
<td>44.8</td>
<td>80</td>
<td>55.2</td>
<td></td>
<td>145</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>57</td>
<td>41.7</td>
<td>79</td>
<td>58.3</td>
<td>137</td>
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<td>4</td>
<td>101</td>
<td>38</td>
<td>30.6</td>
<td>86</td>
<td>69.4</td>
<td>124</td>
</tr>
<tr>
<td>111</td>
<td>64</td>
<td>37.6</td>
<td>106</td>
<td>62.4</td>
<td></td>
<td>170</td>
</tr>
<tr>
<td>121</td>
<td>51</td>
<td>38.6</td>
<td>81</td>
<td>61.4</td>
<td></td>
<td>132</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>51</td>
<td>35.6</td>
<td>91</td>
<td>64.4</td>
<td>142</td>
</tr>
</tbody>
</table>

The top halves of cube 71 and 101 contain significantly less fibres than the top half of the other cubes. Beams 71 and 101 were the first specimen to be casted from each batch. It is plausible that the free water was not yet completely absorbed by the aggregate. This has probably resulted in a slight segregation of the fibres.

The fibre ratio top to bottom is approximately 40 to 60 for both of the batches. This is in agreement with results find by Kuijpers (2012) for FRC. The ratio has been improved in comparison with the ratio of the first series.
The results of the segregation analysis on aggregate are presented in Table 5.18.

**Table 5.18 - Results of the segregation analysis on aggregate.**

<table>
<thead>
<tr>
<th>Batch [#]</th>
<th>Cube [#]</th>
<th>Top half [#]</th>
<th>%</th>
<th>Bottom half [#]</th>
<th>%</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>71</td>
<td>31</td>
<td>44.9</td>
<td>38</td>
<td>55.1</td>
<td>69</td>
</tr>
<tr>
<td>81</td>
<td>31</td>
<td>43.7</td>
<td>40</td>
<td>56.3</td>
<td></td>
<td>71</td>
</tr>
<tr>
<td>91</td>
<td>39</td>
<td>49.4</td>
<td>40</td>
<td>50.6</td>
<td></td>
<td>79</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>46.0</td>
<td>39</td>
<td>54.0</td>
<td></td>
<td>73</td>
</tr>
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<td>101</td>
<td>42</td>
<td>49.4</td>
<td>43</td>
<td>50.6</td>
<td>85</td>
</tr>
<tr>
<td>111</td>
<td>42</td>
<td>48.3</td>
<td>45</td>
<td>51.7</td>
<td></td>
<td>87</td>
</tr>
<tr>
<td>121</td>
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<td>41.3</td>
<td>44</td>
<td>58.7</td>
<td></td>
<td>75</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>46.3</td>
<td>44</td>
<td>53.7</td>
<td></td>
<td>82</td>
</tr>
</tbody>
</table>

The distribution of the aggregate can be considered as homogeneous. The distribution is approximately 50-50.
Fibre orientation

In Table 5.19, the result of the analysis on fibre orientation is presented. In Appendix F, the columns “Amount” and “Goodness” can be found.

Table 5.19 - Results of the analysis on fibre orientation.

<table>
<thead>
<tr>
<th>Current [#]</th>
<th>Effective time of beam in coil [s]</th>
<th>Slice</th>
<th>Region A</th>
<th>Region B</th>
<th>Region C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Direction</td>
<td>Dispersion</td>
<td>Direction</td>
</tr>
<tr>
<td>7.5</td>
<td>180</td>
<td>731</td>
<td>24.5</td>
<td>7.8</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>733</td>
<td>-11.9</td>
<td>31.0</td>
<td>31.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>735</td>
<td>-0.6</td>
<td>11.3</td>
<td>-1.0</td>
</tr>
<tr>
<td>7.5</td>
<td>270</td>
<td>831</td>
<td>23.9</td>
<td>25.0</td>
<td>-56.7</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>27.3</td>
<td>15.1</td>
<td>-53.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>835</td>
<td>13.1</td>
<td>20.5</td>
<td>-12.9</td>
</tr>
<tr>
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<td>180</td>
<td>931</td>
<td>-8.9</td>
<td>27.3</td>
<td>51.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>933</td>
<td>17.6</td>
<td>13.3</td>
<td>-89.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>935</td>
<td>7.7</td>
<td>19.6</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>270</td>
<td>1031</td>
<td>7.8</td>
<td>38.6</td>
<td>43.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1033</td>
<td>12.8</td>
<td>15.8</td>
<td>-43.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1035</td>
<td>0.4</td>
<td>29.9</td>
<td>13.4</td>
</tr>
<tr>
<td>12.5</td>
<td>180</td>
<td>1131</td>
<td>11.5</td>
<td>23.1</td>
<td>-30.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1133</td>
<td>14.7</td>
<td>16.7</td>
<td>32.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1135</td>
<td>-8.0</td>
<td>10.9</td>
<td>-3.2</td>
</tr>
<tr>
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<td>90</td>
<td>1231</td>
<td>-27.6</td>
<td>8.0</td>
<td>43.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1233</td>
<td>13.7</td>
<td>7.8</td>
<td>-29.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1235</td>
<td>12.4</td>
<td>8.0</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Again, the fibres at the bottom slice aligned well to the span direction. Although the fibres of beam 8 were longer exposed to the magnetic field, their angle with respect to the span direction increased. Visual observation on the X-ray images confirmed that they formed a diagonal of clustered fibres through the specimen.
EVALUATION

The specimen were again rated on segregation, homogeneity of the fibre distribution and fibre alignment in Table 5.20.

Table 5.20 – Rating of the specimen.

<table>
<thead>
<tr>
<th>Beam [#]</th>
<th>Segregation Fibres</th>
<th>Fibre distribution Aggregate</th>
<th>Fibre alignment Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>++</td>
<td>0</td>
<td>++</td>
</tr>
<tr>
<td>9</td>
<td>+</td>
<td>++</td>
<td>0</td>
<td>++</td>
</tr>
<tr>
<td>10</td>
<td>+</td>
<td>++</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>12</td>
<td>+</td>
<td>++</td>
<td>--</td>
<td>++</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Increasing the flux density seems to have a positive influence on the orientation of the middle slices. The angle of the fibres with respect to the span direction decreases at increased flux density. The increase in flux density has a negative effect on the horizontal distribution of the fibres. In Figure 5.18, slice 1135 is shown. The blue area contains only one fibre over a height of 30 mm. The slice is located on the bottom side of the specimen. If the beam would be exposed to a four point flexural test, there is a high probability that the first crack would occur in the upper left side of the photo. The crack will then be able to develop itself through the blue area without interference of a fibre.

Figure 5.18 – A high flux density in the coil has a negative influence on the horizontal fibre distribution. Blue: area without fibres.
A mixed configuration of beam 10 and 11 is found to be optimal. The configuration can be found in Table 5.21.

**Table 5.21 - Configuration for bending tests.**

<table>
<thead>
<tr>
<th>Current [A]</th>
<th>Velocity [mm/s]</th>
<th>Effective time in coil [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.0</td>
<td>3.33</td>
<td>270</td>
</tr>
</tbody>
</table>
6.1 INTRODUCTION

An experimental exploration will be carried out to investigate the influence of oriented fibres on the bending moment capacity. Based on the literature discussed in Chapter 2, it can be expected that the post-cracking behaviour improves for oriented beams. The bending moment capacity of oriented beams will be compared with non-oriented, reference, beams, based upon four point flexural test without notch. The advantage this test has over the three point flexural test is that the beam will fail at its weakest cross-section. A three point flexural tests fails at a predefined region, above the notch. In practice, this will not happen either.
6.2 Experimental Program

Two series of six beams were casted using the mixture of Table 5.7. Six of twelve beams were oriented using the configuration presented in Table 5.21. The other six beams were casted from the outside and were not exposed to a magnetic field. The beams were demoulded 7 days after casting. The beams were stored at a relative humidity of 100% at 20°.

