MASTER

The effect of layered manufacturing on the strength properties of printable concrete

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THE EFFECT OF LAYERED MANUFACTURING ON THE STRENGTH PROPERTIES OF PRINTABLE CONCRETE

GRADUATION THESIS

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For completing the Master’s phase of the program Architecture, Building and Planning at the Department of the Built Environment of the TU/e, specialization Structural Design.

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R.J.M. (Rob) Wolfs MSc.
Dr. Ir. F.P. (Freek) Bos
In front of you lies my graduation thesis about the effect of layered manufacturing on the strength properties of printable concrete. This graduation project is performed to complete the master Architecture, Building and Planning, with as specialization Structural Design, at the Department of the Built Environment of Eindhoven University of Technology.

In the summer of 2015 a 3D concrete printer was built in the Structures Laboratory. I was immediately excited and decided that I wanted to graduate on this subject. Because it is a relatively new manufacturing technique, the subject of my graduation project shifted a few times. Despite changing the subject, I am proud of the things I learnt, the pleasure I had and the effort I have put into it.

This graduation project is fulfilled under supervision of Prof. Dr. Ir. T.A.M. (Theo) Salet, R.J.M. (Rob) Wolfs MSc and Dr. Ir. F.P. (Freek) Bos. I would like to thank them for their effort they put into my graduation during the enthusiastic meetings, inspiring discussions and many print sessions.

Also I want to thank the other students which are part of the project 3DConcretePrinting. I am very grateful for the criticism, stimulation, discussions and pleasure we had during print sessions and presentations. Without their time and effort none of my test samples would be printed. As well the employees of the Structures Laboratory of Eindhoven University of Technology thanks for your assistance in the period I performed the tests.

And finally I would like to thank my parents and sister for their support during my study and especially during my graduation project. Furthermore, I appreciate the possibility they give me to develop and realise my ambitions.

Coert Doomen

Eindhoven, September 2016
THE EFFECT OF LAYERED MANUFACTURING ON THE STRENGTH PROPERTIES OF PRINTABLE CONCRETE
ABSTRACT

For the material concrete a new manufacturing technique is developing exponentially: 3D concrete printing. 3D concrete printing is an additive manufacturing technique. 3D concrete printing has a lot of potential advantages, but there is few published about the strength properties and the influence of the manufacturing technique on the strength properties. Due to this lack of published research, this graduation project has as aim to research the effect of layered manufacturing on the strength properties of printable concrete. The research is based on the available 3D concrete printer and print material at Eindhoven University of Technology.

In this report is shown the development and implementation of an experimental research on the strength properties. In an earlier phase the strength development of concrete is experimentally researched by performing different tests for each phase. The dormant period is investigated with a plate stacking test, the setting period with a Vicat test and the hardening phase with hardened tests. Based on these tests, a new test is developed, which takes characteristics of the manufacturing technique into account.

In this relatively new manufacturing technique a lot of variables can be chosen to investigate the influence on the strength properties. These variables arise from the print material and the used parts of the 3D concrete printer. In this stage of the 3D concrete printing research is need to research variables which are always introduced in a print session. The basic variables layer direction and time interval are researched during this project.

The strength properties are gained from a standardized compression test and a tension test. The performed test in tension is a direct tension test, which is not often the case for concrete. The adhesion into the setup and shape of the samples is investigated during the graduation project. Besides testing the strength properties are tested also material properties, like density, Young’s modulus and Poisson’s ratio.

Within the compression and tension test, two different test sets are used to research the effect of test direction and time interval. First a strength development test is performed with zero time interval in the three main directions: print direction (test direction I), perpendicular layer direction (test direction II) and parallel layer direction (test direction III). The test is done 1, 3, 7 and 28 days after printing. This test is designed in order to research the differences in strength development between the directions. Second a time interval test is performed. With this test 11 different intervals varied between zero and 24 hour are introduced. With this test the effect of time interval on the strength of the interface between two layers is investigated. This test is done only 28 days after printing. Besides the tests with the printed samples, casted control samples are tested also. With these casted samples the material is controlled if it has constant material and strength properties at different print sessions.

The results are divided into material properties and strength properties. The results of the strength properties are separately shown for all combinations of test direction, test method and test set. At the end all directions are combined and compared.

Out of the results can be generally concluded that the manufacturing technique provides a decrease in strength compared with casted concrete. The strength development of printable concrete is the same as normal concrete. And the results of the time interval test shows that in only one direction the strength is decreasing at larger time intervals. In this specific direction the samples failed in the interface between layers.
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1. INTRODUCTION

1.1. 3D CONCRETE PRINTING

3D Concrete printing is a relatively new and rapidly developing manufacturing technique. The development of 3D concrete printing grows exponentially by the constant arising of new companies and research groups. This exponential development started by a publication of Khoshnevis, B. (1998). Especially in the last few years research is done about this manufacturing technique at several universities. In 2015 the department of the Built Environment of Eindhoven University of Technology invested in a 3D concrete printer as well. 3D printing is an Additive Manufacturing (AM) technique. This means that material will be added to create a specific shape. The contradiction of AM is Subtractive Manufacturing (SM), whereby a piece of raw material will be cutted in a specific shape. AM consists of layers of material created upon each other. In the 3D concrete printing sector there are a few different AM techniques to create shapes, shown in figure 1. Contour Crafting (CC) is a well-known technique. Layers of concrete are stacked on each other and create the outlines of shapes. Most created shapes are an extraction of the first layer, because it is in this stadium difficult to create overhang, offset or double curved shapes without moulds. These created structures are also called 2.5D structures. Contour Crafting on a smaller scale is called Concrete Printing. This technique is invented by a research group of the Loughborough University. Concrete Printing makes it possible to create finer and more detailed structures. A very different technique is D-shape. Layers of sand are created and injected to harden on a specific place. Afterwards the sand will be removed and a printed shape is visible. The technique used at the TU Eindhoven comes close to Contour Crafting. But why is 3D printed concrete preferable above traditional casted concrete? This question is answered by Wolfs, R. (2015) with the following potential advantages:

- No need of a framework, because the concrete is shape stable;
- A high design freedom, because the main cost will not be the form of the shape or the length of the shape and there is no need for repetitive structures;
- The labour of the employees will be less heavy because the printer will take the hard work;
- High speed construction, due to the use of shape stable material.

A big disadvantage is that there is almost nothing published about the structural performances of 3D printed concrete. A lot of papers does not give away the used mixture of concrete. And if there is a global description of the used concrete, there is no structural performance. This is the main reason to start to do structural performance tests on printable concrete at Eindhoven University of Technology. This research is part of a research group called 3DCP. This research group consists of two PhD students accompanied by graduation and master students.

![Figure 1: Different concrete printing techniques. From left to right: Contour Crafting (contourcrafting.org), Concrete Printing (Lim, et al. (2011)) and D shape (3Dprint.com)](image-url)
1.2. STRENGTH DEVELOPMENT OF CONCRETE

The strength development of concrete is also known as the hardening process. This process can be divided into three phases, called dormant period, setting and hardening. The dormant period starts directly after mixing and ends at the initial setting time. In this phase concrete can adopt a specific geometry. If the concrete is remixed in this phase it could take another geometry. The second phase is the setting. This phase takes place between the initial and final setting time. In this period the concrete becomes stiffer and cannot adopt another geometry or remixed again. This is due to the increase of hydration in the concrete. The last phase is the hardening phase. When the concrete is rigid this phase initiates and ends theoretically never. The non-reacted cement decreases so the strength development will reach a certain limit. To reach this ultimate strength would take an infinite time, because the non-reacted cement decreases. For the convenience the 28 day strength is used as ultimate strength. This all is shown in figure 2 extracted from Di Carlo, T. (2012).

In conventional situations casted concrete is not loaded in the dormant and setting phase due to the used framework. If the casted concrete is in the hardening phase it becomes solid and gains an amount of strength. At this point the framework will be removed. But printable concrete is loaded not only in the hardening phase but also in the first two phases. If the gained strength in these two periods is too low the printed structure collapses. In an earlier phase van Alphen, J. and Doomen, C. (2016) does a first attempt to preformed a couple of tests, which are meant for investigating the strength development of the used printable concrete from zero seconds till 28 days. With these tests it is possible to create an upper bound of the printing strategy without failure.
1.2.1. **PLATE STACKING TEST**

The Plate stacking test is invented to determine the load bearing capacity of a concrete mixture directly after mixing. Doing the test directly after mixing must be possible because printable concrete should be almost shape stable from zero seconds. The test is based on earlier tests by Di Carlo, T. (2012 & 2013), but is invented and changed on the behaviour of the available print material. The printing process is simulated with a casted specimen and placing weights on a regular time interval. The amount of weight and the time gap between two placed weights are the variables. This is due to the length or speed of the printed shape. The total amount of added weights will be different with other time intervals, because of hardening of the concrete. This can be seen in figure 3, where different amount of weights are placed upon the specimens. The small amount of strength must be high enough to bear the upcoming layers. If the time between two additions is too low or the amount of added weight is too high the concrete specimen will fail. With using different combinations of time intervals and amount of weights, it is possible to create a strength curve in time of the very first phase also known as the dormant period. This test is altered and optimized by Van der Krift, C. and Van Roestel, R.P. (2016).

![Figure 3: A photo during the Plate stacking test](image)

1.2.2. **VICAT TEST**

The Vicat test is a penetration test to determine the setting time of a material. It is possible to measure the initial setting time and the final setting time with this standardized test (NEN-EN 196-3:2009). The initial setting time is the point where the material starts to harden and the thixotropic behaviour is over. The initial setting time is found with this test by not fully penetration of the needle through the material. The end of the setting period is called the final setting time. This point is reached when the needle cannot penetrate the material anymore. The penetration depth of the needle is related to the friction of the needle. With the friction of the needle it is possible to calculate the strength of the material according to Lotus, D. et al. (2009). In the period from initial till final setting time the strength of the material has a relative high growth and the bond of the material will be quite low in comparison with the material in the dormant period. If a print strategy will be formulated related to the print shape and the print speed there is need to find an optimum between the strength of the material and the bond of the material at a specific time. There is need of an as strong as possible material which can bear the upcoming layers but if the material becomes stronger it is more hardened and will not (fully) bond to another layer.
1.2.3. HARDENED TEST

Due to the fineness of the dry material, which is used to print, the choice is made to do standardized hardened tests of mortars. Also the dimensions of mortar strength tests are in the same range of an single print path of 25 x 25 millimetres. The standardized mortar strength tests are meant to create a strength development curve of hardened specimens. According to NEN-EN 196-1:2005 the tests must be done at 1, 2, 3, 7 and 28 day(s) after casting or printing the specimens. The created specimens will be used for both compressive strength and flexural tensile strength. In comparison with the previous two tests, only this test is printed. The material of the other two tests are extracted out of the hose and afterwards casted in a mould. With printing the specimens, it could be possible that the manufacturing technique and/or the print direction influences the strength in the different directions. Due to this thought the hardened test are performed in three directions, shown in figure 4a. The used material at Eindhoven University of Technology is compared with other available data of print material. The comparison is made with used material at Loughborough University (Le, et al (2012)) and project partner CyBe. This comparison is shown in figure 4b. This hardened test on one layer is altered and optimized by Dolkemade, E. and Williams, K.K. (2016).

![Figure 4: Different test directions (A) and comparison of compressive strength of different print materials (B)](image-url)
1.2.4. Strength Development Curve

The three explained tests are all a specific part of the load bearing capacity curve and represent a period in the hardening of the concrete. Combining the results of the tests will give a strength development curve till the characteristic 28-day strength. Figure 5 is an illustratively and fictively representation. To get a representation some parts of the graph are omitted, the axis are not in scale and the term strength is used to create an overall term. For the hardened test the term strength is related to the compression strength, for the Vicat test it is a yield strength and for the plate-stacking test it is a load bearing capacity. The curve is showing an upper bound for the strength in the whole printing process. If this upper bound is crossed, the created structure will fail.

**Figure 5: Strength Development Curve of the Print Material.**
1.3. RESEARCH GOAL AND METHODOLOGY

The strength development curve in figure 5 is a first step towards understanding the material printable concrete. Not only the material concrete, but also understanding a bit the influence of the production process of material and the manufacturing technique. For example the addition of weight in a regular time interval and the strength difference in three directions due to the print direction. However, all tests are done with homogeneous concrete, which is never the case due to the layered manufacturing. The layered structure introduces an orthotropic material, like laminated timber or glass. This means that in every main direction (x-, y- and z-direction) the strength properties can differ. This thesis will gain insight in these strength properties of the printable material. The goal of this graduation project can be stated as:

*Researching the effect of the layered manufacturing on the strength properties of printable concrete.*

This thesis aims to investigate the strength properties of printable concrete influenced by layered manufacturing. The strength properties are needed when the printed structures must be able to care loads. Without the strength properties, it is not possible to calculate the dimensions of structures and ensure if a printed structure is safe. And without the calculation it will not be possible to construct printed elements outside a laboratory.

The method to reach the stated goal has an experimental character. The experimental research is based on a literature review performed by Doomen, C. & Van Alphen, J. (2016). The tests in the literature review are summarized and concluded in chapter 1.2. The performed tests based on the literature review are invented, prepared and performed in this graduation project. First of all a choice of the parameters and variables to be studied has to be made. This choice will be made on the material, manufacturing technique and in which way the results should be used.

The goal and the method to reach this goal will be presented in this report. After this introduction the used materials will be explained. Not only the printed material, but also the print equipment which ensures a certain material will be printed. In Chapter 3 the method of the different performed tests will be explained and afterwards the results will be given in Chapter 4. At the end of this thesis conclusions and recommendations for further research will be given.

3D concrete printing is a promising technique, but without knowing the material properties and the influence of the process on these properties it will always be a promising technique. Researching these properties and making them clear for constructing structures are the main motivations for this project.
2. MATERIAL

Besides printing and testing the concrete, it is important to understand the material. Not only the material concrete is interesting in this case, also the used equipment to create and print the concrete. With understanding is meant decently use of the right material for a specific purpose. In our case is need for a printable concrete. This concrete and the materials in the system must satisfy on a specific behaviour in the different stages of a printing process.

2.1 3D CONCRETE PRINTER

In the scheme in figure 6 is globally described how the 3D concrete printer operates at the Department of the Built Environment of TU Eindhoven. The three main parts are coupled to each other and worked together to print concrete structures.

The operating system is a Siemens Numerik which operates as a Computer Numerical Control (CNC) machine. On one hand it controls settings of the mixing pump and on the other hand it controls the movement of the gantry robot. The language of the control of the two different machine is G-Code. With this code it is possible to give commands in terms of movement (G-code) and machine settings (M-code). Each code is made up of a letter followed by a number. And each number will cause another instruction to one of the coupled devices.

