**Title**

# Reinforcements in 3D printing concrete structures: A review

**ABSTRACT:** 3D printing of concrete structures has had a strong development in recent years, enhanced by the advantages it presents over traditional construction. However, it currently still has some limitations. One of those limitations is to incorporate the reinforcements into the automated 3D printing process. The objective of this work is to present a review of the methods that have been used so far to reinforce the structures. The different methods used will be presented focusing on the reinforcement by the use of fibers. The properties of the fibers, lengths, percentages of the same used in the mixtures will be analyzed. The results of the different tests will be shown making a comparison between the values obtained from the tests carried out with the printed and molded materials. Finally, the increases in the results of the tests that these fibers provide with respect to the samples without them will be analyzed.

**KEY WORDS:** 3D concrete printing, additive manufacturing, reinforcement of 3D printing structures, fibers, mechanical properties.

## 1. Introduction

Construction and engineering constantly seek to improve their productivity by implementing new technologies. Currently, efforts and research are focusing on the additive manufacturing (AM) process. AM in the construction field is called 3D concrete printing (3DCP) and encompasses two different printing technologies. The first is called particle-bed 3D printing (Figure 1), a technique that consists of the deposition of a layer of dry material, followed by the spraying of a binding liquid in the specific areas, by means of a nozzle or a printing head composed of numerous nozzles [1], [2]. This technique has been the least used, due to its slower execution time, its impossibility of manufacturing in situ, since it can be affected by time and the particular joining system it has, due to which only a very small number of materials can be used [1]. On the other hand, the second technique called Extruded Material Systems (EMS) (Figure 2, Figure 3) has been the most widely used, especially in large scale products and will be detailed below. It consists of the automatic deposition, layer by layer, of a filament of cementitious or geopolymeric materials, by means of a nozzle that moves, following the patterns established by files elaborated with AutoCAD, and that are introduced into the control system [3], [4]. Within EMS the following printing processes can be distinguished: Contour crafting (CC) and Concrete printing (CP) [5]. The CC consists of extrusion and smoothing by means of a trowel of the outer layers of the elements and later filling them manually [3], [6]– [8]. On the other hand, CP is a process more used on a large scale and similar to the previous one, with the difference that the outer walls are not smoothed with the trowel [4], [9].

These extrusion techniques have presented some substantial advantages over traditional construction, which is why their development has been so remarkable in recent years. One of the most important factors in construction is cost, which can be reduced with this new construction system. This is due to the suppression of the formwork, thanks to the ability to maintain the shape of these new cementitious materials, which are laid layer by layer. Also, the amount of material can be reduced, since the printer can deposit the material in the areas that are needed, without the need of traditional construction that is to fill in the entire mold. In addition, due to the automation of the process, both the labor force, which also improves their working conditions in terms of safety, and the amount of material that is discarded, are considerably reduced, increasing the efficiency and productivity of the process. This offsets the higher cost that these more complex building materials and equipment can have. On the other hand, another factor that also presents a reduction compared to traditional construction methods is time, much shorter in these automated systems. Finally, this technique helps the design of much more complex and elaborate geometric shapes, difficult to obtain with the existing construction systems until now [10]–[13].

This technique is still in continuous development so it also presents some limitations on which work must be done. The first is the lack of a regulation for the use of 3D printing in construction, since it is difficult for it to comply with the technical codes existing so far, adapted to traditional construction. Therefore, in the future, new standards that include this AM process must be adapted or introduced. In the case of the tests that are carried out in the laboratory, such as flexural strength, compressive strength, interlayer bond strength, physical properties, etc., with the printed samples, something similar to the above happens, since there is no regulation for their performance either. In addition, the properties in fresh state of the cementitious and geopolymeric materials that have been developed are not yet perfectly characterized or standardized depending on the different existing printing equipment [10].

**Figure 1**: Pedestrian bridge built through particle-bed 3D printing (Alcobendas, Spain) -courtesy of Acciona-

**Figure 2**: House built through EMS 3D printing built (Valencia, Spain) -courtesy of Bemore3D-

**Figure 3**: Artificial reefs built through EMS 3D printing (Santander, Spain)

Secondly, at present, this technique has mainly focused on the development of vertical walls, mainly intended for the construction of houses. The elaboration of structures with more complex shapes, which may include internal cavities, cantilevers, etc., still requires further development, which allows to implement fillings as a provisional formwork. These could be made with different materials, such as sand, thixotropic sludge, degradable materials, seeking automation in the placement and subsequent stripping of them.

Thirdly, the finishes that are achieved using this technique are much rougher, coarser, and in many cases, they may require a subsequent treatment of the surfaces in the external faces.

Another limitation that can be found when making structures printed by extrusion is the adhesion of the numerous layers that are deposited until the elements are formed. The union that occurs between old and new concrete in a fresh state has been quite investigated, but these new unions of filaments in a fresh state still require further studies. These will help to find out what are the parameters that most affect the structures so that they present lower resistance in these directions and how to increase them [14]–[16].

In addition, one of the fields where 3D printing must still advance notably is in the elaboration of more sustainable mixtures for the environment, using recycled materials either in binders, aggregates, etc., trying to find a balance between cost of these materials, resistance and environmental impact.

On the other hand, another of the great limitations, which is quite linked to the previous one, is the structural resistance that concrete presents without the incorporation of some other element, such as reinforcement or fibers. This limitation leads to the objective of the review, which is to present the state of the art of the structural reinforcements that have been developed so far for 3D printing. The different experimental forms that have been presented so far will be exposed to try to incorporate the reinforcements automatically, since despite the high automation of the printing process, the assembly process is under development. On the other hand, the fibers that have been tested so far will be analyzed, with their corresponding physical characteristics, the optimal values of the parameters necessary for 3D printing, and the mechanical results they provide to the structures.

Finally, as in conventional concrete, porosity is a fundamental factor in the durability of printed mortars. In the case of 3D printing materials, the focus should be on this aspect due to the effect of the filament voids. In this novel form of construction, since no vibrators are used, there is a greater chance of pores forming between the filaments that are deposited layer by layer. In addition, pores can also form within the filaments themselves in the extrusion process. The formation of these pores is directly related to pump pressure, printing speed and fresh material properties, which include extrudability, buildability and open time. Therefore, a good balance between all these parameters should be sought to reduce the formation of these pores as much as possible, thus significantly increasing the durability of the manufactured elements. In addition, with the incorporation of fibers, special attention must be paid to the quantities of fibers and the relationships between their lengths and the diameters of the nozzles, since these can also favor the appearance of voids.

The structure of this review is described in the Figure 1.