After the beams hardened for 28 days, the flexural strength was determined. Four point flexural test were carried out in accordance with the CUR Recommendation 35, deformation controlled and without notching the beam. The CUR 35 recommends to load the beam perpendicular on the casting plane. In the previous chapter it became clear that the orienting of the fibres proceeded best at the bottom side of the beam. It is therefore likely that loading the beam parallel to the casting plane results in a higher ultimate load in comparison with loading the beam perpendicular to the casting plane. Because there are more fibres in the bottom half of the beam, this effect might be enhanced. To check if these assumptions are true, two of twelve beams have been loaded perpendicular on the casting plane.

To achieve a slump flow of 600 mm, the total amount of stabilizer and superplasticizer differs per batch. In Table 6.1 the amount of stabilizer and superplasticizer per specimen is listed along with information on the tests.

**Table 6.1 – Specifics of the beams.**

<table>
<thead>
<tr>
<th>Beam [#]</th>
<th>Oriented</th>
<th>Loading plane = casting plane</th>
<th>Glenium Stream 2006 [kg/m³]</th>
<th>Glenium 51 [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>No</td>
<td>4.40</td>
<td>1.05</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Yes</td>
<td>4.40</td>
<td>1.05</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>No</td>
<td>4.40</td>
<td>1.05</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>Yes</td>
<td>2.70</td>
<td>0.76</td>
</tr>
<tr>
<td>5</td>
<td>Yes</td>
<td>Yes</td>
<td>2.70</td>
<td>0.76</td>
</tr>
<tr>
<td>6</td>
<td>No</td>
<td>Yes</td>
<td>2.70</td>
<td>0.76</td>
</tr>
<tr>
<td>7</td>
<td>No</td>
<td>Yes</td>
<td>3.48</td>
<td>1.29</td>
</tr>
<tr>
<td>8</td>
<td>No</td>
<td>Yes</td>
<td>3.48</td>
<td>1.29</td>
</tr>
<tr>
<td>9</td>
<td>Yes</td>
<td>Yes</td>
<td>3.48</td>
<td>1.29</td>
</tr>
<tr>
<td>10</td>
<td>No</td>
<td>Yes</td>
<td>2.00</td>
<td>0.64</td>
</tr>
<tr>
<td>11</td>
<td>Yes</td>
<td>Yes</td>
<td>2.00</td>
<td>0.64</td>
</tr>
<tr>
<td>12</td>
<td>Yes</td>
<td>Yes</td>
<td>2.00</td>
<td>0.64</td>
</tr>
</tbody>
</table>
In Figure 6.2, the loading of a beam parallel to the casting plane (a.) and perpendicular to the casting plane (b.) is schematically presented. Because the surface of the beam was rough, in case of loading parallel to the casting plane, the load is levelled out by making use of hardboard.

**Figure 6.2** – Beams loaded in a four point flexural test set-up. (a.) Beam loaded parallel to the casting plane. (b.) Beam loaded perpendicular to the casting plane.
6.3 Test results

6.3.1 First series

By accident, 1.8 kg of fly ash has been replaced by blast furnace cement (CEM III 42,5 N) during the mixture process of the first series. The total amount of cement was therefore 7.3 percent higher than supposed to. The load-deflection diagrams are plotted in Figure 6.3. Beam 05 was loaded up to 30 kN when it was discovered that the LVDT did not function correct. The beam was then unloaded and loaded again. Unloading the beam most probably lead to permanent deformation and a lower stiffness.

The two best performing beams were not oriented. The average of the ultimate load of the non oriented beams is higher than the average ultimate load of the oriented beams. The author attributes this to two effects which are caused by the formation of clusters. Firstly, the formation of clusters indirectly increases the inhomogeneity of the composite SCFRC. This effect has most likely a negative effect on the ultimate load. Secondly, because the fibres have a mutual connection they are not totally embedded in the concrete. In the next chapter it becomes clear that the pull out load for a single connected fibre is lower than a single fibre completely embedded in the concrete. It is therefore assumed that this effect also has a negative influence on the ultimate load. All load-deflection curves show a similar post-cracking behaviour.

The average ultimate load of the beams loaded perpendicular to the casting plane is lower than the beams loaded parallel to the casting plane. This was to be expected because more fibres are present at the bottom than on average at the side of a beam. In Appendix G, the results of the four point flexural test and the failure pattern can be viewed in more detail.
Figure 6.3 – Load-deflection diagrams of the first series.

In Table 6.2, the load $F_{br}$ and the corresponding flexural tensile stress $f_{br}$ of the first series are listed. The $F_{br}$ indicates the force at the moment the first crack occurs.

Table 6.2 – $F_{br}$ and flexural tensile stress of the first series.

<table>
<thead>
<tr>
<th>Beam [#]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{br}$ [kN]</td>
<td>48.26</td>
<td>48.65</td>
<td>47.03</td>
<td>56.87</td>
<td>44.69</td>
<td>51.62</td>
</tr>
<tr>
<td>$f_{br}$ [N/mm$^2$]</td>
<td>6.23</td>
<td>6.15</td>
<td>6.05</td>
<td>7.33</td>
<td>5.60</td>
<td>6.58</td>
</tr>
<tr>
<td>Oriented</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Loading plane = casting plane</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
6.3.2 SECOND SERIES

In Figure 6.4, the load-deflection diagrams of the second series are plotted. The second series shows more spread in the load-deflection diagrams than the first series. Beam 11 and 12, both oriented, have the highest ultimate load. Beam 8 and 11 performed best in terms of post-cracking behaviour. It cannot be concluded whether the oriented beams perform better or worse.

![Load-deflection diagrams of the second series](image)

**Figure 6.4** – Load-deflection diagrams of the second series.

In Table 6.3, the load $F_{\text{bri}}$ and the corresponding flexural tensile stress $f_{\text{bri}}$ of the second series series are listed.

<table>
<thead>
<tr>
<th>Beam [#]</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{\text{bri}}$ [kN]</td>
<td>53.71</td>
<td>52.16</td>
<td>57.62</td>
<td>51.57</td>
<td>55.10</td>
<td>65.03</td>
</tr>
<tr>
<td>$f_{\text{bri}}$ [N/mm²]</td>
<td>7.10</td>
<td>6.98</td>
<td>7.32</td>
<td>6.51</td>
<td>7.01</td>
<td>8.15</td>
</tr>
<tr>
<td>Oriented</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Loading plane = casting plane</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
6.3.3 SERIES COMBINED

Tables 6.2 and 6.3 will be compared. The beams loaded perpendicular to the casting plain are left out. It appears that the flexural tensile stress $f_{brl}$ of the second series is on average 11.2 percent higher than the flexural tensile stress of the first series. Although the first series contains more cement, this does not lead to a higher flexural tensile stress. This could be the result of the different packing models in both series. Fly ash has a smaller grain diameter than cement. Being finer than cement, it can fill into the voids between cement grains. The second series contains more fly ash. Kwan and Chen and Mohammed stated that up to a certain level adding more fly ash leads to higher compression strengths because of the higher packing density [25][26].

All load-deflection curves are plotted in Figure 6.5. The beams loaded perpendicular to the casting plane are left out. The blue lines correspond with the oriented beams and the black lines with the non oriented beams. The gradient of all graphs is similar.