The mixing pump, shown in figure 7, is one of the coupled devices to the operating system. This mixing pump blends dry material and water to a fluid material. In this case the dry material is a cement-like material, but it is possible to use other dry materials, like gypsum or plaster, with this mixing pump. The amount of water can be regulated by a tap on the machine. The extracting of dry material to the mixing part is constant. So with a regulated water flow and a constant supply of dry material, it is possible to change the water/cement ratio. The water/cement ratio which will be chosen must be satisfy the properties for this type of manufacturing; in this case there is need of a material with a high workability. A horizontal screw extracts the dry material out of the storage container and at the end of the screw water will be added. After this mixing procedure the mixed material will be stored in a vertical container. In this container are located a sensor and mixing rod. The sensor is used to start and stop the mixing procedure which is explained before. If the sensor feels no material it will start the mixing procedure and vice versa. The mixing rod is continuously rotating in the container which induce that the material
does not start to harden. The frequency of this mixing rod can be controlled by the operating system. The material leaves the container at the bottom where a rotor stator pump is situated. This pump is coupled to the mixing rod, hereby it has the same rotation speed as the mixing rod which is set by the operating system. In the rotor stator pump the material will be mixed again and again, but this time under pressure. This pressure causes a flow of material through the hose which is connected to the rotor stator pump. At the other end of the hose a nozzle is connected. The nozzle is also connected to the gantry robot. The material will be pushed in a specific shape: the shape of the nozzle. The shape of nozzle must have the same surface dimensions as the hose otherwise the material undergoes a higher pressure or it will fall through the nozzle.

The movements of the nozzle is programmed by the operating system and will be performed by a gantry robot. The gantry robot which is used at TU Eindhoven has a printing area of 9.0x4.5x2.8 m$^3$ (l x w x h). In this area the nozzle can move in x, y and z directions and rotate around the z direction.

The 3D concrete printer is situated in the Structures Laboratory of the department of Built Environment at Eindhoven University of Technology. In figure 8 an overview of the system is shown.

**Figure 8:** Overview of the system available in the Structures Laboratory at Eindhoven University of Technology [Rien Meulman]
2.2. PRINT MATERIAL

A first important notice is that the used printing material is a concrete which is able to be pumped through pipes or hoses. The pipes have a specific diameter and the concrete must undergo a constant flow through the pipes. To ensure this constant flow it is stated that the pipe diameter must be at least three times the maximum aggregate size, according to Neville, A.M. (1995). Besides the pipe diameter, the pumped concrete must be well mixed before it is fed into the pump. And the consistency of this pumppable concrete is critical. The mixture must not be harsh or sticky and also not too dry or too wet. Inside the pipe the concrete is subjected to a pressure. With this pressure the concrete will flow out of the hose. The amount of pressure is based on two effects: the head of the material and the friction between the hose and the edges of the flowing material. If the printing material consists of a lot of fines, the surface area becomes higher. This causes a higher frictional resistance and the pressure must be higher to pump or press the concrete through the hose.

To meet the requirements for a printable concrete, a custom concrete mix was developed by SG Weber Beamix. According to Bos, F., Wolfs, R., Ahmed, Z. & Salet, T. (2016) the dry material is composed of:
- Portland cement (CEM I 52,5 R),
- Siliceous aggregate with an optimised particle size distribution
- Limestone filler and specific additives for ease of pumping,
- Rheology modifiers for obtaining thixotropic behaviour of the fresh mortar, and
- A small amount of polypropylene fibres for reducing crack formation due to early drying.

Doomen, C. & Van Alphen, J. (2016) researched the basic strength properties of the applied mortar. In their research is investigated the compressive strength and flexural tensile strength in the three main directions. The compressive strength results are shown in figure 4. The composition of the mortar is based on two important characters for printable concrete, namely no slump and long setting time. The no slump character is important for the geometrical precision. During the print process it is desirable the printed concrete has the same dimensions as the nozzle opening, the outcome is the same as the programmed print path and the layers are stacked almost exactly on top of each other. To create good bonded interfaces between layers, a long setting time is needed. These long setting time will give the layered material almost the same properties as the bulk material.

Because SG Weber Beamix is a partner of the 3D concrete printing project of the TU Eindhoven, it is possible that the composition of the dry material changes. This is due to this new application of the material concrete, so it is logical that it can be improved in the future.

The combination of the 3D concrete printer and the print material transformed the homogeneous print material to a heterogeneous material, also known as an orthotropic material. This is due to the creation of layers. These layers have different properties in the main directions, which is a characteristic of orthotropic material. It is also possible the way of motion of the material through the hose and nozzle provides better properties in the moving direction than perpendicular to this direction.
3. EXPERIMENTAL RESEARCH

3.1. TEST VARIABLES

To research the influence of the manufacturing technique on the strength properties a lot of variables can be taken into account. It is not doable and preferable to research all of the variables. In table 1 the main variables which could have an influence on the strength properties are displayed and explained. These variables can be divided into two groups, namely the composition of the print material and the changeable settings of this specific manufacturing technique. It has to be taken into account that the explained variables are based on the available 3D concrete printing system. It is possible that listed variables are no or not all variable(s) for other printing systems.

**Table 1: Variables in the 3D concrete printing process**

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>COMPOSITION OF THE DRY MATERIAL</td>
<td>With adding different types of cement to the dry mixture it could be possible that a printed layer interacts better with the other layers. The bond between two layers could be coarser and the interlocking of the layers should be better.</td>
</tr>
<tr>
<td>ADMIXTURES</td>
<td>Admixtures can have different effects on the hardening of the material. They can elongate the green phase of the material or can ensure a faster hardening.</td>
</tr>
<tr>
<td>ADDITIVES</td>
<td>Additives, like reinforcement and (plastic) fibres, can be investigated as influence on the strength properties.</td>
</tr>
<tr>
<td>W/C-ratio</td>
<td>Varying with the w/c-ratio changes the composition of the material. The difference in compositions could have an effect on the setting time.</td>
</tr>
<tr>
<td>WATER TEMPERATURE</td>
<td>The temperature has an influence on the chemical reaction speed of hydration. Also the length of the dormant period is influenced by water temperature.</td>
</tr>
<tr>
<td>PUMP PRESSURE</td>
<td>The pump pressure influences the rate of outflow and the frequency of mixing with the rotor stator. Varying the frequency does have an effect on the amount of output through the nozzle. Also the temperature of the printer changes due to frequency of the rotor stator.</td>
</tr>
<tr>
<td>PRINT SPEED</td>
<td>The print speed has an influence on the outcome of the material. The area of bonding surface between two layers is influenced by the print speed.</td>
</tr>
<tr>
<td>HOSE LENGTH</td>
<td>In the hose a lot of remixing is taking place. Due to the remixing the composition can change and the temperature will become higher. Varying in hose length could influence the strength properties.</td>
</tr>
<tr>
<td>NOZZLE SHAPE</td>
<td>The shape of the nozzle influences the shape stability of each layer. Also the height/width-ratio influences the strength properties, because it influences how many bonds between layers are created in a specific height.</td>
</tr>
<tr>
<td>PRINT HEIGHT</td>
<td>The height between the nozzle and printing surface also has an influence on the strength properties. With a too low print height in comparison with the theoretical height of the layer, the printed layer will be compressed. And with a too high print height the layer is not carefully placed in position.</td>
</tr>
<tr>
<td>LAYER/PRINT DIRECTION</td>
<td>Layers occur due to the manufacturing technique. The direction of layers influences also the strength properties. A tensile loaded specimen with a perpendicular layer direction in comparison to the load direction is as strong as the bond between two layers and with parallel layer direction it is as strong as the concrete.</td>
</tr>
<tr>
<td>TIME INTERVAL</td>
<td>With a too high amount of time between two concrete layers, the layers will not stick on already hardened concrete as good as on wet concrete. And if the amount of time is too low the printed structure is not stable enough and could fail.</td>
</tr>
<tr>
<td>ENVIRONMENT</td>
<td>In a laboratory the environment is stable, but when printing in the outside the temperature, relative humidity and weather conditions can change.</td>
</tr>
<tr>
<td>PRINT SHAPE</td>
<td>The shape which will be printed does also have an influence on the strength properties. Straight layers on top of each other have maximum connection. But it is also possible to make free formed layers which are not fully connected to each other due to the shape.</td>
</tr>
</tbody>
</table>
In this stage of the 3D concrete printing research at the TU Eindhoven it is necessary to pick research variables which are always introduced in a printed structure and could be changed. In the print process every step is the same from dry material till the end of the hose. For example the addition of additives has no sense in this stage. The strength properties of the used concrete is not known yet, so there is nothing to compare with. This counts for a lot of other variables. First the material printed in the standard way of using the machines and its supplies must be researched. For this reason is chosen to investigate the influence of the time interval between layers on the strength properties. In the already mentioned load bearing capacity curve (figure 5) is shown that time has a large influence on the strength. In the first stage, dormant period, the built up of strength is logarithmic to a specific point. After some time the material starts to harden and in its hardenings phase it has a relative high increase of strength. And in the last stage, the hardened period, it becomes more and more strong and stiff. But this is only for one layer. If more layers are combined not only the strength of the layer has an influence on the strength but also the bond between two layers has a high impact on the strength of printed structure. The quality of the bond is influenced by the time interval between the last printed layer and upcoming printed layer. The bond strength influenced by time interval is earlier researched by Loughborough University (Le, et al (2012)). In this research was shown that with an increasing time interval the bond strength decreases. Up to an interval of 15 minutes the samples failed in the concrete. And at intervals higher than 15 minutes the samples failed in the interface between two layers of concrete. Figure 9 shows the results of the bond strength test with intervals till 7 days and the two types of failure.

With a short time interval two layers of fresh concrete are bonded. This bond is gaining strength due to chemical reactions between the two layers. Increasing the time interval, the first layer transformed from fresh concrete to hardened concrete. The connection between fresh and hardened concrete is not created due to chemical reactions anymore. The strength of the bond is only caused by Van der Waals forces, interlocking and to some extent hydrogen bond formation (Bijen, J., Roelfstra, P.E. & Salet, T. (1993)). The amount of time between two layers, and if it is a fresh-fresh bond or fresh-hardened bond, will be caused by different components in this manufacturing technique. The speed of movement of the gantry robot, the shape length of the printed structure and the load bearing capacity in fresh state. Also the length of a working day will influence the time interval.
Different time intervals are investigated. The intervals are based on the results of Doomen, C. and Van Alphen, J. (2016). In this research is concluded that the used material has a final setting time of approximately 3 hours. Till the final setting time the material is not fully hardened, thus before the final setting time the material is the most sensitive for a good bond between two layers. After the final setting time the material is hardened and is less sensitive for a good bond. The intervals are also based on if it is possible that an interval can occur during a printing process. For example there are no intervals longer than a day, because this is not often the case and is not desirable in a process. It could be possible that an interval longer than a day will cause that two layers will not bond to each other. Shorter intervals are more common in a printing process. Hence, the difference between the small intervals is smaller than the bigger intervals. Besides the bigger opportunity that a smaller interval occurs, the smaller intervals are also chosen on a higher frequency because in that phase the fresh concrete material is more sensitive for a bond. Due to the stated reasons the chosen intervals are:

<table>
<thead>
<tr>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 hour</td>
</tr>
<tr>
<td>0.5 hour</td>
</tr>
<tr>
<td>1 hour</td>
</tr>
<tr>
<td>1.5 hour</td>
</tr>
<tr>
<td>2 hour</td>
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<tr>
<td>2.5 hour</td>
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<tr>
<td>3 hour</td>
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<tr>
<td>5 hour</td>
</tr>
<tr>
<td>7 hour</td>
</tr>
<tr>
<td>12 hour</td>
</tr>
<tr>
<td>24 hour</td>
</tr>
</tbody>
</table>

Besides investigating the time interval, also the layer direction will be a test variable. The main reason is the creation of the layers is the main characteristic of this manufacturing technique. But in addition that it is characteristic for additive manufacturing, the layer direction probably has an influence on the strength. In figure 10 are the three kinds of test directions shown. Test direction I and III have the same orientation of layers but are still different. The layer orientation of test direction I is the same as the print direction and the orientation of test direction III is perpendicular to the print direction. There is a possibility that way of motion of the material through the nozzle has an influence on the possible difference in strength in test direction I and III. It could be possible that the created bond between two layers is the weakest spot of a sample. It is plausible that a printed specimen will start to fail at the introduced weakest spot. But it is also possible that the weakest part of the structure has less or even no influence on the strength in a specific direction. For example the layer direction is the same as the test direction. The possible weaker bond between layers has less influence in this direction in comparison with a perpendicular layer direction to the test direction. Differences in strengths in the main directions is one of the characteristics of orthotropic materials.
Two different tests are set up to investigate the influence of the manufacturing technique on the strength properties. A compressive strength test and a tensile strength test are performed. The influence of the manufacturing technique is researched with the variables time interval and layer direction. Both tests will be done on test sample of all possible combination between the variables time interval and test direction. So the three different test directions with the two different tests gives six possible combinations in all test series. The used test methods are made clear in the next sub chapter.
3. EXPERIMENTAL RESEARCH

3.2. TEST METHODS
The two performed test methods and the results which will be extracted out of the test data will be described in the next subchapters. The measured parameters vary between the tests. Not only strength properties are measured and researched, but also some material properties. These material properties are extracted out of the results to make it possible to characterize this type of material in a finite element programme. Afterwards the two different test sets are explained in which the variables vary.

3.2.1. COMPRESSION TEST
In principal the compression test is based on the standardized mortar compression test in NEN-EN 196-1:2005. The choice to base the compression test on the mortar standard is due to the fact of the small particle sizes in the material and the maximum specimen size, which will be made clear in 3.3.1. Instead of the standardized load controlled test is this test deformation controlled with a speed of 0.3 millimetres / minute. This is because of the possibility to measure the post peak effect. With this test a few parameters of the material will be tested, namely:

- Compressive stress on sample
- Strain, both transverse strain and axial strain
- Poisson’s ratio
- Young’s modulus

To measure all of these parameters an addition on the standard test has to be made. According to the standard there is only need to know the maximum stress on the sample to calculate the strength. But in this research is also need to know the strains. These strains are measured with four LVDT’s. Two are used to measure the axial strain and the other two are used to measure the transverse strain. The test is performed in an available steel rigid frame. This frame is equipped with connections to easily attach LVDT’s. Within the range of loads needed to let the samples fail, the rigid frame will not deform. The measured deformations in the frame are the sample deformations. In figure 11 is shown on the left an overview of the compression test setup and on the right a schematic overview of the placement of the LVDT’s. The test is conducted in an Instron 5985 test bench with a 250kN load cell.

In figure 11 can be noticed that the LVDT’s for measuring transverse strain, respectively LVDT 7 and LVDT 8, are placed eccentric. This is due to practical reason, because there is not enough space to place the axial and transverse LVDT’s in one line.

