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ORIGINAL ARTICLE

General aspects of 3D printing applied to civil construction: a review

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ABSTRACT: Additive manufacturing, also called 3D printing, has been gaining ground in different sectors of industry, the arts, in addition to the biomedical environment. In recent years, this has been incorporated as a research and practice niche in civil engineering. The execution of works, at the stage where the inclusion of this technology stands, is crucial in understanding the variants and challenges of the process. In this sense, the present study aims to raise and discuss issues involving the 3D printing of cementitious compounds, bringing aspects of the printing system and the materials of the mixtures used, and observing the effects that these can cause on the quality and the final performance of the structure built. It is a review of the literature developed based on the search in the scientific databases ScienceDirect, Scopus, and Francis & Taylor, using selected descriptors, which resulted, after applying the inclusion and exclusion criteria, in a total of 295 findings. Among other characteristics, it was possible to perceive the predominance of the extrusion-based procedure, in addition to how the components of the different execution approaches, as well as constituents of the mixture, modify the characteristics of the product in its fresh and hardened state. In general, additive manufacturing proves to be suitable for use, making the improvements and discoveries brought by researchers an impulse for the technique to be a possible advance in the automation of the sector.

Keywords: 3D printing; additive manufacturing; cement compounds; industrial automation; printing system.

Aspectos gerais da impressão 3D aplicada à construção civil: uma revisão

RESUMO: *A manufatura aditiva, também denominada impressão 3D, vem ganhando espaço em diferentes setores da indústria, das artes, além do meio biomédico. Essa, nos últimos anos, passa a ser incorporada como nicho de pesquisa e práticas na engenharia civil. A realização de trabalhos, na fase em que se encontra a inclusão dessa tecnologia, é crucial no entendimento das variantes e desafios do processo. Nesse sentido, o presente estudo objetiva levantar e discutir questões que envolvem a impressão 3D de compostos cimentícios,* *trazendo aspectos do sistema de impressão e dos materiais das misturas utilizadas, observando os efeitos que esses podem ocasionar na qualidade e no desempenho final da estrutura construída. Trata-se de uma revisão da literatura desenvolvida a partir da busca nas bases de dados científicas ScienceDirect, Scopus e Francis & Taylor, utilizando descritores selecionados, o que resultou, após a aplicação dos critérios de inclusão e exclusão, em um total de 295 achados. Entre outras características, foi possível perceber a predominância do procedimento baseado em extrusão, além de como os componentes das diferentes abordagens de execução e os constituintes da mistura modificam as características do produto em seu estado fresco e endurecido. De modo geral, a manufatura aditiva se mostra adequada para uso, sendo os aprimoramentos e descobertas trazidos pelos pesquisadores um impulso para que a técnica seja um possível avanço na automação do setor.*

Palavras-chave: *automação industrial; compostos cimentícios; impressão 3D; manufatura aditiva; sistema de impressão.*

1 Introdução

The construction sector presents itself as an agent of socioeconomic development, a position conferred due to the nature of its duties, capable of generating employment and income, as well as strengthening other dependent market structures. Among its activities, the production of concrete stands out, as the material most consumed by construction, a fact that can be explained by its properties offered by it, from availability, usability, and cost, among other physical and mechanical characteristics.

As concrete is the predominant material in the current constructions in its different technological and constructive approaches, there are no sudden changes in this reality in the short term, making the automation and use of digital tools in the use of this material be projected as close advances in the areas of civil engineering. In addition, there are several motivations that favor the automation of construction such as the increase in permitted architectural complexity, cost reduction, including those related to the use of forms and production time, conditions related to worker safety, addition to factors sustainability, and waste reduction (Mechtcherine *et al*., 2019, 2020; De Schutter *et al*., 2018; Wu; Wang; Wang, 2016)

From the perspective of construction automation, additive manufacturing (AM), also known as 3D printing, has been gaining space and becoming an intensifying tool in the advances of the construction industry. This technology is based on the joining of materials for the development of a three-dimensional structure based on a projected digital model. Its use has been consolidated in several segments such as the arts, aerospace, automotive, and biomedical fields, among others. This wide application is the result of the possibilities and capabilities that AM offers, mainly linked to geometric precision and computerized control of its execution, responding to some of the demands imposed by these sectors including civil engineering (Albar *et al*., 2020; Asprone *et al*., 2018; Manikandan *et al*., 2020).

Regardless of the application area and the AM method treated, the construction of a printed object has its origin in the development of a graphic file from computer-aided design (CAD) programs, stored in an SLT extension, reference to the term Standard Triangle Language, which is then segmented into two-dimensional planes used by the printing system software to produce the layers and the final structure. At this stage, different processes and mixtures are used according to the expected result, being able to directly influence the characteristics and behavior of the product (Albar *et al*., 2020; Diggs-McGee *et al*., 2019; Khan, 2020).

AM applied to construction presents itself as a growing area and the focus of many studies that seek to understand the aspects involved in 3D printing of concrete and other cement mixtures that can be used, observing, among other factors, the effects of the characteristics of processes and materials for the production of the desired object, making it important to summarize and recognize these works in their different approaches. In this sense, this article seeks, based on a review of scientific databases, to raise and discuss the issues surrounding the technologies employed, as well as the impacts that the elements that make up the manufacturing system can play.

In view of this, the article is divided into sections, in order to succinctly present the solid elements of the study for comprehension and fluency, highlighting the following points: Section 2 provides a brief review highlighting a historical reading of the main forms of additive manufacturing; Section 3 presents the methodological sequence used in the study; Section 4 presents the results found both quantitatively and descriptively from the literature references collected, in addition to presenting relevant characteristics of the two printing processes, materials in mixtures, and the control parameters used in the evaluation of printing, ranging from non-destructive aspects like extrudability to mechanical behavior in the bonding between layers; and, finally, Section 5, in which the study's conclusions are presented.

2 Historical aspects of additive manufacturing

Additive Manufacturing (AM) can be defined as an automated process based on the layered manufacturing of a three-dimensional object from a geometric model developed using a CAD (Computer Aided Design) system (Albar *et al*., 2020; Alhumayani *et al*., 2020). Other terminologies such as Rapid Prototyping, Direct Digital Manufacturing, Solid Freeform Manufacturing, and 3D Printing (currently the most widespread), describe the same family of AM technology, producing its structures by adding materials, as opposed to traditional subtractive and formative methods, founded on the removal and molding of its components (Abdulhameed *et al*., 2019; Al Rashid *et al*., 2020; Buswell *et al*., 2007).

Although it is considered a recent technology, AM has its origin dated back to the 19th century, as highlighted by Bourell *et al*. (2009), linked to the practices of photo-sculpture proposed in 1860 by Frenchman François Willème, and of topography with the construction of layered relief maps patented by Blanther in 1890. However, it was only in the early 1980s that the process gained notoriety with its association with CAD and automated tools, which expanded its use, noting the filing of patents in several places like Japan, France, and the USA, which described from different approaches the manufacture of three-dimensional models through the construction of layers (Gibson; Rosen; Stucker, 2009).