![Figure 6.5 - Load-deflection diagrams of the two series combined. Blue lines: oriented beams, black lines: non oriented beams.](image)

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6.4 CONCLUDING REMARKS

It can be concluded that orienting the fibres with the test-up as used in this research does not improve the flexural tensile stress nor the post-cracking behaviour. It is inherent to the four point flexural test that the specimen fails at the weakest cross-section. The weakest cross-section in case of SCFRC is a cross-section with little to no fibres. In Paragraph 5.3.4 it was observed that an increase in flux density leads to an increase in inhomogeneity. It is therefore likely that the specimen failed on a cross-section where little to no fibres were present.
THE EFFECT OF COUPLED FIBRES ON
THE PULL-OUT BEHAVIOUR

CHAPTER 7

Figure 7.1 – Schematic overview of the test set-up.

7.1 INTRODUCTION

In Chapter 4 it became clear that the magnetization of the fibres leads to clustering of the fibres. In this chapter, the effect of the clustering effect will be investigated. Parallel to this research, Van der Aa studied the influence of biaxial stresses on the pull-out behaviour of a single steel fibre using FEM [27]. Thereby, he made use of experimental results of pull-out tests. The test set-up that he used is also used for the experiments in this research, see Figure 7.1.
7.2 EXPERIMENTAL PROGRAM

To investigate the influence of coupled fibres on the pull-out behaviour, pull-out tests on both coupled and uncoupled fibres are performed. Ten cubes were casted with fibres half embedded in the concrete matrix. Five of them are references, five of them have two coupled fibres. After 7 days of hardening, the fibres were pulled out of the cube by using a tensile testing machine. In the case of coupled fibres, a situation is chosen which could possibly be beneficial for the pull-out behaviour, see Figure 7.2. If a tensile force works on the “top” fibre it is assumed that the fibre eventually has to deform the “coupled” fibre before it can be pulled out. That could result in a higher pull-out force.

The fibres were coupled using UV adhesive. The adhesive hardens if it is exposed to UV light. The coupled fibres were fixed in the mould and subsequently the cubes were casted. The concrete class of the mixture was C28/35. The adhesive dissolves in a aqueous environment, e.g. concrete, in 2 to 24 hours. After hardening, the fibres then can not transfer axial forces anymore.

![Figure 7.2](image.png)

**Figure 7.2** – Scheme of two “coupled” fibres in a concrete cube.

When a single fibre is pulled, Figure 7.3 describes the different stages the fibre passes:

i. debonding of the fibre;
ii. the concrete starts to crack;
iii. the concrete fails;
iv. the fibre deforms plastically;
v. frictional pull-out resistance.
Figure 7.3 – Different stages a single fibre passes when it is pulled.

When a coupled fibre is pulled, Figure 7.4 describes the different stages it is believed to pass:

i. debonding of the fibre;
ii. the concrete starts to crack;
iii. the concrete fails;
iv. the fibres deform plastically;
v. the top fibre deforms more and is pulled out;
vi. frictional pull-out resistance.

Figure 7.4 – Different stages a coupled fibre is believed to pass when it is pulled.

7.3 Test Results

The results of the pull-out tests are plotted in Figure 7.5. The black lines indicate the single fibre pull-out test curves, while the blue lines indicate the coupled fibre pull-out test curves.
Figure 7.5 – Force-slip diagram of the coupled and uncoupled fibres. Black lines: single fibres, blue lines: coupled fibres.

In Figure 7.6, the interpretation of the average of both the coupled and coupled fibres is plotted.

Figure 7.6 – Force-slip diagram of the coupled and uncoupled fibres. Black lines: single fibres, blue lines: coupled fibres.
After a slip of 4-5 mm the coupled fibres show a fast increase in pull-out load. The frictional phase then starts. Figure 4.10 shows a coupled fibre and a single fibre after the pull-out test have been performed. It appears that the hooked end of the coupled fibre is not fully deformed in comparison with the single fibre. The coupled fibre therefore experiences more friction when it is pulled out. Also, the span of the frictional phase of the coupled fibre is wider. After a slip of 17 mm, the single fibre does not experience friction because it is almost fully deformed. The coupled fibre is than not fully deformed and still experiences friction.

The spread in the post-cracking behaviour of the pull-out tests is large. The location of the aggregate with respect to the fibres can be of influence on the test results. If gravel grain is located close to the fibre, the adhesion strength decreases. The tests should be repeated in a mixture with a small maximum grain size or in a mixture with solely cement and water. The pull out-tests were performed 7 days after casting due to time lack.

The splitting tensile strength and modulus of elasticity of plain concrete after 7 days is approximately 80 to 90 percent [28][29]. It is therefore believed that the results of the pull-out curves after 7 days of hardening are representative for the pull-out curves after 28 days of hardening.

In Appendix H, the results of the pull-out tests can be viewed in more detail.

**Figure 7.7** – Fibres after pull-out tests were performed. Left: a coupled fibre. Right: a single fibre.
CONCLUSIONS AND RECOMMENDATIONS
CHAPTER 8

8.1 INTRODUCTION
In this research, the behaviour of a single fibre and the interaction of multiple fibres in a magnetic field is investigated. A method to orient fibres in freshly casted beams is proposed and a SCFRC mixture was designed. The effect of the governing parameters on the orientation process was investigated by making use of X-ray imaging. Finally, the effect of the orientation of fibres on the flexural bending stress was experimentally determined. In this chapter, the conclusions of the research will be presented. The conclusions lead to recommendations for further research and for application of the method in practice.

8.2 CONCLUSIONS

DESIGN OF AN ELECTROMAGNETIC COIL
The experimentally determined flux density of the designed electromagnetic coils were in good agreement with the FEMM model.

ORIENTING A SINGLE FIBRE
A fibre in a magnetic field aligns to the magnetic field lines. The orientation of a fibre is not blocked by gravel. The required time to orient a fibre decreases exponentially at increasing flux density. A magnetic flux density of $2.3 \times 10^{-2}$ T makes it possible to orient a single fibre in a medium with a plastic viscosity of 60 Pa·s in approximately 10 seconds. The fibres do not completely align to the magnetic field lines, at relative low flux intensities. The total angle a fibre rotates depends on the length, volume and alloy of the fibre and the flux density.

ORIENTING MULTIPLE FIBRES
Multiple fibres in a magnetic field have the tendency to attract and repel each other. Hereby, clusters of fibres are being formed. The formation of clusters is unwanted. Pull-out tests on two coupled fibres show that the adhesion strength of the fibre decreases by approximately 20 percent. This is caused by the reduced embedment of the fibre in the concrete matrix. The homogeneity of the magnetic field is of high importance. An
inhomogeneous field leads to fibres tending to move to the area with the highest flux density. This negatively effects the fibre distribution in SCFRC.

MIXTURE COMPOSITION
The final mixture composition had a good workability and segregation resistance. However, the mixture was not optimal. The amount of free water was increased to compensate for the moisture content of the aggregate but this caused segregation. Stabilizer was then added to again bind the free water. The amount of free water and stabilizer could thus be lowered. All mixtures were mixed following a strict procedure. However, for various batches a large spread in workability was observed. This is on the one hand caused by environmental conditions, e.g. temperature and relative humidity, and on the other hand by the relative small batches. Per batch, small additions of superplasticizer or stabilizer were necessary in order to guarantee a slump flow of 600 mm. Small additions of superplasticizer or stabilizer had a great impact on the segregation resistance and workability of the mixture. Segregation analyses on fibres and aggregate showed that fibres are more prone to segregation. The aggregate has a density that is similar to the SCC while the density of steel is three times higher. A vertical fibre distribution of 45 percent fibres at the top half and 55 percent at the bottom half was found. The compressive strength of the cubes was almost equal to the strength found by Grunewald, despite the addition of stabilizer and plasticizer.