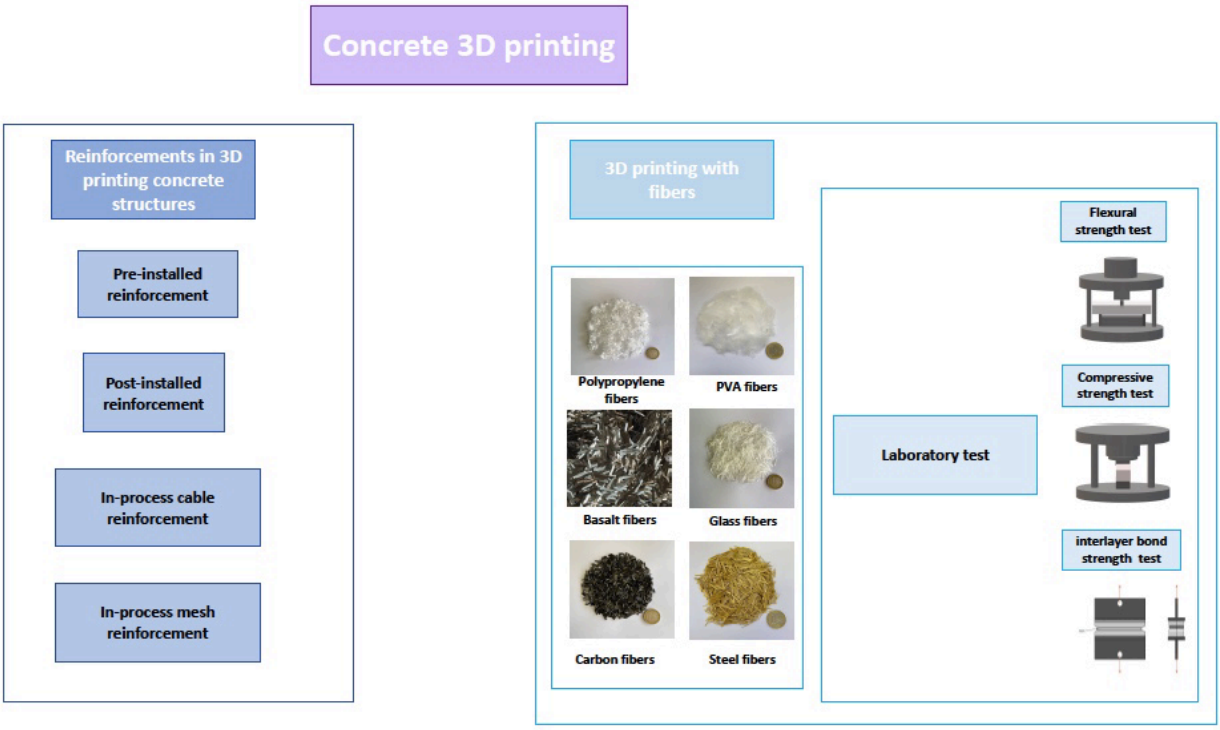


**Figure 4**: **Structure of the review** -

## 2. Reinforcement of 3D printing structures

In traditional construction, reinforcements are used in concrete structures to improve their mechanical performance. For the elaboration of these structures, formwork is used. Inside them the prefabricated reinforcements are placed, well fixed to each other. This allows that once the concrete has been poured and compacted, the adhesion between the bars and the concrete is optimal. This system is not suitable for 3D printing structures, because since they are not made with formwork, the bars would cause problems to the nozzle during printing and much of the automation of the process would be lost.

Currently, different technologies and methods have been developed and tested to incorporate the reinforcements, but none of them are yet considered effective. For this reason, this field keeps on in continuous development and research.

## 2.1 Post-installed reinforcement

The incorporation of the reinforcements once the 3D printing has been carried out has been the solution taken by some authors and construction companies that are beginning to use this construction system. The company Apiscor for the construction of its houses, with mainly vertical walls, uses a system that simulates the traditional construction. They print an outer shell that will serve as formwork and helps the bars to be inserted inside so they pour conventional concrete [17]. With this system, the need for demolding of traditional formwork is eliminated, but much of the automation of the printing process and the possibility of producing more complex forms than vertical walls are lost. In addition, it would be necessary to analyze how the bonding between printed and conventional concrete arises.

Other post-installed method that has been designed and tested by some authors is post-tensioning of the printed elements. Lim et al. designed and printed a wall-like bench using such system [18]. Salet et al. developed the first 3D printed bicycle bridge at the Eindhoven University of Technology [19], [20]. This method used by both authors consists of designing and printing the structures with a series of holes in which the bars will be subsequently inserted and prestressed. The bench was designed with 23 voids, in which once printed, the reinforcing bars were placed to be post-tensioned and grout. On the other hand, the bridge is a more complex and larger structure. It was divided into different parts, which were rotated 90 degrees and joined after printing and then pressed together by post-tensioned prestressing tendons.

Finally, Asprone et al. has proposed a method that has been tested with the elaboration of a beam. This consists of printing several segments with specific holes, which will help subsequent assembly by anchoring the steel elements. Then, the steel rebar reinforcement is installed externally, to fix all segments together and lock them into a continuous structural element. To ensure there are two proper anchoring dowels for insertion into the holes, each steel rebar can be bent at both ends. These are then fixed with a mortar or structural adhesive [21]. This system helps the beams to be partially hollow, reducing the amount of material and the weight of the structure, but like the two previous methods, it continues to present low automation.

## 2.2 Pre-installed reinforcement

This method used by the Chinese company HuaShang Tengda Ltd. to manufacture their homes, consists of the pre-installation in the first place of both vertical and horizontal steel bars manually. Subsequently, the concrete is extruded layer by layer using two nozzles, on both sides of the reinforcement [22]. This system has two limitations. It can only be used for the construction of vertical walls due to the arrangement of its nozzles and the reinforcement must be placed manually and held in place while the successive layers are deposited.

## 2.3 In-process cable reinforcement

This method, which has been developed and tested by different authors, consists of placing a continuous reinforcement at the same time it is being printed. For this, the reinforcement to be introduced must be flexible and the printhead be modifiable. A spool is placed that rotates and continuously feeds the reinforcement, which is introduced through an opening in the back of the nozzle. This helps the printing of a filament with the reinforcement already integrated. Bos et al. tested 3 different steel cables, which had great flexibility and different diameters. The two cables with larger diameters should improve the bond strength, so that their failure strengths can be reached before cable slip occurs. The one of smaller diameter had a good performance in this area, but it seemed not to be strong enough, since the fault was introduced by the cable break [23]. On the other hand, Lim et al. made a hybrid reinforcement in which he combined a steel cable reinforcement with different diameters and the incorporation of PVA fibers. This reinforcement can improve the flexural performance up to 290% and with the incorporation of the fibers the problem of sliding of the cable, shown by the previous author, is alleviated. Also, the increased diameter of the wire presents better fracture toughness [24]. Li et al. tested 5 types of cables: steel, nylon, carbon, aramid and polyethylene. Only the steel cable was adequate, because the rest of the cables are softer and have less stiffness and are knotted in the extruder. Additionally, different cable arrangement patterns were tested, providing good tensile behavior in the configurations that were aligned with the load directions [25]. Finally, Mechtcherine et al. showed different ways of introducing the cables in the printing process, developing his study with carbon reinforcements [26].

### 2.4 In-process mesh reinforcement

Marchment et al. developed a new method to embed mesh reinforcement at the same time when concrete layers are printed. The steel mesh is placed inside each layer, but at a higher height, which becomes the length of the lap of the next layer. To use this method, modifications had to be made in the system, mainly in the nozzle, where a vertical slit had to be made in the middle. The design is carefully made so that the flow of material is directed towards the center, helping to flow around and through the mesh, forming a good bond between the mesh and the material [27]. Further development and research of this system could provide 3D printing with greater automation, in terms of the reinforcement.

Finally, to improve the structural performance of the elements, it has been tested with the incorporation of different fibers types, in the mixtures developed so far for 3D printing. This will be discussed in detail in the next section.

## 3. Cost of 3DCP

In relation to costs, some authors have provided some estimations regarding the use of reinforced 3DCP. However, cost information is still scarce and not always authors provide sufficient information to allow comparisons among bibliography.

Inozemtcev & Duong [28] compare the cost of building a wall using a HSLWFC (high-strength light weight fiber-reinforced concrete) with a 3D printer vs using standard methods, concluding that there could be up to between 30-50% savings, mainly due to reduction of material and machinery hours. Concrete cost was 154.0 USD /m3; however, the authors did not mention whether the cost was actually estimated or accurately calculated.

Kreiger et al., [29] compare 8 different technologies to build a military hut of 47.6m2 area. The technologies compared were CMU (concrete masonry unit)+wood roof, ACC (additively constructed concrete) forms + wood roof, RACC (reinforced additively constructed concrete) straight +wood roof, RACC Chevron+wood roof, cast-in-place + concrete roof, ACC forms, RACC straight, RACC Chevron. It has to be remarked that concrete roof was not executed through 3D printing. No fibers were added to the concrete and rebars were placed manually, not by robots. Concrete cost was estimated taken from databases as 144 USD/m3, but not actually calculated. The same type of concrete was assumed for all cases.

