A textile reinforcement method for 3D printed concrete

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Abstract. The reinforcement of 3D printed concrete elements has proven to be a significant challenge that needs to be addressed. However, before reinforcement can be applied, the behaviour of the consequent composite materials must first be studied. This study, therefore, investigates the macro- mechanical behaviour of AR glass fibre textile material as reinforcement in terms of its flexural performance, to determine whether it is a feasible solution. During this study, elements, consisting of four layers, are printed flat on the surface bed of the printer and are reinforced by a textile mesh in between subsequently printed layers. The specimens are reinforced at different locations, with different geometrical orientations as well as different filament orientations, and are then compared. The flexural performance is quantified by conducting four-point bending tests 28 days after printing. The results of the tests show that by adding this specific mesh, the average flexural strength of the elements increases significantly. Furthermore, elements with the warp yarns aligned with the printed filament have increased flexural strength. During the testing, it is also discovered that voids form underneath the textile mesh when applied between the layers and that these voids influence on the performance of the elements.

1 Introduction

For the past century, the use of concrete as a building material has dominated the construction industry [1]. This dominance can be attributed to the advantageous concrete characteristics such as a high compressive strength, being versatile and durable and having a low cost. However, the use of concrete has its drawbacks. Among them are the anthropogenic CO₂ emissions, the waste produced by using formwork, the large amount of water and aggregates required and the negative environmental impact of clinker production. Furthermore, according to a Ministry of Manpower report [2], the construction industry has a higher rate of fatality, injury and illness than any other industry. This has resulted in a demand for more efficient, sustainable and safer construction methods. Additionally, considering the global trend of automation, new construction methods are consistently being developed and applied in the construction industry to enhance productivity.

One such method is additive manufacturing, also known as 3D concrete printing (3DCP). It involves the utilisation of software and an automated process, where a digital model is physically printed layer-by-layer by using concrete [3]. Although the development of this method is still in its infancy, it has drawn significant attention due to its numerous benefits [4]. This includes a safer working environment, manufacturing of elements without the use of formwork as well as the possibility of complex structural elements along with the geometrical freedom of its design. Furthermore, during construction, this method can reduce the amount of waste material, time, labour and cost [3,4] compared to the traditional method of construction. It also makes it possible to rapidly mass produce and customise prefabricated elements off site.

However, 3DCP still has significant challenges to overcome before it can be fully adopted as a feasible alternative to conventional construction methods [5]. One of the main challenges is the reinforcement of printed elements and according to literature [3-5], it is clear that there are different aspects to this challenge. The lack of clear space above the filament layer being printed is one of the first aspects to take into account [3]. This space is occupied by the printer’s nozzle and makes it difficult to install reinforcement. Another aspect to consider is the difficulty of adding reinforcement in different directions, such as the longitudinal, transverse and orthogonal directions [4]. These directions are illustrated in Figure 1.

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Adding reinforcement to printed elements is further limited by its fresh state strength and stability, leading to the problem of effectively integrating reinforcement into the printing process [6]. Along with the problem of integration is the fact that the reinforcement must align with the universal advantages of DCP as a construction method, for it to be seen as efficient [5]. Various strategies, techniques and materials have been studied to overcome this challenge, with each having its advantages and disadvantages.

These strategies and techniques have been applied in different stages of the printing process with the three major stages including before, during and after printing. Pre- and post-installed reinforcement consists of the application of reinforcement before and after the commencement of the printing process, respectively. However, using these strategies does not integrate well with the printing process as it increases the time of manufacturing elements [5]. Furthermore, reinforcement applied during the printing or mixing process are preferred as this will not extend the time of manufacturing elements, thus keeping in line with the advantages of DCP. The different reinforcements that have been studied in this stage include entrained fibres, entrained cables, mesh, steel fibre links, nail reinforcement, needles and steel rebar [5].

Of these methods, the mesh used by Marchment [4] presented promising results. A split nozzle was used to print on either side of a galvanised steel mesh that was vertically inserted in an overlapping manner. It was concluded that the material significantly increased the flexural moment capacity of the elements, and ensured that interlayer reinforcement was possible thereby strengthening the interlayer. Also, applying the mesh did not consume any extra time. However, DCP specimens are prone to tearing at the interlayer regions and have weak interlayer bond strengths resulting in pathways for chloride ingress, making the specimens more susceptible to corrosion [5]. Steel, is susceptible to corrosion, which can thus lead to durability problems for DPC elements reinforced with steel elements. The idea of using mesh for reinforcement is well suited to adopt other materials such as textiles.

