Designing an interlayer reinforcement solution for printable strain-hardening cement-based composites

Practical research on various bond improvement concepts

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After pivoting from the field of Architecture to Structural engineering, I met up with Diederik Veenendaal to discuss possible graduation subjects. I was in search of a project that would have the engineering content needed for finalizing my structural engineering degree, but at the mean time would keep me connected with my old love, architecture. It was Diederik who suggested me to look into the field of 3d concrete printing, as it had the innovative and material content that I was looking for while still being strongly connected with the architecture world.

So began the search for an interesting graduation project on the subject of 3d printing. It was Professor Schlangen who proposed a graduation research that combined the innovation of strain-hardening composite concrete, with the new production method of 3d concrete printing. For the past ten months I have researched this topic with great interest and dedication. Even though progress and setbacks alternated throughout the process I am proud to present the results in the thesis laying before you.

Special thanks go out to Maiko van Leeuwen, who helped me so much in framing my project in the first somewhat drifting weeks. Stefan Figueiredo, for always finding the time to tutor me on various subjects. My committee, who kept optimistic and enthusiastic in times where I was feeling oh so dissatisfied. And finally, my husband, Michiel Katgert, who at all times was willing to discuss and reflect and walk the dog.

Ir. A.L. van Overmeir
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3D concrete printing is an additive manufacturing method that uses a printing robot to build 3D concrete elements. In the last decade, several 3D concrete printing techniques have been developed and extensive research has been conducted on suitable concrete mixes, the printing process and the material and mechanical properties of the finished product. However, certain challenges have remained unresolved.

Two of these challenges are the low tensile strength and the limited ductility of the printed concrete. As concrete is a brittle material that is weak in tension, traditional structural concrete elements make use of steel reinforcement to ensure tensile strength. The incorporated steel rebars are designed to take over the tensile stress when the concrete cracks. With the linear elastic and eventually plastic behaviour of steel in tension, the steel provides a ductile behaviour to the reinforced concrete. This ductile behaviour is required to comply with modern building regulations, as it ensures structural integrity and safety by timely warning in case of overload. However, for printed concrete the incorporation of steel rebar reinforcement is not evident.

The use of Strain-Hardening Cementitious Composites (SHCC) in the field of digital concrete printing is one of the many possible ways to incorporate reinforcement into printed structural concrete elements. However, just like regular printable concrete, the bond between subsequently printed layers has shown to be a point of concern.

The research presented in this master thesis focusses on the interlayer bond of these printable SHCC's and more specifically on developing improvement methods for this interlayer bond. To better comprehend the origins of problem a thorough literature study was performed on the following topics: printing facilities, 3d printing compatible mix designs, (printable) SHCC, anisotropy and research on related interlayer bond improvement methods.

Additionally, two case studies were conducted. One concerned the printable SHCC mix that was previously developed and that was employed in this research. The other case study applied to the printing facilities of the Delft University of Technology and the applicable printing settings.

On the basis hereof an experimental research was designed and conducted on various methods unrelated to the SHCC mixture and their effect on the interlayer bond. The methods can be divided in three groups: nozzle types, surface modification by brushes and incorporation of vertical steel reinforcement. In total 7 parameters were designed and tested: three nozzles, two brushes and two steel reinforcements.

Tensile interlayer bond tests were performed to assess the influence of the parameters on the interlayer bond strength. To make sure that the overall strain hardening capacities of the material were not negatively influenced by the interlayer bond improvement methods the research also included compressive tests in two directions and uni-axial tensile tests parallel to the printing direction. Finally, the research was extended with a concise CT scan analysis on porosity and reinforcement bonding.

Results show that the type of nozzle has significant influence on all mechanical properties. Surface modification by brushes tend to result in SHCC elements that have higher interlayer bond, but a reduced strain-hardening capacity. Specimens with interlayer steel reinforcement completely lose strain-hardening capacity in printing direction.
In general, it is concluded that there is potential in designing methods to improve the interlayer bond of printed SHCC. However, from the research it is concluded that strain-hardening capacity of printed SHCC is very sensitive to the introduction of initial flaws that lead to stress concentrations and consequently to a reduction of its strain-hardening qualities. Solutions that give good or promising results in the tensile interlayer bond test, unfortunately show a reduction in the tensile strength parallel to the printing direction. For designing interlayer improvement methods, all orientations of the printed SHCC element should be taken into consideration.
Samenvatting

Het 3D-printen van beton is een additieve productiemethode die gebruik maakt van een printrobot om 3D betonelementen te maken. In het laatste decennium zijn er verschillende technieken ontwikkeld voor het printen van 3D beton. Er is veel, uitgebreid en succesvol onderzoek gedaan naar, onder andere, geschikte betonmixen, het printproces en de materiaalkundige en mechanische eigenschappen van het uiteindelijke product. Bepaalde uitdagingen rondom deze nieuwe productiemethode zijn echter onopgelost gebleven.

Twee van deze uitdagingen zijn de lage treksterkte en de beperkte ductiliteit van het geprinte beton. Omdat beton in de basis een bros materiaal is dat zwak is onder trekspanning, maken traditionele constructieve betonelementen gebruik van wapeningstaal om voldoende treksterkte te garanderen. De geïntegreerde wapening is zo ontworpen dat deze de trekspanning kan overnemen zodra het beton scheurt. Dankzij het lineair- elastische gedrag van staal onder trekspanning zorgt het staal voor ductiel gedrag van het gewapend beton. Dit ductiele gedrag is nodig om te voldoen aan de moderne bouwvoorschriften, omdat het de structurele integriteit en de veiligheid garandeert. Echter, voor geprint beton is toepassen van wapeningstaal niet evident.

Het gebruik van Strain-Hardening Cementitious Composites (SHCC) als printmateriaal bij het printen van beton is één van de vele mogelijkheden om wapening te verwerken in geprinte constructieve elementen. Echter, net als bij de toepassing van niet vezelversterkt printbaar beton is de hechting tussen de lagen een zwakke schakel gebleken.

Het onderzoek dat in dit proefschrift wordt gepresenteerd richt zich op de hechting tussen de lagen van geprint SHCC en meer specifiek op het ontwikkelen van verbetermethoden voor deze hechting tussen de printlagen. Om de oorzaak van deze zwakke hechting beter te begrijpen is een literatuurstudie uitgevoerd naar de volgende onderwerpen: printfaciliteiten, het ontwerp van 3D printbare betonmixen, (printbaar) SHCC, anisotropie en onderzoek naar andere ontwikkelde verbeteringstechnieken.

Aanvullend zijn twee casestudies uitgevoerd. Een daarvan betrof een specifiek onderzoek naar de eerder door de TU Delft ontwikkelde en eveneens in dit onderzoek gebruikte SHCC-mix voor 3D printen. De andere case study had betrekking op de printfaciliteiten van de Technische Universiteit Delft en de van toepassing zijnde printinstellingen.

Op basis hiervan is een experimenteel onderzoek ontworpen en uitgevoerd naar verschillende methoden en hun effect op de hechting tussen de lagen. De methoden kunnen worden onderscheiden in drie groepen: printkop types, oppervlaktemodificatie door middel van kammen en het gebruik van verticale staalwapening. In totaal zijn 7 parameters ontworpen en getest: drie printkoppen, twee kammen en twee typen stalen wapening.

Trekproeven haaks op de printlaag zijn uitgevoerd om de invloed van de parameters op de sterkte van tussen de lagen te beoordelen. Om er zeker van te zijn dat algemene mechanische eigenschappen van SHCC in de overige richtingen niet negatief werd beïnvloed door de toegepaste methoden, bevat het onderzoek ook drukproeven in twee verschillende oriëntaties en trekproeven parallel aan de drukrichting. Tot slot bevat het onderzoek een kleine CT-scananalyse naar de poreusheid en naar de binding van de stalen wapening met het beton.

De resultaten tonen aan dat het type printkop een aanzienlijke invloed heeft op alle geteste mechanische eigenschappen. Het aanbrengen van textuur in de laag geeft positieve resultaten, echter zorgt deze methode voor een vermindering van het ductiel vermogen parallel aan de printrichting. Proefstukken waarbij staalversterking tussen de lagen was toegepast verliezen volledig het
ductiel vermogen in de printrichting.

In het algemeen kan men stellen dat er potentie zit in het ontwerpen van methodes om de hechting tussen de lagen van geprint SHCC te verbeteren. Echter, uit het onderzoek kan worden geconcludeerd dat de ductiele capaciteit van geprint SHCC zeer gevoelig is voor de introductie van initiële gebreken die kunnen leiden tot spanningsconcentraties. Oplossingen die goede of veelbelovende resultaten geven in de trektest haaks op de lagen, tonen een vermindering van de treksterkte parallel aan de printrichting. Voor het ontwerpen van verbetertechnieken voor de hechting tussen de lagen dienen derhalve alle oriëntaties van het geprinte SHCC-element in ogenschouw te worden genomen.
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Introduction

3D concrete printing is an additive manufacturing method that uses a printing robot to build 3D concrete elements. In the last decade, several 3D concrete printing techniques have been developed and extensive research has been conducted on suitable concrete mixes, the printing process and the material properties of the finished product. However, certain challenges have remained unresolved [1–3].

Two of these challenges are the low tensile strength and the limited ductility of the printed concrete. As concrete is a brittle material that is weak in tension, traditional structural concrete elements make use of steel reinforcement to ensure tensile strength. The incorporated steel rebars (potentially prestressed) are designed to take over the tensile stress when the concrete cracks. With the linear elastic behaviour of steel in tension, the steel provides a ductile behaviour to the reinforced concrete. This ductile behaviour is required to comply with modern building regulations, as it ensures structural integrity and safety. However, for printed concrete, the incorporation of steel rebar reinforcement is not as evident [4, 5].

To solve this reinforcement challenge, numerous solutions are being developed, but in general there are three main lines of research. The incorporation of passive reinforcement steel is one of these lines of research. This can be realised in multiple ways, for example by the use of reinforcement meshes [6], by connecting an external steel reinforcement framework to the printed concrete element [7] or by the use of a printing robot that prints the concrete as well as the steel reinforcement [8–10]. The second development is the implementation of post tensioned pre-stressed reinforcement. In this method, the concrete elements are printed without any type of reinforcement. Instead, internal slots are required for the implementation of the reinforcement. These slots are either incorporated in the design of the concrete element or drilled from the hardened elements. After the assembling of the concrete elements, the prestressing reinforcement is implemented in the slots and stressed according to design [11, 12].

Finally, there is the development of printable strain-hardening cementitious composites (SHCC). SHCC is a cement-based material that shows a ductile behaviour after the first macrocrack occurs, whereas traditional concrete fails brittle after this first crack, see figure 1.5. This strain-hardening property is the result of the formation of multiple fine cracks when subjected to an increasing tensile load. It is achieved by the incorporation of a high volume of fibres ($≥ 1.5$ vol.-%) in the concrete mix [13, 14]. These fibres bridge a microcrack and sustain the tensile load by which the crack was created. Instead of the crack growing bigger and bigger into a macrocrack, the fibre withstands the increasing load and another microcrack occurs somewhere else in the concrete. This microcrack then again is bridged by the fibre reinforcement. This repeating formation of controlled microcracks results in the strain hardening behaviour [15]. Mechanical research on structural SHCC elements has proven that SHCC elements can indeed deform under tension before failure, see figure 1.6.
1. Introduction

Figure 1.1: External reinforcement, University of Naples [7]

Figure 1.2: Incorporation of a steel wire in printed concrete layer, TU/e [9]

Figure 1.3: 3D printed bench, University of Loughborough [12]

Figure 1.4: Post tensioned cycling bridge, TU/e [11]
When SHCC would be used as a printing material, it would be possible to solve the reinforcement challenge associated with 3D concrete printing. Research on the adoption of SHCC as a printing material is conducted by multiple research groups, and the results are promising [16–18]. However, the challenge of low tensile strength and brittle failure still exists in the direction perpendicular to the printing direction. This is due to the general printing method that is used for 3D concrete printing. The concrete element is built up by extruding layer upon layer. It is the bond between these two subsequently printed layers that is generally seen as the weakest point in the printed element [19]. With the use of SHCC as a printing material this additionally means that the reinforcement fibres will be situated within a layer of extruded material. The fibres don't cross from one layer to another, therewith creating a printed concrete element with mechanical properties that are inherently anisotropic, that has ductile behaviour along the printing direction and brittle behaviour perpendicular to layers. This effect is amplified by the printing process, as the printing direction has a significant influence on the orientation of the fibre. Recent scientific studies conducted by Nematollahi have shown that the bond between two printed layers can be even weaker when reinforcement fibres are used within the concrete mix [20].

![Stress strain relations](image1.png)

**Figure 1.5: Stress strain relations**

![Ductile deformation during four-point bending test](image2.png)

**Figure 1.6: Ductile deformation during four-point bending test, Ducon Europe**
This research focuses on the bond between the layers of printed SHCC elements. It will investigate how the interlayer bond is formed, what the key parameters are and how the interlayer bond can be improved in terms of tensile strength and strain capacity. The overall research object is to increase the interlayer bond strength and strain capacity of printed SHCC elements, by designing and testing multiple interlayer bond enhancement concepts.
2.1. Additive manufacturing

Additive manufacturing is an industrial production technology that fabricates objects by computer-controlled addition of materials. It enables the creation of potentially lighter and stronger parts and objects and has the ability to make objects with a complex shape. In some fields, like the manufacturing industry, computer industry and medicine, the use of additive manufacturing is already daily practice. In medicine for instance, this technology is used for the production of prosthetics and implants. The technology is appreciated for its cost efficiency, high productivity and most of all for the ability to create bespoke products for every patient [21]. This custom-made product is possible because additive manufacturing uses computer-aided-design software. This software directs hardware to print the material in the designed geometric shape.

2.2. 3D Concrete Printing

Three-dimensional concrete printing (3DCP) is one of the additive manufacturing (AM) methods for the construction industry. 3DCP is an AM technology in which the cementitious material gets extruded layer upon layer, by a digitally controlled robot. The technology has both economic benefits (as it speeds up the production process and reduces formwork costs) and environmental benefits (as it optimizes material use). However, even though the benefits are present, this new technology isn't daily practice yet. This has on one hand to do with the fact that the construction industry is a conservative and risk minimizing practice, and on the other hand because there are still multiple technical challenges that need to be overcome [1, 2, 4]. The technical challenges can be divided into three parts: challenges during the printing process, challenges of the mechanical properties of the finished product and durability challenges. These three challenges will be discussed below.

**Challenge 1: Printing process and material properties**

According to de Schutter [2], in order for 3DCP to be successful, high-quality final properties have to be realised. But in order to achieve these "high-quality" properties the concrete element first has to be printed. This implies that fresh concrete mix first has to be able to flow through the printing robot, and when extruded the printed layer should be stable and contain some strength so that it is able to support its self-weight and the weight of additional layers. The consequences that the printing process has on the required material properties of the printable concrete mix will be discussed in paragraph 2.4.
Challenge 2: Mechanical properties
When the concrete element is printed and hydrated, again new challenges arise. Two main aspects, anisotropy and ductility, have already been briefly discussed in the introduction. As this research will research the mechanical properties of printed SHCC, paragraph 2.5 will elaborate on the crack bridging mechanism of traditional SHCC. In paragraph 2.6 the recent research conducted on printable SHCC will be discussed. Paragraph 2.7 will elaborate on the anisotropic properties of the printed material that is introduced by the layer by layer build-up of the printed concrete elements. It will discuss the causes of this anisotropy and how these causes affect the orientation dependent mechanical properties. Finally, paragraph 2.8 gives an overview of the performed research on the improvement of the interlayer bond between two subsequently printed layers.

Challenge 3: Durability
Finally, as the technology is still in the development phase, no real-life knowledge is available with regard to the durability properties of the final product. As a building or structure generally is designed for a period of 30 - 100 years, this also is a line of research that has to be conducted, but that is beyond the scope of this project.

2.3. Printing systems
In practice there are two types of printing robots used for constructive 3D concrete printing: The gantry printer and the robotic arm printer [22]. A gantry printer consists of a steel rectangular frame on which a steel traverse is mounted that can move along the X-axis. The printing head is connected to the traverse and can move independently in Z and Y direction. Most gantry printers also have the facility to let the printing nozzle rotate around its own Z-axis, making it possible to make circular shapes and rounded corners. In total the gantry printer has a maximum of 4 degrees of freedom. Figure 2.2 shows the general set-up of the gantry printer used at the Technical University in Eindhoven. The gantry printer can facilitate a big printing area which makes it possible to print big structural elements. Furthermore the gantry printer has a very stable set-up and prints with minimal vibrations. Vibration during printing can affect the accurate movement of the printing head and therewith introduce printing flaws. The main disadvantages of this type are its permanent location and the limited amount of degrees of freedom in which it is able to print.