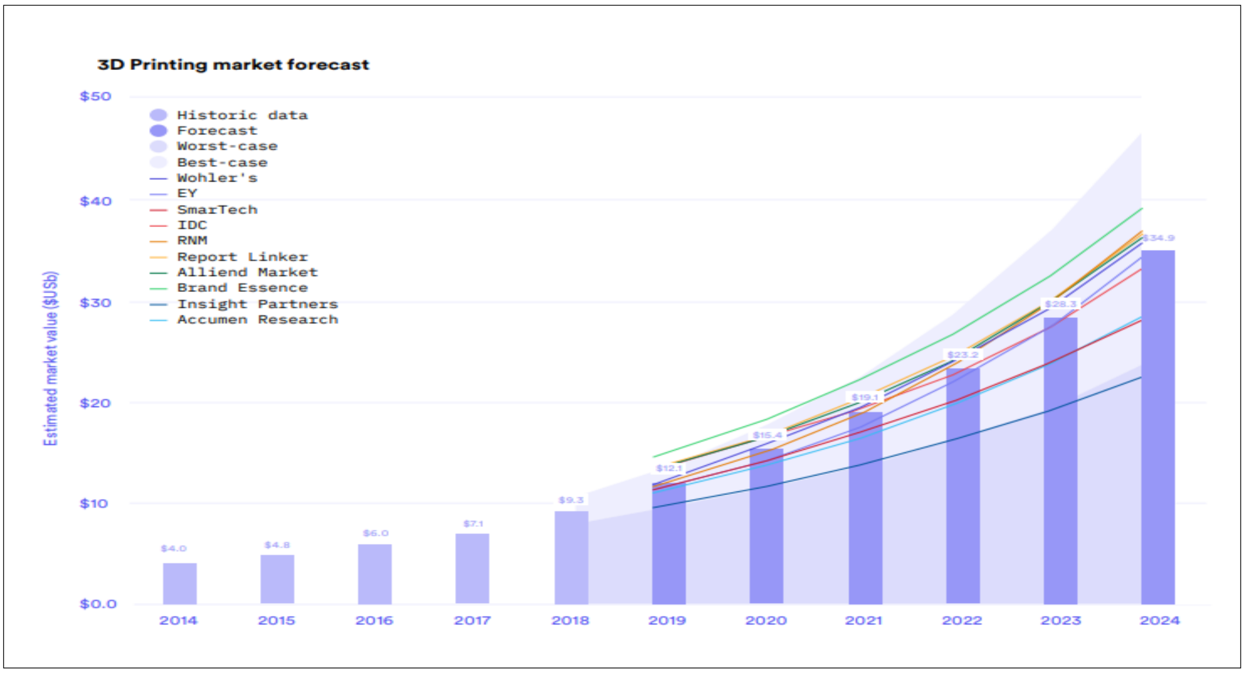
Among the main processes developed in the 1980s, we can highlight the patent filed in 1987 by Charles Hull, one of the most influential names when it comes to 3D printing, cofounder of the American company 3D Systems, the first company to commercialize the AM technology and, until then, one of the largest organizations in the sector. The technique consists of the solidification of thin layers of a liquid polymer sensitive to ultraviolet light (UV), this being called stereolithography (SLA), which began to be sold in 1988 (Abdulhameed *et al*., 2019; Bourell *et al*., 2009; Gibson; Rosen; Stucker, 2009).

Still, in the same decade, other processes were patented and helped boost the MA industry, such as the selective laser sintering (SLS) technology, filed in 1988 by Carl Deckard from the University of Texas, which is based on the use of a laser to sinter or melt a particulate material into layers. In addition to this, there is also fused deposition modeling (FDM) developed by Scott Crump and registered in 1989, which corresponds to the extrusion of heated thermoplastic material building the printed object in layers (Abdulhameed *et al*., 2019; Gibson; Rosen; Stucker, 2009).

It was from the 1990s onwards that significant growth in the commercialization of additive technology occurred, as well as the establishment of specialized companies, among them: Fused deposition modeling (FDM) linked to Stratasys; Cubital's solid base curing (SGC), which uses UV radiation and photosensitive resin to fully solidify the printed layer; Helisys' manufacturing of sheet objects (LOM), based on the construction of sheet-shaped materials (metal, paper or specific polymers) conveniently joined depending on the raw material used, which may occur by ultrasonic consolidation, adhesives, heat, pressure, among other processes; and the direct production casting (DSPC) sold by Soligen, which was developed by Massachusetts Institute of Technology (MIT), a mechanism that uses jets to deposit bonding liquids in ceramic powders for their solidification (Bourell *et al*., 2009).

In recent years, the methods and techniques of AM have been growing and developing at a rapid pace, gaining scope with application in various segments such as automotive, aerospace, medical, food, and construction, besides expanding its market share with a projection of rising over the next few years, as shown in Figure 1.

Figure 1 ▼
Additive manufacturing market trends.
Source: Hubs (2020)

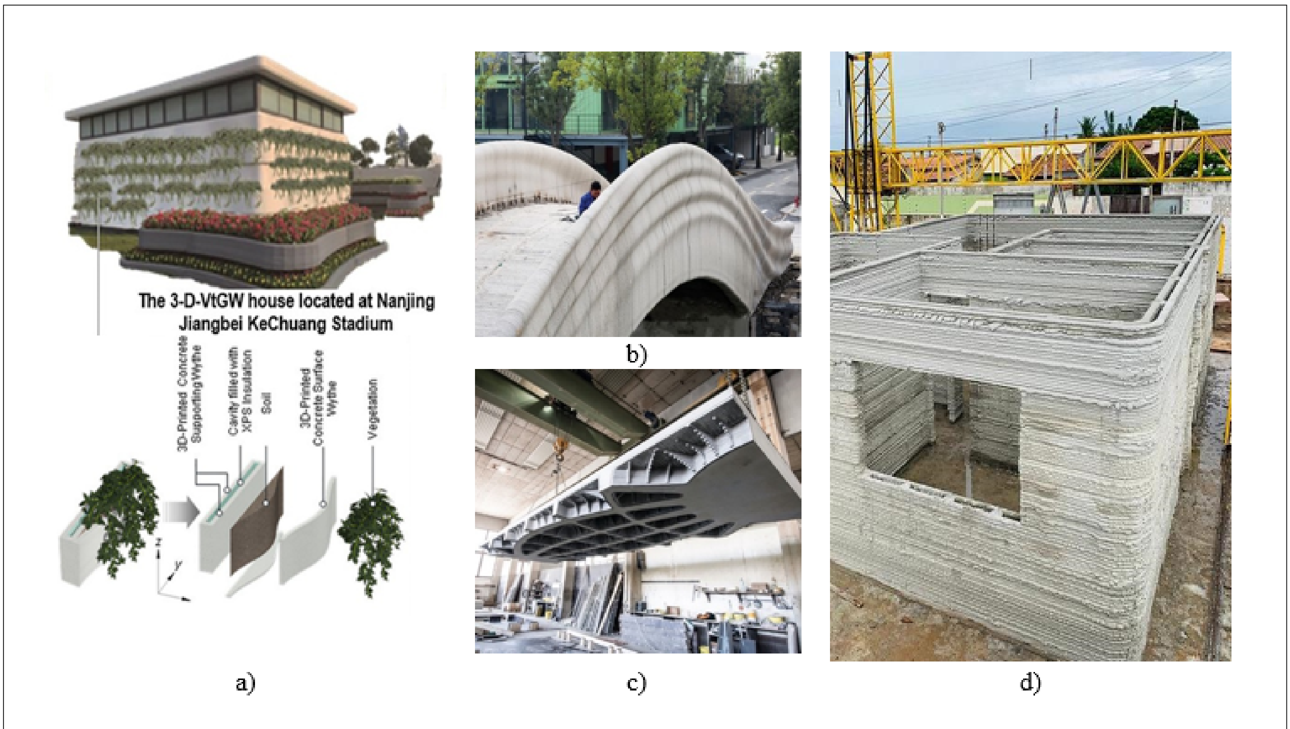


This trend is a result of several factors that, including the increase in accuracy and quality of printed objects, the availability of materials, and reduction of costs related to equipment, among others, contributed to the global 3D printing market to reach, in the year 2019, an estimated value of $12.1 billion, corresponding to average growth of 25% per year since 2014, is expected for the coming years, as shown in Figure 1, that the market will grow on average 24% per year, doubling its size every three years and reaching a value of $35.0 billion in 2024.

Despite the different technologies and advances in AM processes, these were not recurrent in the civil engineering market. It was only in the late 1990s that the methods developed in the pioneering studies by Pegna (1995), with the selective steam-bonding of a sand/cement mixture, and by Koshnevis (2010), with a ceramic material extrusion process called Contour Crafting patented in 2010. These, in addition to revealing the potential of AM in the construction sector, instigated new research, such as powder bed printing, in which the layers are formed with the deposition of powder and joined with a liquid binder, and the most popular currently, extrusion-based printing, based on the layered assembly of the object from a continuous filament with the aid of a nozzle (Al Rashid *et al*., 2020; Khan; Sanchez; Zhou, 2020; Mohan *et al*., 2021).

Since then, several studies on the AM of cementitious materials have been developed, addressing aspects of the preparation of mixtures, as well as the evaluation of the performance and mechanical behavior of printed objects, which enabled further exploration of the possibilities of their use in the construction of buildings and structures. In this case researchers from Southeast University (Nanjing, China), Nanjing Institute for Green Intelligent Additive Manufacturing Co. Ltd. (Nanjing, China) and the University of Tennessee (Knoxville, Tennessee, USA) jointly designed a 3D printed concrete building with the integration of a green wall system to save energy in buildings, prototype located in Jiangbei Kechuang Stadium, Nanjing, China, observed in Figure 2 (Khan; Sanchez; Zhou, 2020).