FIBRE ORIENTATION IN SCFRC BEAMS
Fibres were oriented in SCFRC beams. The increase of the flux density of the magnetic field enhances the alignment of the fibres to the field lines in SCFRC. However, it has negative consequences on the homogeneity of the fibre distribution. If the flux density increases, so does the magnetization of the fibre. The charge at the poles then increases and the attractive force between the fibres increases. X-ray images were successfully taken from samples with a height of 30 mm. X-ray imaging revealed that the fibres indeed have an increasing tendency to cluster. In one beam, only one fibre in an area of 80 cm³ was observed.

EFFECT OF FIBRE ORIENTATION ON THE BENDING MOMENT CAPACITY
The bending moment capacity of oriented specimen was determined by making use of the four point flexural test without notch. Characteristic for the test is that the specimen fails at the weakest cross-section. The weakest cross-section is however artificially created by exposing the specimen to a magnetic field. It is therefore explicable that the oriented
specimen did not show an increasing bending moment capacity with respect to non-oriented specimen. The flux density for the orientation of the specimen could be reduced with 15 percent to prevent areas without fibres. It is expected that if three point flexural tests would have been performed an increase in flexural tensile stress would have been observed. The specimen then fails in a predefined region which is not per se the weakest cross-section.
8.3 RECOMMENDATIONS

8.3.1 FURTHER RESEARCH

8.3.1.1 RESEARCH ON POTENTIAL OF THE METHOD FOR ORIENTING FIBRES

The orientation of the fibres in specimen of 600 x 150 x 150 did not lead to an increase in bending moment capacity in the post-cracking stage. This is most probably caused by the parameters that were used for the process and the inhomogeneity of the magnetic field. It does not necessarily mean that the method for orienting steel fibres in a magnetic field is not successful. Two interim steps should be studied to reveal the potential of the method.

STEP 1 – COMPARISONS OF ALIGNED, ORIENTED AND REFERENCE SPECIMEN

Svec et al. found that the bending moment capacity of a beam with aligned fibres increases with respect to completely non-aligned fibres [4]. A normal casted beam is however not completely non-aligned. The fibres follow the flow front. Research should be done to see to what extend the bending moment capacity of a normal casted beam is lower than the capacity of a completely aligned beam. If it appears that the reference specimen have an equal bending moment capacity, orienting fibres will not help increasing the bending moment capacity. However, this is not expected.

In Figure 8.1, a numerical simulation of a SFRC slab casted from out the lower left corner, indicated by a red circle, can be seen. The blue area indicates the area where the fibres are completely aligned. Specimen with completely aligned fibres could be cut out of this area.

![Figure 8.1 – SFRC slab casted from out the lower left corner (red circle). The blue area indicates completely aligned fibres.](image)
Most likely, the bending moment capacity of specimen oriented by a magnetic field lies in between the capacity of completely aligned specimen and reference specimen. Specimen should be oriented using the electromagnet and tested on bending moment capacity. The comparison will reveal to what extent improving the orientation of fibres contributes to the bending moment capacity. In Figure 8.2, the comparison is visualized.

**Figure 8.2** – Comparison of reference, oriented and completely aligned specimen on bending moment capacity.

The bending moment capacity should be tested by performing a three point flexural test, without notch. In case of the magnetically oriented specimen, the fibres oriented best at the bottom side of the specimen. The fibres will not be activated if a notch is applied. It would not reveal the real potential of the oriented specimen.

To make sure that the inhomogeneity of the magnetic field does not affect the specimen, it could be an option to reduce the height and width of the specimen because the middle 100 mm of the electromagnet is homogeneous. However, if specimen with an altered size, e.g. 400 x 100 x 100 mm would be subjected to a three point flexural test, the failure behaviour could be different than what is expected based on specimen with the standardized dimensions of 600 x 150 x 150 mm. Also, the “reference” specimen will not be an accurate reflection of the reality. The size of the fibres will influence their alignment if the width of the beam is further reduced. Therefore, the standardized format is recommended.

An adjustment to the parameters for the orientation of fibres should be made. For a beam with a cross-section of 150 x 150 mm a reduction of flux density of 15 percent, to 9.4 A, at a similar velocity of 3.33 mm/s is recommended. This will lead to a slightly less oriented specimen, but increases the homogeneity of the fibre distribution. The fibre volume could be best reduced to 0.5 percent by volume of steel fibres. The market demands a lower percentage to be able to produce cost efficient.
STEP 2 – COMPARISON OF ALIGNED FIBRES AND CLUSTERED FIBRES.

The pull-out tests on coupled fibres show that the adhesion strength decreases in comparison with single fibres. After the debonding stage was passed, a sharp decrease was observed for the pull-out load of a coupled fibre. The UV adhesive that was used to couple the fibres possibly caused voids while dissolving. Also, the spread in the post-cracking behaviour of the pull-out tests is large. The tests should be repeated in a mixture with a small maximum grain size, e.g. 4 mm, or in a mixture with solely cement and water without using a dissolving adhesive. Normal adhesive, glucose or wood glue could instead be used.

If the tests gives the same outcome, additional research should be performed. A comparison should be made between the bending moment capacity of specimen with completely aligned, homogenous distributed fibres and specimen with clustered, homogeneously distributed fibres, see Figure 8.3. Standardized specimen can be used. A three point flexural test with notch is recommended because than the area of failure is known. For specimen tested in a three point bending test with a span of 550 mm, the influence zone is 125 mm in total [30]. Fibres should be present in the influence zone. It is of importance that the amount of fibres in both specimen is equal.

**Figure 8.3** – Left: a specimen with aligned, coupled fibres. Right: a specimen with aligned, uncoupled fibres.

The dimensions of the specimen can be reduced to 400 x 100 x 100 mm because all fibres are aligned to the span direction and the test results are only relative to each other. The influence zone for specimen with a reduced size has to be investigated.
8.3.1.2 Shear capacity
If it appears that the bending moment capacity can be increased by orienting steel fibres in small specimen, research should be carried out on the ability to improve the shear capacity of beams. Possibly, the amount of stirrups can be lowered which reduces the labour costs in the prefab industry.

8.3.1.3 Partition of the mould
If the research in Subparagraph 8.2.1.1 shows that uncoupled fibres are beneficial in comparison with coupled fibres, a new method for casting and orienting can be used, see Figure 8.4. Before casting, the mould should be partitioned. The beam should then be casted and oriented. The compartments ensure that the fibres will not be able to cluster, while they can be oriented. Also, this has a positive effect on the horizontal distribution in case of a inhomogeneous field.

After casting the partition could be removed. The beam could be levelled off with a small extra amount of SCFRC.

![Figure 8.4 – Mould divided in compartments. After the orientation process is completed, the compartments can be removed.](image)

The partitioning can affect the homogeneity of the aggregate and fibres and the removal of the compartments can induce torque on the fibres. A study should be conducted to see to what extend the fibre orientation and the homogeneity of the mixture are affected.
8.3.1.4 TYPE OF FIBRE

Another way to minimize the negative characteristics of clustering fibres might be the design of a new type of fibre. The results of the pull-out test show that clustering of the conventional hooked-end fibres has the negative characteristic that the adhesion strength decreases. This negative effect should be prevented. Alternatives for the conventional hooked-end steel fibres are:

i. hooked-end steel fibre with a longer anchorage length;

ii. hooked-end steel fibre with a magnetic spacer.