García de Soto et al. [30] compares the construction costs of a wall using conventional methods vs 3DCP, either with a straight layout or with a curve layout. Both walls, either straight or curve, have the same volume: 4.39 m3. For a straight wall, the cost of using conventional methods was of 7,211 USD while using C3DP was of 22,101 USD. In the case of a curve layout wall, the cost of 3DCP was of 23,268 USD vs 53,955 USD with conventional methods, showing the advantages of 3DCP for building non-standard shapes. The cost of conventional concrete was 193 USD/m3 (955 USD for 4.93 m3) while for 3DCP was calculated as 546 USD/m3 (2693 USD for 4.93 m3). It was not stated clearly if the concrete cost was accurately calculated or just estimated. Fiber was just used to apply a finishing lay of concrete.

Nerella et al. [31] uses a one-floor building with external and internal walls to compare costs using conventional methods vs 3DCP. The concrete that they used was a high-performance concrete of 80 MPa compressive strength at 28 days and had no fibers added to it. The estimated cost was 130€/m3. They compared it with a conventional concrete of 25-30 MPa compression strength at 28 days stating that 3DCP was 70% higher.

Otto et al., [32] compared the construction costs of a wall made through conventional methods and through 3DCP. He assumed a cost of conventional concrete (C30-37) of 85€/m3 and assumed that 3DCP should be 30% higher; however, no actual calculations were done. In none of the cases fibers were used.

Han et al., 2021 [33] made an environmental and cost comparison among conventional concrete and 3DCP for two types of buildings: a silo and a small house. The cost of 14 m3 silo was between 5,810 RMB to 6,831 RMB when using conventional concrete, while the cost of the same silo with 3DCP ranged from 12,195 RMB to 12,913 RMB. Therefore, the unit prices of conventional concrete ranged 58-68 €/m3 and for 3DCP were 130-138 €/m3. Fibers were not used in any case.

Abdalla et al., 2021 [34] carried out an environmental and economical analysis of a house using conventional methods vs 3DCP. However, concrete cost expressed per m3 was not provided so it is difficult to extract any comparison among costs between conventional concrete and 3DCP. Measurements take-off were not mentioned in order to work out price per cubic meter of concrete.

Weng et al., 2020 [35] carried out an environmental and productivity assessment of a concrete bathroom unit. He provided overall costs and assumed for all cases a price of concrete of 115 SGD/m3 (82 €/m3), either for conventional concrete or 3DCP.

Yoris-Nobile et al [36] compared 16 different mortars apt for 3D printing. Some of them were used as a binder geopolymer and some of them used Portland Cement Type IIIB. They provided cost per T of material, ranging from 180.18 €/T to 184.18 €/T for the case of geopolymers and 44.80 €/T to 106.84 €/T for the case of cement mortars. None of them had fibers in the mix. By assuming a density of around 2100 kg/m3, costs could be expressed as 378-387 €/m3 for geopolymeric mortars and 94-224 €/m3 for cement mortars.

## 4. Improvement of the mechanical performance of 3D printing structures with the use of fibers

Fibers are a material that can be natural or synthetic, developed by man, which has been used in numerous processes, such as the manufacture of textile garments or the reinforcement of different materials such as cement. Synthetic fibers, in turn, can be classified as inorganic, where there are fibers such as basalt, carbon, glass and steel and polymeric fibers, where polypropylene (PP), polyethylene (PE), polyvinyl alcohol (PVA), aramids or polyester stand out. On the other hand, among the natural fibers, there are animal, vegetable and mineral fibers. All these fibers can present high modulus and tensile strength, such as basalt, carbon, glass, aramid or steel or low modulus and tensile strength, such as PE, PP, PVA [28]–[30].

Fibers have been used for the reinforcement of cementitious materials over the years with good results. For this reason, with the appearance of 3D printing and the development of new cementitious and geopolymeric materials, some of these fibers have begun to be incorporated into mixtures. In order to successfully print these mixtures, the properties of the material in the fresh state are essential [31]. Therefore, it can be said that the printability of the mix encompasses two fundamental aspects: extrudability and buildability [32]. Extrudability is the ability of fresh materials to pass through the hopper and pumping system to the nozzle, which extrudes and deposits a filament, which must be kept continuous. In turn, buildability can be defined as the ability of printed filaments to maintain their shape, supporting their own weight and the successive layers deposited on later [32], [33] . These two aspects must be kept in balance, since the more fluid materials will present a better extrusion, but on the contrary, they will lose buildability and vice versa [34]. These two factors, accordingly, depend on workability, a property that the mixture exhibits at the end of preparation and that is described by rheological parameters [32]. Finally, this property remains stable and within acceptable tolerances to be able to print a certain period, which is called open time.

**Figure 5: 3D printing with fibers**

Hereafter, the mixtures with fibers that have been tested so far by different authors will be analyzed. Table 1 presents a summary of the different characteristics they possess. On the other hand, Table 2 shows the results obtained in the mechanical properties tests (flexural strength, compressive strength and interlayer bond strength). The results between the traditional construction method and 3D printing and the improvements that the fibers provide in the resistance values with respect to the control samples will be compared.

Flexural strength measurements are carried out with prismatic specimens. In the three points bending test the loading rate is set, until failure. Obtaining the maximum force F, which helps to calculate the flexural strength, by the **(1**

$$\boldsymbol{Fs} = \frac{\boldsymbol{3 * F * l}}{\boldsymbol{2 * b * h}} \qquad (1)$$

The standard used in Spain to carry out flexural strength tests is UNE-EN 196 [35], in which specimens of dimensions 40 * 40 * 160 mm are tested, but there are other international or coming from other countries standards, that have been used by different authors as shown in Table 2.

Mold-cast specimens present the same flexural strength values regardless of the direction, but in 3D printing specimens they present important differences depending on the printing direction. This is also more significant in fiber-reinforced mixtures due to the orientation of the fibers when printing. The directions most analyzed by the different authors, shown in Figure 7, have been parallel and perpendicular. Print path is another factor that also notably affects flexural strength results. The most used until now in 3D printing are parallel and crosshatch, as can be seen in 4.

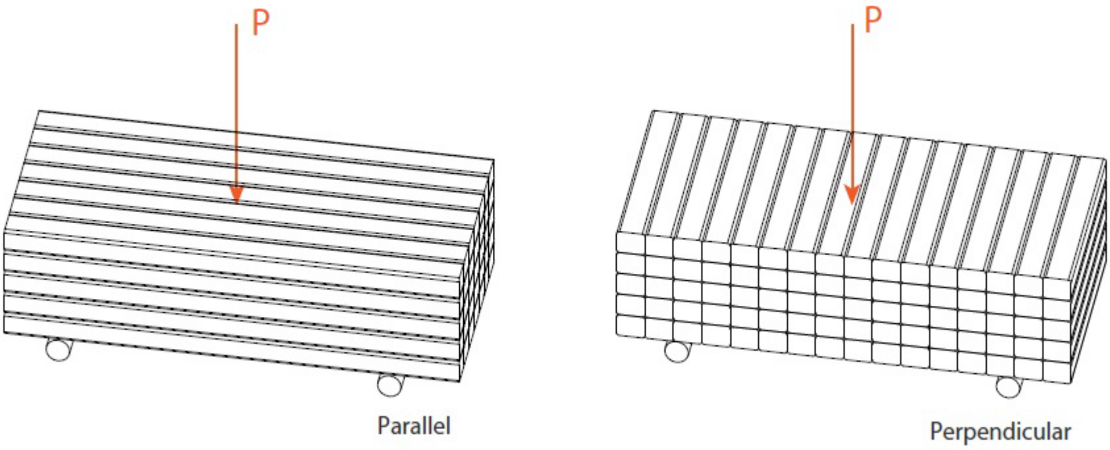


***Figure 6:*** *Flexural strength test directions. Left parallel and right perpendicular*

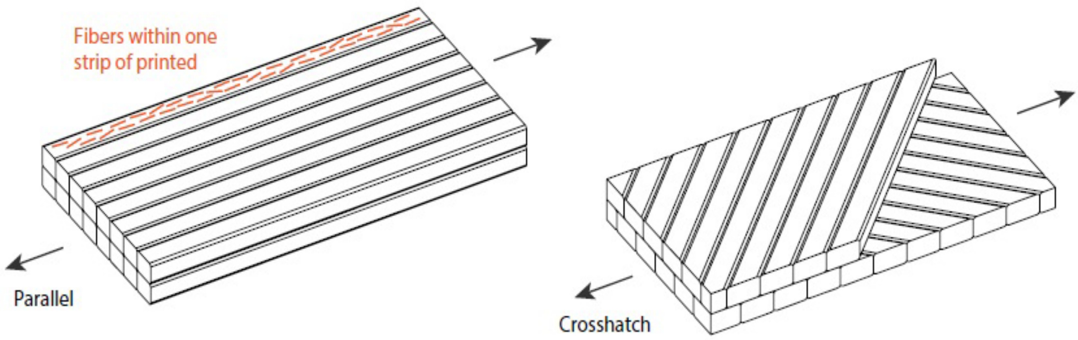


**Figure 7**: Print path. Left parallel and right crosshatch

The compressive strength can be calculated, measuring the maximum force F by the **(2**:

$$\boldsymbol{Fc = \frac{F}{b * h}} \tag{2}$$

In the compressive strength tests of the 3D printing specimens, the same printing directions and paths are found than in flexural strength test. In these tests, just like flexural strength tests, the standard UNE-EN 196 [35] is used in Spain, but the authors have used different standards, as shown in Table 2.

There are no standardized tests yet to measure the interlayer bond strength. Some authors have used the following method. Specimens are extracted from the printed filaments and load in uniaxial tension. Small notches are cut on both edges of the layer interface to ensure the failure of the specimen at the interface. Two metallic brackets are glued to the top and bottom of each printed specimen using epoxy resin. The inter-layer bond strength test is conducted under displacement control [36]–[38]. Moreover, an illustration of the test is included in 5.

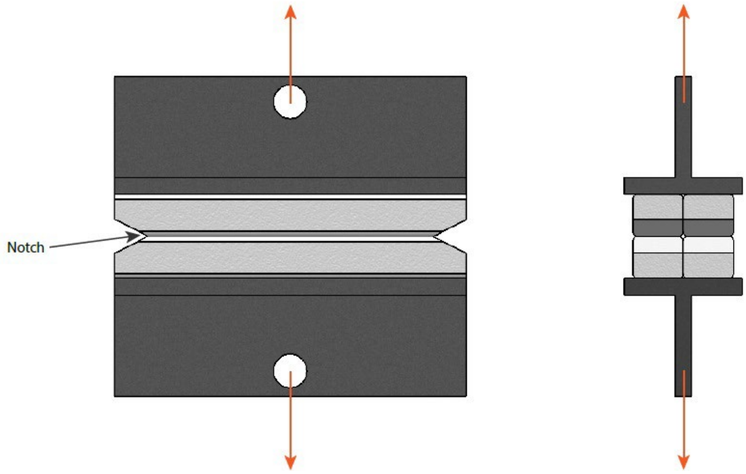


***Figure 8:*** *Interlayer bond strength test*

Another way to analyze the interlayer bond strength could be to make a comparison between the strengths obtained making the molded specimens and the printed specimens.

***Table 1***
Specifications of different types of fibers used in 3D printing

***Table 2***
Results of the mechanical properties tests of different types of fibers used in 3D printing

## 4.1 PP fibers

Polypropylene fibers have been used in conventional concrete to improve their properties, especially to reduce shrinkage cracking. In 3D printing concrete they have also begun to be used in geopolymeric mixtures. They have a low density of 0.9 g / cm³, an elastic modulus of 13.2 GPa and a tensile strength of 880MPa [36], [37], [39].

In conventional concrete the percentages of fibers that have been incorporated are below 1%, because a high quantity of these notably reduces the workability of the mixtures [28], [40]. 3D printing concrete must also maintain low percentages of PP fibers, so that the mix can maintain its workability and no blockages occur in the extrusion nozzle [39].

Al-Qutaifi et al. investigated the effect of introducing fibers with a length of 5 mm and a diameter of 0.022 mm. The ratio in which the fibers were introduced was 0.5% [39]. Nematollahi et al. carried out an investigation introducing different fractions of fibers 0.25%; 0.5%; 0.75%; 1% with a length of 6mm and a diameter of 0.011mm. The optimal ratio of fibers for 3D printing was 0.25% while with 1% workability was lost, having to adjust the mixture [36]. With the same previous characteristics and the optimal value of 0.25% Nematollahi et al. carried out a comparison between PP fibers and two different ones [37].

Regarding the flexural strength, Al-Qutaifi et al. obtained a value of 5MPa, producing only an increase of 3% with respect to the mixture without fibers. This indicates that these fibers do not increase notably flexural strength, but they increase ductility and reduce crack initiation. Nematollahi et al. in his first investigation compared both the parallel and lateral directions and the increase was not very significant in any of the four percentages of fibers, reaching the maximum values of 7.8MPa, with 0.25% in the perpendicular direction and 8.1 MPa with 0.5% on the side. Finally, Nematollahi et al. managed in other investigation to reach 9MPa, with an increase of 17%, but being the lowest value of the 3 types of fibers analyzed.

The compressive strength has only been analyzed by Nematollahi et al. obtaining highly variable values depending on the direction in which the test is carried out. This is due to the anisotropy of the materials and the orientation of the fibers in the printing direction. The notable increase occurred in the perpendicular direction, reaching a value of 35.8MPa in the mixture with 0.25% of fibers, which represents an increase of 60% with respect to the sample without fibers. In the other 2 directions, lateral and parallel, there is no substantial improvement, even reducing the compressive strength values in the lateral.

The interlayer bond strength is the parameter that is reduced with the incorporation of the fibers in the mixture. Nematollahi et al. obtained a maximum decrease in the mixture with 0.5% of fibers of 35% with respect to the sample mixture, one with only 1.7 MPa. In the comparison of fibers by Nematollahi et al. all also had a decrease, being 20% in the case of PP fibers. This reduction may be due to the greater stiffness that the fibers give to the mix in a fresh state, reducing the ability of the layers to deform as soon as they are placed.

### 4.2 PE fibers

Polyethylene fibers PE have also been used as reinforcement in both conventional mortars and 3D printing. These fibers, like PP fibers, have their main characteristic in the ability to reduce both the amount and the site of the shrinkage cracking [41].

These have a density similar to PP fibers, 0.97 g / $cm^3$, a high elastic modulus 116GPa and a tensile strength of 3000MPa [42]. Zhu et al. used fibers with a length of 12mm and a diameter of 0.024 mm and analyzed and made a comparison between mold-cast and printing samples with 3 fiber ratios: 1%, 1.5% and 2%. The flexural strength increased in both types, as the fiber ratio increased, passing in the case of the printed ones from 13.2 to 19.4 MPa. In addition, the results obtained in the 3D printing samples were higher than those of the molded ones, due to the orientation of the fibers with the printing. On the other hand, the compressive strength did not show variations with the increase of the fibers, in either of the two cases. What is appreciated is a greater resistance in the mold-cast samples, which may be due to the formation of some pores between the layers in the printing process [42].

### 4.3 PVA fibers

PVA has been one of the most tested fibers, both in conventional mortars and in 3D printing, presenting tests with cement and geopolymeric mixtures. Due to the greater number of existing studies, the parameters that have been studied are greater than in the previous cases.

PVA fibers have a density of 1.30 g / $cm^3$, with an elastic modulus between 16.9 and 37 GPa, a tensile strength between 1275 and 1600 MPa [37], [38], [43], [44]. Jo et al. was mainly focused on the optimal parameters for the printing process of the mixture incorporating the fibers. He used 3 fiber ratios: 0.1%, 0.2% and 0.3%, of which 0.1% was obtained as optimal. The higher ratios presented printing problems, because they clogged the nozzle and the screw, in short periods of time between 9 to 12 min. Meanwhile, the 0.1% ratio got a good impression, without clogging. In addition, these fibers managed to solve the problem of shrinkage cracks that had occurred in the simple sample, printing a firmer filament, which when hardened did not cause sinking or cracks. Furthermore, the obtained samples were analyzed under compressive strength and good results were obtained between 60.4 and 62 MPa [43].