Figure 2 ▼
3D printed concrete buildings: a) Southeast University's greenhouse; b) Tsinghua University's pedestrian bridge; c) University of Graz's lightweight concrete slab; d) the first single-family residence printed in Brazil.
Source: (a) Khan, Sanchez and Zhou (2020); (b) e (c) Anton et al. (2021); (d) InovaHouse3D (2020)



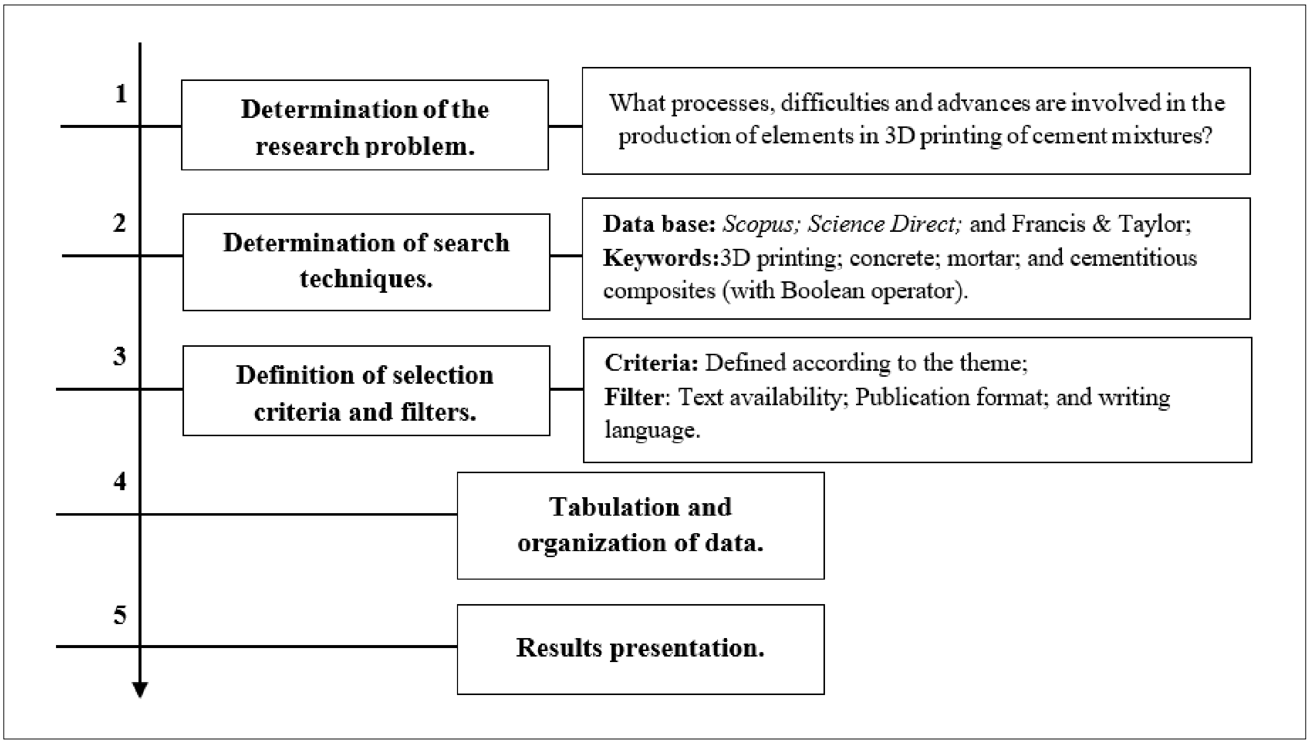
Several bridge designs also extend the range of concrete 3D printing applications, such as the pedestrian bridge, Figure 2b, from Tsinghua University which was produced entirely through AM processes. Another structure to highlight concerns the prototypes of printed slabs, such as the lightweight concrete roof designed at the University of Graz, Australia, Figure 2c, which incorporates automation methodology for the manufacture of ribbed slabs for application in construction (Anton *et al*., 2021).

In Brazil, between the years 2016 and 2017, the project of a printing machine for concrete parts was initiated with the Potiguar University, in Rio Grande do Norte. The equipment is based on an automated Cartesian system and has dimensions of 7.6 m × 12.0 m × 3.0 m (width × diameter × height). In 2019, the team responsible developed the construction of its first building, a house of 66.81 m², Figure 2d, in the municipality of Macaíba, Rio Grande do Norte, this was executed in 48 hours and mounted on conventional foundations (InovaHouse3D, 2020).

3 Research method

This is a literature review, a method that helps to formulate comprehensive explanations of the phenomenon observed from different methodological approaches. To this end, a protocol was established for surveying scientific research in selected databases, shown in Figure 3. In addition, as a way to increase the quality of the review process, these studies were organized and summarized with the aid of the StArt tool (State of the Art by Systematic Review) by LaPES (UFSCar – Federal University of São Carlos).

Figure 3 ▼
Protocol for conducting the systematic review.
Source: prepared by the authors



The research has the understanding of the main processes as a guiding problem, they can be technical in the execution of the elements or the development of the cement mix, the difficulties and advances that involve the practice of 3D printing in civil construction. In an attempt to clarify the issue raised, three electronic literature databases were selected, considering their impact and scope in the scientific environment and in the area of engineering: ScienceDirect; Scopus; and Francis & Taylor.

In the first moment of the survey of the studies the keywords "3D printing", "concrete", "mortar" and "cementitious composites" were defined, which associated with the operators "AND" and "OR" composed the search string: (3D AND printing AND concrete) OR (3D AND printing AND mortar) OR (3D AND printing AND cementitious AND composites).

For this systematic review only articles available in full, with contributions in the area of civil engineering and in English were selected, and these should have the format of publication in periodicals, congresses, or books, with a temporal extension of dissemination limited until March 2020, a period in which the closure of many research centers began due to the Coronavirus pandemic (covid-19), which may reflect on the present course of the growth or decrease of studies. In addition to these, other inclusion criteria were used in the selection of documents: to present characteristics of the production process of parts, including aspects such as types of execution, equipment, and application time, among others; to deal with the composition and properties of the mixtures used; and/or to report the main difficulties involving the previous points.

4 Results and discussion

Regarding the general characteristics of the search, a total of 3,792 publications were returned by the databases and item 1 of Table 1 shows the quantities verified in each database, this amount being subsequently taken for traceability of duplicates and analysis by the selection criteria, as presented in summary in Table 1.

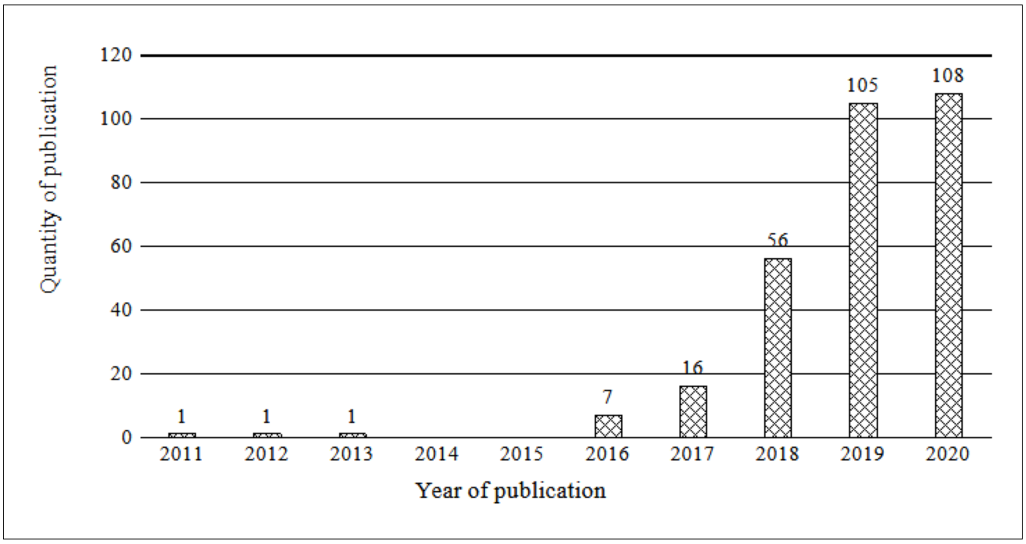
Table 1 ▼
Screening of studies found in the databases.
Source: research data

Stage	Number of papers by bases			
	ScienceDirect	*Scopus*	*Francis & Taylor*	*Total*
1. Final value of studies in response to a defined string.	193	684	2915	3792
2. Observation of relevance in the field of civil engineering and study format.	135	402	16	553
3. Withdrawal of duplicate jobs.	135	301	13	449
4. Application of the selection criteria specific to the topic with the reading of titles and abstracts.	98	192	5	
Total studies				295

In the first moment, item 2 of Table 1, studies that had no relation to the area under study were removed, either through available filters or by a previous reading of the titles, such as those that presented the keywords in their entirety but focused on areas of architecture or design, as well as works that were not part of the established format. The Francis & Taylor database was highlighted, which presented a significant number of studies in the field of pedagogy, health, and computing, among others, which contained isolated terms of the research even with the use of Boolean operators.