A robot arm printer can often be seen in automated parts of the industry, ranging from automotive to medical. A robot arm 3d printer consists of one fixed point on which a robot arm with printing head can freely move and print. The advantage of the robot arm is its six degrees of freedom, which enables it to reach a volume of space from every angle. These degrees of freedom are best described when comparing the robot arm to a human arm [23].

Axis 1: Let your arm hang down. Raise it up front of you, turning only at the shoulder.
Axis 2: Let your arm hang down. Raise it up alongside your body, turning only at the shoulder.
Axis 3: Bend your elbow.
Axis 4: Wave like the Queen of England this is a twist between the wrist and the elbow.
Axis 5: Make a fist, then make it nod up and down.
Axis 6: Imagine holding a coin between your fingers. Turn the coin without moving the rest of your hand.

This freedom of movement makes the robot arm suitable for the printing of more complex and detailed elements. The biggest disadvantage of a robot arm printer is its printing area. Due to the set-up, with a big solid base and a movable robot arm, the base stands in the middle of its printable area. This limits the printable element size. This can, to some extent, be solved by mounting the robot on rails, making it able to move along a fixed axis and therewith introducing an additional degree of freedom. Figure 2.1 shows the set-up of a robot arm printer mounted on rails.
2.4. 3DCP compatible mix design

A concrete mix design for a 3D printing process has to meet multiple and somewhat contradicting requirements. On this topic extensive research has been conducted by N. Roussel et al. One of the publications focusses on the rheological requirements of a printable concrete mix and describes how the cementitious material behaves during the different phases of the printing process [24]. In general three phases are distinguished for concrete printing: pumping, extruding and building. Furthermore, the material properties required for each phase are described. It is also pointed out that, during the printing process, these requirements can be contradictive. For instance: for the printing phase, low yield stress and low viscosity are preferred, for this will increase the initial fluidity, making it possible to extrude a layer of concrete. However, at the moment the layer is printed, the concrete is required to be stable and stiff in order to sustain the loads of subsequent layers without the support of formwork. This asks for a high yield strength and initial elastic shear modulus. These contradicting material property requirements are the challenge within the printing process. With a too high or too low initial yield stress the following failures can be encountered [25]: Elastic failure, plastic collapse and tearing.

Additionally, N. Roussel gives a clear overview of material parameters (initial yield stress, initial modules of elasticity, etc), printing parameters (printing speed, layer thickness, etc) and printing failure parameters (critical resting time, critical object height etc.) that have an influence on the printing process. Related to this research, Marchon et al. published an overview of all potential admixtures that make it possible to tailor a mix design for 3D concrete printing [26]. Like Roussel, Marchon stated that the workability of the concrete mix can be described by fundamental rheology parameters. His research takes into account the initial yield stress and the plastic viscosity. These parameters can be modified by the use of admixtures like superplasticisers, viscosity modifiers, clays, retarders and accelerators. Also, the use of fibres within the mix design can be beneficial to the printability requirements. In general, fibres cause for a higher viscosity that makes the mixture more difficult to pump, but at the same time they increase the homogeneity and stability of the mixture. Over the last decade multiple research groups have investigated the influence of additives and admixtures on the fresh concrete material properties and it’s performance for extrudability and buildability [27–29].

Freshly mixed concrete that meets the requirements in regard to pumping, extruding and building, can still show unfavourable printing results. This is mostly related to the mix design properties “open time” and structuration rate. Open time is the period between the mixing of the concrete mortar to the loss of printability. This loss of printability is related to the time dependent increase of the yield strength due to the formation of hydration products. A critical yield stress is generally obtained halfway through the dormant period of the concrete's hydration curve and when exceeded can result in tearing of the concrete layer. With the choice of specific cement types and with the use of concrete additives like retarders the dormant period can be delayed and/or prolonged, making it
possible to tailor the open time to the printing requirements.

This structuration rate is the speed at which the printed concrete can build-up an internal stable structure. This strongly depends on the thixotropic behaviour of the concrete mix design. Thixotropy refers to the ability for a material to flow when sheared (under pressure in a printing robot) but at the same time can build up a stable internal structure when at rest. For cement based materials this structural build-up is a combination of the structure facilitated by hydration products that are formed between the contact points of cement particles and the structure created by the internal reaction forces between cement particles. Roussel researched thixotropical phenomena of concrete and found that the largest critical strain can be associated with the reaction forces between cement particles, whereas a much smaller strain capacity is directly related to the formation of early hydration products [32]. Additionally it was concluded that it only takes several seconds for the concrete to build up the network of interparticle reaction forces. The formation of the hydration particles follows afterwards and for a longer period of time. This has been presented by figure 2.6.

With the introduction of 3D concrete printing the understanding of the thixotropical behaviour and the associated structuration rate has grown in importance. This has lead to multiple articles on the topic of structural build-up in relation to the buildability of printable concrete [33, 34]. In continuance thereof A. Suiker of the Technical University of Eindhoven developed a calculation model to assess the mechanical performance of an element during printing, taking into account the initial and time dependent mechanical properties [30].
2.5. SHCC

As briefly explained in the introduction, strain hardening cement-based composites are named after their ability to resist increased tensile force, with strain hardening behaviour after the first crack, as shown earlier in figure 1.6 on page 3. In literature this material is also referred to as Engineered Cementitious Composite (ECC). The development is relatively new, as its invention dates from the early 1990’s [13]. It was then, and still is now, assumed to be attractive for a broad range of applications, such as seismic structural design and structural concrete repair. However, even though a lot of progress has been made on the development of SHCC and a large body of SHCC versions has been developed in several countries, the concrete still hasn’t fully commercialized yet. At the moment research is still being conducted on, among other things, the size effect, the durability and fibre type and orientation.

A SHCC element derives its ductile properties from the microfibres. The performance of these fibres strongly depends on the micromechanics and therewith microstructure of the composite. An SHCC element can only show strain hardening behaviour when it meets the two following criteria [15].

**strength criterion** \( \sigma_{\text{tensile, fibre}} > \sigma_{\text{tensile, matrix}} \)

This means that the matrix cracking strength must always be smaller than the fibre bridging strength. This criterion makes sure that an additional crack will occur, instead of rupture of the fibre.

**energy criterion** \( J_b > J_{tip} \)

This criterion describes the energy balance in the crack extension process. It makes sure that the fibre is able to build up enough complementary energy that it can bridge the crack. Namely, when the concrete matrix is too strong, the fibre has no deformation capacity, and this will lead to local failure of the fibre. On the other hand, if the matrix is too weak, the fibre can get pulled out, and again no crack bridging will occur. It is therefore essential that the fibre has just enough freedom to deform: only then can it build up a high complementary energy which is needed to get a steady state crack and therewith its strain hardening behaviour. Composites with low complementary energy will be likely to show strain softening behaviour.

For sufficient complementary energy, the matrix should be tailored to optimize the interface properties between the fibre and the matrix [14]. This of course depends on the type of fibre that is used in the mix design and on the total fibre volume. However, for the the overall strain hardening effect also the following parameters are important: fibre aspect ratio, fibre orientation and state of fibre dispersion.

![Multi scale mechanism of SHCC](image1)
![Delamination PVA](image2)
A wide range of fibres is used within concrete mix designs nowadays. Some are used to reduce cracking as a result of plastic shrinkage, while others are incorporated for crack width control or reduce the effect of freeze and thaw cycles. When it comes to strain hardening behaviour, only a few fibre types are applicable, which are mostly polymer fibres. Fibres that are used most often in SHCC research are the high-density polyethylene microfiber (HDPE) and the polyvinyl alcohol microfibres (PVA). However, strain hardening behaviour has also been achieved with the use of PBO fibres (Zylon*) [35], steel fibres and natural fibres [36].

2.6. PSHCC

In recent years research has been done on the combination of 3D concrete printing and SHCC. The first publication on this topic was the result of a research conducted at the University of Michigan, where a printable strain hardening concrete was developed with the use of PVA fibres [16, 37]. This research has since then been the starting point for further development done by multiple universities including the Technical University of Dresden [18] and Delft University of Technology [17, 38].

The research focusses on designing and testing a pumpable, extrudable and buildable concrete mix, that in hardened state has strain hardening behaviour in tensile direction. As both materials (printable concrete and SHCC) and the method of 3D concrete printing are still under strong development, the research approach varies strongly per research group. In terms of material design a difference can be seen in the type of fibres that were used to generate the tensile strain hardening behaviour. Where the University of Michigan and Delft University of Technology developed and tested a printable SHCC on the basis of PVA fibres, the Technical University of Dresden made use of HDPE microfibres.

The two fibres differ strongly in their interaction with the concrete matrix. Non-post-processed PVA has the tendency to have too much bonding with the matrix. This led to delamination of the fibre during pull-out, therewith reducing the effective bond length of the fibre. This phenomenon has been depicted in figure 2.9. To reduce this delamination, PVA fibres that are used in SHCC are nowadays oil coated. In contrast to PVA fibres, the HDPE fibre is chemically passive when in contact with cement-based substances and therefore does not chemically bond to the cement matrix. The bond strength capacity of the HDPE fibres is based on the generated friction during pull-out only.

The mechanical properties of the fibres are also significantly different. The HDPE fibre has a tensile strength and module of elasticity that is almost twice the value of the PVA fibre. Also, the aspect ratio (L/D) is significantly higher than that of the PVA fibre. This results in a bigger specific bonding surface with the concrete matrix. Due to these mechanical properties it is possible to design a stronger cement-based matrix, for the fibres are able to resist a higher initial crack stress. According to Ogura this is beneficial for 3D printing, as it enables the production of slender elements [18]. Overview of the fibre specifications can be found in table 2.1.

<table>
<thead>
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<th>Table 2.1: Fibre specifications</th>
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<tr>
<td><strong>PVA</strong></td>
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<tr>
<td>Tensile strength (MPa)</td>
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<tr>
<td>Modulus of elasticity (GPa)</td>
</tr>
<tr>
<td>Ultimate strain (%)</td>
</tr>
<tr>
<td>Length (mm)</td>
</tr>
<tr>
<td>Diameter (µm)</td>
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<td>Aspect ratio (L/D)</td>
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Apart from the mix design, variations can also be found in the printing method of the three developed printable SHCC's. Where the mixtures developed by the TU Delft and TU Dresden were printed on 3D printing devices, the mixture of Michigan was printed manually by means of a caulk gun.

All three developed SHCC's did result in strain hardening capacity in the printing direction, as can be seen in figures 2.14 - 2.16. However, the mechanical performance presented in these three articles can, due to the different printing techniques, specimen maturity (28 days versus 35 days) and testing method (clamped versus glued) not be objectively compared.

It is interesting that all three articles state that printed specimens, when tested in the direction of printing, perform better than specimens that were cast. An example hereof from the university of Dresden is demonstrated in figure 2.13. This implies that the method of 3D concrete printing, influences the material and mechanical properties and results in an anisotropic material. This phenomenon doesn't only occur with the printing of SHCC or fibre reinforced concrete. Published research on "plain" printable concretes have presented anisotropic mechanical properties as well. This subject will be discussed in depth in the next paragraph.
2. Literature review

Figure 2.14: Stress-strain diagram printed SHCC tested at 35 days TU Delft

Figure 2.15: Stress-strain diagram printed SHCC tested at 28 days, TU Dresden

Figure 2.16: Stress-strain diagram "printed" (with caulk gun) SHCC tested at 28 days, University of Michigan
2.7. Anisotropy

As a result of the printing method of layers that are subsequently deposited on top of each other, the printed material becomes anisotropic. This influences the mechanical performance, as differences occur between the orientation of the material in relation to the printing direction. The compressive strength is one of the mechanical properties that has often been measured for assessing this anisotropy of 3d printed concrete, as described by Nerella and others, [39–41]. Also mechanical tests on the material’s flexural strength has shown anisotropic properties of printed elements [40, 42]. In regard to the anisotropy of printed strain hardening cement-based composites, two main aspects can be determined: the bond between the printed layers and the orientation of the fibres within the layers. The following paragraphs will discuss these two topics in more detail.

2.7.1. Interlayer bond

The bond between the printed layers is often referred to as the weakest point of a printed concrete element, as potential flaws like enclosed air voids can easily be created between the layers. Literature on bond and adhesion of concrete is mostly found in the field of concrete repairs. The adhesion of a repair mortar on the old concrete substrate is crucial for the performance of the repair and therefore has resulted in a significant amount of research. Even though bonding of a fresh repair mortar on an old concrete substrate involves some different factors than of freshly printed concrete layers, the general mechanisms are the same.

Figure 2.17: System layered composite [43]

Figure 2.18: Concept of mechanical interlocking [43]

The mechanisms behind the formation of an interlayer bond strength between two layers of concrete can be divided into three groups: mechanical interlocking, chemical bonding and physical bonding. Mechanical bond can be seen as the interlocking of the new layer into the voids of the older layer[43]. Chemical bond is the mechanism of hydration products that are forming between the printed layers. The physical bonding is the formation of hydrogen bridges and van der Waal forces. The bonding realized by these two last mechanisms is relatively weak, and do not significantly contribute to the overall bonding strength of the composite.

Principle factors that influence the above mentioned mechanisms can again be categorized into three groups: firstly, the morphological factors, which relates to the texture and/or state of the old
concrete layer surface. Secondly, the physiochemical factors, which relate to the compatibility between the old and the new concrete and the physical properties of the materials. Finally, there is a group of durability factors, which takes into account the deterioration of the layered composite over time due to temperature and humidity fluctuations.

Due to the influence of morphological factors on the interlayer bond strength, surface preparations are often carried out on the old concrete substrate. Texturing of the substrate is done by for example grooving, brushing, grinding and water-jacking.

Research on the use of SHCC as repair mortar and with that the quality of adhesion of SHCC to an old substrate was carried out by Lukovic [44]. Her work researched the following parameters: moisture exchange, interface properties between the two materials and substrate surface preparation. The conclusion was that moisture exchange between substrate (dry) and repair mortar (wet) had significant influence on the quality of adhesion. Also the interface layer, that showed to have variable strength, was found to be an important parameter because it is the zone where cracks initiate. Surface modification of the substrate was found to be less influential on the bond strength itself, but did have a positive influence on the failure cracking pattern [45].

2.7.2. Interlayer bond with 3D printing

When the findings discussed above are translated to 3D concrete printing, we can speak of the following parameters.

• dehydration of printed layer
• chemical bonding
• material compatibility
• mechanical interlocking
• durability

For development of 3D concrete printing, factors regarding the material compatibility and durability aspects are less relevant. However, physical properties of the material that facilitate mechanical interlocking like open time and structuration rate are of more importance, as they are also related to the printability properties of a concrete mortar. In recent research it has been shown that there is a close relation between these physical properties of the material and specific printing settings, which together tend to influence the quality of the interlayer bond. Multiple researchers have investigated the influence of various printing settings on the interlayer bond strength of the printed material.

2.7.3. Gap time

Multiple researchers have found that there is a significant influence of the time gap between the subsequently printed layers on the bond strength [39, 46–49]. It is assumed that for long intervals this is due to the reduction of chemical bond, as the first layer has had time to set and hydrate on its own, leaving a lower percentage of un-hydrated cement and available water to chemically bond with the "new" layer. However, for short interval times (<2 hours) this will not be the case. This has to do with the hydration process of concrete. The rate of heat evolution curve shows the heat energy created during the hydration of concrete. In the field of concrete technology this rate of heat curve is seen as a good indicator for the rate of hydration. As can be seen in figure 2.19 the curve has a dormant period (II) where the generated energy is low and constant. It can therefore be assumed that the production of hydration products is also low and constant. During this period printed concrete becomes stable.
For short time gaps between subsequent layers, which is normally the case for printed concrete elements, the amount of un-hydrated cement particles is thus still sufficiently high. The reduction of interlayer bond can therefore be associated with the dehydration of the first printed layer [25] and with the reduction of the mechanical interlocking due to structural build-up. Roussel and Cussigh researched the influence of the structuration rate on the adhesion of two subsequent extruded layers of concrete. For buildability purposes, the aim is to have a high structuration rate, using the thixotropic behaviour of the concrete mix design to be able to support the subsequent layers that are extruded above. Unfortunately, they proved in their research that a high structuration rate results in a strong reduction of mechanical bond, for the concrete layers aren’t able to sufficiently mix and therefore do not provide adequate mechanical interlocking [51]. Panda et al. researched the relation between the structuration rate and the interlayer bond strength by adjusting the amount of alkaline activator. From the results it was indeed concluded that a higher structuration rate would result in a decrease of interlayer bond strength when the gap time was sufficiently long [52]. Therewith introducing yet another conflicting requirement for the design of a compatible concrete. In regard to the dehydration of the previously printed layer multiple publications have shown that the dehydration of the previous layer can result in a significant reduction of interlayer bond strength. A reduction of 50% of interlayer bond strength has been reported, by both Wolfs et al. and Roussel, for layers that where not protected against dehydration during time gaps [24, 40].