In Figure 8.5, the two alternatives are shown.

![Diagram of fibre types](image)

**Figure 8.5** – Two alternatives for the conventional hooked-end fibre.

A longer anchorage length can improve the adhesion strength of the fibres and neutralize the effect of the clustering fibres (i). The fibre is extended with two magnetic spacers, all made of steel (ii). Because the two magnetic spacers are connected, the electrical charge of the magnetized fibre will move to the outside. Two fibres will couple at the outside of the fibres, at the height of the spacer. The embedment of the hooked-end will then remain sufficient. A study should be conducted to see whether these assumptions are true.
8.3.1.5 Interaction of traditional reinforcement and steel fibres

For successful application in structural elements, steel fibres should be combined with traditional reinforcement, e.g. reinforcement bars or strands. In FEMM, three steel bars have been modelled to study the effect on the magnetic field. In Figure 8.6, the density plot can be seen.

![Density plot of three reinforcement bars in the large electromagnetic coil.](image)

**Figure 8.6** – Density plot of three reinforcement bars in the large electromagnetic coil.

The steel in the magnetic field does not influence the direction of the field lines. The electromagnet causes the charge to move to the outside of the strand or reinforcement bar. If the strands, or reinforcement bars, are continuous, they will only attract fibres in a cross-section at the outside, near the end of the beam. The electromagnet does lose capacity to the magnetization of the strand or reinforcement bar. Research should be carried out on the ability to orient fibres with the presence of traditional reinforcement steel.
8.3.2 PRACTICAL APPLICATION

8.3.2.1 LENGTH OF AN ELECTROMAGNETIC COIL
The magnetic field of the electromagnetic coils that were used during this research had an insufficient homogeneous field. From cost perspective, the length of the coil was chosen to be equal to radius of the coil, $\ell = r$. An increase of the ratio length to radius increases the homogeneity of the field. A ratio length of two times the radius, $\ell = 2r$, is recommended for the design of an electromagnetic coil for the purpose of orienting steel fibres.

8.3.2.2 DESIGN OF THE MANUFACTURING PROCESS
For the application of the method in practice, an adjustment to the current production process should be made. A coil must be able to shift over the span direction of the mould. That requires a rails that should be constructed, which is only possible if a new foundation design is made.
Currently, in the prefab industry use is made of ferromagnetic moulds. The moulds should be replaced by non-ferromagnetic moulds. Otherwise, the capacity of a coil moving over the ferromagnetic moulds would be wasted on magnetizing the mould and the flux density would drastically decrease.


[16] MARKOVIC, I., High-Performance Hybrid-Fibre Concrete, Development and Utilisation, PhD study, Delft, 2006.


<table>
<thead>
<tr>
<th>Appendix</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix A</td>
<td>Drawings of the Trial Electromagnetic Coil</td>
</tr>
<tr>
<td>Appendix B</td>
<td>Drawings of the Full-Scale Electromagnetic Coil</td>
</tr>
<tr>
<td>Appendix C</td>
<td>Model for Designing an Electromagnetic Coil</td>
</tr>
<tr>
<td>Appendix D</td>
<td>Verification of the Flux Density</td>
</tr>
<tr>
<td>Appendix E</td>
<td>Mixture Composition</td>
</tr>
<tr>
<td>Appendix F</td>
<td>Analyses on Fibre Orientation</td>
</tr>
<tr>
<td>Appendix G</td>
<td>Results of the Four Point Flexural Tests</td>
</tr>
<tr>
<td>Appendix H</td>
<td>Results of the Pull-Out Tests</td>
</tr>
</tbody>
</table>
Appendix A - Drawings of the Trial Electromagnetic Coil
koeling m.b.v. koperen waterleiding

koperdraad Ø2,112 mm
61 wikkelingen, 23 lagen

koperen plaat 250x250x6mm

messing buis Ø115 - 2,5mm

alle maten in mm

Luchtspoel
Doorsnede

schaal 1:2
formaat A4

datum 11-03-'13

Mark Wijffels
APPENDIX B - DRAWINGS OF
THE FULL-SCALE ELECTROMAGNETIC COIL
alle maten in mm
beschrijving
Luchtpoel Voor- en Achteraanzicht
schaal en formaat
1:2.5 A4
datum
01-07-'13
naam pagina
Mark Wijffels 1/2
koperdraad Ø2,48 mm (incl. 0,12 coating)
121 wikkelingen, 16 lagen

messing plaat 408x408x4 mm

messing buis Ø308 - 4 mm
APPENDIX C - MODEL FOR DESIGNING AN ELECTROMAGNETIC COIL
INPUT

The input of the model is:

\[\begin{align*}
L_c &= \text{length of the coil} \\
D &= \text{diameter of the coil} \\
d &= \text{diameter of the wire} \\
N &= \text{number of windings of the coil} \\
N_2 &= \text{number of layers of the coil}
\end{align*}\]

EQUATIONS

The models makes use of the following equations.

Determination of the flux density:

\[B = \mu_0 N I\]  \hspace{1cm} (C.1)

with:

\[\begin{align*}
B &= \text{magnetic flux density} \quad \text{[T]} \\
\mu_0 &= \text{permeability of free space} = 4\pi 10^{-7} \quad \text{[-]} \\
N &= \text{number of windings} \quad \text{[-]} \\
I &= \text{current} \quad \text{[A]}
\end{align*}\]

Surface of the wire:

\[A = \frac{1}{4} \pi d^2 \frac{10^6}{10^6}\]  \hspace{1cm} (C.2)

with:

\[\begin{align*}
A &= \text{surface of the wire} \quad \text{[m]} \\
d &= \text{diameter of the wire} \quad \text{[mm]}
\end{align*}\]

Circumference of a winding:

\[L_w = \frac{\pi(D + (N_2\times(d + 0.118)}{1000}\]  \hspace{1cm} (C.3)

\[\begin{align*}
L_w &= \text{circumference of a winding} \quad \text{[m]} \\
D &= \text{diameter of the coil} \quad \text{[mm]} \\
N_2 &= \text{number of layers} \quad \text{[#]} \\
0.118 &= \text{thickness of the coating} \quad \text{[mm]}
\end{align*}\]
Resistance of the wire:

\[ R = \frac{\rho L}{A} \]  \hspace{1cm} (C.4)

\( R \) = resistance \hspace{1cm} [\Omega]
\( \rho \) = resistivity \hspace{1cm} [\Omega \cdot m]
\( \rho_{\text{copper}} \) = 172 \cdot 10^{-8} \Omega \cdot m \hspace{1cm} [\Omega \cdot m]

Required current and voltage of the power supply:

\[ R = U I \]  \hspace{1cm} (C.5)
\( U \) = voltage \hspace{1cm} [V]

Mass of the coil:

\[ m = L_w \cdot A \cdot \rho_c \]  \hspace{1cm} (C.6)
\( m \) = mass of the coil \hspace{1cm} [kg]
\( \rho_c \) = volumetric weight of copper \hspace{1cm} [kg / m^3]
\( \rho_c \) = 8900 \hspace{1cm} [kg / m^3]

The total costs of the copper wire

**OUTPUT**

The output of the model is:

\( B \) = flux density of the field
\( U \) = required voltage
\( \epsilon \) = total costs copper wire

On the next page, the configurations for the small and large electromagnetic coil can be found. To be able to observe the effect of the diameter of the coil, extra configurations have been added.
**TRIAL ELECTROMAGNETIC COIL**