![Figure 11: Test setup of compression test. Left: photo and right: schematic overview with a front view and top view](image-url)
3.2.2. TENSION TEST

According to Neville, A.M. (1995) there are three possible tension test which can be used for concrete, namely a splitting tension test, flexural bending test and a direct tension test. With a splitting tensile test the same setup of the compression test can be used, but two sticks must be added between the loading plates and the sample. Due to the compression of these stick in the sample the sample will fail. The sample will always fail in the line between these two sticks. So if the sample consists not of a homogenous material, it does not give the results of the whole sample but only the material between the two sticks. For the layered material it is possible that the bond between two layers is the weakest part but the sticks are placed on a concrete part and the sample will not fail in the weakest part but in the concrete. Also it is possible that the sticks are not in one line, in that case the results are from a shear test instead of a tensile splitting test. For these reasons the tensile splitting test is rejected. For the flexural bending test the samples needs to consist of specific ratio between width and height. Using the specific ratio in combination with the maximum specimen sizes explained in 3.3.1., the specimens become too small. Also the flexural bending test is not suitable for this specific material with its specific dimensions. The choice is made to perform the tension tests like a direct tension test, although it is known that this is a difficult test to perform. If samples are not straight enough or are not connected well into the setup eccentricities occurs and there are not only tensile stresses in the samples anymore. To prevent eccentricities and bending moments, there is made a huge effort to control the straightness of the samples. Besides creating straight samples, the setup is also tested and changed to get the best possible results. How the specimens are created can be found in chapter 3.3.2 and the evolution of the test setup is added in Appendix A.

The direct tension test is also a deformation controlled test, because of the opportunity to measure the possible post peak effect. The speed of testing has been set at 0.1 millimetres / minute. With these test a few parameters will be tested, namely:

- Tensile stress on sample
- Strain
- Young’s modulus

Figure 12: Test setup of tension test. Left: photo and right: schematic front and top view
In figure 12 is the setup shown of the tension test. The specimens are glued to steel blocks with a two component adhesive. In the centre of the steel blocks a threaded rod can be fixed. The other end of the rod is connected to the load cell or a fixed plated for respectively the top rod and the bottom rod. The bottom rod is full hinged connected to the fixed plate, so that if the sample are not perfect straight also fit into the setup without a huge addition of eccentricities. Also the top rod is hinged connected with a load cell, but this connection has not the same amount of rotational freedom as the bottom one. In schematic representations is made visible that four LVDT’s are used to measure the deformations. With these LVDT’s also the eccentricities can be measured by the differences in deformation of each side. This setup is attached in an Instron 5985 test bench with a 5kN load cell. This 5 kN load cell is used because it is more precise at lower loads than the standard 250 kN load cell.

3.2.3. Test sets
To gain insight in the influence of the manufacturing technique 3D concrete printing on the strength properties two different test sets are established which will be performed in both a compression test and a tension test with the variables test/layer direction and time interval. The first test is a strength development test and the second is a time interval test.

Strength development test
With this test the build-up of strength in time is researched for this specific material. This test is only performed with the zero hour time interval, which means that the samples are extracted out a continuous print. This is due to the fact these samples give an upper bound of the strength, because with a higher open time the material gets a lower strength. According to NEN-EN 196-1:2005 the strength tests must be performed after 1 day, 2 days, 3 days, 7 days and 28 days. Due to practical reasons the tests after 2 days is skipped. The tests are fulfilled in a compression and a tension test. Also the three different test directions are used, which makes it possible to compare the build-up of strength in the different test directions.

Time interval test
Where the strength development test did the same test at different ages of the material, the time interval test are different tests at 28 day ages. This test is only performed after 28 days, because the 28 days strength is normally used in calculations. There are 11 different time intervals selected: between 0 and 3 hours every 30 minutes, 5 hours, 7 hours, 12 hours and 24 hours. With this type of test is researched what the influence is of time between two printed layers on the strength of material. The time interval test is also performed in the three different test direction in both tension and compression test.

Every different test combination consists of three specimens. One test series consists of samples with the same time interval and are meant for both compression test and a tension test in three test directions. So the size of a test series is 18 samples (two different tests x three directions x one time interval x three specimens). In total there are 14 series. An overview of the different test series is given in figure 13. Only one series of a test set is worked out, but for all intervals obtain the same partition after the time interval. With counting all specimens of both tests, the total amount is 252 different tests. The results of each different test will be visualised in a stress strain diagram. These are not shown in this report, because it is about the results of the series and not the single samples. Also basic properties as strengths, strains, Young’s modulus and Poisson’s rate (compression test) are extracted of all single tests to calculate the properties of the specific series.
Figure 13: Schematic overview of different test series
3.3. Specimen Preparation

The specimens are prepared in accordance with experiences in print process and standards specified below. The used standards are not only the ones from the concrete industry. Because it should be a printable material, the used ingredients in the material composition are relative fine materials which is explained in 2.1. It is almost impossible to see a difference in size between cement and aggregates or admixtures. Due to the fineness of the material the standards of mortar material are used also.

3.3.1. Specimen Size

The outcome of the 3D concrete printer must be pushed through a hose with a diameter of 25 millimetres (491 mm²). The nozzle should be almost equal to this size to prevent a huge decrease or increase in pressure at the end of the hose. There are two nozzles available which are tested with different speeds and pressures of printing. The dimensions of these nozzles are 25 x 25 millimetres or 10 x 40 millimetres (h x w). According to NEN-EN 12390-1:2012 it is usual to create specimens in a cubic, cylindrical or prism shape. In the code is stated that the minimum value for the width is equal to 100 millimetres and in case with the cylindrical and prism shapes the length of a specimen must be minimal twice the width. To create specimens of these dimensions with the available nozzles it is not possible to do this without printing layers next to each other. This phenomena is made visible for cubical specimens in figure 14.

![Figure 14: Printed test specimen in accordance with NEN-EN 12390-1:2009](image)

Creating samples of these dimensions gives interfaces in between layers which are printed next to each other besides the interfaces due to layers on top of each other. This will give another variable and could influence the results of the tests. Hereby is chosen to create specimens with only printed layers on top of each other. This leads to specimens with a smaller dimension than prescribed in the code of concrete specimens. Also cylindrical or prism shape specimens are rejected because of the ratio 1:2 for length:width. In one direction the maximum length of a specimen is 40 millimetres, this is the maximum width of the available nozzles, so the width of a specimen is than 20 millimetres. These dimensions are too small. The choice is fallen on a cubic specimen of 40x40x40 millimetres created with the nozzle of 40x10 millimetres. The combination of the dimensions of the specimen and the nozzle tends to specimens consisting of four layers. The dimensions of these specimens are in accordance with the compressive test of mortars described in NEN-EN 196-1:2005. The dimensions of the specimens used for compressive strength test and tensile strength tests are the same, which make it possible to compare results of both tests without size effects.
3.3.2. Creating Specimens

Each specimen is extracted from a larger print. These printed elements are 1000 millimetres in length, 250 millimetres in width and 6 layers high. The bottom and top layer will be sawn off and through this 4 layers remain with a smooth surface on the top and bottom without imperfections through the foil or rough top surface. The two test sets differs a bit in creating the printed elements. This is made visible in figure 15. The strength development test is built up from 6 continuously printed layers (left) and the time interval tests are made in two prints (middle). First three layers are printed and after the specified open time the other three layers will be printed on top of the first layers. This is made clear in the right picture of figure 15. At the first printed element the 6 layers are already printed and at the second element the second 3 layers will be printed. Each print is made with the same print settings. Pump pressure, print speed and print height are categorized as print settings. These three factors are thoroughly tested to get the best layer dimension out of the nozzle.

At the first layer the print height is a bit lower than the height of the cross section, these are respectively 8 millimetres and 10 millimetres. This is done to create a perfect levelled surface for the 5 layers on top of it. The compressed layer will be removed later on, because the first and sixth layer will be sawn off. After the first layer the additional z-height of every layer is the same as the height of the cross section of the nozzle. The movement of the gantry robot and therefore the nozzle is written in a G-code, which is added in Appendix 8. Figure 16 shows the spatula proceeding to divide the printed elements into pieces directly after the sixth layer is finished. This is done to prevent drying shrinkage cracks and to create pieces which are easier to carry. In the period between printing the element and testing the samples, the printed elements are cured as described in 3.3.3. The test samples are sawn out of those elements in the curing period. The samples of the compression test and tension test are slightly different sawn, so the procedure will be separately explained.
To ensure that only the test variables time interval and layer direction are researched a start procedure of a print session is made. This start procedure is invented during previous sessions and is the same for all prints. The proceedings before a print is started are divided into mixing the material, pumping the material, extracting material for control samples and starting the print session. The baseline is that all components are installed, only the horizontal mixing chamber and the vertical container of the mixing pump are uncoupled. First the dry material and water are mixed and extracted out of the system. This is due to the fact that the very first dry material is not mixed with water and will be in the system as dry material. So first is for a period of 30 seconds the material collected in a bucket and thrown away. After these 30 seconds the mixing chamber and vertical container will be closed and the system will be restarted. Now the material will be pumped through the whole system and leaves the system at the nozzle. This phase has a duration of 5 minutes and the material is also collected in a bucket. In this phase the material becomes to its right consistency. The material has not a right consistency from the beginning, due to a small addition of water in the vertical container and the temperature has to build up. After these 5 minutes, a specific amount of material is extracted from the nozzle to cast control samples. This phase takes one minute. During the whole print session the temperature of the system is measured at a specific point below the rotor stator pump.

Compression test samples
Figure 16 shows that the printed elements are divided in straight lines with a spatula. The size of the elements is chosen so that only the long sides of elements needs to be used. With a diamond saw available in the Structures Laboratory of the Eindhoven University of Technology, the straight lines are sawn in small parts of 40 millimetres (step 1). Due to the print process the sides of the elements have a ribbed shape. Each layer is a bit tapered. One of these sides is removed to create a flat surface (step 2). This flat surface is needed to remove the top and bottom layer parallel from the specimens. The tapered surface on the other side is not yet removed, because this make it easy to figure out what the layer direction is. The layer direction is not visible anymore when all sides are removed. After this step the top and bottom layer are removed with a diamond saw with a smaller blade for more precise sawing (step 3+4). Before the other tapered shape side is removed, the layer direction will be marked on each specimen (step 5). With removing the last tapered side the samples for the compression test are made (step 6). This stepwise creation of the samples is made visible in figure 17.
In one go the 18 test samples of a specific test series are made. After the sawing procedure the specimens are numbered. A specific name combination is invented to see easily for what kind of test the specimen is needed. The combination has a format of: AA_BB_123_CC. the AA’s are used for the amount of time interval. The BB’s stands for which day after printing the samples are tested. The number part is a specific number which is written down on the samples. The CC’s stands for the test direction and in which test the sample will be used. A Roman number one, two or three for the test direction is combined with the letter C (compression test) or T (tension test).

Before the sawn samples can be used for a specific test, they have to be measured. With a digital calliper the dimensions of the samples are measured. The direction of the loading is always the length. The other two dimensions are the widths of the other sides. Each dimensions is measured on two places and will be averaged. After measuring the dimensions of the samples, the weight of a sample will be measured with a balance. With these measurements several parameters can be calculated, for example the density, strength, strains and so on.

**Tension test samples**

The creation of the samples explained for compression test samples is also the case for the tension test samples, but there are a few steps added. This is due to the fact that using the same samples as the compression test samples in the described direct tension test a lot of failure in the glue interface occurs. To get rid of failure in the glue interface a lot of changes were made on the samples and also on the test setup. All these changes and a comparison between these changes are expressed in Appendix A. Like Hordijk, D.A. (1991) mentioned it is impossible to describe an experimental principle for direct tension tests which ensures that every specimen will fail in the concrete or interface in the concrete. Failure in the glue could be the case, but with the chosen test set up and samples is this type of failure as far as possible excluded. Failure in the glue can be caused by a too high stress in the glue or a too weak bond between the glue and the concrete. To improve the glued connection the choice is made to improve the glued bond by increasing the surface of the bond. This is done by making a cutting pattern in the top and bottom surface with the use of a small diamond wheel. Also is chosen to decrease the area of the concrete sample at a specific part, which causes a higher stress on the sample at a same amount of load. Different ways of reducing the concrete is compared in Appendix A and shown in figure 18.

![Figure 18: Comparison between different methods of reducing the area of concrete](image)

The best option to reduce the concrete area with less influence of peak stress is the last sample shown in figure 18. But for practical reasons, like manufacturability and available timespan, is chosen the sample with the two half holes. To calculate the strength of a sample only the formula for normal stresses are used. This is because of not every specimen is sawn and drilled exact like the shape having in mind, more difficult calculations with taken peak stresses into account and the results are in this stage only used to compared with each other to research the influence of the variables. Due to this assumption the calculated sample strengths are an underestimation of the realistic strength.
After measuring the samples the two added steps to come from a compression test sample to a tension test sample are performed. First two half holes are extracted out of the samples with a 12 diameter hollow core drill to reduce the concrete area in the middle of the sample (step 7). The last step is to make a cutting pattern in the top and bottom surface which is also concluded out of Appendix A (step 8). With this cutting pattern the amount of surface which can be glued is increased with 140%. In figure 19 can be seen the last two steps of creating the samples.

![Figure 19: Additional steps to create tension test samples](image)

Casted control samples

A lot of parameters which can be varied in the process are shown in table 1. All of these parameters could have an influence on the strength properties of the material. To check if only the variables time interval and layer direction will be researched, a material test of each print session is implemented. Between the start procedure and the start of a print, a bucket of material is extracted out of the nozzle. This bucket is directly covered with a foil to prevent evaporation. When the printing of the elements is finished standardized mortar moulds are filled. Because the used print material is almost a no slump material, the moulds are placed on a shake table for 10 seconds. Afterwards the moulds are covered with a foil and one day later the samples are removed out of the moulds. The name of test series are based on the date (dd-mm) and start time of printing (hmm). For example a print on 5 July started at 14:04h is named 05-07-1404. The samples are marked with the date and start time of a print combined with a roman number I, II or III. The marked samples are cured in a container filled with water. After 28 days the moulded specimens are measured and tested to control of the used material is almost the same. The density, compressive strength and flexural tensile strength will be compared. The tests will be done according to NEN-EN 196-1:2005.