Textiles consist of continuous warp and weft yarns that are connected perpendicular to one another via weaving, knitting or bonding to form a mesh. These textiles are extremely strong in tension, lightweight, flexible and resistant against corrosion and fire [7]. Textile-reinforced concrete has been extensively studied in the last couple of decades. Taking into account the positive results obtained from these studies along with the study conducted by Marchment [4], it can be assumed that textile can be a viable option for the reinforcement of DPC and therefore needs to be studied.

Therefore, the aim of this study is to investigate the use of textile as reinforcement for DPC and the performance of textile-reinforced DPC. It should be noted that only one of the many possible methods of applying the textile as reinforcement has been investigated. Printed elements were subjected to four-point bending tests to determine the flexural strength and behaviour of elements.

2 Experimental procedure

2.1 Materials

2.1.1 3DPC matrix

The binder content for the mix used in this study consisted of three materials. The primary binder was CEM II 52.5N, an ordinary Portland cement containing 7 to 10% Limestone extender. Additionally, two other cement extenders were used to obtain the desired rheological properties for the printed concrete. These included fly ash (DuraPozz Class F) and silica fume (SiliconSmelters Microfume). Coarse aggregate was not used in the DPC mixture for ease of extrusion. A natural quarry sand, locally known as Malmesbury sand, was used. In order to obtain the required flowability for the mix, Chryso Premia 310, which is a modified polycarboxylate polymer superplasticiser, was selected and added as a percentage of the mass of the binder material. The function of the superplasticiser is to disperse the cement grains in order to improve the workability of the concrete. Using a superplasticiser is important in this mix as the water content is low. Finally, potable tap water was used for the mixing of the dry materials.

2.1.2 Textile mesh reinforcement

Figure 2 shows the textile, Alkali-Resistant (AR) glass fibre (Grid Q145/145-AAE-25) used in the study. The yarn of the textile was fully impregnated with epoxy resin and bonded together with heat and glue to form the textile mesh. Glass fibre was specifically selected as it bonds well with cement matrices, has a good cost-performance ratio and costs less than other fibres [10]. It was important to use an AR version of glass fibre as concrete is a high alkaline medium in which normal glass fibre can disintegrate over time. Furthermore, the material was impregnated with epoxy resin to strengthen the bond of the filaments and the fibre within the bundle of yarn, resulting in higher friction and an increase in reinforcing performance.

![Fig.2](image)

The apertures in the mesh were large with a distance of 25mm from the centre of one yarn to the next, to encourage the flow of concrete in between them to fully
envelope the yarns. Additionally, a bonded fabric was chosen as this fabric geometry keeps the load-carrying (warp) yarns as straight as possible, thus improving their performance [10]. The material properties of the textile include a mean characteristic tensile strength of 1500 MPa, Young Modulus of 72GPa and yarn with a cross sectional area of 3.69mm².

2.2 Mix proportions

Only one mix was used throughout the study. This was decided on to keep the mix constant as the elements that were tested already varied in terms of different locations and orientations of applied textile reinforcement. The standard Stellenbosch University mix proportions was modified to suit the current batch of materials present at the lab at the time of the study. Table 1 shows the proportions of the constituents for a 1000L mix.

<table>
<thead>
<tr>
<th>Table 1. Mix Proportions</th>
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<tbody>
<tr>
<td>Constituents</td>
</tr>
<tr>
<td>Cement</td>
</tr>
<tr>
<td>Fly ash</td>
</tr>
<tr>
<td>Silica Fume</td>
</tr>
<tr>
<td>Sand</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Superplas.</td>
</tr>
</tbody>
</table>

The mix had an aggregate to binder ratio of 1.44, which falls in the typical range of 3DPC mixtures that have been used by other researchers, typically, 1.3-1.7 [8]. Furthermore, a water to cement ratio of 0.45 was selected and superplasticiser was added until the desired consistency and flow ability was achieved, resulting in a mini-slump-flow of 150mm and 0.725% of the total mass of the binder. The flow-ability of the mix was important as the mix was required to flow between the yarns of the mesh, completely enveloping them to reduce the risk of voids forming.