With the duplication of studies between the bases, item 3, removed with the aid of the Software StArt, resulted in 449 titles. After reading the titles and abstracts, item 4, in order to observe the specific criteria established in the research protocol, a total of 295 papers were selected for further summarization, with the distribution of publications over the years as shown in Figure 4.

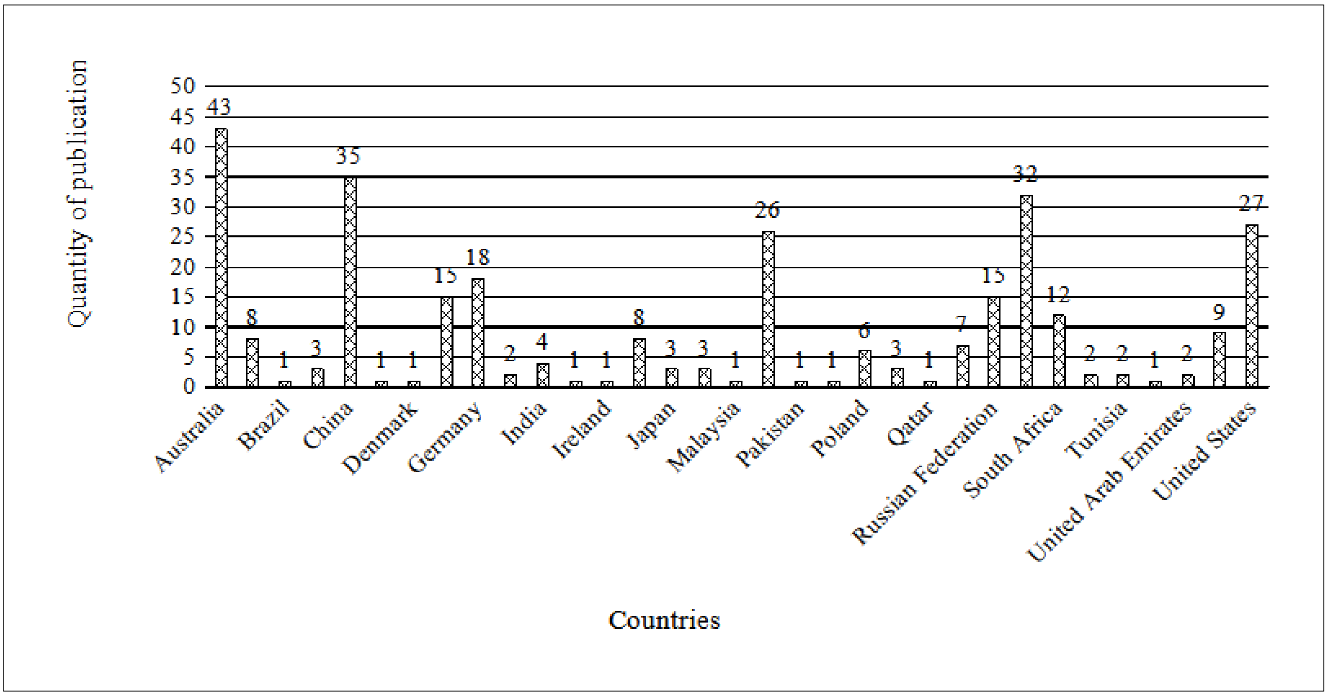
Figure 4 ▶
Yearly distribution of selected publications.
Source: research data



As mentioned, the present review did not limit a temporal extension, being achieved by searching a 10-year publication range, containing works that address the delimited theme and that are present in the chosen bases. Looking at Figure 4, the concentration of studies in the last five years is notable, with emphasis on the expressive increase between 2019 and 2020, in which together they collect 72.20% of the research, of which approximately 44.60% come from conferences or books and the other 55.40% papers indexed in journals. This behavior may be a response to expanding the fields of use of the 3D printing technique, which has now been applied in several areas of science and industry (Tay *et al.*, 2019).

Figure 5 ▼
Contribution of publications by country of origin.
Source: research data

The distribution by country of origin of the selected studies is shown in Figure 5, this contribution being associated only with the affiliation of the first author since the identification of the place of development of the research is not possible in the majority of papers.



It can be seen in Figure 5 that all continents, in greater or lesser numbers, have publications on the subject in question. In addition, among the selected countries, five stand out for the volume of studies carried out, including Australia, China, the Netherlands, Singapore, and the United States of America, which together contribute 55.25% of the total works published over the years.

4.1 Relevant characteristics of printing processes

The construction in an automated approach and linked to a three-dimensional model appears in the studies of this review through one of the processes: the Particle Bed (Particle-bed), based on the jet printing of the binder on a powder basis; or Concrete Printing (Concrete Printing), structured in the extrusion of a cementitious mixture. It is beyond the objective of this article to carry out a technical detailing of all the stages that involve each technology, however, its principles and some findings of the search on the scientific bases will be reported, with emphasis on the printing by extrusion that presents greater representativeness in the quantity of works (Lao *et al*., 2020; Yu; Du; Sanjayan, 2020).

The particle bed process, except for the specificities of its variants, consists of the layered deposition of powdered material, which will solidify in the desired shape. This transformation can occur through methods such as fusion, sintering, or application of a fluid binder phase, as in situations with cementitious materials, in which, through a printing nozzle, the mixture selectively involves the particles that make up the bed. Subsequently, the modeled part is removed from the base and the excess powder is removed and can be reused (Ingaglio *et al*., 2019; Lowke *et al*., 2018; Shakor *et al*., 2020; Tay *et al*., 2019).

One of the characteristics of the particle bed procedure is the possibility of printing complex structures, compared to other methods, with elaborate geometries and different directions. This design is facilitated by the production conditions, which provide support for the part without the need for struts or supports. However, this same factor becomes limiting for an in situ construction, as well as for producing large continuous pieces (Shakor *et al*., 2019; Tay *et al*., 2019).

Still on the particle bed printing approach, it is important to highlight that, as well as conventional methods in the production of concrete structures and other cementitious materials, the execution and post-processing procedures influence the properties and final performance of the printed object. This factor is the basis of studies raised by this review that address aspects such as the time interval between the printing plans, construction orientation and curing temperature.

Shakor, Nejadi, and Paul (2020) present, in their study, the effects that different time intervals in the printing process can have on the mechanical properties of the built structure. The studied samples, produced from a mixture composed of calcium aluminate cement, common Portland cement, and fine sand (75 μm - 150 μm), were submitted to different intervals (100 ms, 200 ms, 300 ms), being analyzed the mechanical behavior at compression in three and seven days. It was observed that the increase in the interval led to a resistance gain, being the 200 ms time the one that presented the best performance, followed by 300 ms. The authors state that this behavior is the result of better spreading and uniformity of the deposited binder since it allows greater penetration in the lateral and vertical directions on the surface of the powder. On the other hand, when this time is extended, the binder can infiltrate the lower layers of the bed and compromise the junction between the filaments, and consequently, the resistance is achieved.

The orientation of the printing plans also has a strong impact on the mechanical performance of the printed structure, as shown in the study by Shakor *et al*. (2019) who evaluated, among other parameters, the influence of different angles (0°, 30°, 37.5°, 45°, 90°), with respect to the bed print plane, in the mechanical flexion and compression resistances. The results showed that the 90º orientation achieved the highest compression performance among the other samples, followed by 0º and having 30º as the critical point with the lowest result. With regard to flexion, the 0º orientation was shown to have superior resistance, followed by the 30º angle and the 37.5º orientation as the lowest point.

The influence of the curing temperature of the printed structures, based on the powder bed process, was also a study conducted by one of the studies raised by this review. Shakor *et al*. (2019) evaluated the effects on the mechanical properties of mortar pieces, composed of calcium aluminate cement, common Portland cement, and fine sand (75 µm - 150 µm), cured in an oven with different temperature ranges (40 ºC, 60 ºC, 80 ºC, 90 ºC and 100 °C). It was observed that the increase in temperature up to the range of 80 ºC increased the resistance to both, compression and flexion. For the authors, as observed in the literature, this may be due to the acceleration in cement reactions, increasing the dissolution of alumina and silica of the unreacted particles, leading to greater availability in the system. This high proportion of alumina is also favored by the composition of the material rich in calcium aluminate cement. Contrary to the observed trend, for temperatures above 80 ºC, there is a decrease in the mechanical performance of the samples. This behavior, according to the authors, occurs since, at its limited temperature, the extra amounts of the dissolved components react and quickly form a layer on the surface of the particles, which inhibits new dissolutions and causes a decrease in the resistance of the samples.