### 3.3.3. Curing specimens

All prints are made and all tests are done in the Structures Laboratory at Eindhoven University of Technology. In this laboratory the temperature and humidity are regulated and measured. The temperature has an average of 23.9 degrees Celsius and the humidity is around 50.8 percent in the used period of time. The printed samples are covered with foil immediately after the print is finished. Due to the foil no more water can evaporate in the air and the climate under the foil gets a high relative humidity. After a maximum of 24 hours the printed elements are removed from the printing table and are cured in water till the day the specimens will be tested. Once before the printed elements will shortly leave the water, because of sawing the specimens out of it and measuring the specimens. The water has a temperature of around 20 degrees Celsius. The described curing method is in accordance with NEN-EN 12390-2:2009 for concrete specimens and NEN-EN 196-1:2005 for mortar specimens.
4. EXPERIMENTAL RESULTS AND DISCUSSION

All experimental test results are stated in this chapter. First the results of the casted control samples are shown. Afterwards the results of the printed samples are expressed. First material related properties, like density, Young’s modulus and Poisson’s ratio, are shown. Thereafter strength properties are expressed. All combinations of test direction and compression or tension test are separately visualized. Afterwards the different test directions are combined in one graph to visualize the differences between the directions. All specifications of the used samples are added in Appendix C for the casted control samples and in Appendix D for the printed samples.

4.1. CONTROLLING THE EXPERIMENTAL TESTS

4.1.1. MATERIAL

Density

In figure 20 are the densities clustered shown for each print session. The average density of the control samples is 2090 kg/m³. All of the samples are in the same margins around the average value except the samples of 12-07-1247. In that specific session are printed all the samples of the strength development test. Printing all these samples takes minimal three times longer than all other prints. The extracted material is too much stiffened and cannot be well compacted. This is shown in figure 21 where the bad compacted samples can be compared with well compacted samples.

![Figure 20: Densities of casted control samples](image)

![Figure 21: Difference between bad compacted (a) and well compacted (b) casted control samples](image)
Flexural strength

![Flexural Strength Chart](image)

The results of the flexural strength test are shown in figure 22. The average of these results is 5.7 MPa. Just like the density results is test session 12-07-1247 a bad results. This is also due to the bad compaction made clear in figure 21. Also in other test sessions are samples which have a large deviation in comparison with the average value. In test session 08-07-1145 are only two results visualized in figure 22, because one sample failed during removing the moulds. The used test setup can be seen in figure 23.

![Test Setup Image](image)
Compressive strength

In figure 24 are stated the results of the compressive strength test. One half of each test sample is used to test the compressive strength. The compressive strength has an average of 30.2 MPa. Again the results of session 12-07-1247 are worse than the other ones. The rest of samples are all deviating around the average value in the same margins. In figure 25 is the setup of the compressive strength test shown.

With the results of the casted control samples can be concluded that the material is every time quite the same. So the start procedure of a print session is a good addition to the print process to keep the outcome constant at different sessions. The occurred differences between samples are not huge and if they are huge it is due to the compaction of the material was not good. When in one print path more than four elements are printed, the time between the extraction and compaction of the control samples is too much and it is not possible to create good compacted samples. So for the next time it is recommended to print a maximum amount of four elements in one print path.
4.1.2. Temperature

Also the temperature of the system is measured during all prints. In figure 26 is shown a graph of the temperature behaviour of the system in time. The temperature is measured during the whole print. The printed elements are printed in a period from 9 minutes till 15 minutes after beginning with the start procedure. The temperature of the system, measured below the pump, builds up logarithmic and is quite constant when it reached a specific value. Also the constant value of the environment temperature is shown in the graph.

The table 2. Temperatures measured during print sessions is added in table 2. One session has no data, because the system failed to measure the temperature. The average value is 33.64 degrees Celsius. The session of 12-07-1247 is in average almost 4 degrees Celsius higher. This print session is divided into two pieces due to the print path. The last part of this print sessions reached an average temperature of 38.30 degrees Celsius. According to Neville, A.M. (1992) for concrete is known that a rise of the curing temperature speeds up the chemical reactions of hydration. This speed up of reactions influences beneficially the early strength of concrete without any effects on the later strength. The test results of this effect were visible in the graphs with a high strength of the one day age test. Due to this the choice is made to redo the one day age strength. This new print sessions has an average value of 38.21 degrees Celsius, which is even worse. Nevertheless is chosen to use the data of the new print session, because not only the temperature was bad of the first attempt of one day age strength tests. This is discussed in 4.2.2.

If there went something wrong during the mixing procedure, it could be seen in the temperature graph. Due to experience is known that if the temperature reached a value above the 40.0 degrees Celsius, something is stuck in pump or hose. The system switches automatically off. Sometimes the rotor stator pump becomes too hot caused by high temperature and friction that the rubber burns and breaks down on the inside. A new rubber sleeve for the rotor stator pump has to be installed before a new print session can started.
4. EXPERIMENTAL RESULTS AND DISCUSSION

4.2. MATERIAL PROPERTIES

4.2.1. DENSITY

In table 3 are expressed the results of the density measurements. For convenience the averages values of all different test series are shown.

<table>
<thead>
<tr>
<th>TEST SERIES</th>
<th>IC</th>
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</tr>
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<td>00_07</td>
<td>1951.4</td>
<td>1941.0</td>
<td>1944.5</td>
<td>1954.7</td>
<td>1948.5</td>
</tr>
<tr>
<td>00_28</td>
<td>1944.5</td>
<td>1959.4</td>
<td>1966.9</td>
<td>1951.8</td>
<td>1959.0</td>
</tr>
<tr>
<td>05_28</td>
<td>1958.4</td>
<td>1953.6</td>
<td>1950.0</td>
<td>1956.9</td>
<td>1948.6</td>
</tr>
<tr>
<td>15_28</td>
<td>1956.9</td>
<td>1954.5</td>
<td>1955.5</td>
<td>1951.5</td>
<td>1946.1</td>
</tr>
<tr>
<td>20_28</td>
<td>1959.5</td>
<td>1945.4</td>
<td>1954.0</td>
<td>1953.4</td>
<td>1937.5</td>
</tr>
<tr>
<td>25_28</td>
<td>1968.9</td>
<td>1943.8</td>
<td>1961.0</td>
<td>1942.5</td>
<td>1958.7</td>
</tr>
<tr>
<td>30_28</td>
<td>1950.2</td>
<td>1952.8</td>
<td>1939.5</td>
<td>1942.0</td>
<td>1944.2</td>
</tr>
<tr>
<td>50_28</td>
<td>1961.5</td>
<td>1955.7</td>
<td>1952.3</td>
<td>1954.2</td>
<td>1937.8</td>
</tr>
<tr>
<td>70_28</td>
<td>1961.7</td>
<td>1945.4</td>
<td>1951.4</td>
<td>1973.2</td>
<td>1966.6</td>
</tr>
<tr>
<td>12_28</td>
<td>1948.1</td>
<td>1941.8</td>
<td>1940.2</td>
<td>1938.1</td>
<td>1949.1</td>
</tr>
<tr>
<td>24_28</td>
<td>1936.4</td>
<td>1940.0</td>
<td>1942.0</td>
<td>1935.7</td>
<td>1933.9</td>
</tr>
</tbody>
</table>

* 00_01* is the re-done test series

Figure 52 shows the density distribution of samples tested after 28 days. The average density is 1953.7 kg/m³ and the standard deviation is 13.0 kg/m³. In the figure is also visualized a blue dotted line of a normal distribution based on the average and standard deviation. From this graph can be concluded that the samples with 28 days age are almost normal distributed and that the average density of the series is a good representation of the used material. For comparison the casted control samples density is 2093.0 kg/m³. The density of the printed samples is 0.93 times the density of the casted control samples. The only difference in production is that the casted control samples are compacted after extracting through the nozzle.

Figure 27: Density distribution
4.2.2. Young’s Modulus

The Young’s modulus is extracted out of the stress-strain diagram of all single tests. It is common to use the stress-strain diagram in compression to calculate this property for concrete. The slope of the line in the linear part is the Young’s modulus. For calculations the first 0.5 MPa is removed out of all graphs, because in this part of the graph loads are introduced to the samples. Also the strains are set to zero at 0.5 MPa due to the same reason. Also the last part of the graph is not considered, because this part is not linear. So the Young’s Modulus is based on values which satisfy the condition:

\[ 0.5 \text{ MPa} \leq \sigma_c \leq 0.8 f_{ck} \]

The taken steps to calculate the Young’s modulus are visualized in figure 28. The results of these calculations are around 4500 MPa, which is approximately six till ten times smaller than conventional concrete. The used test method and or test setup is not the right one to extract the Young’s modulus out of the compressive strength test. Possible reasons are not precise measurement with LVDT or deformation in testing frame. Deformation in the testing frame is not possible, because relative small forces are used and the components of the frame are oversized. Normally strain gauges are used instead of LVDT’s, because strain gauges measures on a very small surface with more precision. In this standard setup the LVDT’s are measuring indirect the deformation of the samples by measuring the movement of the load plate in the rigid steel frame. Using this indirection measuring method the strain of the overall height is measured and with a strain gauges the strain is measured on a small pieces of the sample, which gives a more accurate Young’s modulus. To confirm the thought of underestimating the Young’s modulus a steel sample with the same dimensions is tested in the same range of forces. With this test on a steel samples is measured a Young’s modulus of 21000 MPa, which is ten times smaller than the general used value for steel.

According to fib Model code for concrete structures 2010, two formulas exist to calculate the Young’s modulus for concrete by only knowing the characteristic or average strength. No strains are used in these formulas. The use of these formulas is questioned, due to if the strengths are the same, the Young’s modulus is also the same.
With other materials the tensile strength test is used to calculate the Young’s modulus. For example the tensile strength test of steel with the specific dog bone shape specimens. The results of extracting the Young’s modulus out of the tensile strength test are shown in table 4. The Young’s modulus is extracted out of the stress strain diagrams and is based on the values of the next condition:

$$0.015 \text{ MPa} \leq \sigma_t \leq 0.8 f_{ctk}$$

This is done for the same reasons as explained at extracting the Young’s modulus out of the compression test. The variation between the single results is high. It is not possible to conclude a returning difference in the Young’s modulus of different test directions.

Table 4: Average Young’s modulus of test series

<table>
<thead>
<tr>
<th>Test series</th>
<th>IT</th>
<th>IIT</th>
<th>IIIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_01</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>00_01*</td>
<td>18281</td>
<td>12600</td>
<td>14306</td>
</tr>
<tr>
<td>00_03</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>00_07</td>
<td>34673</td>
<td>24089</td>
<td>50207</td>
</tr>
<tr>
<td>00_28</td>
<td>19749</td>
<td>17318</td>
<td>22245</td>
</tr>
<tr>
<td>05_28</td>
<td>33290</td>
<td>19864</td>
<td>24983</td>
</tr>
<tr>
<td>10_28</td>
<td>29927</td>
<td>18836</td>
<td>51242</td>
</tr>
<tr>
<td>15_28</td>
<td>27780</td>
<td>25833</td>
<td>20428</td>
</tr>
<tr>
<td>20_28</td>
<td>26293</td>
<td>20389</td>
<td>29846</td>
</tr>
<tr>
<td>25_28</td>
<td>32062</td>
<td>21964</td>
<td>54630</td>
</tr>
<tr>
<td>30_28</td>
<td>22462</td>
<td>14297</td>
<td>22539</td>
</tr>
<tr>
<td>50_28</td>
<td>24375</td>
<td>18742</td>
<td>22472</td>
</tr>
<tr>
<td>70_28</td>
<td>43656</td>
<td>27053</td>
<td>32346</td>
</tr>
<tr>
<td>12_28</td>
<td>27494</td>
<td>18128</td>
<td>23755</td>
</tr>
<tr>
<td>24_28</td>
<td>20257</td>
<td>15640</td>
<td>25887</td>
</tr>
</tbody>
</table>

*00_01* is the re-done test series

The results of test series 00_01 and 00_03 are not usable for the Young’s modulus. This is due to a wrong setting in the test bench. The used test bench is for multiple use. This provides that a bolt was not tightened well enough. This causes that a part can slip at a specific load. If the load was around the weight of that part (approximately 1 kN), the part slipped in its right position. The length of slippage was influence by the friction between two steel parts. Due to a deformation controller test, this wrong setting was not recognized by the system. It could only be seen in the stress strain diagram, because there was a plateau at 1 kN. With this plateau and not fully knowing how much the friction influences the stress strain diagram, it is chosen that the results are not usable. After some research the wrong setting was found and all other series are tested with the right setup. Due to the fact that test series 00_01 has a high early strength and a wrong setting in the setup, the choice is made to redo the test. Test series 00_03 is not redone, because there was only a wrong setting which only influences the Young’s modulus.
4.2.3. Poisson’s ratio
The Poisson’s ratio is calculated by dividing the transverse strain with the axial strain. In table 5 the results are shown. The same as the Young’s modulus, the Poisson’s ratio is calculated within a range of values. According to fib model code for concrete structures 2010 the condition for calculating the Poisson’s ratio is:

\[-0.6 f_{ck} \leq \sigma_c \leq 0.8 f_{ctk}\]

The transverse strain is only calculated during the compression test. And the first part of 0.5 MPa is dismissed within this calculation, explained in 4.2.2. So the given condition for calculating the Poisson’s ratio is:

\[0.5 \text{ MPa} \leq \sigma_c \leq 0.6 f_{ck}\]

<table>
<thead>
<tr>
<th>Test series</th>
<th>IC</th>
<th>IIC</th>
<th>IIIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_01</td>
<td>0.039</td>
<td>0.064</td>
<td>0.114</td>
</tr>
<tr>
<td>00_01*</td>
<td>0.107</td>
<td>0.173</td>
<td>0.114</td>
</tr>
<tr>
<td>00_03</td>
<td>0.072</td>
<td>0.088</td>
<td>0.067</td>
</tr>
<tr>
<td>00_07</td>
<td>0.141</td>
<td>0.123</td>
<td>0.168</td>
</tr>
<tr>
<td>00_28</td>
<td>0.121</td>
<td>0.117</td>
<td>0.146</td>
</tr>
<tr>
<td>05_28</td>
<td>0.142</td>
<td>0.067</td>
<td>0.151</td>
</tr>
<tr>
<td>10_28</td>
<td>0.143</td>
<td>0.170</td>
<td>0.118</td>
</tr>
<tr>
<td>15_28</td>
<td>0.100</td>
<td>0.175</td>
<td>0.163</td>
</tr>
<tr>
<td>20_28</td>
<td>0.113</td>
<td>0.087</td>
<td>0.100</td>
</tr>
<tr>
<td>25_28</td>
<td>0.152</td>
<td>0.114</td>
<td>0.181</td>
</tr>
<tr>
<td>30_28</td>
<td>0.129</td>
<td>0.098</td>
<td>0.149</td>
</tr>
<tr>
<td>50_28</td>
<td>0.138</td>
<td>0.150</td>
<td>0.192</td>
</tr>
<tr>
<td>70_28</td>
<td>0.137</td>
<td>0.105</td>
<td>0.141</td>
</tr>
<tr>
<td>12_28</td>
<td>0.095</td>
<td>0.045</td>
<td>0.120</td>
</tr>
<tr>
<td>24_28</td>
<td>0.125</td>
<td>0.133</td>
<td>0.161</td>
</tr>
</tbody>
</table>

* 00_01* is the re-done test series

According to fib model code for concrete structures 2010, the Poisson’s ratio of normal concrete is in the range of 0.14 till 0.26. From the results can be seen that most of results are in the bottom part of this range or just below the range. It is not easy to take conclusions out of these results, because the test series are too small and the deviations are too high. Nevertheless it proves in table 5 that in most series tested after 28 days that the Poisson’s ratio in test direction III is the highest. And it can be concluded that if the layer direction is the same as the test direction, that the layers are not split from each other at the weakest interface. If this was the case the Poisson’s ratio in these directions should be a lot higher.
4. EXPERIMENTAL RESULTS AND DISCUSSION

4.3. STRENGTH PROPERTIES

4.3.1. STRENGTH DEVELOPMENT TEST

Compression test

Test direction I

In figure 29 the results of the strength development test in test direction I are shown. The strength is stepwise build up to 23.15 MPa and is added in table 6. The strength development looks like a normal strength development curve of concrete. All individual tests of a test series are inserted in the graph as a blue dot. It can be noticed that the results deviated more in time. For example after one day testing the individual tests are not visible in the graph and the results after 28 days of curing deviates from approximately 21 MPa to 26 MPa. In figure 30 is a sample shown in different phase of the test. The sample is shown in the setup before (a) and after (b) being tested. Also a close up of the cracks (c) and the specific hour glass shapes (d) of test samples in compression are inserted.