2.7.4. Printing speed
When the term printing speed is used in literature, it generally refers to the speed of the printing nozzle. This nozzle speed is directly linked to the speed at which the concrete is pumped through the hose, the so called pumping speed. For each printing speed, the appropriate pumping speed must be found to ensure the extrusion of a continuous and dimensionally stable layer. When the printing speed is too fast for the set pumping speed, the material will stretch and rupture may occur. If the print speed is too slow in relation to the pumping speed, an excess of material will be printed, resulting in a thicker and wider layer. These two printing parameters should therefore always be determined together.

In regard to the influence of the printing speed on the interlayer bond strength it was found that a higher print speed generally has a negative effect on the interlayer bond. There are generally two reasons for this. One is that the reduction of the surface roughness at higher speeds, the other is the increase of air void content and air void size, within the printed material, at higher printing speeds [47, 49].

2.7.5. Nozzle offset height
The height of the nozzle to the printing bed (table or previous printed layer) has also been investigated by multiple researchers [40, 47]. Where Panda et al. found a clear decrease in bond strength
with increasing nozzle offset height, Wolfs et al. found no clear relation. Both publications do report an increase in scatter of the results with increasing nozzle height. As indicated by Wolfs et al. it is reasonable to expect that the influence of the nozzle offset height on the interlayer bond strength strongly depends on the rheology properties of the printed concrete mix.

2.7.6. Nozzles

One of the things that strongly differs within the publications on 3D printing concrete research is the type of nozzle used. The nozzles differ in regard to opening shape (round vs. rectangular), opening size and angle of extrusion. Some nozzles are extended with trowels on the size and/or top. These trowels mould the extruded concrete and therewith enforce a strain layer shape [53].

The nozzle is often designed based on the required resolution of the printed concrete element or on the specific research subject.

Multiple research groups mention optimization of nozzles shape and size. The university of Loughborough optimized the diameter size of there circular nozzle, by testing multiple diameters varying from 4 to 22 mm. After conducting multiple printing tests the diameter of 9 mm resulted in the highest print quality [12]. The Technical University of Eindhoven conducted a research on the effect of the nozzle angle on the print quality [11]. Three nozzles were designed with varying angles of incidence, but all with a constant nozzle opening of 10 (h) x 40 (w) mm. For the research multiple elements were printed with a (non SHCC) concrete mix design. From the print quality assessment it was concluded that the nozzle with 90 degrees angle of incidence showed the best result.

Marchment et al. used a nozzle with a 45 degrees angle to the printing table [19]. According to him this facilitates a consistent surface texture which has a direct relation to the amount of contact area and the amount of air voids within the interlayer.

"These voids are a direct result of the surface roughness and the stiffness of layers being extruded. The inability of the layers to mould and anchor into the pore structure of the underlying layer therefore exhibits not only poor anchorage but reduced contact area."

Marchment [19, p. 2]

To the best of authors knowledge, no publications addressing the topic of nozzle design provided quantitative data on the influence of the nozzle on the mechanical properties of the hardened concrete.
2.7. Anisotropy

2.7.7. Fibres

When fibres are included into the mix design, the nozzle shape additionally influences the orientation of the fibres. Nozzles with a relatively small opening compared to the fibre length may cause strong fibre alignment within the layer. Fibre orientation is therefore an important topic when using SHCC as extrusion material. The alignment of fibres in printable concrete has been researched by the University of Augsburg [55]. The objective of their research was to optimize the fibre alignment of the printed concrete and to research the mechanical performance of printing different patterns with this strongly inhomogeneous material. This research, conducted by Hambach and Volkmer, has shown that significant fibre alignment can be realized when the nozzle dimensions and printing settings are set accordingly. To generate a strong alignment of the fibres the following parameters are of importance; nozzle diameter, nozzle orientation, print speed and layer thickness.

In continuance of Hambach, Ma et al. researched the mechanical anisotropy of aligned fibre orientation [54]. Like Hambach, the FRC was printed with a small nozzle diameter, ensuring that the fibres were vertically orientated in the nozzle before extrusion, resulting in a strong fibre alignment within the printed element. This research contains tests on the mechanical properties of the printed material in the three main perpendicular directions. As benchmark to the test on the printed specimens, the tests were additionally performed on a cast specimen of the same FRC mix. It is assumed that in the cast specimen the fibres are randomly orientated.

![Printed element of aligned fibre reinforced concrete](image1)

![Anistropic mechanical behaviour for aligned fibre reinforced concrete](image2)

From the mechanical tests it has been found that the mechanical properties are strongly dependent on their direction. For the tensile splitting test low values were found in the FX and FY direction, where FZ shows the highest results. The other mechanical tests, on compressive strength, flexural strength and double shearing strength have also shown a clear dependency on the loading direction, with a minimal strength deviation of 25% between strongest and weakest direction. The publication names two main factors, one being the layer build-up of the printed specimen, the other being the orientation of the fibres within the printed layer.

Apart from the phenomenon of fibre alignment, research has also been conducted on other parameters related to the incorporation of fibres in the printable mix design. A recent scientific study conducted by Nematollahi investigated the influence of the fibre type on the interlayer bond between two printed layers [20]. Four mix designs were tested, three of them were reinforced with one unique fibre type, namely polyphenylene benzobisoxazole (PBO) fibers, polyvinyl alcohol (PVA) and polypropylene (PP). It was concluded that the mix design without any fibres had the highest interlayer bond strength. Between the three fibre reinforced concretes no significant difference in interlayer bond strength was found.

The influence of the fibre length and the amount of fibres on the anisotropic behaviour of printed
FRC has been researched by Panda [42]. The fibre lengths tested were 3 mm, 6 mm and 8 mm. The nozzle used had a rectangular opening of 40 mm (w) by 10 mm (h). The results from the conducted flexural tests clearly show that an increase of the fibre length results in a more anisotropic behaviour. This is in line with the earlier discussed principle of fibre alignment. It is interesting to point out that all the tested fibre lengths were smaller than the height of the nozzle, but still strong fibre alignment occurred. Additionally, the research showed that an increase in fibre volume also resulted in an increase of anisotropic properties.

2.8. Interlayer solutions
Apart from research on the origin of the weak interlayer and the influence of printing parameters, several scientists have been developing and testing methods to improve the interlayer bond of printed concrete. As the limited mechanical interlocking between the layer is found to be one of the leading factors, Marchment et al. researched the concept of adding a low viscosity cement paste in between the printed layers [19]. The cement paste is brushed on the top surface of a recently extruded layer. Due to its low viscosity the cement paste easily flows into the voids that are present in the layer surface. The cement paste keeps its rheology property over the full gap time. When the second layer is extruded, the cement paste is still able to also flow into the voids of this subsequent layer, increasing the overall contact area between the two layers. Bond strength increase of almost 300% was realised with one of the developed cement pastes.

Another research that aims to improve mechanical interlocking was conducted by Zareiyan et al. [56]. The concept of this research was to increase the contact area and mechanical interlocking by means of surface texturing. Multiple texturing patterns were designed by varying the depth/width ratio with a constant width of one inch. The interlayer bond strength was tested by means of tensile splitting tests. From the test results it could be concluded that texturing of the layer surface can result in an improved interlayer bond strength when the depth/width ratio is not higher than 0.5. An interlayer bond strength increase of 26% was found, in comparison to non-textured samples, for a ratio of 0.5.

The most recent publication on interlayer bond improvement discusses multiple methods [57]. The research conducted by Ghent University assessed the individual effect of water, cement, sand and very fine surface texturing between the layers. Texturing was achieved by the use of a fine comb with 34 small needles each having a diameter of 1 mm. Best results for compressive strength and tensile bond strength were realised with this texturing of the layer’s surface.
3

Research framework

3.1. Research justification
The literature study showed that several research groups have established that 3D concrete printed elements exhibit strong anisotropic behaviour. Researchers agree that the interlayer bond is largely responsible for that, which is why the interlayer bond is therefore seen as one of the weakest spots of a 3D printed element. A lot of research has therefore been done into the parameters that influence this adhesion between the layers. It turns out that not only material properties but certainly also the printer settings and printer configurations are at the basis of this. Some articles have been published about possible methods to improve the interlayer bond between the layers of 3D printed concrete. In the newer development of printable SHCC, the anisotropy is even more pronounced because the fibres that are responsible for the strain hardening behaviour are only located within the extruded layers and do not or hardly provide any connection between the layers. This results in not only a weaker but also a brittle connection between the layers. Here too, researchers have determined the anisotropic behaviour and investigated the strength of the interlayer bond. At the time of writing, however, no research has yet been published to develop or investigate a method for strengthening and ductile manage of this SHCC interlayer. It has therefore been decided to devote this research to improving the strength and ductility of this interlayer bond.

3.2. Research objective
The aim of this research is to investigate the interlayer bond of printed SHCC and to develop interlayer bonding solutions for printed concrete elements, which are able to increase the tensile strength and strain capacity between the printed layers, when subjected to uni-axial tensile stress. A main research question is formulated in order to achieve the research objective:

*Which methods for improving the interlayer bond can be designed for 3D printable SHCC elements and how do they influence compressive strength in the direction perpendicular and parallel to the layers as well as the tensile strength and strain capacity parallel to the layers?*

As has been listed in the conclusion of the literature study, multiple studies have been conducted on the improvement of the interlayer bond. Due to the high innovation level and the lack of standards within this vastly developing field, all found research has been performed under unique circumstances and is therefore difficult to relate to each other. This research intends not only to develop and research multiple concepts for improving the interlayer bond of SHCC, but to do this in a standardised way in regard to the mix design, printing facilities, printing settings and test methods.
The research project is a form of a relational study. It will research how input variables (inter-locking methods) affect the outcome variables (interlayer bond strength, compressive strength and uni-axial tensile strength) of a printed concrete element. The research can therefore be divided into two general objectives:

- To design different concepts for the improvement of the interlayer bond of printed SHCC elements
- To assess the mechanical properties of the designed composites

The following paragraphs will mention in short which components are needed to complete the research objective. In 3.1 an flow chart demonstrated the overall outlay of the project.

### 3.3. Bond improvement concepts

From the literature study three groups of parameters were selected to be developed further.

**Parameter 1: Nozzles**

There is a high variety of nozzle designs used within 3D concrete printing. Multiple research groups have developed and tested multiple nozzles, however, the influence of these nozzles on the final mechanical properties of a printed element was never tested. For this reason three printing nozzle have been designed and tested for their influence on the interlayer bond strength, the compressive strength and the tensile strength.

**Parameter 2: Brushes**

Another group of parameters that attracted attention within the literature study is the use of surface modification. This is an often-used method when preparing an "old" concrete surface for the casting of a fresh concrete layer. Adapted methods for SHCC repair mortars and for 3D concrete printing have been researched by multiple scientists. From the findings, the conclusion can be drawn that the effect of surface modification differs strongly. The use of surface modification for SHCC printed layers is therefore chosen to be one of the parameters. Four brushes will be designed and tested on printing quality. Two of these brushes will be selected and tested for their influence on the mechanical properties of the printed SHCC elements.

**Parameter 3: Vertical reinforcement**

Finally the last group of parameters will be the incorporation of vertical steel reinforcement to connect the interlayers. On the subject of vertical reinforcement limited research was found. Most articles that discuss steel reinforcement within the subject of 3D concrete printing primarily investigate the effectiveness of steel along the printing direction. Two types of steel reinforcements will be incorporated and tested for their influence on the mechanical properties.

### 3.4. Case studies

In order to address the research question, accordingly two closely related subjects have been researched by means of the case study principle. Two case studies will be conducted, one case study will research the printable SHCC developed at the TU Delft. The second will look into the 3D printing robot that will be used to print the above-mentioned SHCC mixes. These two case studies are essential, for these components are the starting point of the research.
Case study 1: Analysis of the printable SHCC developed at the TU Delft
From the literature study we have seen that there are multiple research groups active in the field of printable SHCC. For this study we have chosen to continue to work with the SHCC that was developed at the TU Delft by Figueiredo et al [17, 38]. The reason for this choice is twofold, the most pressing one being the availability of the mix design components. Originally it was the idea to compare the printable SHCC developed by TU Dresden to the one developed by the TU Delft. However, it was found impossible to obtain the HDPE fibres within the time frame required for the project. Secondly, the use of the TU Delft mixture made it possible to relate the laboratory results to findings from the previous research that was conducted on this printable SHCC. The case study will include a laboratory test to assess the setting time of the mixture. The setting time will be conducted three times and will be measured with the use of a Vicat needle test.

Case study 2: Analysis of 3D printing Robot of the TU Delft
The role of printing facilities and printing settings has been proven to be significant. For this research the new printing facility of the TU Delft was used. As this was one of the first researches that was printed with a printing robot, skills like coding printing routines, handling of the pump and other aspect that related to the printing facilities had to be learned. Additionally, the optimal printing settings have to be determined in order to print consisted SHCC layers.

To this end the case study includes the following practical tests:

- Printing speed test
- Printing height test for all nozzles
- Printing height test for all brushes

3.5. Laboratory research
In order to research the effect of the composite parameters on the mechanical properties of the printed SHCC the following laboratory research will be carried out.

Mechanical tests:
The general aim of the research is to improve and test the bond between the layers. However, the solutions that have been designed may in some way affect other mechanical properties of the printed SHCC. Per composite parameter the following laboratory research has been designed:

- 6x Bond tests between two layers
- 4 - 6x Uni-axial tensile tests of three layers, parallel to printing direction
- 5x Compression test parallel to the layers
- 5x Compression test perpendicular to the layers

CT scan for porosity analysis.
After conducting the originally planned laboratory tests mentioned above, it was decided to extend the research with a small-scale CT scan analysis. This additional research has been carried out in order to better explain/understand the results from the mechanical tests. With use of the CT-scan the following analysis were carried out:

- 1x Porosity analysis per printed composite
- 1x Analysis on the degree of bonding for the two steel reinforced composites

A more detailed description of the test specimens and the test methods are provided in paragraph 4.4.
Figure 3.1: Project flow chart
Research design

The final research proposal, as set out in the previous chapter, consists of many components. This chapter discusses each of these research components needed to create and test the printed elements. It firstly address research parameters; the designed nozzles, brushes and the selected steel reinforcement. Secondly the results of the case studies on the mix design and on the printing facilities and settings will be presented. Followed by a detailed description of all the test methods and the associated test specimens. In the end of the chapter a flow chart is presented showing the relation of all the research components.

4.1. Design parameters

4.1.1. Nozzles

The literature shows that different types of nozzles have been used for research into printed concrete. These nozzles also vary in angles of incidences. This angle affects the pressure at which the new layer comes into contact with the previous layer, which in turn affects the amount of mechanical bonding achieved. Therefore it was decided to investigate the effect of different angles, namely: $90^\circ$, $45^\circ$ and $0^\circ$. In addition, the literature also mentions the difference in surface roughness that is achieved with different nozzles. Back flow and 45 degrees angle nozzles would have a more consistent surface structure which could lead to less air obstructions between the layers and therefore a higher effective bonding surface. When SHCC is used as printing material another important element plays a role, namely the phenomenon of fibre alignment. As this research aims to improve the interlayer bond strength and reduce anisotropy, a minimal alignment of the fibres within the printed layers is preferred. Literature study showed that fibre alignment decreased with increasing nozzle height. The fibres used in the research have a length of 8 mm, the height of the nozzle opening was designed to be at least 1,5 x the fibre length. All nozzles have a rectangular opening with a width of 40 mm. For the down flow and back flow nozzle the opening has a height of 14 mm. In the design of the nozzles an nozzle offset of 1 mm to the previous layer was assumed. Due to the design of the 45 degrees nozzle, the vertical opening height was decreased to 13 mm. With the additional one mm offset this results in an outflow height of 14 mm. The nozzle designs can be viewed in figures 4.1 - 4.3. Dimensions of the nozzles are shown in figure 4.5.