Table C.1 – Model that was used during the design of the trial coil.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>10000</td>
<td>1</td>
<td>10</td>
<td>0.1008</td>
<td>7.85E-09</td>
<td>2.190</td>
<td>0.365</td>
<td>667.0</td>
<td>1460.6</td>
<td>14606.4</td>
<td>0.05</td>
<td>0.93</td>
</tr>
<tr>
<td>1</td>
<td>1000</td>
<td>10</td>
<td>10</td>
<td>0.1008</td>
<td>7.85E-07</td>
<td>0.022</td>
<td>0.399</td>
<td>667.0</td>
<td>14.6</td>
<td>146.1</td>
<td>4.66</td>
<td>93.24</td>
</tr>
<tr>
<td><strong>2</strong></td>
<td><strong>472</strong></td>
<td><strong>23</strong></td>
<td><strong>25</strong></td>
<td><strong>0.2736</strong></td>
<td><strong>3.14E-06</strong></td>
<td><strong>0.005</strong></td>
<td><strong>0.517</strong></td>
<td><strong>724.1</strong></td>
<td><strong>4.0</strong></td>
<td><strong>99.1</strong></td>
<td><strong>20.24</strong></td>
<td><strong>404.90</strong></td>
</tr>
<tr>
<td>2.5</td>
<td>400</td>
<td>4</td>
<td>100</td>
<td>0.1613</td>
<td>4.90E-06</td>
<td>0.004</td>
<td>0.397</td>
<td>106.7</td>
<td>0.4</td>
<td>37.4</td>
<td>4.66</td>
<td>93.24</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>15</td>
<td>100</td>
<td>0.3024</td>
<td>1.963-05</td>
<td>0.001</td>
<td>0.605</td>
<td>200.1</td>
<td>0.2</td>
<td>17.5</td>
<td>34.97</td>
<td>699.32</td>
</tr>
</tbody>
</table>

Length coil [mm] 129
Diameter [mm] 116
Length winding [m] 0.362442
## FULL-SCALE ELECTROMAGNETIC COIL

**Table C.2** – Model that was used during the design of the full-scale coil.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.36</td>
<td>404</td>
<td>16</td>
<td>13</td>
<td>0.0847</td>
<td>4.37E-06</td>
<td>0.004</td>
<td>1.098</td>
<td>2130.1</td>
<td>8.4</td>
<td>108.9</td>
<td>82.93</td>
<td>1658.58</td>
</tr>
</tbody>
</table>

Length coil [mm] 300
Diameter [mm] 310
Length winding [m] 0.942477
APPENDIX D - VERIFICATION OF THE FLUX DENSITY
DENSITY PLOT

In FEMM, the full-scale electromagnetic coil is modeled. In Figure D.1, the density plot of the FEMM model can be seen.

![Density plot of the FEMM model.](image)

**Figure D.1** – Density plot of the FEMM model.

The verification of the FEMM model with the trial and full-scale coil can be found on the next pages.
VERIFICATION TRIAL ELECTROMAGNETIC COIL

Table D.1 – Verification of the FEMM model with the experimentally determined flux density.

<table>
<thead>
<tr>
<th>B</th>
<th>Position (mm)</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Centerline</td>
<td>Experimental</td>
<td>0.252</td>
<td>0.244</td>
<td>0.240</td>
<td>0.235</td>
<td>0.229</td>
<td>0.226</td>
<td>0.225</td>
<td>0.226</td>
<td>0.229</td>
<td>0.235</td>
<td>0.240</td>
<td>0.244</td>
</tr>
<tr>
<td></td>
<td>FEMM</td>
<td></td>
<td>0.259</td>
<td>0.250</td>
<td>0.243</td>
<td>0.237</td>
<td>0.233</td>
<td>0.231</td>
<td>0.231</td>
<td>0.233</td>
<td>0.237</td>
<td>0.243</td>
<td>0.250</td>
<td>0.259</td>
</tr>
<tr>
<td></td>
<td>35 mm</td>
<td>Experimental</td>
<td>0.223</td>
<td>0.217</td>
<td>0.208</td>
<td>0.204</td>
<td>0.203</td>
<td>0.202</td>
<td>0.201</td>
<td>0.202</td>
<td>0.202</td>
<td>0.204</td>
<td>0.209</td>
<td>0.217</td>
</tr>
<tr>
<td></td>
<td>FEMM</td>
<td></td>
<td>0.245</td>
<td>0.234</td>
<td>0.224</td>
<td>0.218</td>
<td>0.213</td>
<td>0.213</td>
<td>0.211</td>
<td>0.213</td>
<td>0.213</td>
<td>0.218</td>
<td>0.224</td>
<td>0.234</td>
</tr>
<tr>
<td></td>
<td>70 mm</td>
<td>Experimental</td>
<td>0.138</td>
<td>0.140</td>
<td>0.142</td>
<td>0.141</td>
<td>0.141</td>
<td>0.141</td>
<td>0.141</td>
<td>0.140</td>
<td>0.141</td>
<td>0.141</td>
<td>0.139</td>
<td>0.139</td>
</tr>
<tr>
<td></td>
<td>FEMM</td>
<td></td>
<td>0.182</td>
<td>0.168</td>
<td>0.162</td>
<td>0.159</td>
<td>0.157</td>
<td>0.156</td>
<td>0.156</td>
<td>0.156</td>
<td>0.157</td>
<td>0.159</td>
<td>0.162</td>
<td>0.168</td>
</tr>
</tbody>
</table>

Figure D.2 – Comparison of the numerical and experimental found flux density. Left: at the center; middle: 35 mm from the center; right: 70 mm from the center.
**Verification Full-Scale Electromagnetic Coil**

*Table D.2* – Verification of the FEMM model with the experimentally determined flux density.

<table>
<thead>
<tr>
<th></th>
<th>Position (mm)</th>
<th>10</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
<th>110</th>
<th>130</th>
<th>150</th>
<th>170</th>
<th>190</th>
<th>210</th>
<th>230</th>
<th>250</th>
<th>270</th>
<th>290</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Centerline</strong></td>
<td>Experimental</td>
<td>0.086</td>
<td>0.083</td>
<td>0.080</td>
<td>0.078</td>
<td>0.077</td>
<td>0.076</td>
<td>0.075</td>
<td>0.075</td>
<td>0.075</td>
<td>0.076</td>
<td>0.077</td>
<td>0.079</td>
<td>0.081</td>
<td>0.083</td>
<td>0.087</td>
</tr>
<tr>
<td></td>
<td>FEMM</td>
<td>0.081</td>
<td>0.078</td>
<td>0.076</td>
<td>0.074</td>
<td>0.072</td>
<td>0.071</td>
<td>0.071</td>
<td>0.071</td>
<td>0.071</td>
<td>0.071</td>
<td>0.071</td>
<td>0.076</td>
<td>0.078</td>
<td>0.081</td>
<td></td>
</tr>
<tr>
<td><strong>150 mm</strong></td>
<td>Experimental</td>
<td>0.078</td>
<td>0.075</td>
<td>0.071</td>
<td>0.069</td>
<td>0.067</td>
<td>0.066</td>
<td>0.065</td>
<td>0.065</td>
<td>0.066</td>
<td>0.067</td>
<td>0.069</td>
<td>0.071</td>
<td>0.074</td>
<td>0.078</td>
<td></td>
</tr>
<tr>
<td>From center</td>
<td>FEMM</td>
<td>0.077</td>
<td>0.074</td>
<td>0.070</td>
<td>0.068</td>
<td>0.066</td>
<td>0.065</td>
<td>0.064</td>
<td>0.064</td>
<td>0.065</td>
<td>0.066</td>
<td>0.068</td>
<td>0.070</td>
<td>0.074</td>
<td>0.077</td>
<td></td>
</tr>
<tr>
<td><strong>300 mm</strong></td>
<td>Experimental</td>
<td>0.044</td>
<td>0.046</td>
<td>0.046</td>
<td>0.046</td>
<td>0.046</td>
<td>0.047</td>
<td>0.047</td>
<td>0.047</td>
<td>0.047</td>
<td>0.046</td>
<td>0.046</td>
<td>0.046</td>
<td>0.046</td>
<td>0.046</td>
<td>0.044</td>
</tr>
<tr>
<td>From center</td>
<td>FEMM</td>
<td>0.058</td>
<td>0.052</td>
<td>0.050</td>
<td>0.048</td>
<td>0.048</td>
<td>0.047</td>
<td>0.047</td>
<td>0.047</td>
<td>0.047</td>
<td>0.047</td>
<td>0.048</td>
<td>0.048</td>
<td>0.050</td>
<td>0.052</td>
<td>0.058</td>
</tr>
</tbody>
</table>