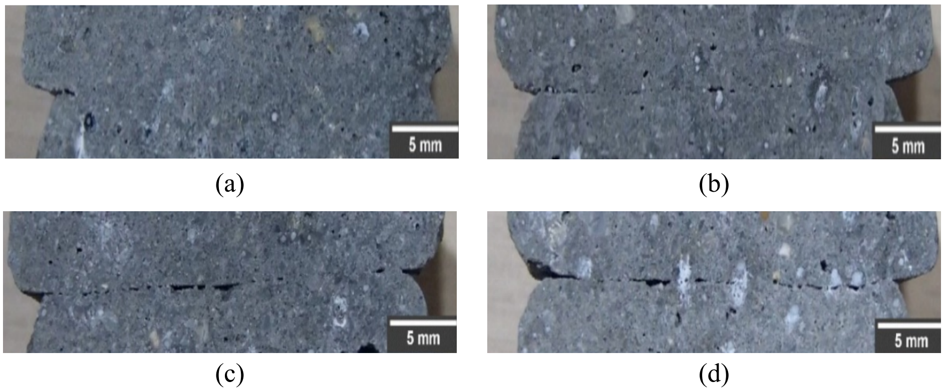
The concrete printing process (concrete printing) is based on extrusion, it consists of the deposition of the cement material in overlapping layers of a continuous filament (approximately 6 mm to 50 mm) following a path defined by computational modeling. This system consists of two main parts: the feeding, transport, and extrusion tools (including the conveyor/impeller shaft and the exit nozzle); and the automated and positional bearing set (Buswell *et al*., 2018; Panda *et al*., 2019).

Unlike the particle bed method, extrusion printing allows the construction of structures in situ and with less limited dimensions continuously. This is due to the characteristics of the equipment used, usually large gantries or robots with mechanical arms that promote an upward construction of the layers, including in permanent locations. However, a challenge in this process concerns the stability of the printed object, since the extruded filaments are continuously loaded, which must self-sustain to avoid significant deformations or even collapse. This behavior leads to the limitation of design concepts with complex geometries, requiring temporary support in some situations (Buswell *et al*., 2018; Nerella; Hempel; Mechtcherine, 2019).

The guarantee of the quality of the printed structures, as in the previous method, is not only a function of the characteristics of the materials or the properties of the mixture used, but it also depends on the control of the printing standards. Among the studies raised in this article that deal with extrusion-based technology, the interference of some of these processes were evaluated as, the time interval between the deposition of layers, the effects of the shape of the outlet nozzle on the geometry of the extruded material, and its stability, material flow rate and print speed.

Tay *et al*. (2019) investigated the effects of different intervals between the initial and subsequent filament printing from macroscopic and mechanical observations. The mixture had in its composition common Portland cement, active silica, fly ash, and natural river sand, printed at intervals of 1, 5, 10, and 20 minutes. With regard to the bonding force between the layers, this was measured by means of direct traction, with a logarithmic reduction being observed with a sharp drop between the intervals of 1 and 5 minutes, and little significance between the other values. This behavior can be caused by changes in the interfacial connection of the layers, as seen in Figure 6, the appearance of a physical separation formed by voids.

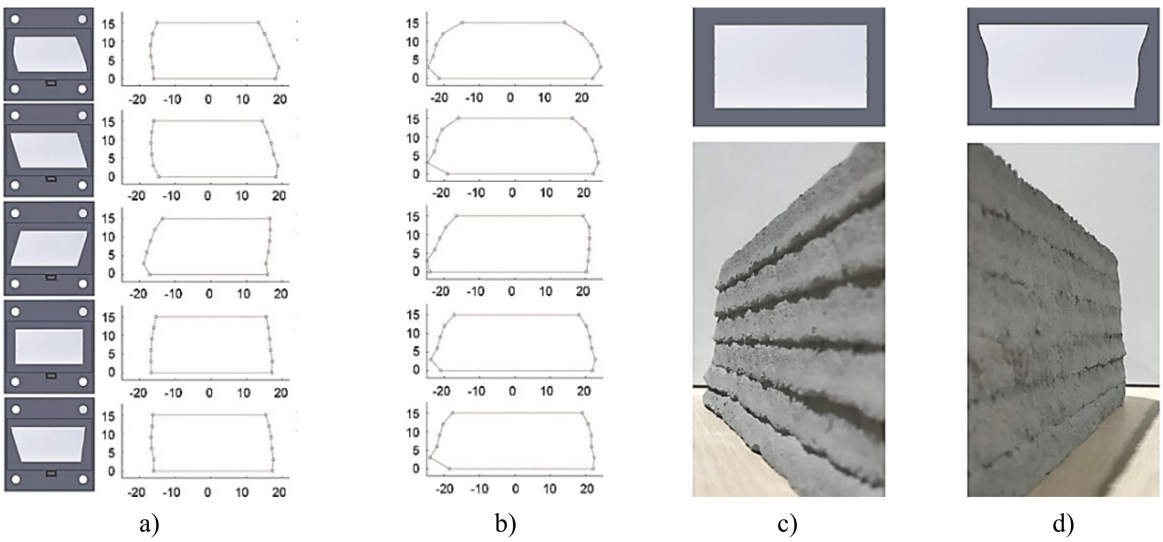
Figure 6 ▶
Cross section of the samples printed in: a) 1 minute time interval; b) 5 minutes time interval; c) 10 minutes time interval; and d) 20 minutes time interval.
Source: adapted from Tay et al. (2019)



Even for short periods of time, between the first and second samples, the layer's interface reacts in different ways. For the authors, as the new layer is superimposed on the surface of the lower filament, it can be reorganized in order to accommodate the stresses imposed and promote the connection between the faces. As time progresses, the material's stiffness increases, and thus the interaction is impaired, resulting in the voids shown in the images in Figure 6, since the deposition energy is no longer sufficient to promote reorganization at the interfaces.

Another aspect that is sought to control in printing is the finish quality of its surfaces. In this perspective, Lao *et al.* (2020) explore the possibility of controlling the geometry of the extrudate through the shape of the print nozzle for the improvement of the faces, using an experimental approach and an Artificial Neural Network model. Samples of thirteen different nozzles were made, the cross sections of which were subjected to image analysis with the aid of Matlab and using a predictive model a database with possible nozzles/extrudates was set up, with the intent of determining an ideal format for the desired situation. The authors found that the beak significantly influences the final filament formation, as seen in the images in Figure 7.

Figure 7 ▼
Extruded section geometry at a flow rate of: a) 1.1; and b) 1.4. Printed structure with the same process conditions and material with nozzle: c) straight pattern; and d) designed.
Source: adapted from Lao et al. (2020)



It was also found that the influence of the nozzle on the shape of the extrudate is affected by the flow rate of the material used, as shown in Figure 7, images a and b. The increased flow causes a horizontal elongation in the samples, mainly in the lower region. These deformations become increasingly independent of the shape of the extrusion nozzle as the rates are higher, thus requiring double control to achieve the desired final geometry (Lao *et al*., 2020).

Another factor that combined with material flow affects the mechanical and aesthetic properties of the printed structure concerns the output nozzle speed. This phenomenon was observed in the studies by Tay, Li, and Tan (2019), in which 32 samples were produced at distinct speeds and flow rates of 60 mm/s, 80 mm/s, 100 mm/s, 120 mm/s, 140 mm/s, 160 mm/s, and 200 mm/s and 37.9 ml/s, 45.0 ml/s, 48.0 ml/s, and 51.3 ml/s, respectively. Observing the sections and the integrity of the extruded filament, the authors verified that at low speeds and higher flows the printed area is larger than in opposite situations, due to the larger volume of deposited material, bringing an improvement in the bond between the layers and consequently in the mechanical behavior, however, the excess of material causes accentuated deformations, especially laterally, which reflects directly on the final surface finish of the structure.

In a contrary situation, with low flow and high speeds, a sharp number of fractures was verified along the filament, caused by friction between the material and the substrate that was associated with the rapid displacement which led to the shear of the extrudate (Tay; Li; Tan, 2019).

This characteristic of the variation of the velocity over the extrudate section was also found by Shakor *et al*. (2020), who applied different speeds (11.96; 23.78; 34.99; 46.56; 60.32; 70.97; 81.56 and 98.88 mm/s) obtained similar behavior to the ones mentioned before, with fractures for high velocities and change of the filament geometry compared to the nozzle diameter reaching up to 6 mm of amplitude.