2.3 Preparing the samples

2.3.1 Mixing

The materials were prepared and weighed off for a 40L mix. Thereafter, the dry constituents were added into a 50L two-bladed pan mixer and were mixed for 1min. Water was added in a slow and controlled manner, and mixing of the dry constituents done for another 1min. Finally, the superplasticiser was added after which the mixing of the materials continued for a final 3min. During the mixing process, care was taken to ensure that the dry constituents did not stick to the inner side of the pan or on the face of the blades. After the mixing of the constituents, the mini-slump-flow test was conducted to determine whether the material was acceptable for printing. The materials were batch mixed on separate days; however, a mini-slump-flow of approximately 150mm was achieved on each occasion. After the mixing process, the mixture was placed into a hopper from which it was extracted for the printing process using a rotator screw concrete pump.

2.3.2 Printing

A 1m³ gantry 3D concrete printer was used to move a hose with a circular nozzle (diameter of 25mm) to conform to its designated path. Prior to the commencement of the printing process, the pump was primed until the extrusion of the material was satisfactory. Thereafter, the material was extracted from the hopper, with the rotator screw, through the hose and was extruded in a layer-by-layer fashion, following a predefined coordinate path. The printing speed was set to 60mm/s and the extrusion rate of the pump was altered throughout the printing process to achieve the desired filament dimensions of 30mm x 10mm (W x L).

Figure 3 shows the elements which were printed flat on the surface bed, with filaments being printed next to each other in an overlapping fashion, increasing in height when the coordinate path was completed. This process was repeated until a height of approximately 40 mm was achieved, consisting of 4 printed filament layers. Additionally, Figure 3 illustrates the placement of the textile in between the layers.

Fig.3. The printed element from which the specimens were extracted with illustration of textile mesh placement in between layers.

The printing of the elements occurred in a climate-controlled room with an ambient temperature of 25°C and a relative humidity of 60% with no airflow in the room. The elements were left in the room for 28 days to cure, after which specimens were extracted via saw-cutting with dimensions of 160mm x 40mm x 40mm. Two different printing files were created for this study, each with different filament orientations and the resulting specimens of these printing files are displayed in Figures 4 and 5. In both these figures, the arrows indicates the printing direction of the filaments, which is seperated by the dashed lines.

Fig.4. Specimen with perpendicular orientated filament (arrows indicate filament printing direction
2.3.3 Applying Textile reinforcement

The method of applying the textile chosen for this study is one where the textile was applied during the printing process so as not to extend the time of printing. Furthermore, it was chosen as it could be well used in the offsite pre-manufacturing of elements, which ties in with the advantages of 3DCP. The textile mesh was placed between the layers at desired locations after the specific amount of layers were printed. This method can realistically be used to print wall and beam elements in the industry. However, elements such as columns will not be possible when using this method.

As mentioned in Section 2.3.3, two main sets of elements were printed for testing. One was reinforced with the load-carrying yarns parallel to the printed filament, and the other reinforced perpendicular to the printed filament. The specimen further varied in terms of where the textile mesh was placed. It was placed after 1 layer, 2 layers and 3 layers, with the latter being rotated 360 degrees before being tested. Elements were also printed without the inclusion of the textile mesh in order to quantify the improvement in strength due to the mesh. At least 3 specimens of each variation were printed.

During the application of the textile, it was noted that the process was not time-consuming and was also not labour intensive as the mesh was applied whilst the previous layer was completed, and the nozzle was moving up to print the next layer.

2.4 Testing of the specimen

At 28 days, the saw-cut specimens were tested in flexure with the four-point bending test using an Instron machine, with a 250kN load cell and a loading rate of 50N/s as stipulated by the European code [9]. The filament layers of the specimens were aligned horizontally. Additionally, for the method where the load carrying yarn was aligned with the printed filaments, the specimens were orientated with the printed filaments running lengthwise across the span. In contrast, for the method where the load carrying yarn was perpendicular to the printed filament, the filaments were aligned perpendicular across the span. The test setup and the orientation of the elements are displayed in Figure 6.

During testing, the load applied by the machine, as well as the displacement of the testing rig, was recorded. Thereafter, the data was used to calculate the flexural moment strength of the tested specimens using the following equation:

\[ M_{\text{flexure}} = \frac{(P \cdot L)}{(b \cdot h^2)} \]  

where \( P \) is the applied load, \( L \) is the distance between the supports, \( b \) is the width of the cross-section of the specimen and \( h \) is the height of the cross-section of the specimen.