*Figure D.3* – Comparison of the numerical and experimental found flux density. Left: at the center; middle: 150 mm from the center; right: 300 mm from the center.
APPENDIX E - MIXTURE COMPOSITION
<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (kg)</th>
<th>Specific Weight (kg/l)</th>
<th>Volume (l)</th>
<th>Weight per 50 liter (kg)</th>
<th>Weight per 20 liter (kg)</th>
<th>Weight per 60 liter (kg)</th>
<th>Weight per 70 liter (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 52,5 R</td>
<td>269</td>
<td>3.15</td>
<td>85.40</td>
<td>13.450</td>
<td>5.380</td>
<td>16.140</td>
<td>18.830</td>
</tr>
<tr>
<td>CEM III 42,5 N</td>
<td>143</td>
<td>3.15</td>
<td>45.40</td>
<td>7.150</td>
<td>2.860</td>
<td>8.580</td>
<td>10.010</td>
</tr>
<tr>
<td>Fly ash</td>
<td>173</td>
<td>2.34</td>
<td>73.93</td>
<td>8.650</td>
<td>3.460</td>
<td>10.380</td>
<td>12.110</td>
</tr>
<tr>
<td>Superplasticizer Glenium 51</td>
<td>0.635</td>
<td>1.09</td>
<td>0.582</td>
<td>0.032</td>
<td>0.013</td>
<td>0.038</td>
<td>0.044</td>
</tr>
<tr>
<td>Superplasticizer Glenium 27</td>
<td>5.504</td>
<td>1.05</td>
<td>5.241</td>
<td>0.275</td>
<td>0.110</td>
<td>0.330</td>
<td>0.385</td>
</tr>
<tr>
<td>Stabilizer Glenium Stream 2006</td>
<td>2</td>
<td>1.02</td>
<td>1.961</td>
<td>0.100</td>
<td>0.040</td>
<td>0.120</td>
<td>0.140</td>
</tr>
<tr>
<td>Free water</td>
<td>0.44</td>
<td>191</td>
<td>1.00</td>
<td>9.550</td>
<td>3.820</td>
<td>11.460</td>
<td>13.370</td>
</tr>
<tr>
<td>Air</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>423.5</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand 0.125-0.25</td>
<td>96.7</td>
<td>2.64</td>
<td>36.63</td>
<td>4.836</td>
<td>1.934</td>
<td>5.803</td>
<td>6.720</td>
</tr>
<tr>
<td>Sand 0.25-0.5</td>
<td>314.2</td>
<td>2.64</td>
<td>119.03</td>
<td>15.713</td>
<td>6.285</td>
<td>18.855</td>
<td>21.997</td>
</tr>
<tr>
<td>Sand 0.5-1</td>
<td>314.2</td>
<td>2.64</td>
<td>119.03</td>
<td>15.712</td>
<td>6.285</td>
<td>18.855</td>
<td>21.997</td>
</tr>
<tr>
<td>Sand 1-2</td>
<td>193.6</td>
<td>2.64</td>
<td>73.33</td>
<td>9.679</td>
<td>3.872</td>
<td>11.615</td>
<td>13.551</td>
</tr>
<tr>
<td>Sand 2-4</td>
<td>121.7</td>
<td>2.64</td>
<td>46.11</td>
<td>6.087</td>
<td>2.435</td>
<td>7.304</td>
<td>8.521</td>
</tr>
<tr>
<td>Gravel 4-8</td>
<td>170.2</td>
<td>2.64</td>
<td>64.49</td>
<td>8.512</td>
<td>3.405</td>
<td>10.214</td>
<td>11.917</td>
</tr>
<tr>
<td>Gravel 8-16</td>
<td>311.2</td>
<td>2.64</td>
<td>117.88</td>
<td>15.560</td>
<td>6.224</td>
<td>18.672</td>
<td>21.784</td>
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<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>576.5</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPZHT 50 x 1.0 steel fibres 0.75%</td>
<td>2.85</td>
<td></td>
<td></td>
<td>1.18</td>
<td>3.53</td>
<td>4.12</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2306</strong></td>
<td></td>
<td></td>
<td><strong>1000</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX F - ANALYSES ON FIBRE ORIENTATION
<table>
<thead>
<tr>
<th>Location</th>
<th>Region A Direction Dispersion</th>
<th>Amount Goodness</th>
<th>Region B Direction Dispersion</th>
<th>Amount Goodness</th>
<th>Region C Direction Dispersion</th>
<th>Amount Goodness</th>
</tr>
</thead>
<tbody>
<tr>
<td>131</td>
<td>-</td>
<td>5.8</td>
<td>0.37</td>
<td>0.61</td>
<td>3.4</td>
<td>0.67</td>
</tr>
<tr>
<td>133</td>
<td>3.0</td>
<td>-</td>
<td>0.61</td>
<td>0.81</td>
<td>7.0</td>
<td>0.77</td>
</tr>
<tr>
<td>135</td>
<td>0.2</td>
<td>14.6</td>
<td>0.65</td>
<td>0.81</td>
<td>20.5</td>
<td>0.77</td>
</tr>
<tr>
<td>231</td>
<td>0.4</td>
<td>11.2</td>
<td>0.54</td>
<td>0.85</td>
<td>1.0</td>
<td>0.80</td>
</tr>
<tr>
<td>233</td>
<td>8.6</td>
<td>9.4</td>
<td>0.60</td>
<td>0.85</td>
<td>8.2</td>
<td>0.23</td>
</tr>
<tr>
<td>235</td>
<td>5.2</td>
<td>9.0</td>
<td>0.48</td>
<td>0.89</td>
<td>5.6</td>
<td>0.78</td>
</tr>
<tr>
<td>331</td>
<td>12.5</td>
<td>10.0</td>
<td>0.61</td>
<td>0.84</td>
<td>47.5</td>
<td>2.0</td>
</tr>
<tr>
<td>333</td>
<td>11.8</td>
<td>10.0</td>
<td>0.53</td>
<td>0.77</td>
<td>68.7</td>
<td>5.4</td>
</tr>
<tr>
<td>335</td>
<td>3.2</td>
<td>17.1</td>
<td>0.67</td>
<td>0.85</td>
<td>1.5</td>
<td>26.5</td>
</tr>
<tr>
<td>431</td>
<td>1.1</td>
<td>18.3</td>
<td>0.75</td>
<td>0.71</td>
<td>79.5</td>
<td>9.5</td>
</tr>
<tr>
<td>433</td>
<td>24.7</td>
<td>23.4</td>
<td>0.72</td>
<td>0.70</td>
<td>80.0</td>
<td>40.5</td>
</tr>
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### Second Session – Beam 07 T/M 12