Soltan et al. used fibers of 12mm in length and a content thereof of 2%. It should be noticed that in the case of this test it was a simulation of 3D printing by injection, and without an extruder screw, which could have allowed a higher fiber ratio. He made a comparison between mold-cast and 3D printing specimens and in the case of the compressive strength, the values did not show very significant differences. In addition, he analyzed the interlayer bond strength obtaining a value of 0.9 MPa and showing in all the tests a break in the lines of union of the filaments despite presenting more cracks [38].

On the other hand, J. Yu et al. analyzed the anisotropy exhibited by 3D printing samples which contained fibers. Therefore, 3 directions were used to carry out the tests: parallel, perpendicular and cross. The compressive strength tests presented the lowest values in the parallel direction with 16.45 MPa, being the failures in this case due to separation of the layers. Showing once again the problem of adhesion between layers, which is one of the biggest problems that are still present in 3D printing. The results in the other two directions were very similar to each other and with the cast sample. In the tensile strength tests, the results were contrary to those of compressive strength, the parallel being the best one, since it has highly aligned fibers parallel to the load direction [44].

Finally, Nematollahi et al. used 6mm length fibers with a 0.25% ratio to make a comparison with other fibers such as those of PP mentioned above. The results in flexural strength increased by 20% with respect to the sample without fibers, reaching a value of 9.5MPa, the increase being also higher than that of PP fibers. The interlayer bond strength results, as in the case of PP fibers, suffered a considerable reduction compared to the mixture without fibers, with a value of 2.58MPa [37].

## 4.4 Basalt fibers

Basalt fibers are obtained from natural basalt rock, an abundant material on the earth's surface. This means that its cost is not very high. Furthermore, this material is known as the "twenty-first century nonpolluting green material", because it comes from a natural material and no chemical additives are added in the manufacturing process. It can also be recycled, by incineration to obtain basalt powder [45].

These fibers have a high density, around 2.55 g / $cm^3$, with a high elastic modulus, even higher than that of glass fibers, between 87 and 93GPa and a tensile strength of 2180 and 4200 MPa [46], [47].

Basalt fibers have been widely used in conventional concrete due to their good strength properties, along with their abundance and sustainability. In recent years, they have also been tested in cement and geopolymer mixtures. Hambach et al. in his comparison of several fibers included those of basalt. The ratio used was 1%, because the test with 1.5% caused blocking of the extrusion nozzle. The diameter they present is 0.013mm and the length is 6mm, exceeding the diameter of the nozzle to promote the alignment of the fibers in the extrusion process. This author analyzed two print patterns, parallel and crosshatch. The flexural strength tests showed the increase that occurred with the incorporation of the fibers and the use of the parallel pattern, reaching 13.8MPa, while with the crosshatch pattern there was no improvement in the results. In the compressive strength test in addition to the two patterns, 2 directions of application of the loads were analyzed, perpendicular and longitudinal. The results in the perpendicular direction of both patterns were much higher, being the crosshatch pattern the one that presented an increase with respect to the sample without fibers, reaching a resistance of 85MPa [46].

Ma et al. [13] analyzed different contents of fibers: 0.1%, 0.3%, 0.5% and 0.7%, selecting 0.5% as optimal because when testing the higher ratio, blockages occurred in the nozzle. Their diameter was 0.012mm and the length was much higher than in the previous case, 18mm, but following the same instructions, tried to achieve a greater alignment of the fibers with a length greater than the diameter of the nozzle. The tests this time analyzed the application of the loads (load) in the 3 directions: X, Y, Z. These showed the great anisotropy that these samples present, with results in the compressive strength test of 39.6MPa, 37MPa and 28.8MPa. Direction X was the only one that did not present a reduction in properties with respect to mold casts. The flexural strength test also reflects this anisotropy, with an increase of 56% and 20.6% with respect to the mold cast in the Y and Z axes. In this case, the X axis was the one that presented bad results. This is explained by the alignment of the fibers in the printing direction, which will be perpendicular to the Y and Z loads [47].

## 4.5 Glass fibers

Glass fibers are considered mineral due to the materials included in their manufacturing process, among which are limestone or kaolin clay [48]. These fibers also have a high elastic modulus, although it is lower than that of basalt fibers, being around 72GPa. The tensile strength has a value of 3500MPa and a density that ranges between 1.7 and 2.2 g / $cm^3$ [46], [49].

These fibers have been tested in 3D printing by two authors, one with cement mixtures and the other geopolymeric. Panda el al. included these fibers in the geopolymer blends, tested 4 different fiber ratios: 0.25%, 0.5%, 0.75% and 1% with 3 lengths: 3, 6 and 8 mm. A previous study had the fiber content limited to 1% to avoid blockages. In the flexural strength, an increase in resistance was observed with the increase in the percentage of fibers. In this case, different test directions were also analyzed and the best results, as in previous studies with other fibers, were perpendicular to the impression. Furthermore, increasing the length of the fibers also produced a slight improvement in strength, but much less substantial than the percentage of the fibers. In the compressive strength tests, the addition of higher percentages of fibers did not have a great impact on resistance, presenting similar values in all cases [49].

Hambach et al. in his comparison, in which the basalt fibers were also found, used a ratio of 1% and a fiber length of 6mm. For the tests he used two patterns parallel and crosshatch. The flexural strength tests showed an improvement in the resistance compared to the mold cast using the parallel pattern, although these fibers were the ones that presented lower values than those tested, with 12.4MPa. In the compression tests together with the patterns, 2 directions of application of the loads were analyzed, perpendicular and longitudinal. The results in the perpendicular direction of both patterns were the highest, being the crosshatch pattern the one that reached the highest resistance with 84.5MPa [46].

### 4.6 Carbon fibers

This type of fiber has a very high elastic modulus, reaching values between 230 and 240GPa, with a tensile strength that ranges between 2800 and 5000MPa and a density between 1.6 and 2 g / cm³ [46], [50], [51].

So far, three have been the authors who have tested this type of fiber. Hambach et al. carried out a first study on the incorporation of fibers into cement pastes by injection. This focused on the alignment of the fibers, making a comparison between samples without fibers and those that incorporate a content of 1% and 3%, randomly oriented and aligned, through the nozzle. The length of the fibers for these tests was 3mm and the diameter of the injection nozzle 2mm to get the fibers to come out aligned. It was verified that this condition was fulfilled by optical micrographs that showed how the molded samples did not have any fiber orientation, while those with 1% had 62% of the fibers oriented at $0 \pm 20$ °, reaching up to 71 % for the sample with 3%. The flexural strength tests showed a great increase with the aligned fibers and with the increase in their content, reaching 46.5MPa with 1% and 119.6MPa with 3%. On the contrary, the compressive strength was a decrease when incorporating the fibers into the mixture, and another reduction when increasing the amount of fibers. This may be due to the increase in porosity with respect to the base matrix [51].

Later, Hambach et al. made a comparison with three types of fibers, among which were carbon fibers. The fibers had the same characteristics as in the previous study, but their content was 1%. In this case, fiber contents as high as in the previous case were not used, because an increase in them produced blocking of the extrusion nozzle. The flexural strength tests showed a notable increase in resistance, reaching 29.1MPa with the parallel printing pattern, a value much higher than that of the rest of the fibers tested. In the case of the compressive strength tests, very similar values were obtained to the other fibers analyzed, reaching the best results with the crosshatch pattern in the perpendicular direction, with a value of 82.3 MPa [46].