![Figure 29: Strength development test results of IC](image)

### Table 6: Compressive strength of strength development test in test direction I

<table>
<thead>
<tr>
<th>Test series</th>
<th>Compressive strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_01_IC</td>
<td>9.29</td>
</tr>
<tr>
<td>00_03_IC</td>
<td>15.27</td>
</tr>
<tr>
<td>00_07_IC</td>
<td>19.76</td>
</tr>
<tr>
<td>00_28_IC</td>
<td>23.15</td>
</tr>
</tbody>
</table>

![Figure 30: Different phases of the compressive strength test in test direction I](image)
Test direction II

In figure 31 is visualized the strength development of test direction II in compression. The strength at 28 days is 20.96 MPa. In table 7 can be seen the average values of all test days. The single samples deviates around these average values. The amount of deviation is random, but is the highest and best visible at 28 days. In figure 32 are added different pictures during the test added. Shown is a sample before (a) and after (b) conducting the test. A close up of the cracks at the back of the sample (c) and the hourglass shape of samples (d) are exposed too.

<table>
<thead>
<tr>
<th>TEST SERIES</th>
<th>COMPRESSIVE STRENGTH [MPA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_01_IIC</td>
<td>7.78</td>
</tr>
<tr>
<td>00_03_IIC</td>
<td>13.80</td>
</tr>
<tr>
<td>00_07_IIC</td>
<td>17.37</td>
</tr>
<tr>
<td>00_28_IIC</td>
<td>20.96</td>
</tr>
</tbody>
</table>
Test direction III

In table 8 are shown the average values of the compressive strength at different ages for test direction III. In figure 27 are these results combined in a graph. The maximum strength is 21.49 MPa. For normal concrete the increase in strength between 7 and 28 days is not big, but in this case the strength increased almost 35 percent. The deviation of the single samples is not remarkable for this test direction. Figure 29 shows different phases of compressive test. A sample placed in the setup before (a) and after (b) the test, close up of the cracks at the back of the sample (c) and samples without the cracked parts (d) are all shown.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Compressive strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_01_IIIC</td>
<td>8.62</td>
</tr>
<tr>
<td>00_03_IIIC</td>
<td>13.59</td>
</tr>
<tr>
<td>00_07_IIIC</td>
<td>16.01</td>
</tr>
<tr>
<td>00_28_IIIC</td>
<td>21.49</td>
</tr>
</tbody>
</table>

Figure 33: Strength development test results of IIIC

Figure 34: Different phases of the compressive strength test in test direction III
Combined

![Compressive Strength Graph](image)

**FIGURE 35:** COMBINED COMPRESSIVE STRENGTH RESULTS OF THE STRENGTH DEVELOPMENT TEST

The results of the three different test direction in compression are combined and shown in figure 35. From this graph can be concluded that the layer direction has almost no influence on the compressive strength. The only noticeably difference is that if the layer direction is parallel to the print direction (test direction I) is approximately 8-10% stronger than the other two layer directions at 28 days after printing. It is not possible to state that this effect is due to the layer direction because the layer direction in test direction I and III is the same. The difference in strength could be imposed to the way of motion of the material through the print system. The movement of the material through the system is in the direction of test direction I. It could be possible that in the direction of movement the particles are placed and compacted better than the other directions and provides a higher compressive strength. It is not possible to conclude that printed material loaded in direction II is the weakest. This is because the deviations of test direction II and test direction III are in the same ranges and the average value is based on only three samples. If one sample has a higher compressive strength the average is directly affected. With bigger test series the influence of one sample is less and it is rather possible to conclude the difference between test direction II and III.

Comparing the results of the printed samples with the casted control samples, there is a larger difference visible. The maximum compressive strength of printed concrete is 23.15 MPa and is only 0.77 times the average strength of the casted control samples. This is due to additional compacting process on a shake table for the casted control samples. This compacting process is common for casted concrete but is not possible for printed concrete.

The main conclusion of the developing of the compressive strength is that the strength at 28 day ages is almost the same, but material in test direction I has an approximately 8-10% higher compressive strength.
Tension test
Test direction I

In figure 36 are shown the results of the tensile strength development in test direction I. In table 9 are stated the average values of the different test series. The maximum tensile strength is 1.88 MPa. The build-up of strength in time is not logical due to the peak at one day age. This peak will be discussed in the combined part. In figure 37 can be seen a specific sample before (a) and after (b) applying a load. Also the cracking surface of all specimens in test direction I are added (c). These cracking surfaces are irregular in width and depth, because the samples failed in the concrete and not in the interface. During the test photos (d) are taken with a high speed camera. With these photos the occurrence of the crack is visualized in detail.

![Tensile strength - test direction I](image)

**Table 9: Tensile strength of strength development test in test direction I**

<table>
<thead>
<tr>
<th>Test series</th>
<th>Tensile strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_01_IT</td>
<td>1.84</td>
</tr>
<tr>
<td>00_03_IT</td>
<td>1.45</td>
</tr>
<tr>
<td>00_07_IT</td>
<td>1.60</td>
</tr>
<tr>
<td>00_28_IT</td>
<td>1.88</td>
</tr>
</tbody>
</table>

![Figure 36: Strength development test results of IT](image)

![Figure 37: Different phases of the tensile strength test in test direction I](image)
**Test direction II**

In figure 38 are shown the results of the tensile strength development in test direction II. In table 10 are included the average values of the different test series. The maximum tensile strength is 1.32 MPa. Each test series consists of a relative high deviation. It is striking that there are always two results clustered of a series. The build-up of strength in time is not logical due to the peak at one day age. This peak will be discussed in the combined part. A sample before (a) and directly after (d) testing, close up of the sample in the setup (b) and an overview of the cracking surfaces (c) are added in figure 39. At the left and middle sample of figure 39c can be seen through the straight cracking surface that the sample is failed in the interface. Due to zero hour interval not all samples are failing in the interface, which can be seen in the right sample of figure 39c.

**Figure 38: Strength development test results of IIT**

**Table 10: Tensile strength of strength development test in test direction II**

<table>
<thead>
<tr>
<th>Test series</th>
<th>Tensile strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_01_IIT</td>
<td>1.30</td>
</tr>
<tr>
<td>00_03_IIT</td>
<td>1.08</td>
</tr>
<tr>
<td>00_07_IIT</td>
<td>1.21</td>
</tr>
<tr>
<td>00_28_IIT</td>
<td>1.32</td>
</tr>
</tbody>
</table>

**Figure 39: Different phases of the tensile strength test in test direction II**
4. Experimental Results and Discussion

**Test direction III**

![Graph: Tensile strength - Test direction III](image)

<table>
<thead>
<tr>
<th>Test series</th>
<th>Tensile strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_01_IIIT</td>
<td>1.52</td>
</tr>
<tr>
<td>00_03_IIIT</td>
<td>1.57</td>
</tr>
<tr>
<td>00_07_IIIT</td>
<td>1.54</td>
</tr>
<tr>
<td>00_28_IIIT</td>
<td>1.61</td>
</tr>
</tbody>
</table>

**Figure 40: Strength development test results of IIIT**

The results of the tensile strength development in test direction II are added in figure 40. The corresponding mean values of all the series are expressed in table 11. The maximum tensile strength is 1.61 MPa. Also in this graph can be seen that each test series consists of a relative high deviation. In contradiction with the other two test directions, in this test direction there is no remarkable peak at one day age. In figure 41 are shown a sample before (a) and after (b) testing and the cracking surfaces of samples (c). Just like figure 37 these cracking surfaces are irregular in width and depth, because the test direction is parallel with the interface. The samples must fail in the concrete.

![Images: Sample before (A), after (B), and cracking surfaces (C)](image)

**Figure 41: Different phases of the tensile strength test in test direction III**
The results of the three different test directions in tension are combined and shown in Figure 42. The first conclusion is that the layer direction has an effect on the strength in tension. Test direction III is 0.85 and test direction II is 0.70 times the strength of test direction I on 28 days. Test direction II is the weakest, because in this direction the layers are pulled off each other and the samples failed on the interface. The other two directions are loaded parallel to layer direction, so the samples failed in the concrete. This can be concluded from the cracking pattern of the failed samples in Figures 37, 39, 41.

The difference between test direction I and III is more complicated to explain, but the thought is the same as the way of motion explained at compressive direction. This conclusion is not well-founded till a microscope is used to evaluate the particle distribution.

The differences between the test directions could also be caused by inclination in the top or bottom surface of the samples. Due to the inclination there is not only tensile load in the samples but also a bending moment. These bending moments could provide an addition of the tensile stresses in the sample. The sample will fail on a lower amount of external loads. From the measurements of the samples can be concluded that the maximum inclination is one degree. With a simple hand calculation in Appendix E it is concluded that these inclinations does not influence the results significantly.

At the results of the specific test directions is already remarked that the strength development of tensile strength in time is not as normal concrete. The strengths after one day are in the test directions I and II higher than the three days strength and in test direction III the strength is almost the same as three days strength. In chapter 4.1.2 is explained that the test series of one day age are done over again due to a too high temperature. But the new test series also have a too high temperature. The temperature in this stage of the research is difficult to control, so the temperature could vary and influence the results. Another reason to redo the 1 hour time interval test was that the results were influenced by a wrong setting of the test setup. This mistake is made clear in 4.2.2.
4.3.2. Time interval test
Compression test
Test direction I

The results from the time interval test of compression in test direction I are shown in figure 43. The values corresponding to the average of the different time intervals are in table 12. The averages of the small intervals fluctuates a lot, due to the higher frequency at small intervals. The average strengths are relatively constant from zero hour time interval till 24 hour time interval. The average strength of all time intervals is 25.43 MPa. In figure 44 is a sample of the 12 hour time interval series shown before (a) and after (b) applying the load. The cracks, visible in figure 44b, represent the hourglass shape of the sample at failure.
**Test direction II**

In figure 45 is visualized the graph from the time interval test of compression in test direction II. The average strengths are shown in table 13. The compressive strength at different intervals is relatively constant. The average strength of all different time interval series is 22.20 MPa. In figure 46 are shown different phases of the open time compression test in test direction II. A sample is shown in the setup before (a) and after (b) testing and without the cracked regions (c).

**Table 13: Compression strength of time interval test in test direction II**

<table>
<thead>
<tr>
<th>Test series</th>
<th>Compressive strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_28_IIC</td>
<td>20.96</td>
</tr>
<tr>
<td>05_28_IIC</td>
<td>20.43</td>
</tr>
<tr>
<td>10_28_IIC</td>
<td>22.61</td>
</tr>
<tr>
<td>15_28_IIC</td>
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<td>23.91</td>
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<td>25_28_IIC</td>
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<td>22.85</td>
</tr>
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<td>70_28_IIC</td>
<td>22.96</td>
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<tr>
<td>12_28_IIC</td>
<td>23.37</td>
</tr>
<tr>
<td>24_28_IIC</td>
<td>20.41</td>
</tr>
</tbody>
</table>

**Figure 45: Open time test results of IIC**

**Figure 46: Sample loaded in test direction II during test (A) and after test (B) & (C).**
Test direction III

The graph from the time interval test of compression in test direction III is presented in figure 47. The amount of strength of all different intervals is added in table 14. Also in this test direction the difference between average values of tests series are quite high and good visible. But in time the average values are balancing around a constant value of 19.73 MPa. In figure 49 are pictures added of this specific test. A sample before (a) and after (b) testing and a close up of the cracks at backside (c) are shown.
In figure 49 is shown the graph of all compressive strength results of the time interval test. The main conclusion of these results is that the compressive strength is in all test directions relatively constant at different time intervals. Till approximately 3 hour time interval all test directions have a high deviation around this constant value. This is due to the high frequency of chosen intervals till three hours and the deviation in all test series. Comparing the deviations of the results from the 1, 3 and 7 days age strength development test with the deviations of the time interval test, can be seen that the deviation from tests after 28 days have a relatively higher deviation. And with only three sample in all test series, the averages are sensitive for an extremely good or bad result from one of the sample in the series.

The hypothesis was that samples loaded in test direction II have the highest strength. This was based on the layer direction. In the direction I and II the samples are loaded in parallel layer direction, which can induce splitting of the samples by the interface. Test direction II is loaded perpendicular to layer direction, which cannot cause splitting. This idea of highest strength cannot be concluded from the results. This may due to various reasons: amount of compressive strength is not influenced by layer direction, the earlier mentioned influence of way of motion of the nozzle or the also mentioned deviations of the small test series.

As stated before the compressive strength in a specific direction is constant at different time intervals. This will lead to difference in compressive strength in the different test directions. As shown in figure 49 is the compressive strength in test direction I the highest one. The compressive strength in test direction II is 0.87 times the compressive strength of test direction I and compressive strength in test direction III is only 0.78 times the compressive strength in test direction I.
Tension test
Test direction I

In figure 50 is shown the graph of the tensile strength time interval test in test direction I. The average value of each test series is expressed in table 15. The averages of the test series are quite constant, but have a high deviation at the small time intervals. Also is visible the relatively high deviation of each test series. The average tensile strength of all test series is 1.69 MPa. The series of 1.5 hour, 3.0 hour and 7.0 hour time interval consists of only two samples, because one of the samples failed in the glued connection between concrete and steel plate. In figure 46 are shown samples of three different test series. All of the specimens have an irregular cracked surface due to the failure in concrete.