Additionally, the failure modes of the respective specimens were observed as well as the cracking pattern, sequence and void formation.

Saw-cutting the specimen in their hardened state proved to be difficult in terms of cutting all the specimen precisely the same and it is acknowledged that this, along with the uneven surface under the applied load, can affect the results. For both mesh printing direction methods, 4 different variations were printed and tested via the four point bending test, which included unreinforced samples as well as samples that were reinforced after 1 layer (Reinf-1), 2 layers (Reinf-2) and 3 layers (Reinf-3).

3 Results and discussion

3.1 Flexural performance

3.1.1 Perpendicular filaments

The data obtained from the tests are shown in Table 2. For the tested specimens, there is a significant increase in the peak load carried and flexural strength when the textile mesh is applied, which indicates the effectiveness of the reinforcement material. The textile increased the mean flexural strength of the specimens by 446% (Reinf-1), 389% (Reinf-2) and 376% (Reinf-3), respectively. Additionally, the covariance of the reinforced specimen is high which is reasoned to be due in part to the voids that form under the yarn as discussed later in Section 3.2. As expected, the results show that the specimens that is reinforced after the 1st printed layer performs optimally. This is due to the stress distribution across the depth of the specimen, where the highest stress is experienced at the bottom of the specimen under bending, due to the applied loads. When the textile layer is placed at the bottom of the specimen (after the 1st layer) it creates a bigger moment arm to carry the stress resulting in better performance.
Table 2. Results of perpendicular filament specimens

<table>
<thead>
<tr>
<th>Description</th>
<th>Mean Peak load (kN)</th>
<th>Mean flexural strength (MPa)</th>
<th>Cov (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreinforced</td>
<td>0.92</td>
<td>2.16</td>
<td>2.37</td>
</tr>
<tr>
<td>Reinf-1</td>
<td>5.04</td>
<td>11.81</td>
<td>6.7</td>
</tr>
<tr>
<td>Reinf-2</td>
<td>4.51</td>
<td>10.57</td>
<td>15.47</td>
</tr>
<tr>
<td>Reinf-3</td>
<td>4.4</td>
<td>10.3</td>
<td>27</td>
</tr>
</tbody>
</table>

The raw data obtained from the tests were further used to create a load vs. displacement graph, as shown in Figure 7. This graph shows the cross head displacement versus the load applied by the machine. The graph is plotted with the data of all the perpendicular orientated filament specimens. The legend describes the graphs according to whether it was reinforced or not, followed by the layer after which the textile was applied and the sample number.

For Reinf-1, Reinf-2 and Reinf-3 of the perpendicular orientated specimens, Figure 7 clearly shows the increased flexural performance, caused by the addition of the textile reinforcement. The unreinforced specimens failed in a brittle manner, as expected. Additionally, all textile-reinforced specimens show an increase in the ductility producing a strain hardening behaviour, as the load-carrying capacity of the specimens progressively increased after the initial cracking of the specimens until complete failure. A notable observation from the graph is that the majority of specimens experienced three drops in the load carried before it reached its peak load. These drops in the load carried are attributed to the three main cracks that occurred, namely initial vertical crack up to textile layer, horizontal crack across the textile layer and further vertical crack towards the top of the specimens. The specimens that were reinforced at the bottom (Reinf-1) and the middle (Reinf-2) experienced the most displacement before failure, where as in contrast the specimens that were reinforced at the top and flipped (Reinf-3) experienced higher peak loads with less displacement. Ultimately, the load vs. displacement graph shows that reinforcing specimen with the warp yarns perpendicular to the printed filaments can be an effective method to significantly improve the flexural performance.

3.1.2 Longitudinal filaments

Table 3 shows the results of the tests conducted on the longitudinal filament specimens. The unreinforced longitudinal specimens were significantly stronger than the unreinforced perpendicular specimens. This is due to the perpendicular specimens containing shear planes across the span of the specimens, resulting in weaker flexural performance. Furthermore, the mean flexural strength of the Reinf-1 of this method is similar to that of the perpendicular specimens. However, the increase in strength from the unreinforced specimens is significantly less, with 48% (Reinf-1), 3% (Reinf-2) and 65% (Reinf-3). This means that adding the textile mesh has a greater influence when aligned perpendicular to the printed filaments than when it is aligned longitudinally with the printed filaments.