Finally, Korniejenko et al. made a comparison between carbon fibers and green tow flax fibers in geopolymers, simulating 3D printing by injection. They have a length of 6mm, and the selected ratio was 1%. In the flexural strength test, there was no outstanding increase with the incorporation of carbon fibers, while green flax fibers showed very good results, reaching an increase of 36% with respect to mold cast [50].

### 4.7 Steel fibers

Steel is the most used material for the reinforcement of structures in the construction field. It is used for the elaboration of reinforcement and for the development of fibers. This type of fiber can have a smooth or rough surface, the latter being used to improve adherence to concrete. In 3D printing they can present some complication in the extrusion process due to their greater rigidity. These fibers have very high values, being density 7.85 g / $cm^3$ and the elastic modulus 200GPa [39], [52], [53]. The diameters are much greater than those presented by the rest of the fibers mentioned above, ranging between 0.15 and 0.615mm.

In the field of 3D printing, this type of fiber has also turned out to be one of the most tested so far, especially in cement mixtures. Al-Qutaifi et al. has carried out a study in which it incorporates 1% of fibers of a great length, 40mm. The addition of these reduced the workability of the mixture by 4%. Flexural strength increased by 20% compared to samples printed without fibers. But despite this improvement, the adhesion between the layers was not good, because the fibers are distributed in a way that some can stand out, creating an irregular surface which can block the complete adhesion between subsequent layers. Also, it was found that the shorter the printing time between successive layers, the better the adhesion, but even so, this does not recommend the use of steel fibers in mixtures with geopolymers [39]

Arunothayan et al. analyzed the adhesion of reinforced concrete fibers incorporating 2% with a length of 13mm. He also stated that workability was slightly reduced with addition of fibers. The flexural and compressive strength tests were performed in 3 directions: perpendicular, parallel and lateral. The compressive strength of the 3D print samples was lower, in any of the 3 directions, than that of the molded samples. This is due to the higher porosity of the printed samples. The best compressive strength is obtained in the longitudinal direction because the pressure applied to the material during extrusion contributes to better compaction in this direction. In this direction a value of 144.2MPa is reached, but which is still lower than in the mold-cast samples. In contrast, the bending performance of the 3D printed was clearly superior. In addition, results of the bonding strength between layers were obtained that were much higher than those obtained by the rest of the authors who carried out this test, reaching a value of 5.1MPa. These results will be analyzed by the author in future research [52].

Pham et al. analyzed 2 fiber lengths, 3 and 6 mm with 4 different ratios: 0.25%, 0.5%, 0.75% and 1%. In this case, 3mm length fibers do not produce an improvement in flexural strength, as occurs with 0.25% and 0.5% of 6mm fibers. On the contrary, the 6mm fibers with the highest percentages showed a notable increase in the Z direction up to 15.4%. This highlights the importance of finding the optimal amount of fibers to incorporate. The compressive strength presents values that oscillate between 70 and 111MPa depending on the fiber content and the test direction. Fibers of 3mm length only have a positive influence in the Y direction, producing an increase between 10 and 24% compared to samples without fibers. In turn, 6mm fibers improve resistance in all directions between 6 and 23%. The set of 2D radiographic images helped to show the great orientation of the fibers with extrusion, as Hambach et al. had previously mentioned. 90% of the 3mm fibers are oriented between 0±30 °, reaching 95% with the 6mm fibers [53].

When steel fibers are used as reinforcement in mixtures, the length of these fibers is of great importance. Due to the hardness and rigidity of this type of fibers, the lengths of these fibers cannot be very long, since an excessive length can cause the number of pores that are formed to increase notably, due to the problems of the nozzle to extract these fibers, even blocking it. Or on the other hand in the worm screw can also cause problems, even blocking it.

## 5. Conclusions

3D printing is having great development and research in recent years in the construction field, due to the great benefits it can bring. This paper has focused on the reinforcements applied and developed so far. Existing methods have been described, focusing primarily on the inclusion of different fiber types in the printing process. For this reason, the physical characteristics of the fibers and the results of the different tests have been summarized. The most relevant conclusions are described next:

- Despite the different reinforcements that have been developed and tested so far, none has reached a high level of automation yet, with good resistance results. Further development of continuous methods, with cable or mesh, or the combination of these methods with other existing or future development could give a good boost to reinforcement automation.
- There is a lack of standardisation in carrying out tests in 3DCP. Therefore, references reviewed have used different curing conditions, methods to include the fibers in the mortar, sample size, definition of the control sample, etc. what hinders sometimes the comparison of results. Some authors have compared molded samples vs. printed samples, others mortars with different types of fibers, others directions of printing, and finally others compare samples with fibers vs. other without fibers. In this context, authors have adopted the increment in strength to respect a reference sample (mortar without fibers) to compare the performance of different formulations.
- The results of flexural strength with the incorporation of the fibers make the anisotropy of these materials even more accentuated. Important increases in

resistance are found in the direction parallel to the printing, which as shown in Table 2 oscillates between 3 and 30%. There are 2 cases in which higher resistance increases have been achieved. However, these are simulations of 3D printing process by using a small syringe and then placing the fibers manually in the mold which is not a very realistic method. Generally speaking, the compressive strength is not so much affected by the incorporation of the fibers

- Regarding the types of fibers, if we observe the increases in flexural strength with respect to the reference samples without fibers in the cement mixtures, the basalt fibers have been the ones that have obtained the greatest increase, reaching 30%, while in geopolymer blends, PVA fibers have achieved an increase of 23%. On the other hand, in the comparisons between the molded and printed specimens an increase is also observed despite the higher porosity that the printed samples present. This observation could lead to think that 3D printing process enhances fiber orientation and therefore increases the strength; however, further investigations should be carried out.
- Another aspect that is fundamental in the higher flexural strengths that have been obtained in the printed samples with respect to the molded ones, is the great alignment in the printing direction that the fibers present. This has been verified by some authors, obtaining values of 70% of the fibers oriented between 0±20 ° [51], reaching values higher than 90% between 0±30 ° [53]. This seems more noticeable when the length of the fibers is greater than the diameter of the nozzle.
- In addition, the content of fibers that is incorporated in many cases cannot be very high, due to the blockages that the fibers generate in the endless screw or in the nozzle. This can be seen in Table 2, in fibers such as basalt where an optimal ratio of 0.5% was obtained, in polypropylene with 0.25% or in PVA with 0.1%, despite the fact that in all cases the authors had tested higher values.
- The high modulus fibers have been the ones that have presented the greatest resistance. For this reason, other types of fibers that have already been studied in other fields should be investigated further, such as aramids, zylon, vectran, etc.
- In addition, seeing the good results of green flax fibers, other natural fibers could be tested in the future looking for materials that are more sustainable with the environment.
- The adhesion between the layers that are deposited in the impression needs to be further studied in the future, with new test methods such as the comparison of resistance shown by the molded specimens and the printed specimens.
- There is a lack of studies that analyse both cost and environmental impacts (through an LCA) of fiber reinforced 3DCP to be able to take a decision of what mortar and fibers formulation is the most efficient in terms of cost/resistance and environmental impacts/resistance.

## 6. Conflict of interest

The authors declare they have no conflict of interest.

## 7. Ethical statement

The authors state that the research was conducted according to ethical standards.

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## 9. References

[1] D. Lowke, E. Dini, A. Perrot, D. Weger, C. Gehlen, and B. Dillenburger, "Particle-bed 3D printing in concrete construction – Possibilities and challenges," *Cem Concr Res*, vol. 112, pp. 50–65, Oct. 2018, doi: 10.1016/j.cemconres.2018.05.018.

[2] G. Cesaretti, E. Dini, X. de Kestelier, V. Colla, and L. Pambaguian, "Building components for an outpost on the Lunar soil by means of a novel 3D printing technology," *Acta Astronaut*, vol. 93, pp. 430–450, 2014, doi: 10.1016/j.actaastro.2013.07.034.