![Graph of Tensile Strength - Test Direction I](image.png)

**Figure 50: Time interval test results of IT**

<table>
<thead>
<tr>
<th>Test series</th>
<th>Compressive strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_28_IT</td>
<td>1.88</td>
</tr>
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<td>05_28_IT</td>
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<td>1.84</td>
</tr>
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<td>25_28_IT</td>
<td>1.64</td>
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<td>30_28_IT</td>
<td>1.78</td>
</tr>
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<td>50_28_IT</td>
<td>1.53</td>
</tr>
<tr>
<td>70_28_IT</td>
<td>1.67</td>
</tr>
<tr>
<td>12_28_IT</td>
<td>1.75</td>
</tr>
<tr>
<td>24_28_IT</td>
<td>1.61</td>
</tr>
</tbody>
</table>

**Table 15: Tensile strength of time interval test in test direction I**

![Cracked surfaces of samples with different open time tested in direction I](image.png)

**Figure 51: Cracked surfaces of samples with different open time tested in direction I**
Test direction II

The graph of the tensile strength time interval test in test direction II in figure 52. In table 16 the average values of all test series are shown. Till 3 hour time interval the average values have a high fluctuation. This due to the relatively high deviation of each test series. The time intervals higher than 3 hour have a lower deviation in comparison with the lower intervals. The tensile strength is decreasing at bigger time intervals. In figure 53 are three different test series shown. It can be seen that the cracking surface is almost perfect straight. This is due to that the samples fail in the interface.

Table 16: Tensile strength of time interval test in test direction II

<table>
<thead>
<tr>
<th>Test series</th>
<th>Compressive strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_28_IIT</td>
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<td>10_28_IIT</td>
<td>1.10</td>
</tr>
<tr>
<td>15_28_IIT</td>
<td>1.37</td>
</tr>
<tr>
<td>20_28_IIT</td>
<td>1.57</td>
</tr>
<tr>
<td>25_28_IIT</td>
<td>1.20</td>
</tr>
<tr>
<td>30_28_IIT</td>
<td>1.01</td>
</tr>
<tr>
<td>50_28_IIT</td>
<td>1.00</td>
</tr>
<tr>
<td>70_28_IIT</td>
<td>0.88</td>
</tr>
<tr>
<td>12_28_IIT</td>
<td>0.87</td>
</tr>
<tr>
<td>24_28_IIT</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Figure 52: Open time test results of IIT

Figure 53: Cracked surfaces of samples with different open time tested in direction II
4. EXPERIMENTAL RESULTS AND DISCUSSION

**Test direction III**

![Graph: Tensile strength - test direction III](image)

**Figure 54: Time interval test results of IIIT**

Figure 54 shows the results of tensile strength time interval test in direction III. Table 17 shows the average tensile strength per time interval in direction III. The average strengths of different time intervals are varying around a constant value of 1.59 MPa. All series consist of relative high deviation. The average strength of 2.0 hour time interval is based on only two samples, because one sample failed in the adhesive interface. Different time interval test series are visualized in figure 50. Just like test direction I, all samples have an irregular cracked surfaces due to the failure in concrete.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Tensile strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_28_IIT</td>
<td>1.61</td>
</tr>
<tr>
<td>05_28_IIT</td>
<td>1.51</td>
</tr>
<tr>
<td>10_28_IIT</td>
<td>1.65</td>
</tr>
<tr>
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<tr>
<td>20_28_IIT</td>
<td>1.65</td>
</tr>
<tr>
<td>25_28_IIT</td>
<td>1.49</td>
</tr>
<tr>
<td>30_28_IIT</td>
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<tr>
<td>50_28_IIT</td>
<td>1.52</td>
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<tr>
<td>70_28_IIT</td>
<td>1.63</td>
</tr>
<tr>
<td>12_28_IIT</td>
<td>1.76</td>
</tr>
<tr>
<td>24_28_IIT</td>
<td>1.51</td>
</tr>
</tbody>
</table>

**Figure 55: Cracked surfaces of samples with different open time tested in direction III**

![Image of cracked surfaces](image)
Figure 56 shows the time interval tensile strength test combined for all test directions. From this graph can be concluded directly that test direction II has a significantly lower strength than the other two directions. This is because of in test direction II the interface between layers are pulled off and in the other directions the specimens failed in the concrete. This difference is good visible in figures 51, 53 and 55 which show the cracked surfaces.

Also a difference between test direction II and test direction I and III is the strength development at an increase of time interval. At one hand the tensile strengths are rather constant for test direction I and III and on the other hand the tensile strength in test direction II decreases at an increasing time interval. The constant value of test direction I and II are respectively 1.69 MPa and 1.59 MPa. The difference between these two is only 5 percent. In test direction II it is difficult to conclude till which time interval the amount of strength is constant. The high frequency of testing and the small test series with a relatively high deviation tend to the fluctuation of first part of the graph. For convenience is chosen that till 5 hour time interval is constant and the average of this part is 1.20 MPa. This means that till 5 hour time interval the difference between failure in the concrete and interface is a factor of around 0.75. At time intervals higher than 5 hours this value is almost linear decreasing to 0.4. Comparing the results of test direction II with each other than can be concluded that there is only 0.56 times the tensile strength of time intervals till 5 hour left after a time interval of 24 hour. This factor is for a time interval of 7 hour and 12 hour respectively 0.83 and 0.73. So after a specific time, in this case 5 hour, the first material is hardened too much and it is not able anymore to create a bond which is as good as a bond between two fresh materials.

The main conclusion of the results from the interval time test in tension is that there is a difference in tensile strength at different test directions, but this difference is constant till a time interval of 5 hour. After these 5 hour, the tension strength in test direction II is linear decreasing till 56 percent at 24 hour time interval of its initial value.
The research of Loughborough University introduced in chapter 1.3. is compared with the results of test direction II. In this research is investigated the influence of the time interval on the bond strength. This is also tested in test direction II. Not in test direction I and III because in these directions is not the interface tested. In these directions is the concrete tested. The results of Loughborough University and this research are combined shown in figure 57.

The graph shows that the maximum tensile strength at the different time intervals is higher for concrete tested by Le, et al (2012) at the Loughborough University. This concrete is an ultra-high performance concrete (UHPC), so it is not remarkable that the strength is higher. The decrease in strength of the UHP concrete is at the small intervals higher, and relatively low at bigger intervals. The printable concrete used at Eindhoven University of Technology is only decreasing after a time interval of 5 hour. In both researches is deviation between single samples relatively high.

The comparison between the two researches is not entirely fair. The samples of Le, et al (2012) consists of another size and shape. In that specific research a cylindrical shape is used. The samples have dimensions of 58 x 120 millimetres. To create these samples are also layers printed next to each other, what is prevented with the cubical samples of this research. The comparison is still made, because it gives a good overview on the published research about the bond strength influenced by time interval between layers.
THE EFFECT OF LAYERED MANUFACTURING ON THE STRENGTH PROPERTIES OF PRINTABLE CONCRETE
5. **CONCLUSIONS AND RECOMMENDATIONS**

In the first part of this report is expressed the goal of the graduation: Researching the effect of the layered manufacturing on the strength properties of printable concrete. Based on the performed tests and presented results, conclusions can be drawn and recommendations can be given.

### 5.1. **CONCLUSIONS**

The main conclusion of this research is that there exists an influence of the manufacturing technique on the strength properties. This influence appears in comparing the printed samples with the casted samples and comparing the printed samples with each other. The difference in strength between the casted control samples and printed samples is caused by one addition in the manufacturing. The casted control samples are compacted after extracting the material out of the nozzle. With the layered manufacturing technique it is not possible to compact the material after it is printed and this induces that the compressive strength of printed samples is only 0.77 times the compressive strength of the casted samples.

The printed samples are compared on strength properties with varied time interval and layer direction. If the time interval is kept constant at zero the strength development in time in compression is the same as normal concrete. Also the different layer directions does not give remarkable differences in compression. Test direction I (test direction is print direction) is 8% - 10% higher than the other two directions, probably due to the way of motion of the material. In tension the strength development in time is not like normal concrete. Due to an increase of temperature during manufacturing in the used prints, the early age strength is also increased. This causes a one day strength of almost the 28 days strength. And in tension the layer direction does have an effect on the strength properties. Test direction I has the highest strength, probably due to the way of motion of the material. Test direction III (parallel layer direction) is 0.85 times the strength of test direction I and test direction II (perpendicular layer direction) is only 0.70 times the strength of test direction I. Test direction II has the lowest strength due to the fact that in this direction layers are pulled off (bond strength) and in the other directions the samples must fail in the concrete.

With also varying the time interval between zero and 24 hour, another effect on the strength properties is researched. Due to this variation of time the bond between layers will be made between an already hardening material and a fresh material. In compression the interval has no additional effect on strength properties compared with a zero time interval, the results are quite constant at different time intervals for all directions. This is not entirely the case in tension. In test direction I and III the results are also constant at different time intervals, because the interfaces between layers are in the same direction as the test direction. But test direction II is not constant at all time intervals. Till 5 hour interval the tensile strength is almost constant, but after 5 hour the tensile strength is decreasing to 56 percent of the initial strength at 24 hour time interval. This is due to the bond is created between a more and more hardened layer and a fresh layer.
With the normal distributed results of the density measurement of the printed samples can be concluded that the outcome of the material is almost the same at all print sessions and that the print process is in control. Also can be concluded from the casted control samples that the print process is in control. The samples gives the same results for different print sessions. The introduced start procedure of all sessions is a good addition to the print process, because it ensures that every session starts the same. Besides the start procedure, the temperature measurement during the whole print session also indicates the progress during the sessions. Nevertheless it is difficult to control the temperature. A raise in temperature provides a higher early age strength of the concrete, which is not in line with the normal strength development. And if temperature raises to high due to an error in the system, the print sessions is failed.

In this stage it is not possible to conclude that the results are statistically significant. Due to the small series size of three samples, there is a possibility that the results depends on change. At the beginning of the project the intention was to globally map the effects on the strength properties and not to create results which are statistically significant. To map the effects there are used a lot of different series of only three samples.

The use of LVDT’s for calculating the strains and indirect the Young’s modulus and Poisson’s ratio is proved that it was not the right choice. The deformation measured with these devices is not the precise one to calculate the strains. A better option was to use strain gauges, but these are time and money consuming.
5. Conclusions and Recommendations

A lot of recommendations can be given, because it is a relatively new manufacturing technique. This subchapter is divided into two parts. The first part consists of improvements on this specific research. The second part are extensions on this specific research. Some of them are explained more in detail, because in these is already invested time and effort during this graduation project.

5.2. Recommendations

A lot of recommendations can be given, because it is a relatively new manufacturing technique. This subchapter is divided into two parts. The first part consists of improvements on this specific research. The second part are extensions on this specific research. Some of them are explained more in detail, because in these is already invested time and effort during this graduation project.

5.2.1. Improvements

In this report is mentioned that it was not possible to get the Young’s modulus out of the compression test. This was due to calculating the strains from the deformations of the LVDT’s. These LVDT’s measured the deformations over whole height. With this method the strains are not measured accurate enough, while the LVDT’s are really accurate. A better alternative is the use of strain gauges. These are measuring the strains on a small part of the samples. Because of costs and available time was chosen to do it with LVDT’s. To reduce the costs it is better to do small series of tests to measure the Young’s modulus. Also it can be chosen to attach the strain gauges both axial and longitudinal to recalculate the Poisson’s ratio.

In the conclusions is already stated that it is not possible to make a decision whether the results are statistically significant or not. This is due to all different test series consists of only three samples. By these small series the probability of a Type II error is very high. A Type II error means that a statistically hypotheses is accepted wrongly. To prevent this error a minimum series size is recommended. According to Montgomery, D.C. and Runger, G.C. (2011) the calculation of this minimum series size is related to formula 1 for one sided alternative hypothesis and formula 2 for two sided alternative hypothesis. A two sided alternative hypothesis is that the two series are not the same and a one sided alternative hypothesis is that one series is only higher or only lower than the other series.

\[
\begin{align*}
    n &= \frac{(z_a + z_\beta)^2 (\sigma_1 + \sigma_2)^2}{(\Delta - \Delta_0)^2} \quad \text{(Formula 1)} \\
    n &= \frac{(z_{a/2} + z_\beta)^2 (\sigma_1 + \sigma_2)^2}{(\Delta - \Delta_0)^2} \quad \text{(Formula 2)}
\end{align*}
\]

In which:

- \( n \) minimum sample size
- \( z_a \) boundary of significance level of one-side test
- \( z_{a/2} \) boundary of significance level of two-side test
- \( z_\beta \) boundary of type II error based on \( \beta \)
- \( \sigma \) standard deviation
- \( \Delta_0 \) based on the null hypothesis. \( \mu_1 - \mu_2 = \Delta_0 \), the standard value is 0.
- \( \Delta \) True difference in mean of interest.

Three different comparisons are taken from the experimental research. From these comparisons a recommendation will be formulated for a minimum sample size to provide statistical significant statements. For all comparisons is set the confidence level at 90% and the power of a test at 80% (1-\( \beta \)). This means that with the calculated sample size the given answer is for 90% true and the type II error for 80% does not appear. In table 18 are shown all used values for the three different comparisons.
**Table 18: Data for statistical comparisons**

<table>
<thead>
<tr>
<th>COMPARISON 1</th>
<th>COMPARISON 2</th>
<th>COMPARISON 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>00_28_55_IC</td>
<td>50_28_181_IC</td>
<td>00_28_58_IT</td>
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<td>1.81 MPa</td>
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<td>00_28_56_IC</td>
<td>50_28_182_IC</td>
<td>00_28_59_IT</td>
</tr>
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<td>1.82 MPa</td>
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<td>50_28_183_IC</td>
<td>00_28_60.IT</td>
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<td>AVERAGE</td>
<td>AVERAGE</td>
</tr>
<tr>
<td>23.15 MPa</td>
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<td>STANDARD DEV.</td>
<td>STANDARD DEV.</td>
</tr>
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<td>N</td>
</tr>
<tr>
<td>15</td>
<td>26</td>
<td>3</td>
</tr>
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</table>

**Comparison 1**

With comparison 1 is calculated how many samples are needed to conclude with a 90% confidence level that the strength of series 00_28_IIIC is significantly lower than 00_28_IC. The differences can be seen in figure 35. This is a one-sided test. The result is that a minimum amount of 15 samples are needed to conclude the above.

**Comparison 2**

With comparison 2 is calculated how many samples are needed to conclude with a 90% confidence level that the strength of series 50_28_IC is the same as 50_28_IIC. The differences between the series can be seen in figure 49. This is a two-sided test, because if it is not the same it could be lower or higher. The result is that a minimum amount of 26 samples are needed to conclude the above.

**Comparison 3**

With comparison 3 is calculated how many samples are needed to conclude with a 90% confidence level that the strength of series 00_28_IIT is significantly lower as 00_28_IT. The differences between the series can be seen in figure 42. This is a one-sided test. The result is that a minimum amount of 3 samples are needed to conclude the above.