4.2 Materials used in mixtures

3D printing having the aspect of automated production does not exempt from the development of a planning and selection of processes and materials used in the composition of the product to be printed. The steps must be carefully planned since they can compromise the product's performance.

Several factors affect the quality of the printed structure, and it is no different for the materials that make up the mix. Based on the results observed from the search in scientific databases, many works are directed to understand the effect of concrete, mortar, and cement composite composition on the final properties of the printed structure. Below the main materials found and some of their impacts on 3D printing are shown.

- Aggregate: within the studies surveyed a variety of aggregates were identified, such as river sand (Panda *et al*., 2018, 2019; Zhu *et al*., 2019); calcareous sands (Baz *et al*., 2020; Khalil *et al*., 2017); as well as sand with high lime content (Hosseini *et al*., 2019); and recycled aggregates coming from construction (Ding *et al*., 2020a, 2020b). The grain size ranges are predominantly fine and medium, with maximum dimensions of up to 4.75 mm being recorded (Zareiyan; Khoshnevis, 2017a), however, the use of expanded clay lightweight aggregate with a diameter of up to 10 mm has been identified (Rahul; Santhanam, 2020), as well as aggregates with a maximum diameter of 12.5 mm (Zareiyan; Khoshnevis, 2017b). A limiting mentioned in grain selection concerns the diameter of the injector nozzle and the thickness of the printed filament (El Cheikh *et al*., 2017; Mohan *et al*., 2020);

- Binder: the main cement found in the literature is of the following types: Portland cement of high initial strength, with greater representativeness for those classified by the Brazilian designation as CP V, being verified also the use of types CP II and CP IV (Ding *et al*., 2020a, 2020b; Kruger; Zeranka; Zijl, 2019); besides sulfoaluminous cement (CSA) (Chen *et al*., 2020a; Khalil *et al*., 2017; Zhu *et al*., 2019); and calcium aluminate cement (CAC) (Kruger, Zeranka; Zijl, 2020; Shakor *et al*., 2020; Soltan; Li, 2018). According to Long *et al*. (2019) Portland cement presents itself as a suitable material for 3D printing due to its inherent thixotropic properties, however, among other motivations, the high consumption and the improvement of the mixture properties lead to formulations with the use of additions and additives;
- Additions/Additives: among the additions and additives employed in the selected studies, the use of: Fly ash (Kruger; Zeranka; Zijl, 2019; Ma *et al*., 2020; Xu; Šavija, 2019); silica fume, also presented as silica fume and microsilica (Chougan *et al*., 2020; Ding *et al*., 2020b; Panda *et al*., 2018); other rheological modifiers such as methyl and microcrystalline cellulose (Chen *et al*., 2020b; Ding *et al*., 2020a; Long *et al*., 2019); clay materials such as nano clays and calcined clay (Ding *et al*., 2020a; Moeini, Hosseinpoor; Yahia, 2020; Zhang *et al*., 2019); limestone filler (Baz *et al*., 2020; Chen, 2020c; Furet, Poullain; Garnier, 2019); blast furnace slag (Chougan *et al*., 2020; Li, Wang; Ma, 2020; Lu *et al*., 2020); and metakaolin (Chen *et al*., 2020a, 2020b; Dedenis *et al*., 2020); in addition to steel, polypropylene, and glass fibers (Falliano *et al*., 2019; Fioretti *et al*., 2020; Hameed *et al*., 2020; Xu *et al*., 2020).

A study that presents itself in this context is the one conducted by Zareiyan and Khoshnevis (2017b), on mixtures produced with calcium sulfoaluminate cement, common Portland cement type I, and with an aggregate of distinct maximum sizes (2.3 mm; 4.7 mm; 6.25 mm; and 12.5 mm), with an aggregate/cement ratio of 1.15, in addition to superplasticizer and viscosity modifier additives. In which the effects of grain content on the mechanical performance of the extrusion printed object were observed. Compression tests at 14 and 28 days showed that the sample with smaller aggregates showed greater strength, with an increase of 104% being recorded for the 2.3 mm range compared to a mixture with 12.5 mm.

Another study that portrays the influence of aggregate in the printing process was developed by El Cheikh *et al*. (2017), investigating, from a numerical and experimental approach, the blockage in mortar extrusion caused by aggregate. To this end, the effects of the lower nozzle opening dimension, and rheological properties of the cement paste and paste volume on the blockage were evaluated. A simulation of the material flow using the discrete element method (DEM) was numerically performed and two mortars were used for the verification and experimental step: one prepared by mixing 4.0 mm glass beads with cement and water, tested in a nozzle with a bottom opening of 9 mm, 13 mm and 17 mm; and another with CEN (2009) standard sand, in compliance with EN 196-1 and of ISO 679, cement and water, with a nozzle of 6 mm and 9 mm.

It was numerically verified that for bottom opening diameter/aggregate diameter ratios greater than 4 no blocking occurred, suggesting that this behavior is not affected by the yield stress nor by the volumetric proportion of the paste. This behavior was similar for paste volume greater than 0.54 for both mixtures tested. However, at a ratio of approximately 4.25, and a volume ratio of exactly 0.54, a blockage was detected. According to the authors, this is due to the fact that in the model the layer formed by the cement paste flows together with the aggregates, while experimentally, during blockage the paste can separate from the grains and becomes similar to the medium composed of dry granules.

As for the effects of the other components of the mixture, Chen *et al.* (2020a), evaluate in their work the impact of using different levels of the viscosity modifier based on hydroxypropyl-methylcellulose (HPMC), a water retainer derived from cellulose ether, (in the proportions of 0.14%, 0.24% and 0.48% of the binder mass) in a Portland cement and calcined clay mortar, with quartz sand of maximum diameter of 2 mm, observing the imprint effects and the mechanical performance. Among the mixtures tested the one composed of 0.24% of the modifier presented the best characteristics compared to the others. In relation to the first proportion, the 0.24% dosage obtained better stability of shape and construction capacity, while in relation to the 0.48%, it exhibited a more adequate extrusion pressure, longer open time (which is related to its setting time, being the period that the mixture maintains an extrudable workability) and construction capacity equivalent to the others. Another point highlighted by the authors is the delay in cement hydration with increasing additive content, which may have been caused by a possible control of C-S-H adsorption and the massive precipitation of portlandite.

Tao *et al.* (2020) also evaluated the effects of additions in printing mixtures, in this case, cement replacement with limestone powder, on the fresh and hardened properties of the mortar. Six different mixes were prepared varying the sand (maximum diameter 2 mm)/agglutinant ratio (1.79 and 1.39 by volume) and promoting substitutions by the addition (0%, 25%, and 50% by volume of cement). In the fresh state, it was observed, through the squeeze flow test, that the increase in the substitution led to a decrease in stability, proving negative by offering risks of collapse. When it comes to the hardened state, the increased addition caused an increase in shrinkage and a reduction in compressive and flexural strengths, obtaining for the mixtures with 25% of limestone powder a compressive strength higher than 30 MPa, 28%, and 13% of the strength of their control samples.

Soltan and Li (2018) also conducted a study observing the effects that the components of their mixture produce on the workability of printing mortar. A total of five samples were assembled by varying their constituents, they are: calcium aluminate cement, hydroxypropyl methylcellulose, micro silica, ground silica, and attapulgite nano clay, in addition to polyvinyl alcohol (PVA) synthetic fiber, which was not varied. The evaluation of the workability was done by the fluidity test on the slump table, performed in two moments: at 28 min with half the volume of the mixture and at 43 min with the rest of the mortar that remained in the tank with the mortar mixer on, allowing to verify the loss of consistency with continuous agitation. The authors observed that the hydroxypropyl methylcellulose was efficient in controlling the initial fluidity, however, it caused changes in the hardening, unlike the calcium aluminate cement that proved to be effective in both situations. The nano clay reduced the setting time and consistency of the mixture, while the micro silica and ground silica that were replaced by a fraction of silica sand caused an increase in the rate of hardening, while maintaining the initial consistency.

4.3 Control parameters

As observed, numerous factors interfere with the quality and performance of a printed structure, from characteristics linked to the execution of the process to those related to the materials and mixtures used. Thus, as in other constructive approaches, controlling and measuring the properties, as well as defining relevant technical parameters is essential for the development of any construction, as well as the basis for improving the methods that involve the technology in question.

Among the parameters presented and raised in the review, the attributions that in a more representative way are presented in the studies, are those linked: extrudability, which is linked to the property of the mixture being pumped and transported by the devices associated with the printing equipment to the output; the buildability, related to the deformations of the printed filament, more specifically that of maintaining its shape with the overlapping of the layers and its own weight; and the mechanical performance, including the adhesion between the faces of the extrudates and resistance to compression and bending (Panda *et al*., 2019; Soltan; Li, 2018).