[3] B. Khoshnevis, "AUTOMATED CONSTRUCTION BY CONTOUR CRAFTING-RELATED ROBOTICS AND INFORMATION TECHNOLOGIES," 2004. [Online]. Available: www.calearth.org

[4] B. Panda, G. B. Singh, C. Unluer, and M. J. Tan, "Synthesis and characterization of one-part geopolymers for extrusion based 3D concrete printing," *J Clean Prod*, vol. 220, pp. 610–619, May 2019, doi: 10.1016/j.jclepro.2019.02.185.

[5] A. al Rashid, S. A. Khan, S. G. Al-Ghamdi, and M. Koç, "Additive manufacturing: Technology, applications, markets, and opportunities for the built environment," *Automation in Construction*, vol. 118. Elsevier B.V., Oct. 01, 2020. doi: 10.1016/j.autcon.2020.103268.

[6] D. Hwang, B. Khoshnevis, and D. J. Epstein, "CONCRETE WALL FABRICATION BY CONTOUR CRAFTING." [Online]. Available: www.contourcrafting.org.

[7] J. Zhang and B. Khoshnevis, "Contour Crafting Process Plan Optimization Part I: Single-Nozzle Case," 2010.

[8] B. Khoshnevis *et al.*, "Mega-scale fabrication by contour crafting," 2006.

[9] S. Lim *et al.*, "DEVELOPMENT OF A VIABLE CONCRETE PRINTING PROCESS."

[10] S. El-Sayegh, L. Romdhane, and S. Manjikian, "A critical review of 3D printing in construction: benefits, challenges, and risks," *Archives of Civil and Mechanical Engineering*, vol. 20, no. 2. Springer, Jun. 01, 2020. doi: 10.1007/s43452-020-00038-w.

[11] J. Zhang, J. Wang, S. Dong, X. Yu, and B. Han, "A review of the current progress and application of 3D printed concrete," *Composites Part A: Applied Science and Manufacturing*, vol. 125. Elsevier Ltd, Oct. 01, 2019. doi: 10.1016/j.compositesa.2019.105533.

[12] G. de Schutter, K. Lesage, V. Mechtcherine, V. N. Nerella, G. Habert, and I. Agusti-Juan, “Vision of 3D printing with concrete — Technical, economic and environmental potentials,” *Cement and Concrete Research*, vol. 112. Elsevier Ltd, pp. 25–36, Oct. 01, 2018. doi: 10.1016/j.cemconres.2018.06.001.

[13] G. W. Ma, L. Wang, and Y. Ju, “State-of-the-art of 3D printing technology of cementitious material—An emerging technique for construction,” *Science China Technological Sciences*, vol. 61, no. 4. Springer Verlag, pp. 475–495, Apr. 01, 2018. doi: 10.1007/s11431-016-9077-7.

[14] S. H. Bong, B. Nematollahi, A. Nazari, M. Xia, and J. Sanjayan, “Method of optimisation for ambient temperature cured sustainable geopolymers for 3D printing construction applications,” *Materials*, vol. 16, no. 6, Mar. 2019, doi: 10.3390/ma12060902.

[15] B. Panda, S. C. Paul, N. A. N. Mohamed, Y. W. D. Tay, and M. J. Tan, “Measurement of tensile bond strength of 3D printed geopolymer mortar,” *Measurement (Lond)*, vol. 113, pp. 108–116, Jan. 2018, doi: 10.1016/j.measurement.2017.08.051.

[16] Y. W. D. Tay, G. H. A. Ting, Y. Qian, B. Panda, L. He, and M. J. Tan, “Time gap effect on bond strength of 3D-printed concrete,” *Virtual Phys Prototyp*, vol. 14, no. 1, pp. 104–113, Jan. 2019, doi: 10.1080/17452759.2018.1500420.

[17] “ApisCor, available online: https://www.apis-cor.com/as-masonry (accessed on 12 January 2020).”

[18] S. Lim, R. A. Buswell, T. T. Le, S. A. Austin, A. G. F. Gibb, and T. Thorpe, “Developments in construction-scale additive manufacturing processes,” *Autom Constr*, vol. 21, no. 1, pp. 262–268, Jan. 2012, doi: 10.1016/j.autcon.2011.06.010.

[19] T. A. M. Salet, Z. Y. Ahmed, F. P. Bos, and H. L. M. Laagland, “Design of a 3D printed concrete bridge by testing*,” *Virtual Phys Prototyp*, vol. 13, no. 3, pp. 222–236, Jul. 2018, doi: 10.1080/17452759.2018.1476064.

[20] T. A. M. Salet, Z. Y. Ahmed, F. P. Bos, and H. L. M. Laagland, “3D printed concrete bridge,” in *Proceedings of the International Conference on Progress in Additive Manufacturing*, 2018, vol. 2018-May, pp. 2–9. doi: 10.25341/D4530C.

[21] D. Asprone, F. Auricchio, C. Menna, and V. Mercuri, “3D printing of reinforced concrete elements: Technology and design approach,” *Constr Build Mater*, vol. 165, pp. 218–231, Mar. 2018, doi: 10.1016/j.conbuildmat.2018.01.018.

[22] “N.C. TV, World’s first 3D-printed house that can withstand 8.0-magnitude quake available online: https://www.youtube.com/watch?v=OloOc21_u80 (accessed on 12 Janary 2020).”

[23] F. P. Bos, Z. Y. Ahmed, E. R. Jutinov, and T. A. M. Salet, “Experimental exploration of metal cable as reinforcement in 3D printed concrete,” *Materials*, vol. 10, no. 11, Nov. 2017, doi: 10.3390/ma10111314.

[24] J. H. Lim, B. Panda, and Q. C. Pham, “Improving flexural characteristics of 3D printed geopolymer composites with in-process steel cable reinforcement,” *Constr Build Mater*, vol. 178, pp. 32–41, Jul. 2018, doi: 10.1016/j.conbuildmat.2018.05.010.

[25] Z. Li, L. Wang, and G. Ma, “Mechanical improvement of continuous steel microcable reinforced geopolymer composites for 3D printing subjected to different loading conditions,” *Compos B Eng*, vol. 187, Apr. 2020, doi: 10.1016/j.compositesb.2020.107796.

[26] V. Mechtcherine, A. Michel, M. Liebscher, and T. Schmeier, “Extrusion-based additive manufacturing with carbon reinforced concrete: Concept and feasibility study,” *Materials*, vol. 13, no. 11, Jun. 2020, doi: 10.3390/ma13112568.

[27] T. Marchment and J. Sanjayan, “Mesh reinforcing method for 3D Concrete Printing,” *Autom Constr*, vol. 109, Jan. 2020, doi: 10.1016/j.autcon.2019.102992.

[28] A. Inozemtcev and T. Q. Duong, “Technical and economic efficiency of materials using 3D-printing in construction on the example of high-strength lightweight fiber-reinforced concrete,” in *E3S Web of Conferences*, 2019, vol. 97. doi: 10.1051/e3sconf/20199702010.

[29] E. L. Kreiger, M. A. Kreiger, and M. P. Case, “Development of the construction processes for reinforced additively constructed concrete,” *Addit Manuf*, vol. 28, pp. 39–49, 2019, doi: 10.1016/j.addma.2019.02.015.

[30] B. García de Soto *et al.*, “Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall,” *Autom Constr*, vol. 92, pp. 297–311, 2018, doi: 10.1016/j.autcon.2018.04.004.

[31] V. N. Nerella, M. Krause, and V. Mechtcherine, “Direct printing test for buildability of 3D-printable concrete considering economic viability,” *Autom Constr*, vol. 109, 2020, doi: 10.1016/j.autcon.2019.102986.

[32] J. Otto, J. Kortmann, and M. Krause, “Cost calculation of concrete 3D printing [Wirtschaftliche Perspektiven von Beton-3D-Druckverfahren],” *Beton- und Stahlbetonbau*, vol. 115, no. 8, pp. 586–597, 2020, doi: 10.1002/best.201900087.

[33] Y. Han, Z. Yang, T. Ding, and J. Xiao, “Environmental and economic assessment on 3D printed buildings with recycled concrete,” *J Clean Prod*, vol. 278, 2021, doi: 10.1016/j.jclepro.2020.123884.