The nozzles are designed with the use of the 3D design software Rhino3d and printed on an Ultimaker 2+, 3d printer. For the back flow nozzle, poly lactic acid (PLA) was used as filament. The down flow nozzle and 45 degrees nozzle are made with acrylonitrile butadiene styrene (ABS). There is no scientific reason behind the choice to use different materials. After printing the nozzles were sanded down prior to assembling. In printing performance and pressure resistance all nozzles performed equally.
The down flow nozzle was used in combination with the brushes and the reinforcement. The printed composites created with the down flow nozzle, back flow nozzle and the 45 degrees nozzle will from here on be referred to as composite *Down flow*, *Back flow* and *45 degrees* respectively.

### 4.1.2. Brushes

For the purpose of surface modification four brushes were designed. The concept is to increase the specific bond surface between the layers. The design of the four brushes can be seen in 4.4. The design of brush 3 and brush 4 is based on the findings of Zareiyan, in his research on the effects of interlocking [56]. All four were tested during printing. Mounted on the back end of the *Down flow* nozzle the brushes created a texture within the freshly printed SHCC filament. A 3D impression on the nozzle-brush set-up is shown in 4.6.

The width of the brush ridge spacing played an important role in the consistency of surface imprint: too large or too small a spacing yielded in a build-up of SHCC in front of the brush, resulting in a reduced groove depth/surface modification. Brush 1 and Brush 3 showed the most constant imprint and were used to print the brushed composites. Drawings with measurements of the two selected brushes can be found in 4.7.

![Figure 4.4: Brushes 1-4](image1.jpg)

The printed composites created with Brush 1 and Brush 3 will from here on be referred to as composite *Brush 1* (B1) and *Brush 2* (B2) respectively.
Figure 4.5: Dimensions of the three nozzles [mm], top: Down flow, center: Back flow, bottom: 45 degrees.
Figure 4.6: Impression brush set-up

Figure 4.7: Dimensions Brush 1 [L] and Brush 2 [R], measurements in mm
4.1. Design parameters

4.1.3. Vertical steel reinforcement

For the reinforcement parameter one hooked and one straight steel fibre was selected. Specifications on the fibres and the methods of placing will be described hereunder.

Reinforcement method 1
This composite was made with the HE++75/50 hooked-end steel fibres from Arcelor Mittal. The fibres have a length of 5 cm steel fibre and a diameter of 0.75 mm. The tensile strength is 1900 MPa. These types of fibres are commonly used in steel fibre reinforced concrete. The fibres were manually inserted with a spacing of 2 centimetres on the centreline of the printed SHCC beam. For the 4-layer beam, the reinforcement was inserted after the 3rd layer and afterwards the fourth layer was added. This fourth layer was printed on top of the reinforcement which protruded the 3rd layer. This could only be achieved by using the downflow nozzle, since it has enough vertical clearance over the protruding reinforcement. For the 2-layer beam, the reinforcement was cut in half and inserted into the first layer, after which the 2nd layer was printed on top. This manual method of inserting reinforcement fibres resulted in some execution problems which will be discussed during the analysis.

Reinforcement method 2
For the other reinforced composite, a straight steel wire (Ø 1 mm) of the brand REELY was used. The steel wire has a tensile strength capacity of >2200 MPa. To ensure an equal aspect ratio \( L/D \) to reinforcement 1 the steel wire was cut in lengths of 5 cm and was also inserted into the printed concrete beam with a spacing of 2 cm. Having learned from the difficulties with placing from the reinforcement 1 composite, a bridge like structure was made that passed along the entire length of the beam. In the deck of the bridge 3 mm diameter holes were drilled to ensure vertical penetration of the steel reinforcement. On the low end of the bridge the holes covered with tape, making it possible for the reinforcement to be placed before the start of the printing process. After printing four layers of SHCC, the bridge was placed over the concrete beam and the reinforcement got pushed through the tape and inserted into the steel beam. Afterwards a fifth layer of concrete was printed on top to further compact the initial 4 layers. For mechanical testing only the first four layers were used. For the 2-layer beam, the reinforcement was cut in half and inserted after the 2\textsuperscript{nd} layer, after which a third was printed on top.

![Figure 4.8: Hooked fibres - R1](image1.png) ![Figure 4.9: Straight steel from which fibres were cut - R2](image2.png)

The composites generated with the two types of reinforcement will from here on referred to as composite Reinforcement 1 (R1) and Reinforcement 2 (R2).
Figure 4.10: Set-up Reinforcement 2 placement [mm]

Figure 4.11: Printing of the fifth layer after placing Reinforcement 2

Figure 4.12: Vicat test
4.2. Mix design

All the composites were printed with a printable SHCC (P-SHCC), developed at the Delft University of Technology by Figueiredo et al. [17]. The mix design has been tailored for adequate printing properties in fresh state and strain hardening properties in the hardened state. In order to achieve the required printing properties, like pumpability, extrudability and buildability, multiple admixtures were used. A super plasticizer was incorporated to improve viscosity properties and ensure pumpability and a viscosity modifier was added to improve the extrudability of the mixture. Fly ash and Limestone powder were used to improve the packing density and therewith the buildability of the printable SHCC mixture. The specific mix design of the used SHCC (YVA4 PVA20-S05) can be found in table 4.1.

As the open time is an important material property when it comes to concrete printing, the setting time of the utilized SHCC was determined by means of Vicat tests, see figure 4.12. Three samples were tested. During testing the samples were continuously wetted to eliminate false test results, due to surface dehydration. From these tests it was found that the SHCC had a setting time of approximately 22 hours (± 2 hours). This long setting time makes it very suitable for longer printing sessions, where the time between mixing and the last printing activities is significant.

Figueiredo et al. determined several mechanical properties of this printable SHCC mix. These mechanical properties are stated below as a reference only, as the material was mixed and printed in another printing facility and with different printing settings. The mechanical properties can be found in table 4.2.

<table>
<thead>
<tr>
<th>YVA4 PVA20-S05</th>
<th>kg/m3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 42.5</td>
<td>480,2</td>
</tr>
<tr>
<td>Fly ash</td>
<td>567,6</td>
</tr>
<tr>
<td>Limestone powder</td>
<td>109,1</td>
</tr>
<tr>
<td>Sand (125 - 250) µm</td>
<td>186,3</td>
</tr>
<tr>
<td>Sand (250 - 500) µm</td>
<td>294</td>
</tr>
<tr>
<td>*PVA fibre</td>
<td>26</td>
</tr>
<tr>
<td>**Viscosity modifier</td>
<td>6,5</td>
</tr>
<tr>
<td>***Superplasticizer</td>
<td>13</td>
</tr>
<tr>
<td>Water</td>
<td>327,4</td>
</tr>
</tbody>
</table>

* Kuraray PVA fibre, for specification see table 2.1
** Methyl cellulose, viscosity of 201 000 mPa
*** Glenium 51, concentration 35%, BASF

<table>
<thead>
<tr>
<th>Mechanical properties P-SHCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength</td>
</tr>
<tr>
<td>Bond strength</td>
</tr>
<tr>
<td>Tensile strength first crack</td>
</tr>
<tr>
<td>Maximum tensile strength</td>
</tr>
</tbody>
</table>
4.3. Printer
The department of Materials and Environment of the TU Delft has recently invested in a small-scale gantry printing robot. The printing robot has been purchased in order to realise small scale printed concrete elements for material and micro-mechanical research. This research is the first published research that made use of this printing robot. As no reference can be made to earlier publications regarding the concrete printing robot, this chapter will elaborate in on the printer, the printing procedure and the specific printing settings used for this research.

4.3.1. General printer specifications
The 3D printer purchased by the TU Delft has an effective printing size of 960 mm (l) x 600 mm (w) x 350 mm (h). The print-table is situated on a height from the floor of 900 mm and a sliding traverse beam is installed at 1400 mm from the floor. This traverse beam is free to move in X-direction. On this beam the printing head is mounted, which can individually move in Y and Z-direction. The concrete pump is situated alongside the print table and has an engine power of 1.5 kW. At full speed, it runs at 204 rpm and can supply a flow of 9 l/min in optimal conditions. A hose of 5 meter length connects the pump to the printing nozzle.

4.3.2. Printing settings
As discussed in the chapter on literature research, the settings of the printer have a high influence on the material and mechanical properties of the printed element. For this research project with the SHCC design of TU Delft as its base mix, the pressure that was generated by pumping the SHCC mixture through the 5-meter hose was decisive for the overall printing settings. In order to ensure that this pressure did not exceed 25 bar, the pump speed had to be limited to level 2 (48 rpm). For this pump speed, multiple printing speeds (nozzle speeds) were subsequently tested, whereby the printed filaments were visually assessed for the constancy of their shape. Too high a printing speed
resulted in the filament being stretched too much, while a too low speed caused an excess of mortar, resulting in a thicker and more irregular filament. Best results were found with a printing speed of 20 mm/s. This speed was kept throughout the printing sessions. The printing speed and required length for the printed beams resulted in an interval time of 120 second. This interval time between the layers was kept constant for all the printed elements.

Table 4.3: Printing settings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printer speed</td>
<td>20</td>
<td>mm/s</td>
</tr>
<tr>
<td>Pumping frequency</td>
<td>48</td>
<td>rpm</td>
</tr>
<tr>
<td>Material flow</td>
<td>0.672</td>
<td>L/min</td>
</tr>
<tr>
<td>Interval time</td>
<td>120</td>
<td>s</td>
</tr>
<tr>
<td>Layer width</td>
<td>40</td>
<td>mm</td>
</tr>
<tr>
<td>Layer height</td>
<td>14</td>
<td>mm</td>
</tr>
<tr>
<td>Nozzle height</td>
<td>14</td>
<td>mm</td>
</tr>
<tr>
<td>Hose diameter</td>
<td>25.4</td>
<td>mm</td>
</tr>
<tr>
<td>Hose length</td>
<td>5</td>
<td>m</td>
</tr>
</tbody>
</table>

4.3.3. Mixing and printing procedure

For each of the seven researched composites, two batches of 4.5 litres were mixed in a planetary mixer, resulting in a total volume of 9 litres of SHCC per printed composite. The mixing procedure described by Figueiredo [17] was defined more clearly to reduce big alterations between different mix batches throughout the research.

- All dry materials, including the fibres, were mixed for two minutes at speed 1, 60 rpm.
- While mixing at speed 1, water with super-plasticizer was slowly added over a period of one minute;
- All components were mixed for the next two minutes at speed 1, until a dough like mixture was observed.
- Continued with at moderate speed (speed 2 - 124 rpm) for a duration of four minutes. At this phase the mixture opens up inside the mixing bowl, and the fibres get dispersed.

The SHCC mix was manually pushed into the pump reservoir. This was done firmly, to reduce the amount of entrapped air as much as possible. Prior to printing, the SHCC was pumped through the hose and the two litres of SHCC was recollected at the nozzle, again for the purpose of reducing entrapped air in the printed elements. After filling of the pump reservoir, the mortar was covered with a plastic foil to prevent the SHCC mixture from dehydrating.

An average printing session had a duration time, from mixing until final print, of maximum two hours. From visual inspection and the results of the Vicat tests this caused no concerns in regard to open time. As all the test were planned to take place 28 days after printing, the printing of the composites was separated in multiple printing sessions. Due to the limited effective printing area it was decided to print a maximum of two composites per session.

Per composite 4 elements were printed with a length of 940 mm, of which 3 with a height of 4 layers (± 56 mm) and one with a height of 2 layers (± 28 mm). Each layer has a rectangular cross section shape with a thickness of 14 mm and a width of 40 mm.

After some printing tests, it was concluded that the initially assumed nozzle offset height of 1 mm resulted in the scraping of the concrete of the previous layer, as can be seen in figure 4.15.
The nozzle offset therefore was increased. In regard to the printing table/previous layer this means that the height of the down flow nozzle was set to 17 mm, for the back flow and 45 degrees nozzles it was set to 3 mm. To guarantee this vertical offset the nozzle height was increased with 14 mm after completion of every layer. As the brushes generate an additional downward pressure onto the printed filaments an additional settling of the brushed layer was observed. To compensate for this loss in layer height and to ensure consistent surface imprint of the brush, the nozzle height increase was reduced from 14 mm per layer to 13.5 mm per layer. To solve this issue the printing routine had to be adjusted. For the general printing routine, a so-called G-code was written. The full text of the G-code for the back flow and down flow nozzle can be found in Appendix A - G code.
4.4. Test methods

After printing, the SHCC beams were covered with wet cloths and plastic film and were left to harden on the printing table for an additional 30 hours. After that, they were stored in a climatic chamber at a constant temperature of 20°C and a relative humidity of approximately 98%. Further specification on test specimens and test methods will be discussed per laboratory test in more detail in the following paragraphs.

4.4.1. Interlayer bond Test

After seven days of curing, the bond test specimens were sawn from the two-layer SHCC beam with an overall size of 20 x 20 x 26 mm. In order to ensure cracking failure at the interlayer, an incision of 2 mm high and 2 mm deep was made all around the test specimen, at the location of the interlayer. This reduced the cross-sectional area to 16 x 16 mm. See figures 4.19 and 4.20. After sample preparation the samples were placed back into the climate chamber.

The bond strength was measured, after 27 days of curing, on an Instron machine making use of the deformation-controlled mode. The specimens were glued on steel plates that were bolted upon the testing machine. The displacement rate was set to 0.13µm/s, resulting in a strain rate of 5 microstrain/s. Linear variable differential transformer sensors, in short LVDT sensors, were utilized to control the vertical displacement of the tensile test. The bond test set-up can be viewed in 4.21.

The acquired output data from the Instron machine was processed with Excel software to come to the following mechanical properties.

Interlayer bond stress

* Tensile strain
* Maximum interlayer bond stress
** Tensile strain @ maximum bond stress
** Young’s modulus

\[
\begin{align*}
\sigma_{\text{bond}} &= \frac{F}{A_{\text{reduced, cross-section}}} \\
\varepsilon_c &= \frac{\Delta Z}{H_{\text{specimen}}} \\
\sigma_{\text{bond,max}} &= \varepsilon_{c,max} \\
E &= \frac{\sigma_{\text{bond}}}{\varepsilon_c}
\end{align*}
\]

* Tensile strain is calculated from the average displacement measured by the lvdt’s.
** The young’s modulus is calculated based on the values from the linear elastic part of the stress-strain curve.

For future research the front of the specimens was prepared for image analysis. This however fell out of the scope of the graduation project.
4. Research design

4.4.2. Compressive test

For the compressive test, cubes with an edge of 35 mm were sawn from the four-layer high beams. This was done after seven days of curing in the climate chamber. To investigate the anisotropic behaviour of the printed SHCC, the compressive test was performed on orientation 1 (perpendicular to the layers) and orientation 2 (parallel to the layers). Orientation 3 (parallel to the printing direction) was not assessed. Prior to sawing, the printing direction was clearly marked on the beams to enable correct orientation during testing. Per orientation, a minimum of 5 samples was tested. All steel reinforced test specimens contained one steel fibre. After the preparation the samples were placed back into the climate chamber.

Compressive strength was measured 28 days after printing in a servo hydraulic machine with a constant load rise of 2 KN/s. The test was carried out in accordance with ASTM C-39, using two hardened steel bearing plates. The upper bearing plate being able to rotate in order to be perfectly parallel to the upper edge of the test specimen.
4.4. Test methods

4.4.3. Tensile test

After seven days in the curing room, specimens were sawn from the 4-layer high beams using a wet stone saw with diamond powder coated blade. The specimens had a rectangular shape with the following dimensions: 20 mm [w] x 40 mm [h] x 250 mm [l], see figure 4.23. Fibre reinforced concrete, as described in table 4.5, was cast on both outer ends to enlarge the cross-sectional area and therewith ensuring tensile failure to occur in the region with a smaller cross-section which was monitored during testing. For these castings, customized moulds were designed and constructed to ensure perfect alignment of the two cast ends. Figures 4.25 and 4.26 demonstrate the mould and its dimensions. The cast specimens within the moulds were again covered with wetted cloths and plastic film. After 30 hours the specimens were demoulded and placed back into the climate chamber.