Table 3. Results of longitudinal filament specimens

<table>
<thead>
<tr>
<th>Description</th>
<th>Mean Peak load (kN)</th>
<th>Mean flexural strength (MPa)</th>
<th>Cov (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreinforced</td>
<td>3.33</td>
<td>7.8</td>
<td>4.19</td>
</tr>
<tr>
<td>Reinf-1</td>
<td>4.94</td>
<td>11.58</td>
<td>12</td>
</tr>
<tr>
<td>Reinf-2</td>
<td>3.42</td>
<td>8.03</td>
<td>10.58</td>
</tr>
<tr>
<td>Reinf-3</td>
<td>5.52</td>
<td>12.93</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Figure 8 shows the load versus displacement graph of the longitudinal reinforced specimens.

From Figure 8, the specimen of Reinf-1, Reinf-2 and Reinf-3 experienced their first crack at a lower load than the unreinforced specimens. The unreinforced specimens again failed in a brittle manner. Furthermore, applying the textile mesh to this orientation of specimens increased the ductility of the specimens and produced strain-hardening characteristics. However, as evident in
the graph, these reinforced specimens were less ductile than the perpendicularly oriented specimens; hence, absorbing less energy prior to failing. Most of the specimens experienced multiple drops in load carrying capacity before completely failing. Again, the specimens reinforced in the lower and middle layers were the most ductile, whilst not carrying the biggest peak loads. In contrast, the specimens that were reinforced at the top and flipped (Reinf-3) were the strongest and the stiffest. Notably, the specimens reinforced at the bottom (Reinf-1) were neither the strongest nor the stiffest, but performed well in both categories and produced the optimal reinforcement option.

3.2 Voids

3.2.1 Origin

After the specimens were saw-cut from the printed elements, voids were observed to have formed underneath the textile mesh. The voids can be seen in the specimens shown in Figure 9 with varied severity.

![Specimen printed from left to right](image1)

![Specimen printed form right to left](image2)

Fig.9. Voids that formed due to the pivoting action of the textile relative to the printing direction

A close inspection of the specimens show that voids formed more frequently at the end of the the specimen that was printed last. Additionally, these voids are more severe than voids forming in the middle of the specimen or at the end of the specimen where printed started. It could, therefore, be said that while printing over the textile from left to right, the left side of the textile was pushed into the previous layer whilst pivoting the right side upwards, thus causing voids to form on the right side as the concrete fully encapsulates the textile. The stiff nature of the textile mesh used in this study could have caused the phenomena, allowing and intensifying the pivot action. However, the flowability of the printed mix could also have had an influence.

Additionally, as seen in Figure 9, larger voids form under the yarns when the textile was placed after the 3rd layer than when placed after the 1st layer. This could be due to the weight of the layers printed on the 1st layer, pressing down into the layer below, thus decreasing the size and possibility of a void.

3.2.2 Influence on results

The influence of the voids on the performance of the specimens is determined by comparing the results of the specimens reinforced after the 1st layer with specimens reinforced after the 3rd layer and rotated 180 degrees. This comparison was possible as the layers of reinforcement were in the same position for both variations, with the only difference being the voids (location, severity and frequency).

During testing, the voids are underneath the mesh for Reinf-1 and Reinf-2 specimens. For the Reinf-3 specimens, the air voids are above the yarns, more severe in size and occurred more frequently, resulting in varied results with the covariance of both the perpendicular and longitudinal filaments being higher than that of the Reinf-1 specimens. Moreover, the void location drastically influenced the perpendicular specimens, as the covariance increased by 400% and the mean flexural strength and peak load both decreased by 13%.

This could have resulted from the voids forming in shear planes between printed filaments, decreasing the strength of such elements. Furthermore, the bigger size and frequency of the voids could have decreased the bond strength between the matrix and textile, decreasing its performance and increasing the variability of the results. The influence of the voids can further be attributed to the cracking sequence of the specimens during failure as well as how the specimens fail as discussed next.