[34] H. Abdalla, K. P. Fattah, M. Abdallah, and A. K. Tamimi, “Environmental footprint and economics of a full-scale 3d-printed house,” *Sustainability (Switzerland)*, vol. 13, no. 21, 2021, doi: 10.3390/su132111978.

[35] Y. Weng *et al.*, “Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach,” *J Clean Prod*, vol. 261, 2020, doi: 10.1016/j.jclepro.2020.121245.

[36] A. I. Yoris-Nobile *et al.*, “Life cycle assessment (LCA) and multi-criteria decision-making (MCDM) analysis to determine the performance of 3D printed cement mortars and geopolymers,” *J Sustain Cem Based Mater*, 2022, doi: 10.1080/21650373.2022.2099479.

[37] D. Zhang, J. Yu, H. Wu, B. Jaworska, B. R. Ellis, and V. C. Li, “Discontinuous micro-fibers as intrinsic reinforcement for ductile Engineered Cementitious Composites (ECC),”

*Composites Part B: Engineering*, vol. 184. Elsevier Ltd, Mar. 01, 2020. doi: 10.1016/j.compositesb.2020.107741.

[38] M. Amran *et al.*, “Fibre-reinforced foamed concretes: A review,” *Materials*, vol. 13, no. 19. MDPI AG, pp. 1–36, Oct. 01, 2020. doi: 10.3390/ma13194323.

[39] C. J. Slebi-Acevedo, P. Lastra-González, P. Pascual-Muñoz, and D. Castro-Fresno, “Mechanical performance of fibers in hot mix asphalt: A review,” *Construction and Building Materials*, vol. 200. Elsevier Ltd, pp. 756–769, Mar. 10, 2019. doi: 10.1016/j.conbuildmat.2018.12.171.

[40] T. T. Le, S. A. Austin, S. Lim, R. A. Buswell, A. G. F. Gibb, and T. Thorpe, “Mix design and fresh properties for high-performance printing concrete,” *Materials and Structures/Materiaux et Constructions*, vol. 45, no. 8, pp. 1221–1232, Aug. 2012, doi: 10.1617/s11527-012-9828-z.

[41] D. G. Soltan and V. C. Li, “A self-reinforced cementitious composite for building-scale 3D printing,” *Cem Concr Compos*, vol. 90, pp. 1–13, Jul. 2018, doi: 10.1016/j.cemconcomp.2018.03.017.

[42] S. Lim, R. A. Buswell, T. T. Le, S. A. Austin, A. G. F. Gibb, and T. Thorpe, “Developments in construction-scale additive manufacturing processes,” *Autom Constr*, vol. 21, no. 1, pp. 262–268, Jan. 2012, doi: 10.1016/j.autcon.2011.06.010.

[43] M. Papachristoforou, V. Mitsopoulos, and M. Stefanidou, “Evaluation of workability parameters in 3D printing concrete,” in *Procedia Structural Integrity*, 2018, vol. 10, pp. 155–162. doi: 10.1016/j.prostr.2018.09.023.

[44] “UNE-EN_196-1, Methods of testing cement. Part 1: Determination of strength., AENOR - Asociación Española de Normalización y Certificación, 2018.”.

[45] B. Nematollahi *et al.*, “Effect of polypropylene fibre addition on properties of geopolymers made by 3D printing for digital construction,” *Materials*, vol. 11, no. 12, Nov. 2018, doi: 10.3390/ma11122352.

[46] B. Nematollahi, M. Xia, J. Sanjayan, and P. Vijay, “Effect of type of fiber on inter-layer bond and flexural strengths of extrusion-based 3D printed geopolymer,” in *Materials Science Forum*, 2018, vol. 939, pp. 155–162. doi: 10.4028/www.scientific.net/MSF.939.155.

[47] D. G. Soltan and V. C. Li, “A self-reinforced cementitious composite for building-scale 3D printing,” *Cem Concr Compos*, vol. 90, pp. 1–13, Jul. 2018, doi: 10.1016/j.cemconcomp.2018.03.017.

[48] S. Al-Qutaifi, A. Nazari, and A. Bagheri, “Mechanical properties of layered geopolymer structures applicable in concrete 3D-printing,” *Constr Build Mater*, vol. 176, pp. 690–699, Jul. 2018, doi: 10.1016/j.conbuildmat.2018.04.195.

[49] A. A. Ramezanianpour, M. Esmaeili, S. A. Ghahari, and M. H. Najafi, “Laboratory study on the effect of polypropylene fiber on durability, and physical and mechanical characteristic of concrete for application in sleepers,” *Constr Build Mater*, vol. 44, pp. 411–418, 2013, doi: 10.1016/j.conbuildmat.2013.02.076.

[50] Y. C. Banthia N, “Shrinkage cracking in polyolefin fiber-reinforced concrete. Mater.J 2000;97(4):432–7. ”.

[51] B. Zhu, J. Pan, B. Nematollahi, Z. Zhou, Y. Zhang, and J. Sanjayan, “Development of 3D printable engineered cementitious composites with ultra-high tensile ductility for digital construction,” *Mater Des*, vol. 181, Nov. 2019, doi: 10.1016/j.matdes.2019.108088.

[52] J. H. Jo, B. W. Jo, W. Cho, and J. H. Kim, “Development of a 3D Printer for Concrete Structures: Laboratory Testing of Cementitious Materials,” *Int J Concr Struct Mater*, vol. 14, no. 1, Dec. 2020, doi: 10.1186/s40069-019-0388-2.

[53] C. K. Y. L. J Yu, “Impact of 3D Printing Direction on Mechanical Performance of Strain-Hardening Cementitious Composite (SHCC),” *RILEM Bookseries 19*, pp. 255–265, 2019.

[54] H. Jamshaid and R. Mishra, “A green material from rock: basalt fiber – a review,” *Journal of the Textile Institute*, vol. 107, no. 7. Taylor and Francis Ltd., pp. 923–937, Jul. 02, 2016. doi: 10.1080/00405000.2015.1071940.

[55] D. V. M. Hambach, “Properties of 3D-printed fiber-reinforced Portland cement paste,” *Cement and Concrete Composites 79*, pp. 62–70, 2017.

[56] G. Ma, Z. Li, L. Wang, F. Wang, and J. Sanjayan, “Mechanical anisotropy of aligned fiber reinforced composite for extrusion-based 3D printing,” *Constr Build Mater*, vol. 202, pp. 770–783, Mar. 2019, doi: 10.1016/j.conbuildmat.2019.01.008.

[57] A. B. T. Tam, “High-performance ballistic fibers and tapes, 2016. doi:10.1016/B978-0-08-100406-7.00001-5. ”.

[58] B. Panda, S. Chandra Paul, and M. Jen Tan, “Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material,” *Mater Lett*, vol. 209, pp. 146–149, Dec. 2017, doi: 10.1016/j.matlet.2017.07.123.

[59] K. Korniejenko *et al.*, “Mechanical properties of short fiber-reinforced geopolymers made by casted and 3D printing methods: A comparative study,” *Materials*, vol. 13, no. 3, Feb. 2020, doi: 10.3390/ma13030579.

[60] M. H. N. T. Hambach M, “Portland cement paste with aligned carbon fibers exhibiting exceptionally high flexyral strength ,” *Cement and concrete research* , pp. 80–86, 2016.

[61] A. R. Arunothayan, B. Nematollahi, R. Ranade, S. H. Bong, and J. Sanjayan, “Development of 3D-printable ultra-high performance fiber-reinforced concrete for digital construction,” *Constr Build Mater*, vol. 257, Oct. 2020, doi: 10.1016/j.conbuildmat.2020.119546.

[62] L. Pham, P. Tran, and J. Sanjayan, “Steel fibres reinforced 3D printed concrete: Influence of fibre sizes on mechanical performance,” *Constr Build Mater*, vol. 250, Jul. 2020, doi: 10.1016/j.conbuildmat.2020.118785.