Tensile tests were carried out 28-29 days after printing. The specimens were glued on steel plates that were bolted upon the testing machine. To eliminate failure at the glue-line, a rectangular reservoir was made on top of the steel plate ensuring a glue height of at least 10 mm. Additionally incisions were made at top and bottom of the specimen to increase specific surface of the specimen-glue interface, see figure 4.24.

Table 4.5: FRC mix design

<table>
<thead>
<tr>
<th>Material</th>
<th>grams</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEN standard sand EN 196-1</td>
<td>1350</td>
</tr>
<tr>
<td>CEM I 52,5 R</td>
<td>500</td>
</tr>
<tr>
<td>Water</td>
<td>200</td>
</tr>
<tr>
<td>PVA fiber</td>
<td>4</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>1</td>
</tr>
</tbody>
</table>

The uni-axial tensile tests were performed in a manner similar as was developed by the TU Dresden [21]. The tests were carried out in an Instron machine making use of the deformation-controlled mode. The displacement rate was set to 0.5 \( \mu \text{m/s} \), resulting in a strain rate of 5 microstrain/s. The average displacement measured by the LVDT sensors was utilized to control the vertical displacement of the tensile test. Full test set-up can be viewed in figure 4.27. The acquired output data from the Instron machine was processed as described in 4.4.1, to come to the corresponding tensile stress and tensile strain.
4. Research design

Figure 4.25: Mould for tensile specimen

Figure 4.26: Dimensions of the mould [mm]

Figure 4.27: Tensile test set-up, measurements in mm
4.4.4. CT scan

Computed tomography (CT) is a non-destructive technique that provides insight into the internal microstructure of a material. Although the technique is best known from its application in medicine, this technique is also used by civil and material engineers to visualize internal imperfections of the material [58]. The technique uses X-rays and their ability to travel through matter. The machine emits X-rays with a certain energy in the direction of the material. This X-ray then travels through the material to a detector positioned behind it. This detector registers the remaining energy. It is the energy loss, or in other words the absorption capacity of the material, that makes it possible for the machine to calculate the density of the material and reconstruct the internal structure. In order to get a reconstruction of the full specimen a slice by slice scan is carried out by the tomographical device. For every slice the specimen is scanned around its full circumference. This can either be done by rotating the emitter and detector, as we see with medical devices, or by revolving the specimen around its Z-axis. The resolution of the final image is dependent on the angle and height increments.

![CT scan set-up](image)

The printed SHCC’s were subjected to X-ray CT scans with a Phoenix Nanotom X-ray, situated at the Delft University of Technology. In this machine, as it has a fixed emitter and detector, the specimen revolves around its Z-axis. Due to this set-up the test specimens are preferably of a cylindrical shape. This ensures minimization of beam hardening artefacts, as the path through the specimen has equal length from all projection angles while the cylinder rotates around its axis.

Per printed composite, one cylindrical test specimen with a 20 mm diameter was drilled out of the 2-layer high SHCC beams. The cores had a height of ± 28 mm, except for the composites Reinforcement 1 and Reinforcement 2, these samples were drilled from the four-layer beam to ensure sufficient fibre length within the specimen to assess the steel fibre - matrix bond. Therefore these samples have a height of ± 34 mm. The resolution of the scans was set to 15 \( \mu \text{m/pixel} \).

![CT scan specimens](image)

Figure 4.29: CT scan specimens, from left to right; Down flow, Back flow, 45 degrees, B1, B2, R1, R2
With the software package VG studio the images created by the CT-scan were reconstructed into the original volume. A median filter was used to clarify the raw data and remove noise. For the bond analysis, no additional post-processing was acquired, analysis was done based on the cross-sectional slices generated by the VG studio software.

For the analysis of the air void content and the air void distribution, the software package Fiji was used. This program makes it possible to distinguish between the concrete and air voids within the scanned specimen. This is done by setting a threshold value for every individual specimen. The threshold value was taken from the data histogram, being the value between the peak of the material curve and the air curve [60]. By applying the threshold, the cross-sectional slice changes to a black and white image, where the black represents the air voids and all that is white the SHCC. This black and white image is used to assess the air void content per slice of 15 \( \mu m \). By the writing of a simple script routine this procedure can be automated for all the slices in one specimen volume, resulting in output data that describes the void distribution over the specimen height. The used script for this routine can be found in Appendix B.
Figure 4.30: Flow chart: Experimental research
5.1. Interlayer bond test

Per composite a large amount of test specimens were tested. During testing different failure modes were observed:

- Crack propagation in interface zone.
- Crack propagation through layer, mostly due to big air voids.
- Glue line failure.

The graphs and tables in this section present only the test specimens that failed at the interface. The strains reported in the graphs and tables are presented in permille (‰).
Appendix C contains a selection of images of the tests and the cracked specimen.

5.1.1. Down flow

![Stress-strain curve interlayer bond test](image)

Figure 5.1: Stress strain diagram *Down flow* interlayer bond
### Table 5.1: Mechanical properties Down flow interlayer bond

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cross-section $mm^2$</th>
<th>Young's modulus MPa</th>
<th>Ultimate strength MPa</th>
<th>Strain @ ultimate stress %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>272.25</td>
<td>15608</td>
<td>1.525</td>
<td>0.128</td>
</tr>
<tr>
<td>2</td>
<td>240.25</td>
<td>13446</td>
<td>1.029</td>
<td>0.101</td>
</tr>
<tr>
<td>3</td>
<td>272.25</td>
<td>14689</td>
<td>1.342</td>
<td>0.152</td>
</tr>
<tr>
<td>4</td>
<td>256.00</td>
<td>11897</td>
<td>1.156</td>
<td>0.151</td>
</tr>
<tr>
<td>5</td>
<td>272.25</td>
<td>11768</td>
<td>1.447</td>
<td>0.147</td>
</tr>
<tr>
<td>6</td>
<td>289.00</td>
<td>14370</td>
<td>1.894</td>
<td>0.185</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>-</td>
<td>13234</td>
<td>1.374</td>
</tr>
<tr>
<td>S.D. (%) Avg.</td>
<td></td>
<td>-</td>
<td>2260 (12%)</td>
<td>0.144</td>
</tr>
</tbody>
</table>

*S.D.* = Standard deviation  
% Avg = Percentage of average value

### 5.1.2. Back flow

#### Stress - strain curve interlayer bond test

**Back flow**

![Stress-strain curve](image)

Figure 5.2: Stress strain diagram Down flow interlayer bond

### Table 5.2: Mechanical properties Back flow interlayer bond

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cross-section $mm^2$</th>
<th>Young's modulus MPa</th>
<th>Ultimate strength MPa</th>
<th>Strain @ ultimate stress %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>272.25</td>
<td>11676</td>
<td>1.311</td>
<td>0.153</td>
</tr>
<tr>
<td>2</td>
<td>272.25</td>
<td>15434</td>
<td>1.507</td>
<td>0.147</td>
</tr>
<tr>
<td>3</td>
<td>272.25</td>
<td>15349</td>
<td>1.274</td>
<td>0.150</td>
</tr>
<tr>
<td>4</td>
<td>272.25</td>
<td>9756</td>
<td>1.750</td>
<td>0.260</td>
</tr>
<tr>
<td>5</td>
<td>272.25</td>
<td>11858</td>
<td>1.210</td>
<td>0.130</td>
</tr>
<tr>
<td>6</td>
<td>272.25</td>
<td>13731</td>
<td>1.526</td>
<td>0.141</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>-</td>
<td>12967</td>
<td>1.430</td>
</tr>
<tr>
<td>S.D. (%) Avg.</td>
<td></td>
<td>-</td>
<td>2261 (17%)</td>
<td>0.164</td>
</tr>
</tbody>
</table>

*S.D.* = Standard deviation  
% Avg = Percentage of average value
5.1. Interlayer bond test

5.1.3. 45 degrees

![Stress strain curve interlayer bond test 45 degrees](image)

Figure 5.3: Stress strain diagram 45 degrees interlayer bond

Table 5.3: Mechanical properties 45 degrees interlayer bond

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cross-section $mm^2$</th>
<th>Young's modulus MPa</th>
<th>Ultimate strength MPa</th>
<th>Strain @ ultimate stress %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>240</td>
<td>9918</td>
<td>1.032</td>
<td>0.219</td>
</tr>
<tr>
<td>Sample 2</td>
<td>240</td>
<td>10043</td>
<td>1.065</td>
<td>0.200</td>
</tr>
<tr>
<td>Sample 3</td>
<td>240</td>
<td>10931</td>
<td>0.823</td>
<td>0.204</td>
</tr>
<tr>
<td>Sample 4</td>
<td>255.75</td>
<td>11382</td>
<td>1.368</td>
<td>0.184</td>
</tr>
<tr>
<td>Sample 5</td>
<td>255.75</td>
<td>12201</td>
<td>1.453</td>
<td>0.204</td>
</tr>
<tr>
<td>Sample 6</td>
<td>272.25</td>
<td>9758</td>
<td>1.671</td>
<td>0.308</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>10706</td>
<td>1.27</td>
<td>0.207</td>
</tr>
<tr>
<td>S.D. (% Avg.)</td>
<td>-</td>
<td>969.7 (9%)</td>
<td>0.27 (21%)</td>
<td>0.054 (26%)</td>
</tr>
</tbody>
</table>

5.1.4. Comparison nozzle types

![Comparison nozzle types](image)

Figure 5.4: Mechanical properties nozzle composites: a) Young's modulus b) Tensile strength c) Strain @ ultimate tensile stress
5.1.5. Brush 1

Figure 5.5: Stress strain diagram Brush 1 interlayer bond

Table 5.4: Mechanical properties Brush 1 interlayer bond

<table>
<thead>
<tr>
<th></th>
<th>Cross-section $mm^2$</th>
<th>Young’s modulus MPa</th>
<th>Ultimate strength MPa</th>
<th>Strain @ ultimate stress %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>256</td>
<td>12152</td>
<td>1.072</td>
<td>0.179</td>
</tr>
<tr>
<td>Sample 2</td>
<td>256</td>
<td>10793</td>
<td>1.151</td>
<td>0.200</td>
</tr>
<tr>
<td>Sample 3</td>
<td>280.5</td>
<td>14329</td>
<td>1.359</td>
<td>0.148</td>
</tr>
<tr>
<td>Sample 4</td>
<td>225</td>
<td>11767</td>
<td>0.988</td>
<td>0.188</td>
</tr>
<tr>
<td>Sample 5</td>
<td>225</td>
<td>11315</td>
<td>0.983</td>
<td>0.157</td>
</tr>
<tr>
<td>Sample 6</td>
<td>256</td>
<td>1378</td>
<td>1.311</td>
<td>0.181</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>12288</td>
<td>1.094</td>
<td>0.176</td>
</tr>
<tr>
<td>S.D. (% Avg.)</td>
<td>-</td>
<td>1403 (11%)</td>
<td>0.16 (15%)</td>
<td>0.021 (12%)</td>
</tr>
</tbody>
</table>
5.1. Interlayer bond test

5.1.6. Brush 2

Figure 5.6: Stress strain diagram Brush 2 interlayer bond

Table 5.5: Mechanical properties Brush 2 interlayer bond

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cross-section $\text{mm}^2$</th>
<th>Young's modulus MPa</th>
<th>Tensile strength MPa</th>
<th>Strain @ ultimate stress %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>196</td>
<td>10505</td>
<td>1.424</td>
<td>1.187</td>
</tr>
<tr>
<td>Sample 2</td>
<td>169</td>
<td>12543</td>
<td>1.545</td>
<td>0.174</td>
</tr>
<tr>
<td>Sample 3</td>
<td>232.5</td>
<td>13105</td>
<td>1.614</td>
<td>0.136</td>
</tr>
<tr>
<td>Sample 4</td>
<td>232.5</td>
<td>13354</td>
<td>1.491</td>
<td>0.131</td>
</tr>
<tr>
<td>Sample 5</td>
<td>232.5</td>
<td>8643</td>
<td>1.037</td>
<td>0.538</td>
</tr>
<tr>
<td>Sample 6</td>
<td>256</td>
<td>14392</td>
<td>2.010</td>
<td>0.195</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>11630</td>
<td>1.513</td>
<td>0.433</td>
</tr>
<tr>
<td>S.D. (% Avg.)</td>
<td>-</td>
<td>2010 (17%)</td>
<td>0.314 (21%)</td>
<td>0.454 (105%)</td>
</tr>
</tbody>
</table>

5.1.7. Comparison brushed composites

Figure 5.7: Mechanical properties reinforced composites: a) Young's modulus b) Tensile strength c) Strain @ ultimate tensile stress
5.1.8. Reinforcement 1

Figure 5.8: Stress strain diagram *Reinforcement 1* interlayer bond

Table 5.6: Mechanical properties *Reinforcement 1* interlayer bond

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cross-section (mm²)</th>
<th>Young's modulus (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Strain @ ultimate stress (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>225</td>
<td>14514</td>
<td>1.396</td>
<td>0.140</td>
</tr>
<tr>
<td>Sample 2</td>
<td>225</td>
<td>12434</td>
<td>1.363</td>
<td>0.157</td>
</tr>
<tr>
<td>Sample 3</td>
<td>225</td>
<td>9728</td>
<td>1.308</td>
<td>0.191</td>
</tr>
<tr>
<td>Sample 4</td>
<td>225</td>
<td>14342</td>
<td>1.392</td>
<td>0.150</td>
</tr>
<tr>
<td>Sample 5</td>
<td>217.5</td>
<td>14398</td>
<td>1.061</td>
<td>0.104</td>
</tr>
<tr>
<td>Sample 6</td>
<td>210</td>
<td>15465</td>
<td>1.075</td>
<td>0.501</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>13083</td>
<td>1.266</td>
<td>0.207</td>
</tr>
<tr>
<td>S.D. (% Avg.)</td>
<td>-</td>
<td>2064 (16%)</td>
<td>0.156 (12%)</td>
<td>0.147 (21%)</td>
</tr>
</tbody>
</table>
5.1. Interlayer bond test

5.1.9. Reinforcement 2

Figure 5.9: Stress strain diagram Reinforcement 2 interlayer bond

Table 5.7: Mechanical properties Reinforcement 2 interlayer bond

<table>
<thead>
<tr>
<th></th>
<th>Cross-section</th>
<th>Young's modulus</th>
<th>Tensile strength</th>
<th>Strain @ ultimate stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm²</td>
<td>MPa</td>
<td>MPa</td>
<td>%</td>
</tr>
<tr>
<td>Sample 1</td>
<td>240</td>
<td>15725</td>
<td>1.755</td>
<td>0.156</td>
</tr>
<tr>
<td>Sample 2</td>
<td>225</td>
<td>16995</td>
<td>1.546</td>
<td>0.180</td>
</tr>
<tr>
<td>Sample 3</td>
<td>225</td>
<td>13421</td>
<td>1.135</td>
<td>0.317</td>
</tr>
<tr>
<td>Sample 4</td>
<td>224</td>
<td>15292</td>
<td>1.268</td>
<td>0.259</td>
</tr>
<tr>
<td>Sample 5</td>
<td>195</td>
<td>14769</td>
<td>0.960</td>
<td>0.108</td>
</tr>
<tr>
<td>Sample 6</td>
<td>210</td>
<td>14104</td>
<td>1.385</td>
<td>0.196</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>15051</td>
<td>1.341</td>
<td>0.203</td>
</tr>
<tr>
<td>S.D. (% Avg.)</td>
<td>-</td>
<td>1259 (8%)</td>
<td>0.29 (22%)</td>
<td>0.075 (37%)</td>
</tr>
</tbody>
</table>

5.1.10. Comparison reinforced composites

Figure 5.10: Mechanical properties brushed composites: a) Young's modulus b) Tensile strength c) Strain @ ultimate tensile stress
5.1.11. Typical values
From every composite one bond test curve has been selected that best represents the character of the average curve. Curves that were selected are:

- *Down flow* Sample 5
- *Back flow* Sample 1
- *45 degrees* Sample 1
- *Brush 1* Sample 2
- *Brush 2* Sample 1
- *Reinforcement 1* Sample 6
- *Reinforcement 2* Sample 4

![Figure 5.11: Stress strain diagram typical curves](image)

The table below shows the average values per composite of the interlayer bond test.