3.2 Failure modes and Cracking

The majority of all the specimens that were tested did not experience flexural failure, but rather experienced shear failure. The textile used in this study was too strong for the concrete, and therefore flexural failure did not occur. The specimens that were unreinforced all failed in a brittle manner, with the failure occurring between the two applied loads where the maximum moment occurred. In contrast, all the specimens that were reinforced displayed ductile behaviour before failing, which is a result of the strain-hardening behaviour of the textile reinforcement. The failure modes of the reinforced specimens are shown in Figure 10.

![Shear failure b) Delamination](image3)

Fig.10. a) Shear failure b) Delamination

The reinforced specimen experienced an initial vertical crack that formed between the locations of the two applied loads. In all of the specimens, these vertical cracks occurred in the vicinity of the weft yarns. Where multiple vertical cracks formed, all originated at the weft
yarns. These initial vertical cracks formed until they reached the layer of reinforcement, where the cracks then started to spread out horizontally. From this point onwards, the specimen either kept on cracking horizontally, leading to delamination of the printed layers below the mesh and sudden decrease in the load carried, or vertical cracking resumed and continually progressed until the top of the specimen was reached, and shear failure occurred. In Figure 11, the cracking sequence is shown on a specimen before failure occurred.

![Cracking sequence of the specimen](image)

**Fig.11.** Cracking sequence of the specimen

Where the filaments were orientated perpendicularly across the span, the specimen tended to experience further vertically cracking up to the top of the specimen, followed by shear failure. This failure sequence can be attributed to the shear planes of the filaments printed next to each, acting as a weak point (much like interlayers) and thus failing in shear before delaminating. On the other hand, the specimens that were orientated longitudinally across the span experienced delamination instead of shear failure as the horizontal crack kept progressing until the bottom layers of concrete broke away.

Regardless of the orientation of the printed layers, where voids were present, the cracks formed into the voids. Moreover, where multiple voids were present in the specimens, the cracks formed from void to void, which compromised the regular cracking pattern of the specimens leading to abnormal behaviour and early failure. When the voids were beneath the textile mesh (Reinf-1), the initial cracks formed into the voids, followed by horizontal cracking. However, when the voids were above the textile mesh, the initial vertical cracks progressed past the textile mesh layer and thus continued in a vertical or diagonal path to the top of the specimen leading to early failure.

4 Conclusions

In this study, the flexural performance and behaviour of 3DPC elements reinforced with textile mesh were investigated. Only one possible application method was considered by applying the mesh during the printing process in between the layers, whilst printing the elements flat on the surface bed. Different variations of this method were printed to be tested in flexure via the four-point bending test. After analysing and discussing the results, the following conclusions were made:

1. The application of textile reinforcement significantly increases the flexural performance of 3DPC elements printed flat on the surface bed and reinforced in between the layers. Additionally, this reinforcement improves the ductility of the elements and ensures that strain-hardening behaviour occurs.
2. The initial cracking of the elements occur in the region between the two applied loads and only progresses until it reaches the reinforcement layer. The specimens then either fail in shear due to further vertical cracking occurring or fail due to the delamination of the printed layers below the reinforcement layer.
3. The results indicate that the textile has a much more significant impact when orientated perpendicular to the printed filaments, across shear planes, instead of longitudinally with the printed filaments.
4. Voids form underneath the textile due to the stiffness of the yarn, which creates a pivoting action lifting the one side upwards when being printed over. Moreover, the presence of the voids around the reinforcement negatively influences the performance, cracking sequence and failure mode of the tested specimen. If the formation of voids, however, is inevitable, specimens will perform better and more consistent if it is orientated such that the voids are below the textile reinforcement.

5 Recommendations

This study was conducted to improve the literature available on the performance and behaviour of textile reinforced 3DPC elements and to serve as a foundation for further studies on the topic. After the conclusion of this study, the following recommendations were made for the improvement of future endeavours:

1. Investigate different application methods of the textile mesh, including pre- or post-installed methods as well as vertical printing methods and the use of split nozzles.
2. When a strong textile mesh like the one in this study is used, bigger specimens must be tested, preferably with T-jackets to prevent shear failure from occurring. Specimen can also be tested using other dimension ratios.
3. Investigate the behaviour of textiles consisting of different fibres, textile geometries and aperture sizes.
4. Investigate the bond strength between the textile and the printed matrix to see what role it plays in the performance of the specimen.
5. Investigate the use of more ductile textiles to determine whether less voids will form in the specimen.
Lastly, it is recommended that the formation of voids must be prevented in future studies as it severely affects the performance of the specimen.

References