Extrudability and printability are parameters related to the rheology of the blend and are influenced in opposite ways. While the former requires high workability to enable material movement to extrudate deposition, the latter needed greater stability to mitigate deformation and enable stacking of the printed filaments. The mechanical properties are not exempt from this influence; depending on the consistency of the material, failures may occur at the junction of the layers or in the filament itself. Thus, a balance must be sought for these characteristics, measuring and controlling the mixtures and process to obtain the best structural performance (Chen *et al*., 2020a; Lao *et al*., 2020; Soltan; Li, 2018).

In this sense, the main measurement methods addressed by the studies surveyed will be presented, observing the parameters of extrudability, constructive capacity, and mechanical performance in compressive strength, flexural strength, and adhesion between the layers.

4.3.1 Extrudability and buildability

Among the studies that deal with the fresh characteristics of the material related to extrudability, these seek to evaluate, based on the flow behavior of the mixture, a state that meets the transport of the material, from storage to the system output nozzle. As for constructability, they are based on filament stacking, observing the deformations generated.

Chen *et al*. (2020a) evaluated the effects of hydroxypropyl methylcellulose in a 3D printing mortar, determining the fluidity by performing the shake table test based on ASTM C1437 (ASTM, 2015), with the spreading diameters measured in the interval from 10 to 120 minutes of rest, every 10 minutes, observing the instant of its reduction. Associated with this test and to obtain greater extrudability characteristics, the authors determined the material flow rates and extrusion pressures, these being recorded at different mix flow rates, modified, and measured by the pump controller. With respect to constructability, this was verified by means of shape stability, from the relationship between the final height of a structure printed in five layers, at a constant speed and after 30 minutes of rest, and the height of an object designed to have 67.5 mm.

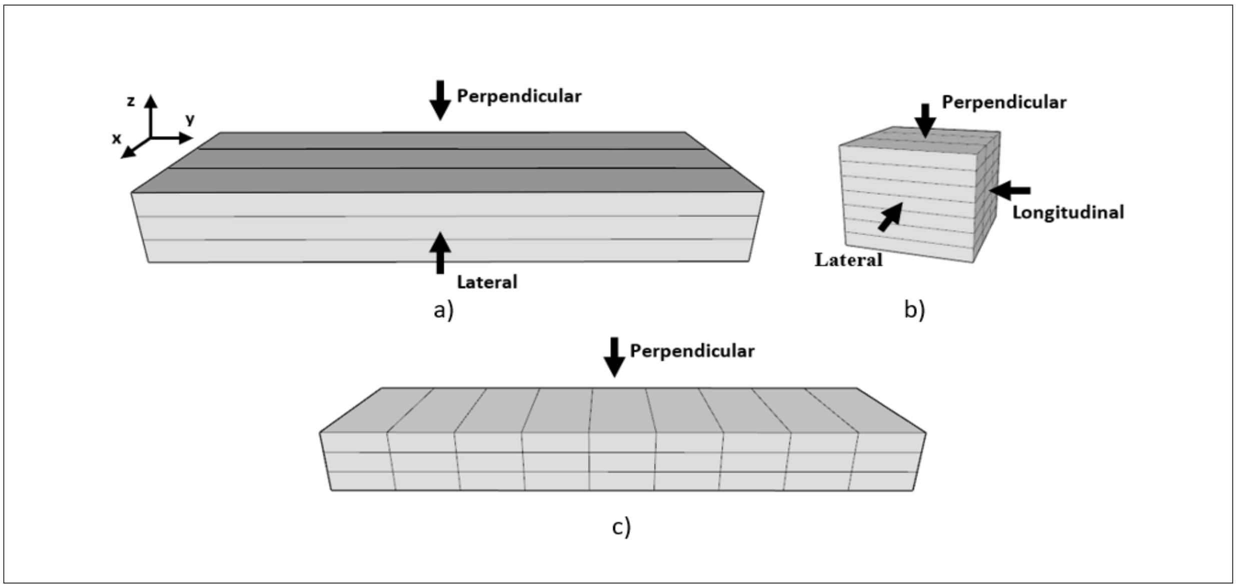
Baz, Aouad, and Remond (2020) analyzed in their research the bond between steel reinforcement and printed mortar as a function of their fresh properties, observing among other parameters the behaviors of extrudability and buildability. For the first parameter, the fluidity of the material was measured based on the ASTM C1437 test (ASTM, 2015). As for the buildability, the deformation of the printed material in layers was visually verified, comparing the values of the studied mixtures, being this manually built in the wall format by means of a gun with a 1 cm diameter nozzle.

Long *et al*. (2019) sought in their study the development of a sustainable cementitious mixture containing microcrystalline cellulose, evaluating the characteristics in the fresh state of the material. With regard to flowability, this was determined based on the shake table test according to GB/T 2419 (China National Standard, 2005), with the spreading diameter measured at 0 minutes, 20 minutes, 40 minutes, and 60 minutes. With respect to the constructability, it was verified by means of the deformation of the printed structure making a comparison with an object designed in five layers with a total height of 100 mm.

4.3.2 Mechanical resistance and bonding between layers

Most of the papers selected from the databases evaluate the mechanical properties by observing the compression, flexion, and tensile loads, the latter to verify the state of adhesion between the layers. The compressive strength tests are carried out on molded samples obtained directly from printed structures. Another important point concerns the anisotropic characteristics provided by the filament composition, which leads to the need of applying loads in multiple directions, as shown in Figure 8.

Figure 8 ▼
The direction of loading in extruded samples.
Source: adapted from Zhang et al. (2019)



Zhang *et al*. (2019) studied a high thixotropy cementitious mixture, in which among other properties, the mechanical characteristics are part of their methodological approach. To evaluate this behavior a 500 mm × 500 mm × 110 mm printed block was sawed into 100 mm × 100 mm × 100 mm specimens, targeted for uniaxial compression testing with a loading rate of 2 kN/s in the directions of image b of Figure 8, in addition to 100 mm × 100 mm × 400 mm specimens for bending with a rate 10 N/s in the directions of images a and c of Figure 8, all tested at 28 days in wet curing.

Le *et al*. (2012) also evaluated the hardened properties of 3D concrete with high-performance fiber-reinforced fine aggregate by analyzing molded and printed specimens tested at 1, 7, and 28 days in wet curing. The samples for compression are made up of 100 mm edge cubes, formed from conventionally molded specimens and taken by sawing extruded slabs with 350 mm × 350 mm × 120 mm and 500 mm × 350 mm × 120 mm, and tested according to BS EN 12390-3 (BSI, 2009a), in the directions of image b in Figure 8, at a loading rate of 0.4 N/mm^2. For bending, beams measuring 100 mm × 100 mm × 500 mm were molded, and three samples measuring 100 mm × 100 mm × 400 mm were extracted from a printed plate measuring 500 mm × 350 mm × 120 mm. These were tested by four-point bending according to BS EN 12390-5 (BSI, 2009b), in the directions of images a and c in Figure 8, following the direction of the filaments. The adhesion between the layers was measured in accordance with BS EN 14488-4 (BSI, 2008) by direct tensile testing on tubular cylinders of 58 mm diameter and 120 mm height taken from a 100 mm × 100 mm × 500 mm plate.

Arunothayan *et al*. (2020) evaluated the mechanical behavior of an ultra-high-performance fiber-reinforced printing mixture. For compressive strength, 25 mm edge cubes were molded and extracted from a printed specimen, tested at 90 days with a loading rate of 20 MPa/min in the directions of image b of Figure 8. Similarly molded and printed specimens were subjected to flexural strength determination performed by the three-point test, with the format evaluated as 25 mm × 25 mm × 280 mm dimensions for both situations, with loading in the directions of image b of Figure 8, at a rate of 1 mm/min. To evaluate the adherence between the layers, samples of 50 mm × 25 mm × 25 mm, composed of two layers with notches of 5 mm depth at the ends of the interfaces, had their upper and lower surfaces fixed on T-shaped support and were subjected to direct uniaxial traction at a displacement of 1 mm/min.

5 Conclusion

Additive manufacturing applied in construction, related to the printing of cement mixtures from a three-dimensional model, shows great potential for application, mainly in facing and mitigating problems such as costs linked to forms, waste, shortage of qualified labor, construction speed, and reproducibility, among others. In theory, the different techniques and approaches that were raised in the review and discussed throughout this article are in line with the statement of the potential of the association of these processes with civil engineering practices.