<table>
<thead>
<tr>
<th>Composite</th>
<th>Tensile strength (S.D.) MPa</th>
<th>Strain @ ultimate stress (S.D.) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Down flow</td>
<td>1.37 (0.30)</td>
<td>0.144 (0.028)</td>
</tr>
<tr>
<td>Back flow</td>
<td>1.43 (0.20)</td>
<td>0.164 (0.048)</td>
</tr>
<tr>
<td>45 degrees</td>
<td>1.27 (0.27)</td>
<td>0.207 (0.054)</td>
</tr>
<tr>
<td>Brush 1</td>
<td>1.09 (0.16)</td>
<td>0.176 (0.021)</td>
</tr>
<tr>
<td>Brush 2</td>
<td>1.51 (0.31)</td>
<td>0.433 (0.454)</td>
</tr>
<tr>
<td>Reinforcement 1</td>
<td>1.27 (0.16)</td>
<td>0.207 (0.147)</td>
</tr>
<tr>
<td>Reinforcement 2</td>
<td>1.34 (0.35)</td>
<td>0.203 (0.075)</td>
</tr>
</tbody>
</table>
5.2. Compressive test

Figure 5.12: Diagram: Average compressive strength

*Due to an error in the compressive test machine, the Back flow composite in orientation 2 was tested 31 days after printing.

The full value chart with the raw data and calculations can be found in Appendix D.

After testing a clear difference in crack patterns was observed between the two orientations, as can be seen in figures 5.13 and 5.14.

Figure 5.13: Compressive test with orientation of horizontal layer, Down flow

Figure 5.14: Compressive test with orientation of vertical layer, Down flow
5.3. Uni-axial tensile test

All the tested specimens failed within the reduced cross-sectional area, as intended. The strains reported in the graphs and tables are presented in permille (\%\).

Appendix E contains a selection of images of the tests and the crack propagations.

5.3.1. Down flow

![Stress-strain curve uni-axial tensile test](image)

Figure 5.15: Stress strain diagram *Down flow* uni-axial tensile test

<table>
<thead>
<tr>
<th></th>
<th>Cross-section $mm^2$</th>
<th>Youngs modulus MPa</th>
<th>Ultimate strength MPa</th>
<th>Strain @ ultimate stress %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>880</td>
<td>13102</td>
<td>2.464</td>
<td>4.643</td>
</tr>
<tr>
<td>Sample 2</td>
<td>880</td>
<td>13278</td>
<td>2.468</td>
<td>2.079</td>
</tr>
<tr>
<td>Sample 3</td>
<td>902</td>
<td>14318</td>
<td>2.972</td>
<td>8.013</td>
</tr>
<tr>
<td>Sample 4</td>
<td>880</td>
<td>13295</td>
<td>2.630</td>
<td>5.997</td>
</tr>
<tr>
<td>Sample 5</td>
<td>902</td>
<td>14750</td>
<td>3.031</td>
<td>6.210</td>
</tr>
<tr>
<td>Sample 6</td>
<td>880</td>
<td>14779</td>
<td>2.708</td>
<td>5.619</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>13920</td>
<td>2.712</td>
<td>5.427</td>
</tr>
<tr>
<td>S.D. (% Avg)</td>
<td>-</td>
<td>782 (6%)</td>
<td>0.244 (9%)</td>
<td>1.974 (36%)</td>
</tr>
</tbody>
</table>
5.3.2. Back flow

![Stress-strain curve for uni-axial tensile test](image)

Figure 5.16: Stress strain diagram Back flow uni-axial tensile test

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cross-section [mm²]</th>
<th>Youngs modulus [MPa]</th>
<th>Ultimate strength [MPa]</th>
<th>Strain @ ultimate stress [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>880</td>
<td>11842</td>
<td>2.785</td>
<td>0.267</td>
</tr>
<tr>
<td>Sample 2</td>
<td>880</td>
<td>11472</td>
<td>2.530</td>
<td>2.121</td>
</tr>
<tr>
<td>Sample 3</td>
<td>880</td>
<td>11283</td>
<td>2.499</td>
<td>0.260</td>
</tr>
<tr>
<td>Sample 4</td>
<td>880</td>
<td>10580</td>
<td>2.281</td>
<td>0.284</td>
</tr>
<tr>
<td>Sample 5</td>
<td>880</td>
<td>10904</td>
<td>2.555</td>
<td>2.894</td>
</tr>
<tr>
<td>Sample 6</td>
<td>880</td>
<td>11423</td>
<td>2.524</td>
<td>3.583</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>11251</td>
<td>2.521</td>
<td>1.568</td>
</tr>
<tr>
<td>S.D. (% Avg)</td>
<td>-</td>
<td>447 (4%)</td>
<td>0.160 (6%)</td>
<td>1.495 (95%)</td>
</tr>
</tbody>
</table>
5.3.3. 45 degrees

![Stress-strain curve for 45 degrees uni-axial tensile test](image)

Figure 5.17: Stress strain diagram 45 degrees uni-axial tensile test

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cross-section $mm^2$</th>
<th>Youngs modulus MPa</th>
<th>Ultimate strength MPa</th>
<th>Strain @ ultimate stress %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>840</td>
<td>9769</td>
<td>2.269</td>
<td>0.282</td>
</tr>
<tr>
<td>Sample 2</td>
<td>880</td>
<td>9774</td>
<td>2.570</td>
<td>0.326</td>
</tr>
<tr>
<td>Sample 3</td>
<td>840</td>
<td>10666</td>
<td>2.335</td>
<td>1.705</td>
</tr>
<tr>
<td>Sample 4</td>
<td>880</td>
<td>9309</td>
<td>2.383</td>
<td>0.333</td>
</tr>
<tr>
<td>Sample 5</td>
<td>840</td>
<td>10420</td>
<td>2.201</td>
<td>0.240</td>
</tr>
<tr>
<td>Sample 6</td>
<td>880</td>
<td>9259</td>
<td>2.126</td>
<td>0.285</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>9866</td>
<td>2.314</td>
<td>0.528</td>
</tr>
<tr>
<td>S.D. (% Avg)</td>
<td>-</td>
<td>573 (6%)</td>
<td>0.156 (7%)</td>
<td>0.577 (109%)</td>
</tr>
</tbody>
</table>

5.3.4. Comparison nozzle composites

![Comparison of mechanical properties](image)

Figure 5.18: Mechanical properties nozzle composites: a) Youngs modulus b) Tensile strength c) Strain @ ultimate tensile stress
5.3.5. *Brush 1*

![Stress-strain diagram for Brush 1](image)

Figure 5.19: Stress-strain diagram for Brush 1 uni-axial tensile test

<table>
<thead>
<tr>
<th></th>
<th>Cross-section $mm^2$</th>
<th>Youngs modulus [MPa]</th>
<th>Ultimate strength [MPa]</th>
<th>Strain @ ultimate stress [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>800</td>
<td>11891</td>
<td>2.713</td>
<td>0.263</td>
</tr>
<tr>
<td>Sample 2</td>
<td>800</td>
<td>10897</td>
<td>2.196</td>
<td>0.243</td>
</tr>
<tr>
<td>Sample 3</td>
<td>800</td>
<td>11651</td>
<td>2.637</td>
<td>0.270</td>
</tr>
<tr>
<td>Sample 4</td>
<td>800</td>
<td>9714</td>
<td>2.290</td>
<td>5.934</td>
</tr>
<tr>
<td>Sample 5</td>
<td>800</td>
<td>10769</td>
<td>2.278</td>
<td>0.260</td>
</tr>
<tr>
<td>Sample 6</td>
<td>800</td>
<td>9909</td>
<td>2.433</td>
<td>0.341</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>-</strong></td>
<td><strong>10805</strong></td>
<td><strong>2.424</strong></td>
<td><strong>1.219</strong></td>
</tr>
<tr>
<td><strong>S.D. (% Avg)</strong></td>
<td><strong>-</strong></td>
<td><strong>883 (8%)</strong></td>
<td><strong>0.210 (9%)</strong></td>
<td><strong>2.310 (189%)</strong></td>
</tr>
</tbody>
</table>

Table 5.12: Mechanical properties for Brush 1 uni-axial tensile test
5.3.6. Brush 2

![Stress-strain diagram](image)

**Figure 5.20:** Stress strain diagram *Brush 2* uni-axial tensile test

**Table 5.13:** Mechanical properties *Brush 2* uni-axial tensile test

<table>
<thead>
<tr>
<th></th>
<th>Cross-section [mm²]</th>
<th>Youngs modulus [MPa]</th>
<th>Ultimate strength [MPa]</th>
<th>Strain @ ultimate stress [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>800.00</td>
<td>10750</td>
<td>2.163</td>
<td>1.986</td>
</tr>
<tr>
<td>Sample 2</td>
<td>800.00</td>
<td>10775</td>
<td>2.150</td>
<td>3.514</td>
</tr>
<tr>
<td>Sample 3</td>
<td>760.00</td>
<td>10856</td>
<td>2.468</td>
<td>0.278</td>
</tr>
<tr>
<td>Sample 4</td>
<td>800.00</td>
<td>10212</td>
<td>2.228</td>
<td>1.947</td>
</tr>
<tr>
<td>Sample 5</td>
<td>840.00</td>
<td>9772</td>
<td>2.105</td>
<td>3.525</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>10473</td>
<td>2.223</td>
<td>2.250</td>
</tr>
<tr>
<td>S.D. (% Avg)</td>
<td>-</td>
<td>468 (4%)</td>
<td>0.144 (6%)</td>
<td>1.348 (60%)</td>
</tr>
</tbody>
</table>

5.3.7. Comparison brushed composites

![Mechanical properties comparison](image)

**Figure 5.21:** Tensile test: Mechanical properties brushed composites: a) Youngs modulus b) Tensile strength c) Strain @ ultimate tensile stress
5.3.8. **Reinforcement 1**

![Stress-strain diagram for Reinforcement 1](image1)

**Figure 5.22:** Stress-strain diagram **Reinforcement 1** uni-axial tensile test

<table>
<thead>
<tr>
<th>Cross-section ($mm^2$)</th>
<th>Young's modulus (MPa)</th>
<th>Ultimate strength (MPa)</th>
<th>Strain @ ultimate stress (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>861</td>
<td>9121</td>
<td>2.078</td>
</tr>
<tr>
<td>Sample 2</td>
<td>840</td>
<td>9342</td>
<td>2.350</td>
</tr>
<tr>
<td>Sample 3</td>
<td>840</td>
<td>9719</td>
<td>2.233</td>
</tr>
<tr>
<td>Sample 4</td>
<td>840</td>
<td>10035</td>
<td>2.289</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>-</strong></td>
<td><strong>9554</strong></td>
<td><strong>2.238</strong></td>
</tr>
<tr>
<td>S.D. (% Avg)</td>
<td>-</td>
<td>404 (4%)</td>
<td>0.116 (5%)</td>
</tr>
</tbody>
</table>

5.3.9. **Reinforcement 2**

![Stress-strain diagram for Reinforcement 2](image2)

**Figure 5.23:** Stress-strain diagram **Reinforcement 2** uni-axial tensile test
### Table 5.15: Mechanical properties Reinforcement 2 uni-axial tensile test

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cross-section $mm^2$</th>
<th>Youngs modulus MPa</th>
<th>Ultimate strength MPa</th>
<th>Strain @ ultimate stress %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>924</td>
<td>10341</td>
<td>2.491</td>
<td>0.302</td>
</tr>
<tr>
<td>Sample 2</td>
<td>882</td>
<td>10102</td>
<td>2.694</td>
<td>0.332</td>
</tr>
<tr>
<td>Sample 3</td>
<td>861</td>
<td>11322</td>
<td>2.155</td>
<td>2.059</td>
</tr>
<tr>
<td>Sample 4</td>
<td>861</td>
<td>8927</td>
<td>2.370</td>
<td>0.348</td>
</tr>
<tr>
<td>Sample 5</td>
<td>840</td>
<td>10718</td>
<td>2.316</td>
<td>2.305</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>10282</td>
<td>2.405</td>
<td>1.069</td>
</tr>
<tr>
<td>S.D. (% Avg)</td>
<td>-</td>
<td>886 (9%)</td>
<td>0.202 (8%)</td>
<td>1.020 (95%)</td>
</tr>
</tbody>
</table>

#### 5.3.10. Comparison reinforced composites

![Graphs showing mechanical properties](image)

Figure 5.24: Tensile test: Mechanical properties brushed composites: a) Youngs modulus b) Tensile strength c) Strain @ ultimate tensile stress
5.3.11. Typical curves
From every composite one stress-strain curve has been selected that best represents the character of the average curve. Curves that were selected are:

| Down flow | Sample 6 | Brush 2 | Sample 1 |
| Back flow | Sample 6 | Reinforcement 1 | Sample 2 |
| 45 angle | Sample 4 | Reinforcement 2 | Sample 1 |
| Brush 1 | Sample 4 |

![Typical stress-strain curves uni-axial tensile test](image)

Figure 5.25: Typical stress-strain curves tensile test

The table below shows the average values per composite of the uni-axial tensile test.

Table 5.16: Average properties uni-axial tensile test

<table>
<thead>
<tr>
<th>Composite</th>
<th>Tensile strength (S.D.)</th>
<th>Strain @ ultimate stress (S.D.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>%</td>
</tr>
<tr>
<td>Down flow</td>
<td>2.71 (0.24)</td>
<td>5.43 (1.97)</td>
</tr>
<tr>
<td>Back flow</td>
<td>2.52 (0.16)</td>
<td>1.57 (1.49)</td>
</tr>
<tr>
<td>45 degrees</td>
<td>2.31 (0.16)</td>
<td>0.53 (0.58)</td>
</tr>
<tr>
<td>Brush 1</td>
<td>2.42 (0.21)</td>
<td>1.22 (2.31)</td>
</tr>
<tr>
<td>Brush 2</td>
<td>2.23 (0.14)</td>
<td>2.25 (1.35)</td>
</tr>
<tr>
<td>Reinforcement 1</td>
<td>2.34 (0.12)</td>
<td>0.30 (0.03)</td>
</tr>
<tr>
<td>Reinforcement 2</td>
<td>2.41 (0.20)</td>
<td>1.07 (1.02)</td>
</tr>
</tbody>
</table>
5.4. Porosity analysis
All test composites were examined on porosity by the use of computed tomography (CT) with a resolution of 15 µm. The results of these tests are presented by means of graphs illustrating the air void content over height. On the left side of every graph one longitudinal cross section of the test specimen is shown with corresponding height.

Table 5.17: Average porosity per test specimen, air voids depicted in black

<table>
<thead>
<tr>
<th>Composite</th>
<th>Porosity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Down flow</em></td>
<td>6.27</td>
</tr>
<tr>
<td><em>Back flow</em></td>
<td>8.28</td>
</tr>
<tr>
<td><em>45 degrees</em></td>
<td>10.33</td>
</tr>
<tr>
<td><em>Brush 1</em></td>
<td>7.43</td>
</tr>
<tr>
<td><em>Brush 2</em></td>
<td>6.03</td>
</tr>
<tr>
<td><em>Reinforcement 1</em></td>
<td>11.52</td>
</tr>
<tr>
<td><em>Reinforcement 2</em></td>
<td>7.64</td>
</tr>
</tbody>
</table>

Figure 5.26: Average porosity per test specimen

Figure 5.27: Air void distribution *Down flow*
5.4. Porosity analysis

Figure 5.28: Air void distribution Back flow

Figure 5.29: Air void distribution 45 degrees

Figure 5.30: Air void distribution Brush 1
5. Laboratory results

Figure 5.31: Air void distribution Brush 2

Figure 5.32: Air void distribution Reinforcement 1

Figure 5.33: Air void distribution Reinforcement 2
5.5. Bonding steel reinforcement

For each test sample, 2300 cross-sectional images with 15 µm resolution were generated. Figures 5.34 and 5.35 show a selection of the cross-sections. For the assessment of the bonding, the percentage of bonded surface area of the reinforcement was calculated for multiple cross-section, with a height increment of 0.75 mm (50 x 15 µm).