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APPENDIX G - RESULTS OF THE FOUR POINT FLEXURAL TESTS
BEAM 01

Cast date: 25-09-2013
Test date: 23-10-2013
Curing period: 28 days
Plane of loading: Perpendicular
Oriented: Yes
Deformation rate: 0.5 mm / min
Span: 450 mm
Width: 154.5 mm
Height: 150.2 mm

\[
F_{\text{bri}} = 48.26 \text{ kN} \\
f_{\text{bri}} = 6.22 \text{ N/mm}^2
\]
BEAM 02

Cast date: 25-09-2013
Test date: 23-10-2013
Curing period: 28 days
Plane of loading: Parallel
Oriented: Yes
Deformation rate: 0.5 mm / min
Span: 450 mm
Width: 150.7 mm
Height: 153.7 mm

\[
F_{\text{bri}} = 59.54 \text{ kN}
\]
\[
f_{\text{bri}} = 7.53 \text{ N/mm}^2
\]
BEAM 03

Cast date: 25-09-2013
Test date: 23-10-2013
Curing period: 28 days
Plane of loading: Perpendicular
Oriented: No
Deformation rate: 0.5 mm / min
Span: 450 mm
Width: 155.0 mm
Height: 150.3 mm

$$F_{bri} = 59.32 \text{ kN}$$
$$f_{bri} = 7.63 \text{ N/mm}^2$$
Cast date: 25-09-2013
Test date: 23-10-2013
Curing period: 28 days
Plane of loading: Parallel
Oriented: No
Deformation rate: 0.5 mm / min
Span: 450 mm
Width: 150.0 mm
Height: 152.6 mm

\[ f_{bei} = \frac{F_{bei}}{A_{bei}} = \frac{68.85 \text{ KN}}{8.88 \text{ N/mm}^2} \]
BEAM 05

Cast date: 25-09-2013
Test date: 23-10-2013
Curing period: 28 days
Plane of loading: Parallel
Oriented: Yes
Deformation rate: 0.5 mm / min
Span: 450 mm
Width: 150.4 mm
Height: 154.5 mm

\[ F_{\text{bri}} = 50.68 \text{ kN} \]
\[ f_{\text{bri}} = 6.35 \text{ N/mm}^2 \]
BEAM 06

Cast date: 25-09-2013
Test date: 23-10-2013
Curing period: 28 days
Plane of loading: Parallel
Oriented: No
Deformation rate: 0.5 mm / min
Span: 450 mm
Width: 150.8 mm
Height: 153.0 mm

\[ F_{\text{bri}} = 63.35 \text{ kN} \]
\[ f_{\text{bri}} = 8.10 \text{ N/mm}^2 \]
Cast date: 25-09-2013
Test date: 23-10-2013
Curing period: 28 days
Plane of loading: Perpendicular
Oriented: No
Deformation rate: 0.5 mm / min
Span: 450 mm
Width: 150.5 mm
Height: 150.4 mm

$F_{br} = 53.71$ kN
$f_{br} = 7.10$ N/mm$^2$
BEAM 08

Cast date: 01-10-2013
Test date: 29-10-2013
Curing period: 28 days
Plane of loading: Parallel
Oriented: No
Deformation rate: 0.5 mm / min
Span: 450 mm
Width: 150.5 mm
Height: 149.4 mm

\[ F_{\text{bri}} = 52.16 \, \text{kN} \]
\[ f_{\text{bri}} = 6.98 \, \text{N/mm}^2 \]
BEAM 09

Cast date: 01-10-2013
Test date: 29-10-2013
Curing period: 28 days
Plane of loading: Parallel
Oriented: Yes
Deformation rate: 0.5 mm / min
Span: 450 mm
Width: 150.2 mm
Height: 153.4 mm

\[ F_{bri} = 57.62 \text{ kN} \]
\[ f_{bri} = 7.32 \text{ N/mm}^2 \]
**BEAM 10**

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\[
F_{bri} = 51.57 \text{ kN} \\
\sigma_{bri} = 6.51 \text{ N/mm}^2
\]
BEAM 11

Cast date: 01-10-2013
Test date: 29-10-2013
Curing period: 28 days
Plane of loading: Parallel
Oriented: Yes
Deformation rate: 0.5 mm / min
Span: 450 mm
Width: 150.6 mm
Height: 153.2 mm

\[
F_{\text{bri}} = 55.10 \text{ kN}
\]
\[
f_{\text{bri}} = 7.01 \text{ N/mm}^2
\]
Cast date: 01-10-2013
Test date: 29-10-2013
Curing period: 28 days
Plane of loading: Parallel
Oriented: Yes
Deformation rate: 0.5 mm / min
Span: 450 mm
Width: 151.7 mm
Height: 153.8 mm

$f_{fcr} = 65.03$ kN
$f_{fcr} = 8.15$ N/mm²
APPENDIX H - RESULTS OF THE PULL-OUT TESTS
**PULL-OUT TEST 1**

- Cast date: 14-06-2013
- Test date: 21-06-2013
- Curing period: 7 days
- Coupled: Yes
- Deformation rate: 0.5 mm / min
- Fracture Energy: 1552 Nmm
- Max. pull-out load: 150 N

**PULL-OUT TEST 2**

- Cast date: 14-06-2013
- Test date: 21-06-2013
- Curing period: 7 days
- Coupled: Yes
- Deformation rate: 0.5 mm / min
- Fracture Energy: 1745 Nmm
- Max. pull-out load: 156 N
## Pull-out Test 3

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## Pull-out Test 4

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<td>Max. pull-out load</td>
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**PULL-OUT TEST 5**

- Cast date: 14-06-2013
- Test date: 21-06-2013
- Curing period: 7 days
- Coupled: Yes
- Deformation rate: 0.5 mm / min
- Fracture Energy: 543 Nmm
- Max. pull-out load: 108 N

**PULL-OUT TEST 6**

- Cast date: 14-06-2013
- Test date: 21-06-2013
- Curing period: 7 days
- Coupled: No
- Deformation rate: 0.5 mm / min
- Fracture Energy: 1256 Nmm
- Max. pull-out load: 180 N
### PULL-OUT TEST 7

- **Cast date:** 14-06-2013
- **Test date:** 21-06-2013
- **Curing period:** 7 days
- **Coupled:** No
- **Deformation rate:** 0.5 mm / min
- **Fracture Energy:** 1437 Nmm
- **Max. pull-out load:** 176 N

![Graph for PULL-OUT TEST 7](image1)

### PULL-OUT TEST 8

- **Cast date:** 14-06-2013
- **Test date:** 21-06-2013
- **Curing period:** 7 days
- **Coupled:** No
- **Deformation rate:** 0.5 mm / min
- **Fracture Energy:** 1925 Nmm
- **Max. pull-out load:** 234 N

![Graph for PULL-OUT TEST 8](image2)
**Pull-out Test 9**

- **Cast date:** 14-06-2013
- **Test date:** 21-06-2013
- **Curing period:** 7 days
- **Coupled:** No
- **Deformation rate:** 0.5 mm / min
- **Fracture Energy:** 1359 Nmm
- **Max. pull-out load:** 206 N

**Pull-out Test 10**

- **Cast date:** 14-06-2013
- **Test date:** 21-06-2013
- **Curing period:** 7 days
- **Coupled:** No
- **Deformation rate:** 0.5 mm / min
- **Fracture Energy:** 678 Nmm
- **Max. pull-out load:** 103 N