With this three comparisons has been demonstrated that the required sample size varies a lot. To do a recommendation about the sample size the calculated sample sizes are averaged. The minimum amount of samples per test series becomes 15. With more samples per series shall change the average and standard deviation of a series. With this change the minimum sample size will also change due to formula 1 and formula 2. In order to prevent a constant change of minimum sample size is decided to fix the series size to 15.

With a higher series size, it is not possible to do an addition of 12 samples for all test series shown in this project. It is recommended to redo only the interval test in compression and tension. And to choose a few intervals of this test. The best is to pick intervals in the whole range and then more in small intervals than big intervals. For example 0 hour, 1.5 hours, 3.0 hours, 5.0 hours and 24 hours.
Another improvement of this research is a more general one and is intended for the print process. In the begin phase of this graduation project is a lot of time invested in getting control of the whole print process. The w/c-ratio, print speed, pump pressure, hose length, nozzle shape and so on are researched and combined to get a controlled print process. Still there is need to keep more control of the print process. For example the temperature is fluctuating between different print sessions. And the temperature is influencing the results which is shown at the results of the strength development test. Without keeping the temperature under control, the material will always remain different.

In this thesis a few times is referred to the way of motion of the material through the hose. That the way of motion has an influence on the difference in strengths in test direction I and III is fully based on presumptions. To invigorate this presumption it is possible to check the build-up of layers with a microscope in the three different directions. It could be possible that the material is better orientated in one of the direction.

5.2.2. Extensions
In this research is the influence of the variables time interval and layer direction investigated for the strength properties. In table 1 are listed a lot more variables which could be chosen. The easiest ones, but also interesting, are changing the settings of the manufacturing technique. For example the water temperature. This variable is easy to change and could have a high influence on the strength. To change the dry material or add some additives is more difficult, because the used print process is optimized for this type of dry material without additives.

Also is recommend to use these results to create print paths. Up until now is the maximum amount of printed layers based on failure in fresh state. A print sessions is as long as the structure does not collapse. But in the future the goal is to create full structures like houses and pavilions. In this type of structures it is maybe better to print in sessions of one hour printing, one hour hardening, one hour printing and so on. This will give better bonds between printed parts than printing a structure for hours, stop just before it will collapse and restart after a few hours till the whole structure is hardened enough. An optimum has to be found between the load bearing capacity in fresh phase and the (bond) strength properties in hardened phase.

Up until now is only tested failure in mode I. But there are two other failure modes which could be researched. All failure modes are shown in figure 5.8. With testing the other failure modes the material and the manufacturing technique will be clearer and a numerical model will give a better representation of the material.

![Figure 5.8: Failure modes of concrete](image)

5. Conclusions and recommendations
To place the experimental research in a wider context, it is recommended to develop a numerical model. Structural elements can be modelled to evaluate the influence of the manufacturing technique. In previous research of Cox, S.B. (2015) and Schoenmakers, S.J. (2013) is investigated how to model the failure behaviour of concrete. In this research is used a Cohesive Zone Model (CZM) to model the concrete. This model is divided into continuum elements and interface elements. The division of the continuum elements and interface elements in the structural element has to be fully random, to prevent preferred directions of cracking. The interface elements describe the damage in the material and show the discrete cracking. The damage in elements can be modelled by traction separation laws. The interface elements can be described by a subroutine called user material (UMAT) developed by Alfaro et al (2009). In UMAT different properties of the interface elements have to be described, like the maximum strength in mode I, mode II and mode III (figure 58). In figure 59 are shown simple tests to research the properties of cohesive elements in basic.

Different cases can be worked out to investigate the influence of the manufacturing technique. To research the influence a stepwise built up to a printed structural element can be made. For example a wall element with a wind loading on it. First a simplistic linear elastic model of a specific structural element can be made. This linear elastic model represents a structural element constructed in casted concrete. In casted concrete without reinforcement the material behaves like an isotropic material. A first addition to the model to investigate the influence of the manufacturing technique is to model the material like an orthotropic material. The introducing of layers induces an orthotropic material behaviour of the whole material in the model. In this model are no layers introduced. But in the last addition to research the effects of the layered manufacturing are the layers with the biggest effect modelled. These layers are introduced in a last model of the numerical research. In principal is this model the same as the orthotropic model, but here are layers introduced. These layers occurred on places where the print has to be stopped for a few hours, due to reaching the maximum load bearing capacity or end of a printing session. These layers consists of a weaker material with another traction separation law. Also the mesh is placed less random in the last case, which influences the cracking pattern. In all cases the maximum load, stress distribution and cracking pattern should be different. These differences shows the influence of the manufacturing technique of concrete printing. The described cases are shown in figure 60.

![Figure 59: Basic research on cohesive elements (Schoenmakers, S.J. (2013))](image)

![Figure 60: Cases for numerical model: I: L.E. material, II: Orthotropic material and III: Print material](image)
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**CODES**


FIB MODEL CODE FOR CONCRETE STRUCTURES 2010.

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APPENDIX A: EVOLUTION OF THE TENSION TEST SETUP

To come to the actual test setup, many possibilities are checked. First of all the initial situation will be explained and afterwards the improvements will be shown and compared. The improvements are divided into two groups, namely the improvements on the samples and the improvements on the setup.

**INITIAL SITUATION**

In the initial situation the test samples are created in the same manner as explained for compression test samples in 3.2.2. The only addition is that a pattern is made with a hacksaw on the surfaces which will be glued to the steel blocks. This pattern is created to get more amount of glued surface in comparison with the cracking surface. The depth of the sawn lines is approximately one millimetre.

On the top and bottom surface are steel blocks glued. This connection is made with a two-component adhesive. Normally this type of adhesive will be used to connect strain gauges onto test samples. The steel blocks are 40 x 40 millimetres like the test samples. A hole is drilled in the middle of each steel block. This hole is also tapped with screw threads, which makes it possible to connect the samples on the top and bottom to a threaded rod. These threaded rods are connected to a machine. The top one to the load cell of the machine and the bottom one is connected to a fixed plate. The test setup can be seen in figure A1.

![Figure A1: Direct Tensile Test Setup](image)

There is made use of a 5 kN load cell. This is due to the fact that the force needed to let these samples fail will be less than 5 kN. This load cell is also more accurate than the standard one of 250 kN. The rod on the top of the sample is screwed into the load cell. The screw and load cell are connected with a horizontal pin, visible in figure A1. The use of this type of connection provides a hinged connection. If the top surface is not perfect straight or the steel block is not glued straight on the sample, it can be corrected with the hinge. Too big defects on the straightness cannot be correct with the upper hinge. The connection between the bottom rod and plate is also made with a hinge. In contrast to the other, this one is able to correct huge difference. But at many samples is this possibility not necessary. Also is visible in figure A1 the way of measuring deformations. There was made use of two LVDT’s and a digital
strain meter. After processing the data of the first samples it became clear that the digital strain meter could not be used. This was due to the fact that the measurable height of maximum 35 millimetres in combination with the very small deformation cannot be measured correctly. Afterwards are two LVDT’s added and is not made use of the digital strain meter anymore. With four LVDT’s on each side of the sample the deformation is measured.

Using this test setup it became clear that it was not possible to get the right results out of the direct tension test. From the first 36 tests failed only 10 samples in the concrete. The other 26 failed in the interface between the adhesive and concrete. This appearance is shown in figure A2. The conclusion of these results is that the bond between the adhesive and the concrete can bear less stress than the concrete samples. Improvements on the samples and maybe on the setup are required to get useful results.

**IMPROVEMENTS ON THE SAMPLES**

At a specific part on the sample the area of concrete has to be reduced to let the sample fail on a lower stress level. Hopefully this will ensure that the bond between glue and concrete will not fail and the specimen will fail in the concrete. The location of the decreased area is situated in the middle of the length of the specimens. This location is chosen, because in test direction II the bond with the variable time interval will lie in the middle of the sample. If not this part of the sample consists of a reduced area, it is possible that the strength of the bond will not be tested. The strength of the concrete in the reduced area will be tested. In the other test directions it does not matter where the decrease in area is made, because in perpendicular section the samples are everywhere the same over the height. For convenience the middle of the height is chosen to reduce the area. A few different manners of reducing the surface are considered. The new created shapes are compared to each other with finite element programme Abaqus. In figure A3 are the different samples shown with the reduced area.
The best alternative shape of test specimen is the one with the lowest ratio between peak stress and simplified average stress on the reduced concrete area. The simplified average stress is the normal stress according to formula A1. In Table A1 is made the comparison between the samples with reduced concrete area in 2D. For convenience is the initial specimen shape added in the table. On all samples is the same load applied as on the initial situation.

\[ \sigma = \frac{F}{A} \]  

(Formula A1)

**Table A1: Comparison of different sample shapes**

<table>
<thead>
<tr>
<th>SHAPE</th>
<th>WIDTH OF REDUCED AREA [mm]</th>
<th>SIMPLIFIED AVERAGE STRESS (FORMULA 1) [MPa]</th>
<th>PEAK STRESS ACCORDING TO ABAQUS [MPa]</th>
<th>PEAK STRESS / AVERAGE STRESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>1.33</td>
<td>3.484</td>
<td>2.62</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>1.33</td>
<td>3.752</td>
<td>2.82</td>
</tr>
<tr>
<td>4</td>
<td>28</td>
<td>1.43</td>
<td>3.078</td>
<td>2.15</td>
</tr>
<tr>
<td>5</td>
<td>28</td>
<td>1.43</td>
<td>2.824</td>
<td>1.97</td>
</tr>
</tbody>
</table>

Specimen shape 5 is best alternative shape, because the ratio between peak stress and average stress is the lowest. So in order to get the most constant stress distribution over the reduced area, it would be logical to take shape 5. But in practice it is hard to create that kind of sample in the available timespan and with the available tools. The choice is made to take shape 4 as tensile test specimen, because it has the second best ratio between peak stress and average stress and is possible to make in the available time span with the available tools.
The effect of layered manufacturing on the strength properties of printable concrete

After all samples are measured the tensile test samples will be drilled with a hollow core drill of 12 millimetres in section. To test if this gives a better result the samples are not sawn at the top and bottom with a pattern. The results of these samples were not significantly better than the previous samples. In figure A4 is a sample of this test shown. Also the new manner of measuring the deformations with four LVDT’s is shown.

The test setup is still not good with only reducing the area of concrete. The bond between glue and concrete must be improved. First was made use of a hacksaw, but the choice is made to use a multi-tool system with a diamond cutting wheel of 38 millimetres in cross-section. With this machine a more accurate cutting pattern can be made on the top and bottom surface. Also the cutting pattern can be varied by angles. With varying the cutting pattern is tested if it is possible to get more grip in the concrete. Seven different samples with six different cutting patterns are compared with each other. The specifications of these samples are shown in table A2. The cutting patterns are shown in the second column. A side view is given of the bottom surface with the small cutting patterns. If there is a twice sign in the corner the pattern is used two times, which induces a squared pattern. All samples, which are used in this test, are in test direction I. In this direction the layered structure has less influence than in test direction II. Sometimes is made use of test direction III, which is almost the same as test direction I. The samples of this specific test are also reduced in concrete area. Only sample T3 is failed in the bond between glue and concrete. Because the bond between glue and concrete has to be improve to choice is fallen on the sample which can bear the most stress in the glued surface. Sample T6 meets this condition the best. From now on if the cutting pattern is used it is always like the pattern of T6. With this cutting pattern is the connection surface between adhesive and concrete increased with approximately 140%.

Table A2: Specifications of the sample with varied cutting pattern

<table>
<thead>
<tr>
<th>NAME</th>
<th>CUTTING PATTERN</th>
<th>DIMENSIONS CRACKING SURFACE [mm]</th>
<th>DIMENSIONS GLUED SURFACE [mm]</th>
<th>LOAD [kN]</th>
<th>STRESS CRACKED SURFACE [MPa]</th>
<th>STRESS GLUED SURFACE [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td></td>
<td>19.87 x 39.86</td>
<td>40.07 x 34.47</td>
<td>2.014</td>
<td>2.54</td>
<td>1.46</td>
</tr>
<tr>
<td>T2</td>
<td></td>
<td>23.02 x 34.84</td>
<td>34.80 x 34.80</td>
<td>2.326</td>
<td>2.91</td>
<td>1.92</td>
</tr>
<tr>
<td>T3</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>T4</td>
<td></td>
<td>17.70 x 32.58</td>
<td>32.31 x 33.00</td>
<td>1.627</td>
<td>2.82</td>
<td>1.50</td>
</tr>
<tr>
<td>T5</td>
<td></td>
<td>29.45 x 36.95</td>
<td>33.64 x 37.43</td>
<td>2.714</td>
<td>2.49</td>
<td>2.16</td>
</tr>
<tr>
<td>T6</td>
<td></td>
<td>29.19 x 36.80</td>
<td>37.81 x 37.15</td>
<td>3.378</td>
<td>3.14</td>
<td>2.40</td>
</tr>
<tr>
<td>T7</td>
<td></td>
<td>24.23 x 36.12</td>
<td>36.29 x 35.90</td>
<td>2.919</td>
<td>3.34</td>
<td>2.24</td>
</tr>
</tbody>
</table>
After this small test another test is performed. The order of creating the sample is tested. Normally it is the case to create first the cubes and afterwards drilling the holes. But this order can be turned around to first drilling the holes and afterwards sawing the cubes. But with this second order the reduced area of a sample is less, because due to the width of the diamond saw to make cube samples it is not possible to make two half holes out of one hole. Material is removed and there will be less than a half hole remain. All samples consists of the sawing pattern, but the two orders of creating the samples and only sawing patterns and no reduced concrete area are varied. Besides this variation also the length of drying of the adhesive is varied. Normally the samples are glued in the afternoon to the steel blocks are tested the day after in the morning. The two components adhesive is drying for a time span of about 18 hours. The suggestion was that in this period the adhesive could shrink and induces stresses and or cracks in the samples. But from the other side, normally this adhesive will be used for connecting strain gauges to samples. In this case the adhesive cannot afford to shrink because it influences the test results. But with testing the influence of the drying length on the results it is possible to reject this suggestion. A short drying length is received by creating the samples in the afternoon and gluing to samples in the morning after. Than a period of three hours the glue can harden and afterwards they will be tested. In table A3 the specification of each sample can be seen.