Table 5.18: Average percentage bonded area

<table>
<thead>
<tr>
<th>Composite</th>
<th>Effective height with reinforcement [cm]</th>
<th>slices [-]</th>
<th>Bonding area [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforcement 1</td>
<td>1.95</td>
<td>25</td>
<td>45.2</td>
</tr>
<tr>
<td>Reinforcement 2</td>
<td>1.575</td>
<td>21</td>
<td>78.8</td>
</tr>
</tbody>
</table>

Figure 5.34: Air voids around R1, percentage bonded area is: 60%, 10%, 70% and 55% (respectively)

Figure 5.35: Air voids around R2, percentage bonded area is: 80%, 65%, 95% and 85% (respectively)
6 Analysis

6.1 Bond test
In section 5.1 the stress-strain curves of the interlayer bond test have been presented per composite type. Additionally, in figure 5.8 typical stress-strain curves per composite type were shown. From the results the following conclusions can be drawn. First and foremost, the bond tests show potential ductile behaviour for the composites Brush 2, Reinforcement 1 and Reinforcement 2. These composites have one or several samples in which (potential) ductile behaviour was observed. Secondly, all composites showed high variation in tensile interlayer bond strength between the tested specimens.

6.1.1 Nozzles
For the composites Down flow, Back flow and 45 degrees, no ductile behaviour was observed in the tensile interlayer bond test. Also the average values per nozzle type found for the ultimate stress doesn’t show significant differences: Down flow: 1,37 MPa, Back flow: 1,43 MPa and 45 degrees: 1,27 MPa. Surprisingly the Back flow resulted in nozzle with the highest interlayer bond strength. This seems counter-intuitive as the down flow nozzle introduces higher printing pressures when printing a layer upon a previous layer. However, due to the increased nozzle offset, the high viscosity of the mix design and the low pump speed setting, the vertical pressure induced of the previous layer was presumably low. It is plausible that the smoothness of the surface, created with the back flow nozzle, was of higher influence than the pressure that was induced on the previous layer during printing.
6.1.2. Brushes
For Brush 2, sample 1 has clearly shown a form of ductile behaviour, see figure 5.6 on page 45. Even though the initial crack stress isn't maintained and the stress-strain curve drops after the first peak, the stress is able to build up towards a final peak stress that is higher than the initial crack stress. The curve of sample 3, even though it has the same basic shape, doesn't reach the initial crack stress at its second stress peak, probably due to the high initial crack stress. When analysing the stress-strain curves and the relief of the cracked surface, it is plausible that the concept of surface modification can indeed generate ductile behaviour between the layers. The brush design, and consequently the texture that is imprinted in the surface, has a big influence on the occurrence and magnitude of ductile behaviour; for example, the composite of Brush 1, which was designed to generate a more shallow texture, didn't show any ductile behaviour between the layers. In fact, Brush 1 together with Reinforcement 1 has shown the weakest Interlayer bond strength with an average of 1.09 MPa.

Figure 6.2: Fracture surface Down flow, sample 6
Figure 6.3: Fracture surface Back flow, sample 4
Figure 6.4: Fracture surface 45 degrees, sample 1
Figure 6.5: Fracture surface Brush 1, sample 2
Figure 6.6: Fracture surface Brush 2, sample 1
Figure 6.7: Fracture surface Brush 2, sample 3
6.1.3. Vertical steel reinforcement
In the test results of Reinforcement 1, only sample 6 showed ductile behaviour, see figure 5.8 on page 46. Due to the printing procedure of Reinforcement 1, the vertically placed reinforcement fibres were pushed when printing the second layer and as a result rotated over an angle. During the preparation of the bond test specimens, this presented challenges. Even though the location of the fibres was marked on the printed beams, the angle made it difficult to saw the samples and make the incisions in a way that the fibres were located in the middle of the prepared sample. This caused a high variation in effective bond length of the fibres between the test specimens. Therefore, insufficient bond length is presumably one of the reasons for the lack of ductile behaviour in samples 1 to 5.

In the test results of Reinforcement 2, see figure 5.9 on page 47, none of the samples showed ductile behaviour. However samples 2 and 6 showed a curve shape similar to sample 4 that was used for the typical curve graph shown in figure 5.11 on page 48. This curve consists of two parts, the first part being the crack propagating through the concrete, after which the stress drops and then raises again for the second part of the curve; the pull-out of the reinforcement. In all the samples the pull-out stress was lower than the initial cracking stress of the concrete and therefore no ductile behaviour was observed. The low pull-out stress of samples 2, 4 and 6 was one of the reasons for extending the research with a bonding analysis by means of CT scans.
6.2. Compressive test

The results of the compressive tests show significant differences between the composite types. The weakest compressive strength was found for Reinforcement 1 in orientation 2, namely a compressive strength of 17.49 MPa. The highest value of 31.07 MPa was found for the Down flow in orientation 1, which is a factor 1.8 higher. In general, the results show that the compressive strength is lower when tested in the orientation 1. It therewith supports the findings by Nerella and Ma [39, 54] that the compressive strength is lower in the direction perpendicular to the layers. This however is not the case for composite Brush 2. Here, orientation 1 was clearly stronger with 25.25 MPa (orientation 1) versus 23.41 MPa (orientation 2).

Strong anisotropic behaviour in compression was only found in the Down flow composite and to a smaller extent for Brush 1, Brush 2, Reinforcement 1 and Reinforcement 2.

<table>
<thead>
<tr>
<th>Composite</th>
<th>Average compressive strength orientation 1 MPa</th>
<th>Average compressive strength orientation 2 MPa</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Down flow</td>
<td>24.76</td>
<td>31.07</td>
<td>1.20</td>
</tr>
<tr>
<td>Back flow</td>
<td>19.01</td>
<td>19.17</td>
<td>1.01</td>
</tr>
<tr>
<td>45 degrees</td>
<td>22.71</td>
<td>22.57</td>
<td>0.99</td>
</tr>
<tr>
<td>Brush 1</td>
<td>21.47</td>
<td>24.14</td>
<td>1.11</td>
</tr>
<tr>
<td>Brush 2</td>
<td>25.25</td>
<td>23.41</td>
<td>0.92</td>
</tr>
<tr>
<td>Reinforcement 1</td>
<td>17.49</td>
<td>19.68</td>
<td>1.11</td>
</tr>
<tr>
<td>Reinforcement 2</td>
<td>20.61</td>
<td>23.32</td>
<td>1.12</td>
</tr>
</tbody>
</table>

The composites of Figueiredo et al. [38] were all printed with a down flow nozzle and the compression strength was measured for orientation 1 and 3. Therefore, for the comparison with the values presented by Figueiredo et al. only the results of the down flow nozzle tested in orientation 1 can be considered. Where Figueiredo reports an average value of 17.66 MPa (s.d.: 0.24), the average measured value in this research is 24.76 MPa (s.d.: 4.99), a difference of 28.7%. This shows the same mix design, printed on another printing facility with different printing settings can result in large differences with regard to hardened mechanical properties.
6.3. Uni-axial tensile test

The uni-axial tensile tests parallel to the printing direction have shown three types of failure behaviour; strain-softening, "quasi" strain-hardening and strain-hardening. These three failure types are presented in figure 6.13

- The strain-softening curve shows an initial crack stress (cracking of matrix), after this first crack the specimen is unable to build up a higher stress.

- The "quasi" strain-hardening curve shows the initial cracking of the matrix, after which the stress drops. The stress builds up again when the crack opens up, under the resistance of the crack bridging fibres. The stress needed to open up the crack is higher than the initial crack stress and therewith the specimen shows some strain capacity. However, as only one crack is generated this officially can't be categorized as strain-hardening behaviour.

- The strain-hardening curve shows multiple cracks and significant strain capacity.

![Strain-softening curve](image1)

!["Quasi" strain-hardening curve](image2)

![Strain-hardening curve](image3)

Figure 6.13: Uni-axial tensile test failure behaviours

In table 6.2 an overview is given of the found failure modes per parameter. This section will first analyse the test results per parameter group and end with an overall conclusion of the tensile test.
Table 6.2: Failure types: number of occurrence

<table>
<thead>
<tr>
<th>Composite</th>
<th>Soft-hardening</th>
<th>&quot;Quasi&quot; strain-hardening</th>
<th>Strain-hardening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Down flow</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Back flow</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>45 degrees</td>
<td>5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Brush 1</td>
<td>5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Brush 2</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Reinforcement 1</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reinforcement 2</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

6.3.1. Nozzles

From the three nozzles the Down flow composite has the best strain-hardening properties parallel to the printing direction. All samples showed multiple cracking and were able to rebuild a tensile stress that was higher than the initial crack stress. The number of cracks differed per test specimen, 5.15 on page 50. Where sample 4 showed multiple cracking along the cross-section and a nice equal energy build-up per microcrack, samples 3 and 5 showed fast concentration of microcracks.

The Back flow composite also showed multiple cracking for all tested specimens but only 3 of the 6 tested specimens showed strain-hardening behaviour. From the stress-strain curves it can be concluded that it was difficult for the test specimen to rebuild a stress that was higher than the tensile stress at first crack. A significant stress drop occurred directly after the first crack and even though all the specimens showed multiple cracking, not all of them were able to develop a stress higher than the first cracking stress.

For the 45 degrees composite none of the test samples were able to show strain-hardening behaviour. For all samples a strong stress drop was measured after the first crack stress. Only sample 3 was able to rebuild a tensile stress that was higher that the first crack stress, as can be seen in 5.17 on page 52. The sample is qualified as strain-hardening according to the definition described above. However only two cracks occurred and the strain capacity was rather limited. In general all the specimens cracked at the outer ends of the smaller cross-section or at the location of a bigger air void.

It is possible that the loss of strain-hardening capacity is related to the increased nozzle offset height. This increased height was needed in order to eliminate scraping of the previous layer, but for the 45 degrees nozzle this changed the effective nozzle opening. Making the effective opening of the nozzle 40 mm (w) x 16 mm (h) instead of 40 mm (w) x 14 mm (h). This enlargement can have resulted in a reduction of the fibre alignment and therewith in the loss of the strain-hardening capacity.

When analysing the average tensile strain capacity of nozzle composites, it can be stated that the Down flow composite, with an average strain capacity of 5.43%\textsuperscript{o}, gave the best results. In comparison with the Down flow composite the Back flow (with an average strain capacity of 1.57%\textsuperscript{o}) has 71% less strain capacity. The 45 degrees (with an average strain capacity of 0.53%\textsuperscript{o}) has 90% less strain capacity than the Down flow composite. The highest average Young's modulus was also found for the composite created with the down flow nozzle, with a value of 13920 MPa. In comparison to the Down flow a reduction of 19% was measured for the Back flow and a reduction of 29% was found for the 45 degrees. Differences in the tensile strength are more limited. Where the Down flow has an average tensile strength of 2.71 MPa, the Back flow and 45 degrees have a tensile strength of 2.52 MPa and 2.31 MPa, respectively. This corresponds to a decrease of respectively 10% and 15% in comparison to the Down flow composite.
6.3.2. Brushes

The composites Brush 1 and Brush 2 were created in combination with the down flow nozzle. In comparison with the uni-axial test results of the Down flow composite it can be concluded that with the introduction of surface modification the composite loses its tensile strain-hardening behaviour parallel to the printing direction. Where the Down flow composite could maintain the initial crack stress and create multiple microcracks prior to failure, both Brush 1 and Brush 2 were unable to structurally rebuild the stress level of the first crack and rapidly showed a concentration of microcracks. According to the definition of strain-hardening stated in this section, both parameters have only one test specimen that showed strain-hardening behaviour, namely sample 4 and sample 5 respectively, as can be seen in 5.19 and 5.20. These samples have shown multiple cracking and strain capacity. However, in both cases it was only the second crack that was able to resist a higher tensile stress than the initial cracking of the matrix.

The average strain capacity of the brushed composites confirms this lack of strain-hardening behaviour. When comparing the average tensile strain capacity of the brushed composites to the Down flow composite, it can be concluded that Brush 1 (with an average strain capacity of 1.22%) has 77.5% less strain capacity. The Brush 2 composite (with an average strain capacity of 2.25%) has 58.6% less strain capacity.

In comparison to the Down flow a reduction of 22% for Brush 1 and 25% for Brush 2 was found for the Young’s modulus. For the tensile strength of the Brush 1 and Brush 2 composites a value of 2.42 MPa and 2.23 MPa was measured, respectively. This corresponds to a decrease of respectively 11% and 18% in comparison to the Down flow composite.

Additionally it was observed that cracks initiated at locations of big air voids. Figures 6.17 - 6.19 show the crack propagation and air voids within these composites.
Figure 6.17: Big void works as crack initiator in *Brush 2*, sample 4

Figure 6.18: Crack propagation
*Brush 1*, sample 4

Figure 6.19: Crack propagation
*Brush 2*, sample 4
6.3.3. Vertical steel reinforcement

In comparison with the other parameters, the composites with vertical steel fibre reinforcement showed the weakest tensile stress parallel to the printing direction. For **Reinforcement 1** and **Reinforcement 2** none of the samples showed strain-hardening behaviour. During the tensile test, the first crack always initiated at the location of a steel fibre. Some samples showed a clean horizontal crack through the specimen. Other samples started cracking horizontally along a steel fibre, as soon as they reached the interlayer, the crack continued vertically over the interlayer until reaching the next steel fibre and then continued horizontally again. Figures E.9 - E.11 show several characteristic crack propagations.

Like the brushed composites, the average strain capacity of the reinforced composites, measured during the tests, confirms this lack of strain-hardening behaviour. When comparing the average tensile strain capacity of the brushed composites to the **Down flow** composite, it can be concluded that **Reinforcement 1** (with an average strain capacity of 0.30 %) has 94.5% less strain capacity. The **Brush 2** composite (with an average strain capacity of 1.07 %) has 58.6% less strain capacity.

In comparison to the **Down flow** a reduction of 31.4% for **Reinforcement 1** and 26.1% for **Reinforcement 2** was found for the Young's modulus.

For the tensile strength of the **Brush 1** and **Brush 2** composites a value of 2.24 MPa and 2.41 MPa was measured, respectively. This corresponds to a decrease of respectively 17% and 11% in comparison to the **Down flow** composite.

6.3.4. General findings

Looking at the matrix strength, it is clear that the tensile stress at the first crack does not differ significantly per composite, but at the same time there is a large variation in the strain-hardening capacity. What stands out are the results of the **Down flow** composite. The only composite where all the samples showed strain-hardening behaviour in the tensile stress-strain curve. Therefore it can be stated that the PVA fibres are able to take up the tensile stress when the matrix cracks. Based on this, it is assumed that the lack of strain-hardening behaviour for some parameters is caused
by initial flaws within the printed composite. These internal flaws result in stress concentrations within the composite which leads to failure.

Table 6.3: Anisotropy tensile strength

<table>
<thead>
<tr>
<th>Composite</th>
<th>Avg. tensile strength</th>
<th>Avg. tensile strength</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parallel to printing direction</td>
<td>Interlayer bond</td>
<td>[-]</td>
</tr>
<tr>
<td>Down flow</td>
<td>2.69</td>
<td>1.37</td>
<td>0.51</td>
</tr>
<tr>
<td>Back flow</td>
<td>2.53</td>
<td>1.43</td>
<td>0.57</td>
</tr>
<tr>
<td>45 degrees</td>
<td>2.25</td>
<td>1.27</td>
<td>0.56</td>
</tr>
<tr>
<td>Brush 1</td>
<td>2.41</td>
<td>1.09</td>
<td>0.45</td>
</tr>
<tr>
<td>Brush 2</td>
<td>2.23</td>
<td>1.50</td>
<td>0.67</td>
</tr>
<tr>
<td>Reinforcement 1</td>
<td>2.24</td>
<td>1.09</td>
<td>0.49</td>
</tr>
<tr>
<td>Reinforcement 2</td>
<td>2.37</td>
<td>1.34</td>
<td>0.57</td>
</tr>
</tbody>
</table>

In regard to the anisotropy it can be concluded that none of the tested solutions solved the problem of anisotropic behaviour in tensile loading, as can be seen in table 6.3. All composites showed significant difference between the tensile strength parallel and perpendicular to the printing direction. A tensile strength reduction factor of 0.45 was found. In this respect it should be noted that the tensile strengths perpendicular and parallel to the printed layers were measured via different test set-ups and therefore the results can’t be compared directly. However the significance of the variation between the found tensile strengths in both directions indicates that the anisotropy in tensile loading remains unresolved.

6.4. CT- scans
6.4.1. Air void content

From the porosity analysis it can be concluded that there is a high variation in porosity between the seven composites. The composites that stand out the most are 45 degrees and Reinforcement 1, with an average air void content of more than 10%. For the 45 degrees composite this most likely is due to the increased nozzle offset height, resulting in a larger effective nozzle opening and therewith in a higher material flow and reduced pressure. For the Reinforcement 1 composite it was thought that this was due to the placement of the reinforcement. However, the high air void content is also present in locations where no steel reinforcement was inserted.