### Table A3: Specifications of the test samples

<table>
<thead>
<tr>
<th>NAME</th>
<th>CHARACTERISTICS</th>
<th>GLUE</th>
<th>DIMENSIONS CRACKING SURFACE [mm]</th>
<th>DIMENSIONS GLUED SURFACE [mm]</th>
<th>LOAD [kN]</th>
<th>STRESS CRACKED SURFACE [MPa]</th>
<th>STRESS GLUED SURFACE [MPa]</th>
<th>FAIL LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1T</td>
<td>First sawing*</td>
<td>Short</td>
<td>20.40 x 33.01</td>
<td>32.77 x 32.95</td>
<td>Failed</td>
<td>-</td>
<td>-</td>
<td>Concrete</td>
</tr>
<tr>
<td>2T</td>
<td>First sawing</td>
<td>Short</td>
<td>23.67 x 35.78</td>
<td>34.97 x 35.97</td>
<td>1.545</td>
<td>1.82</td>
<td>1.23</td>
<td>Concrete</td>
</tr>
<tr>
<td>3T</td>
<td>First sawing</td>
<td>Short</td>
<td>37.99 x 37.31</td>
<td>37.99 x 37.31</td>
<td>2.670</td>
<td>1.90</td>
<td>1.90</td>
<td>Glue</td>
</tr>
<tr>
<td>4T</td>
<td>First holes**</td>
<td>Short</td>
<td>23.71 x 40.02</td>
<td>33.93 x 40.07</td>
<td>1.422</td>
<td>1.50</td>
<td>1.05</td>
<td>Concrete</td>
</tr>
<tr>
<td>5T</td>
<td>First holes</td>
<td>Short</td>
<td>19.41 x 40.00</td>
<td>34.31 x 40.02</td>
<td>1.252</td>
<td>1.61</td>
<td>0.91</td>
<td>Concrete</td>
</tr>
<tr>
<td>6T</td>
<td>First holes</td>
<td>Short</td>
<td>25.24 x 39.66</td>
<td>35.51 x 39.67</td>
<td>2.622</td>
<td>2.62</td>
<td>1.86</td>
<td>Concrete</td>
</tr>
<tr>
<td>7T</td>
<td>Only pattern***</td>
<td>Short</td>
<td>34.31 x 33.36</td>
<td>34.31 x 33.36</td>
<td>2.245</td>
<td>1.96</td>
<td>1.96</td>
<td>Concrete</td>
</tr>
<tr>
<td>8T</td>
<td>Only pattern</td>
<td>Short</td>
<td>34.39 x 34.07</td>
<td>34.39 x 34.07</td>
<td>2.366</td>
<td>2.02</td>
<td>2.02</td>
<td>Concrete</td>
</tr>
<tr>
<td>9T</td>
<td>Only pattern</td>
<td>Short</td>
<td>36.07 x 36.82</td>
<td>36.07 x 36.82</td>
<td>2.650</td>
<td>2.00</td>
<td>2.00</td>
<td>Concrete</td>
</tr>
<tr>
<td>10T</td>
<td>First sawing</td>
<td>Long</td>
<td>24.06 x 31.80</td>
<td>33.57 x 32.05</td>
<td>2.889</td>
<td>3.78</td>
<td>2.68</td>
<td>Concrete</td>
</tr>
<tr>
<td>11T</td>
<td>First sawing</td>
<td>Long</td>
<td>24.47 x 34.78</td>
<td>37.07 x 34.99</td>
<td>3.088</td>
<td>3.63</td>
<td>2.38</td>
<td>Concrete</td>
</tr>
<tr>
<td>12T</td>
<td>First sawing</td>
<td>Long</td>
<td>23.08 x 39.40</td>
<td>37.30 x 39.43</td>
<td>1.869</td>
<td>2.06</td>
<td>1.27</td>
<td>Concrete</td>
</tr>
</tbody>
</table>

*first sawing* = create cubes and afterwards drilling holes, *first holes* = vice versa and only pattern*** = no holes

From the results in table A3 can be concluded that the order of creating samples has no influence on the results. But for measuring the dimensions and the weight to get the density of the sample it is better to create first cube specimens and afterwards drill the holes. Also the dry length of the adhesive has no influence on the results. But for practical reasons is chosen to keep the dry length short. Also can be seen in the results that the specimens with no holes (7T, 8T and 9T) also failed in the concrete. So the question arises: Is there need to drill the holes? Or in other words: Is it possible to keep the preparation time as short as possible?
**IMPROVEMENTS ON THE TEST SETUP**

If there is need to drill holes, will be tested in combination with a variation on the test setup. In figure A1 is shown the initial situation. Watching this figure the first thing which will be noticed is the length of the upper rod. This length is randomly picked and will be compared with other two rods. The rod on the bottom side of the setup is not replaced. The three different rods are shown in figure A5.

The first rod in the figure is the initial one. This rod has a length of 34.3 centimetres. If the top surface of a sample is not straight enough, it is possible that the sample is not in line with the load cell. In this case small bending moments are introduced. If the top surface of the sample is the same as the previous one and the connecting rod between the load cell and the sample is shorter, the eccentricities and/or bending moments are smaller. This is due to the fact that the angle is the same but the length of the rod is less. In this case the length of the rod is 9.3 centimetres. This causes a smaller deflection from the centreline, thus a smaller eccentricity. The last used rod has a length of 30.0 centimetres. This length is a bit shorter than the initial one, but it has also two narrowed pieces at circa 3.0 centimetres of both ends. The intention if this rod is to get more flexibility to pull the samples more straight during the tests. These three rods are compared to each other with samples without drilled holes. The specification of these samples are collected in table A4. For these tests are the test directions and time interval varied, which can be seen in the names. It is remarkable that only 50 percent of the samples is failed in the concrete. This is due to the fact that the specimens were older than 28 days, were not cured in right way and do not had reduced concrete areas. But if the test specimens were failed in the concrete, the stresses are way higher than previous tests. There is no significant difference in the use of different rods. But the statements made about the eccentricity and bending moments cause the choice to use the short rod in the future.
END SITUATION

In the end situation the test setup is a bit changed in comparison with the initial situation. The samples consists now of a reduced concrete area. This is reached with drilling two half holes out of the middle of the specimen. Also the adhesive connection is improved by making a specific patter with a small diamond cutting wheel. Besides these changes on the test sample there are two alterations made on the setup. The first one is that the video strain meter is replaced by two LVDT’s. In total there are now four LVDT’s, one on each side. With the four LVDT’s also the differences in deformations can be observed. And the last one is the length of the rod between the top of the sample and the load cell is shorten. Figure A6 shows the test setup of the end situation. This setup will be used for the described direct tension test.

<table>
<thead>
<tr>
<th>NAME</th>
<th>TENSION ROD</th>
<th>DIMENSIONS CRACKING SURFACE [mm]</th>
<th>LOAD [kN]</th>
<th>STRESS CRACKED SURFACE [MPa]</th>
<th>FAIL LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1-B7-I</td>
<td>Short</td>
<td>32.01 x 34.08</td>
<td>4.189</td>
<td>3.84</td>
<td>Glue</td>
</tr>
<tr>
<td>P2-B7-III</td>
<td>Short</td>
<td>40.90 x 31.62</td>
<td>3.285</td>
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**Figure A6: The used test setup**
THE EFFECT OF LAYERED MANUFACTURING ON THE STRENGTH PROPERTIES OF PRINTABLE CONCRETE
APPENDIX B: G-CODE SCRIPT

Two G-code script are added. Both are used for the same samples, but the first script consists the first three layers of three and 12 hour open time printed elements and the second script consists the second three layers of the three hours open time printed elements and the first three layers of the 24 hour open time printed elements. Each script start with some settings for the used printer, like pump frequency, printer speed and rotation of the nozzle. The part after “START SCRIPT” are the movements of the nozzle.

;---------- PRINT SETTINGS ----------
PUMP FREQUENCY & PRINT SPEED
;----------START SCRIPT ----------
X-1000 ;element1.1 DeltaT=3.0
Y-225
X1000
y75
y75 Z10
y75
X-1000 ;element1.2
Y-225
X1000
y75
y75 Z10
y75
X-1000 ;element1.3
Y-225
X1000
y75
y75 Z10
y75
X100
Y300 Z-30
X-100
X-1000 ;element2.1 DeltaT=3.0
Y-225
X1000
y75
y75 Z10
y75
X-1000 ;element2.2
Y-225
X1000
y75
y75 Z10
y75
X-1000 ;element2.3
Y-225
X1000
y75
y75 Z10
y75
X100
Y300 Z-30
X-100
X-1000 ;element3.1 DeltaT=12.0
Y-225
X1000
y75
y75 Z10
y75
THE EFFECT OF LAYERED MANUFACTURING ON THE STRENGTH PROPERTIES OF PRINTABLE CONCRETE

X-1000;element3.2
Y-225
X1000
y75
y75 Z10
y75
X-1000;element3.3
Y-225
X1000
y75
y75 Z10
y75
X100
Y300 Z-30
X-100
X-1000;element4.1 DeltaT=12.0
Y-225
X1000
y75
y75 Z10
y75
X-1000;element4.2
Y-225
X1000
y75
y75 Z10
y75
X-1000;element4.3
Y-225
X1000
y75
y75 Z10
y75
X100
;============== END ===============
Z100 M50
M30
;======= PRINT SETTINGS ========
PUMP FREQUENCY & PRINT SPEED
;=====START SCRIPT ======
X=1000
Y=225
X1000
Y75
y75
Y75 Z10
y75
Y=1000
Y=225
X1000
Y75
y75
Y75 Z10
Y75
Y75
X=1000
Y=225
X1000
Y75
Y75 Z10
Y75
X=100
Y300 Z-30
X=100
X=1000
Y75
y75
Y75 Z10
Y75
Y=1000
Y=225
X1000
Y75
Y75 Z10
Y75
Y=1000
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X1000
Y75
Y75 Z10
Y75
X=1000
Y900 Z-60
X=100
X=1000
Y225
X1000
Y75
Y75 Z10
Y75
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Y=225
X1000
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Y75 Z10
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Y75 Z10
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X1000
Y75
Y75 Z10
Y75
X=1000
Y=225
X1000
Y75
Y75 Z10
Y75
X=1000
Y=225
X1000
Y75
Y75
Y75

;element1.4
DeltaT=3.0

;element1.5

;element1.6

;element2.4
DeltaT=3.0

;element2.5

;element2.6

;element5.1
DeltaT=24.0

;element5.2

;element5.3
THE EFFECT OF LAYERED MANUFACTURING ON THE STRENGTH PROPERTIES OF PRINTABLE CONCRETE

y75 Z10
y75
X100
Y300 Z-30
X-100
X-1000 ;element6.1 DeltaT=24.0
Y-225
X1000
y75
y75 Z10
y75
X-1000 ;element6.2
Y-225
X1000
y75
y75 Z10
y75
X-1000 ;element6.3
Y-225
X1000
y75
y75 Z10
y75
x100
;========== END ===========
Z100 M50
M30
**APPENDIX C: SPECIFICATIONS OF CASTED CONTROL SAMPLES**

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### The Effect of Layered Manufacturing on the Strength Properties of Printable Concrete

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THE EFFECT OF LAYERED MANUFACTURING ON THE STRENGTH PROPERTIES OF PRINTABLE CONCRETE
## APPENDIX D - SPECIFICATIONS OF PRINTED TEST SAMPLES

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**Test series 00_03**

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## APPENDIX D - SPECIFICATIONS OF PRINTED TEST SAMPLES

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### APPENDIX D - SPECIFICATIONS OF PRINTED TEST SAMPLES

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## Test series 20_28

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**The Effect of Layered Manufacturing on the Strength Properties of Printable Concrete**

**Test series 20_28**
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### Appendix

## Specifications of Printed Test Samples

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APPENDIX E: INFLUENCE OF INCLINED SURFACES

It is not doable to create perfect rectangular samples with the already mentioned specimen preparation. It is possible that the surfaces which will be glued to the steel plates have a small inclination and cause additional stresses. The idea behind the tensile strength test is that only direct tensile stress are introduced. With an inclination also a bending moment is introduced. The maximum inclination is concluded out of the measurements and is one degree. The test is simplified to control the influence of the inclined surface. The simplification is expressed in figure E1. Besides the inclination of surface it is also possible that the steel plates are not centred glued to the samples. If the plate is not placed in the centre the force is not equally divided on the surface. The assumption is made that the steel plate is always centred glued to the specimen, because this is easier to control than the inclined surfaces.

Below is first explained the maximum stress with only direct tensile stresses and afterwards is explained the influence of a sample with an inclined surface. The calculations are made on 2D samples and the maximum tensile stress is set on 1.50 MPa. The forces needed to reach this maximum tensile stress are calculated and evaluated.
**ZERO DEGREE INCLINATION**

In figure E2 is shown the situation of pure tensile stress on the sample. In this situation formula E1 for normal stress is used. Because a 2D simplification is used the area consists only of the sample width.

\[ \sigma = \frac{F}{A} \quad \text{(Formula E1)} \]

\[ 1.50 = \frac{F}{40} \]

\[ F = 40 \times 1.50 = 60 \, N \]

![Figure E2: Exact rectangular sample](image1)

So with 60N tensile force the sample reaches the tensile strength of 1.5 MPa.

**ONE DEGREE INCLINATION**

The force is always introduced perpendicular to the surface, due to the fact that the plates are glued on the top and bottom surface. So if the surface has a specific inclination, the load is attached with the same inclination. In figure E3 is made clear that an inclined surface introduces a parallel load and a small perpendicular. Due to this perpendicular load a bending moment is introduced. The influence of this perpendicular load is checked at a half height, because this is the weakest part of the sample. This is due to the reducing the concrete or the possibility of an interface on that height. The stresses due to a bending moment are in formula E2 and the total amount of stresses is in formula E3.

\[ \sigma = \frac{Mz}{I} \quad \text{(Formula E2)} \]

\[ \sigma = \frac{F}{A} \pm \frac{Mz}{I} \quad \text{(Formula E3)} \]

![Figure E3: Sample with inclined surface](image2)
At one degree of inclination:

\[ F_1 = \cos(1) \cdot F \approx 0.99985 F \]

\[ F_2 = \sin(1) \cdot F \approx 0.001745 F \]

\[ \sigma = \frac{F_1 \cdot \frac{1}{2} h \cdot z}{A} + \frac{F_2 \cdot \frac{1}{2} h \cdot z}{l} \]

\[ \sigma = \frac{\cos(1) \cdot F}{40} + \frac{\sin(1) \cdot F \cdot 20 \cdot 20}{\frac{1}{12} \cdot 40^4} \]

\[ \sigma = 0.024996 F + 0.000032719 F \]

\[ F = \frac{\sigma}{0.025028719} = \frac{1.5}{0.025028719} = 59.93 \text{ N} \]

So if the sample has a one degree inclination of the load surface the maximum tensile stress of 1.50 MPa is reached with a load of 59.93 N. If it was not known that the sample consists of inclined surfaces, which introduces bending moments, the maximum tensile strength of the sample is calculated with Formula E1.

\[ \sigma = \frac{F}{A} = \frac{59.93}{40} = 1.49828 \text{ MPa} \]

The maximum tensile strength is calculated as 1.498 MPa. This is value is 0.115% underestimated, which is negligible. From this can concluded that the maximum inclination of the top or bottom surface has no effect on the maximum tensile strength of the sample. The inclination is too small to introduce bending moments in the samples which are influencing the results normative.