There is also a noteworthy variation in the porosity of the other composites, although these are not as significant. It is believed that this is a consequence of the multiple printing sessions in combination with batch mixing. It is plausible that, even though the mixing procedure was strictly followed, some SHCC batches contained more enclosed air prior to printing than others. At first glance, no clear relation is found between the porosity and the printing sessions.

Table 6.4: Printing sessions and porosity

<table>
<thead>
<tr>
<th>PRINTING SESSION</th>
<th>COMPOSITE</th>
<th>POROSITY [%]</th>
<th>COMPOSITE</th>
<th>POROSITY [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Down flow</td>
<td>6.27</td>
<td>Back flow</td>
<td>8.28</td>
</tr>
<tr>
<td>2</td>
<td>45 degrees</td>
<td>10.33</td>
<td>Brush 1</td>
<td>7.43</td>
</tr>
<tr>
<td>3</td>
<td>Reinforcement 1</td>
<td>11.52</td>
<td>Brush 2</td>
<td>6.03</td>
</tr>
<tr>
<td>4</td>
<td>Reinforcement 2</td>
<td>7.64</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
One element that does stand out from the results are the porosity values of composites *Down flow, Brush 1 & Brush 2*. Normally one would expect a lower or equal porosity for composites *Brush 1 & Brush 2* in comparison to the *Down flow* composite, as the composites are printed with the same nozzle and an additional compression force is induced by brushing the surface. However, composites *Brush 1* contains 23% more air voids. On that aspect it is plausible that SHCC mix used in printing session two, did indeed contain a higher air void content prior to printing.

Another outcome of the CT-scan analysis is that the porosity differs quite strongly over the height. In general the location of the interlayer is visible in the porosity graphs. In test specimens including big air voids, or clustering of smaller air voids, the interlayer is more difficult to distinguish.

6.4.2. Bonding steel reinforcement

From the reinforcement bonding analysis it was found that the bond between the steel reinforcement and the SHCC was poor, especially for composite *Reinforcement 1*. The hooked shaped reinforcement that was placed manually, showed big voids alongside the steel fibre throughout the height of the CT scan specimen. The bond between the straight reinforcement that was placed with the use of a spacer was clearly better. Due to a different placement technique between the two composites no conclusions can be made on the influence of the steel fibre shape. The bonding analysis additionally showed that the steel fibres in *Reinforcement 2* have a stronger vertical orientation than the steel fibres in *Reinforcement 1*, which can be seen as a direct result from the adjusted placing method.
Conclusion

The conducted research presented in this report aimed to design and test interlayer improvement method for printable SHCC. To this end the following research question was formulated:

Which methods for improving the interlayer bond can be designed for 3D printable SHCC elements and how do they influence compressive strength capacity in the direction perpendicular and parallel to the layers as well as the tensile strength and strain capacity parallel to the layers?

In this research three methods for improving the interlayer bond have been devised: nozzle types, surface texturing and vertical steel reinforcement. To evaluate these methods on mechanical performance multiple variation have been designed, namely three nozzle types, four brushes (of which two were mechanically evaluated) and two types of vertical steel reinforcement.

This chapter will first present the solutions per method and will finish with the general conclusion of the research.

7.1. Conclusion per method

7.1.1. Nozzles

The design of the printing nozzle has no significant influence on the interlayer bond strength of printed SHCC, as average values vary 11% at most. The nozzle type however, does have a strong influence on the tensile strain-hardening capacity in parallel direction. The Down flow composite showed the most constant strain-hardening behaviour (with an average strain capacity of 5.43%), the composite printed with the 45 degrees nozzle wasn’t able to generate multiple microcracks. This resulted in an average tensile strain capacity of 0.53%, a factor of 0.1 compared to the Down flow composite. Also the results of the compression test show that the nozzle design impacts the compressive strength of the printed SHCC. The highest value of 31.07 MPa was found for the Down flow composite in orientation 2. The Back flow with an average of 19.17 MPa in orientation 2, showed a reduction of compressive strength of 28% compared to the Down flow composite.

7.1.2. Brushes

The results from this research show that the method of surface texturing can improve the interlayer bond. The design of the texture and the amount of initial flaws it creates within the composite are therewith normative. Brush 2 not only showed samples with ductile behaviour in the interlayer bond test, but it also improved the average interlayer bond strength compared to the Down flow composite with 10%. Brush 1 didn’t have any ductility nor improvement on the interlayer bond strength. In comparison with the Down flow composite, the interlayer bond strength even reduced
with 20.4%. Both brushed composites showed loss of tensile strain-hardening capacity in the direction parallel to the printing layer. Under compressive loading both brushed composites showed average result with values between the 21.5 MPa and 25.2 MPa.

### 7.1.3. Vertical steel reinforcement

From this research it can be concluded that the steel fibres potentially have the ability to introduce ductile behaviour perpendicular to the printing direction. The two types of steel fibre reinforcement researched in this graduation project showed potential, but both were unable to systematically display ductile behaviour perpendicular to the printing direction. This was due to insufficient bond length and poor steel fibre - matrix bonding which resulted in a limited pull out strength. Additionally, with the implementation of the steel fibres, both composites lost their tensile strain-hardening properties when stressed parallel to the printing direction. The lowest strain capacity of 0.30%, was found for the Reinforcement 1 composite. Reinforcement 2 showed an average strain capacity of 1.07%. This results in a factor of respectively 0.055 and 0.20 when compared to the average value of the Down flow composite.

To achieve tensile strain-hardening properties perpendicular to the interlayer it is believed that straight steel fibres with sufficient surface roughness should be used. During placement it is essential to minimize the amount of voids. Preferably the steel fibres are placed under an angle to enlarge the pull out strength under uni-axial tensile stress.

### 7.2. General conclusion

There is potential in designing methods to improve the interlayer bond of printed SHCC. However from the deducted research it can be concluded that strain-hardening capacity of printed SHCC is very sensitive to the introduction of initial flaws that lead to stress concentrations. Solutions that give good or promising results in the tensile interlayer bond test, show a reduction in the tensile strength parallel to the printing direction. Crack initiators in parallel direction are easily created with texturing of the surface and with the implementation of vertical reinforcement. These initial flaws result in loss of tensile strain-hardening behaviour in the direction parallel to printing. For designing interlayer improvement methods, all orientations of the printed SHCC element should be taken into consideration.
Discussion and recommendations

8.1. Discussion

8.1.1. Printing procedure

• Assessment of the beams printed with the 45 degrees nozzle showed that the nozzle was incorrectly designed. At time of designing the nozzle, a nozzle offset of 1 mm was anticipated and it was thought that the table or previous layer would give efficient resistance to the extruded material, making the effective vertical height opening 14 mm. Therefore the nozzle was designed with a vertical opening of 13 mm, the opening height under the 45 degrees plane was 16.7 mm. However, due to the irregularity of the printed surface the nozzles a nozzle offset of 3 mm was needed in order not to scrape the previous layer. Due to this increase, the effective vertical height of the nozzle opening became 16 mm. This lead to an irregular shape of the extruded layer. Additionally, it is believed that this also influenced the fibre orientation within the printed layer.

• Every consecutive printing session, the pressure was slightly lower than during the previous session (± 1 bar). As the installation of the pump and the hose were new when used for this research it might be that over time the friction in the 5-meter hose reduced. With the reduction of the printing pressure it is likely that the flow rate of the SHCC at the nozzle also changed during the sessions. However, the printing speed has been kept the same throughout all the printing sessions. Resulting in a variation of the amount of material printed per unit length.

• Due to the use of a small mixing machine, the printable SHCC had to be mixed in multiple batches per printing session. Even though the design mix and the mixing procedure was clearly defined, variations in the material porosity that was demonstrated in the CT-scan can be a result to the batch mixing, as the mix design has previously proven to be sensitive to mixing procedures.

• To reduce material consumption, material was collected and reused at the times that the printer returned to the beginning of the printing path. It should be noted that the reuse of material may affect the material and mechanical properties in hardened state, as the pumping of the material through the printing system introduces temperature increase of the material. This effect has not been taken into account in this research.
8.1.2. Interlayer bond test

- Results generated with the bond test of Brush 2 are still under discussion. Due to the deep grooves this brush creates, it is unsure whether the interlayer is located at the location where the incision is located. For future research it is advised to create a sample with a larger notch in terms of height.

- Due to the printing procedure of Reinforcement 1, the vertically placed reinforcement fibres were pushed under an angle when printing the second layer. During the preparation of the bond test specimen this was taken into account. However, it caused for a high variation in bond length along the steel fibre and the SHCC matrix.

- Presented Young’s moduli are an approximation based on data recorded during the interlayer bond test and uni-axial tensile test. These values were not obtained with a specific test to measure the Young’s modulus. They are incorporated to indicate the differences in elasticity between the composites. The values have been calculated based on the linear elastic part of the stress-strain curve.

8.1.3. Uni-axial tensile test

- The choice for the types of tests conducted in the research is based on the assumption that indeed there is a weak or non-existing strain hardening behaviour perpendicular to the printing direction. With the type of tests performed for this research it is not assessed whether this assumption was indeed the correct.

- Enlarging the cross-sectional area of the tensile specimen by casting fibre reinforced concrete on the specimen ends has worked. However, as discussed in the analysis a large part of the tested specimens had their first crack in the transition zone from these different cross-sections. For most of the samples this was also the location where the final failure occurred.

8.1.4. CT scan

- The analysis of the porosity of the different composites and the bond between the steel reinforcement and the matrix was performed with a very small group of samples. The results therefore are not representative for the general composite. The analysis was conducted only to verify the plausibility of some hypotheses regarding the mechanical test results.

8.2. Recommendations

The results presented in this thesis and the conclusions that emerged from it, provide a basis for improving the interlayer bond of SHCC. However, it should be taken into account that the research was conducted on a conceptual basis, wherein the general concepts of multiple variables were researched. The research should be seen as a first step towards a better interlayer bond and an improved isotropic strain hardening printed composite.

During the project, a number of specific, in depth topics emerged that could be addressed in future research. Based on the results, conclusion and discussion presented in this thesis, the recommendations for further research are:

- Research on the interlayer bond for different SHCC mixes including different fibres.

- Research on the failure modes and crack propagations per direction, as to better understand the specific role of the interlayer bond during failure.

- Research on the correlation between crack plane and failure behaviour by colouring the subsequently printed layers with different pigments.
8.2. Recommendations

• Uni-axial tensile tests in the 3rd direction on specimens that do not contain an interlayer. With this additional data the reduction of tensile strength within the interlayer can be correlated and quantified.

• Another approach for improving the interlayer bond might be to focus on the bridging of the interlayer by the fibres themselves. Brushing against the printing direction may generate additional upward orientated fibres, improving the bond between the two layers.

• Future research should avoid the introduction of additional crack initiators like those that have been presented in the conclusion. For the brushes this might be solved by incorporating the brush shape into the nozzle design.

• A more elaborate research can be conducted on microscale. As mentioned in the discussion the air void analysis with use of the CT scan has been rather limited. A more elaborate research with multiple samples per composite type and additional analysis of the fibre distribution will be helpful to understand the influence of certain parameters on the final properties of the printed composite.

• Research on the same material on different printing facilities. An elaborate study on the influence of printing facilities and specifically pumping pressures on the hydrated composite will give essential insight into the relation between printing technique and quality of the printed material.
Bibliography


G-code
Back flow

; default CNC header example
; g17 : reset g2 g3 motion to XY plane
; g21: reset back to mm mode
; g40 : cancel radius compensation
; g49 : cancel height compensation
; G64P0.1 : smooth motion mode
; 0.1mm radius allowed
; g90 : revert back to absolute progr.
; g94 : revert back to units/m mode

; from here the actual G-code starts
; G-code back flow nozzle

; feed rate
#101 = 1200
#102 = 2400
#103 = 3600

F[#103] G1 X-20.0000 Y40.0000
F[#102] G1 Z3
F[#101] G1 X-980.0000 Y40.0000
F[#103] G1 Z200
F[#103] G1 X-20.0000 Y40.0000
G4 P20
F[#102] G1 Z17
F[#101] G1 X-980.0000 Y130.0000
F[#103] G1 Z200
F[#103] G1 X-20.0000 Y130.0000
G4 P20
F[#102] G1 Z31
F[#101] G1 X-980.0000 Y220.0000
F[#101] G1 Z45
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F[#103] G1 X-20.0000 Y220.0000
G4 P20
F[#102] G1 Z45
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F[#103] G1 Z200
F[#103] G1 X-20.0000 Y310.0000
G4 P20
F[#102] G1 Z17
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F[#102] G1 X-20.0000 Y400.0000
G4 P20
Down flow

;G-code down flow nozzle
F[#103] G1 Z17
F[#101] G1 X-980.0000 Y400.0000
F[#101] G1 Z200
F[#102] G1 X-20.0000 Y400.0000
G4 P20
F[#103] G1 Z31
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G4 P20

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F[#101] G1 X-980.0000 Y670.0000
F[#101] G1 Z200
G4 P20
F[#102] G1 X0.00 Y0.00
Script for air void analysis in Fiji
run("Image Sequence...", "open=[/Volumes/Seagate Expansion Drive
afstuderen CITG/CT scan (6 sept 2019)/B2/DicomTop2/top0000.dcm]
number=425 starting=300 sort");
makeRectangle(468, 214, 540, 540);
//setTool("oval");
makeOval(173, 149, 1278, 1278);
setBackgroundColor(0, 0, 0);
run("Clear Outside", "stack");
run("Crop");
setForegroundColor(255, 0, 0);
i = 0;
while (i<=425) {
  floodFill(1188, 82);
  floodFill(1168, 1194);
  floodFill(146, 1154);
  floodFill(114, 88);
  run("Next Slice [>"]) ;
  i = i +1;
}
setAutoThreshold("Default");
//run("Threshold...");
setThreshold(39, 4500);
run("Convert to Mask", "method = Default background = Dark black");
run("Analyze Particles...", "size=10-Infinity pixel show=Outlines display
clear summarize stack");
Figures tensile interlayer bond test
Figure C.1: Failure in test set-up
*Down flow*, sample 3

Figure C.2: Failure in test
*Back flow*, sample 1

Figure C.3: Failure in test set-up
*45 degrees*, sample 2

Figure C.4: Failure in test set-up
*Brush 1*, sample 6

Figure C.5: Failure in test set-up
*Brush 2*, sample 2

Figure C.6: Failure in test set-up
*Reinforcement 1*, sample 3

Figure C.7: Failure in test set-up
*Reinforcement 2*, sample 2

Figure C.8: Crack propagation in glueline and thick cross-section in a *45 degrees* sample

Figure C.9: Fracture surface with big air void figure C.8

Figure C.10: Crack propagation
*Down flow*, sample 6

Figure C.11: Fracture surface
*Back flow*, sample 4

Figure C.12: Fracture surface
*45 degrees*, sample 1
Figure C.13: Fracture surface
Brush 1, sample 2

Figure C.14: Fracture surface
Brush 2, sample 1

Figure C.15: Fracture surface
Brush 2, sample 3

Figure C.16: Fracture surface
R1, sample 4

Figure C.17: Fracture surface
R1, sample 6

Figure C.18: R1 specimen, with insufficient bond length

Figure C.19: Fracture surface
R2, sample 6

Figure C.20: Fracture surface
R2, sample 4
Compressive test calculation sheets
### Perpendicular

![Diagram of perpendicular direction](image)

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<td>35</td>
<td>1225</td>
<td>39596</td>
<td>32,32</td>
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<td>1225</td>
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Figure D.1: Compression test results in perpendicular direction
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Figure D.2: Compression test results in perpendicular direction
Figures uni-axial tensile test
Figure E.1: Crack propagation 
*Down flow*, sample 6

Figure E.2: Crack propagation 
*Back flow*, sample 6

Figure E.3: Crack propagation 
*45 degrees*, sample 3

Figure E.4: Crack propagation 
*45 degrees*, sample 1

Figure E.5: Crack propagation 
*Brush 1*, sample 4

Figure E.6: Crack propagation 
*Brush 2*, sample 4
Figure E.7: Big voids works as crack initiators in sample E.4

Figure E.8: Big void works as crack initiator in sample E.6

Figure E.9: Crack propagation
Reinforcement 1, sample 3

Figure E.10: Crack propagation
Reinforcement 1, sample 2

Figure E.11: Crack propagation
Reinforcement 2, sample 3