Among the studies evaluated, the predominance of the extrusion-based process is notorious, showing promise and relevance among the other techniques. However, it is worth mentioning that the printing processes listed in this review have different characteristics, mainly depending on the motivation of their application, which makes it difficult to point out a technique that has the greatest advantage. Regardless of the method, it was possible to observe that several factors intervene in the quality and performance of the structure to be printed, which in a specific way can be concluded:

- Control of printing processes is crucial to obtain the desired characteristics of the product. Factors such as print speed and material flow have a strong influence on the geometry of the extruded material and the integrity of the printed filament, which is reflected in the connection between the layer interfaces. In addition factors such as the shape of the outlet nozzle coupled to the system can improve the quality of the built structure, when planned and designed for specific situations.
- Materials and mixtures are essential to achieve the properties for the proper functioning of the equipment that is involved in the printing process, as well as in the construction, stability, aesthetics, and performance of the final structure. The components of a mixture need to provide a fluid enough behavior in the fresh

state so that it can be transported through the system ducts and when extruded and deposited on the other filaments, they must have stability with a minimum deformation level, without compromising the cohesion between the layers and performance of the hardened compound.

- The mentioned behaviors require a control and monitoring protocol to achieve the expected performance. The studies of this review pointed out fundamental characteristics that appeared in the midst of other parameters with greater predominance, being these: Extrudability and construction capacity, aimed at the characteristics in the fresh state of the material until it hardens, is measured from the observation of the fluidity of the mixture and its stability in the face of deformations; and in the hardened state, the mechanical behaviors to compression, bending and verification of adhesion between the layers by direct traction are addressed within the specificities of the printed structure, highlighting the anisotropic properties attributed to the final object of the impression, leading to the need to evaluate the different planes of printing loading.

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Conflict of interests

The authors declare no conflict of interest.

References

ABDULHAMEED, O.; AL-AHMARI, A.; AMEEN, W.; MIAN, S. H. Additive manufacturing: challenges, trends, and applications. **Advances in Mechanical Engineering**, v. 11, n. 2, p. 1-27, 2019. DOI: https://doi.org/10.1177/1687814018822880.

AL RASHID, A.; KHAN, S. A.; AL-GHAMDI, S. G.; KOÇ, M. Additive manufacturing: Technology, applications, markets, and opportunities for the built environment. **Automation in Construction**, v. 118, n. 1, 103268, 2020. DOI: https://doi.org/10.1016/j.autcon.2020.103268.

ALBAR, A.; CHOUGAN, M.; AL-KHEETAN, M. J.; SWASH, M. R.; GHAFFAR, S. H. Effective extrusion-based 3D printing system design for cementitious-based materials. **Results in Engineering**, v. 6, n. 1, 100135, 2020. DOI: https://doi.org/10.1016/j.rineng.2020.100135.

ALHUMAYANI, H.; GOMAA, M.; SOEBARTO, V.; JABI, W. Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete. **Journal of Cleaner Production**, v. 270, n. 1, 122463, 2020. DOI: https://doi.org/10.1016/j.jclepro.2020.122463.

ANTON, A.; REITER, L.; WANGLER, T.; FRANGEZ, V.; FLATT, R. J.; DILLENBURGER, B. A 3D concrete printing prefabrication platform for bespoke columns. **Automation in Construction**, v. 122, n. 1, 103467, 2021. DOI: https://doi.org/10.1016/j.autcon.2020.103467.

ARUNOTHAYAN, A. R.; NEMATOLLAHI, B.; RANADE, R.; BONG, S. H.; SANJAYAN, J. Development of 3D-printable ultra-high performance fiber-reinforced concrete for digital construction. **Construction and Building Materials**, v. 257, n. 1, 119546, 2020. DOI: https://doi.org/10.1016/j.conbuildmat.2020.119546.

ASPRONE, D.; AURICCHIO, F.; MENNA, C.; MERCURI, V. 3D printing of reinforced concrete elements: Technology and design approach. **Construction and Building Materials**, v. 165, n. 1, p. 218-231, 2018. DOI: https://doi.org/10.1016/j.conbuildmat.2018.01.018.

ASTM – AMERICAN SOCIETY FOR TESTING AND MATERIALS. **ASTM C1437-15**: Standard test method for flow of hydraulic cement mortar. West Conshohocken: ASTM, 2015.

BAZ, B.; AOUAD, G.; LEBLOND, P.; AL-MANSOURI, O.; D'HONDT, M.; REMOND, S. Mechanical assessment of concrete – Steel bonding in 3D printed elements. **Construction and Building Materials**, v. 256, n. 1, 119457, 2020. DOI: https://doi.org/10.1016/j.conbuildmat.2020.119457.

BAZ, B.; AOUAD, G.; REMOND, S. Effect of the printing method and mortar's workability on pull-out strength of 3D printed elements. **Construction and Building Materials**, v. 230, n. 1, 17002, 2020. DOI: https://doi.org/10.1016/j.conbuildmat.2019.117002.

BOURELL, D. L.; BEAMAN, J. B; LEU, M. C.; ROSEN, D. W. A brief history of additive manufacturing and the 2009 roadmap for additive manufacturing: looking back and looking ahead. *In*: RAPIDTECH: US – TURKEY WORKSHOP ON RAPID TECHNOLOGIES, 2009, Istanbul. **Proceedings** [...]. Ankara: Scientific and Technical Research Council of Turkey, 2009. Available at: https://www.turkcadcam.net/haber/2009/rapidtech-workshop/presentations/Presentation02.pdf. Accessed on: 21 Sep. 2022.

BSI – BRITISH STANDARDS INSTITUTION. **BS EN 12390-3**: Testing Hardened Concrete - Compressive Strength of Test Specimens. Milton Keynes, 2009a.

BSI – BRITISH STANDARDS INSTITUTION. **BS EN 12390-5**: Testing Hardened Concrete - Flexural Strength of Test Specimens. Milton Keynes, 2009b.

BSI – BRITISH STANDARDS INSTITUTION. **BS EN 14488-4**: Testing Sprayed Concrete - Bond Strength of Cores by Direct Tension. Milton Keynes, 2008.

BUSWELL, R. A.; SILVA, W. R. L.; JONES, S. Z.; DIRRENBERGER, J. 3D printing using concrete extrusion: A roadmap for research. **Cement and Concrete Research**, v. 112, n. 1, p. 37-49, 2018. DOI: https://doi.org/10.1016/j.cemconres.2018.05.006.

BUSWELL, R. A.; SOAR, R. C.; GIBB, A. G. F.; THORPE, A. Freeform Construction: Mega-scale Rapid Manufacturing for construction. **Automation in Construction**, v. 16, n. 2, p. 224-231, 2007. DOI: https://doi.org/10.1016/j.autcon.2006.05.002.

CEN – EUROPEAN COMMITTEE FOR STANDARDIZATION. **Standard sand certified in accordance with EN 196-1** – ISO Standard Sand Conforming to ISO 679. Bruxelles, 2009.

CHEN, M.; YANG, L.; ZHENG, Y.; HUANG, Y.; LI, L.; ZHAO, P.; WANG, S.; LU, L.; CHENG, X. Yield stress and thixotropy control of 3D-printed calcium sulfoaluminate cement composites with metakaolin related to structural build-up. **Construction and Building Materials**, v. 252, n. 1, 119090, 2020a. DOI: https://doi.org/10.1016/j.conbuildmat.2020.119090.

CHEN, Y.; FIGUEIREDO, S. C.; LI, Z.; CHANG, Z.; JANSEN, K.; ÇOPUROĞLU, O.; SCHLANGEN, E. Improving printability of limestone-calcined clay-based cementitious materials by using viscosity-modifying admixture. **Cement and Concrete Research**, v. 132, n. 1, 106040, 2020b. DOI: https://doi.org/10.1016/j.cemconres.2020.106040.

CHEN, Y.; RODRIGUEZ, C. R.; LI, Z.; CHEN, B.; ÇOPUROĞLU, O.; SCHLANGEN, E. Effect of different grade levels of calcined clays on fresh and hardened properties of ternary-blended cementitious materials for 3D printing. **Cement and Concrete Composites**, v. 114, n. 1, 103708, 2020c. DOI: https://doi.org/10.1016/j.cemconcomp.2020.103708.

CHINA NATIONAL STANDARD. **GB/T 2419-2005**: Test method for fluidity of cement mortar. Beijing: China Standards Press, 2005.

CHOUGAN, M.; GAFFAR, S. H.; JAHANZAT, M.; ALBAR, A.; MUJADDEDI, N.; SWASH, R. The influence of nano-additives in strengthening mechanical performance of 3D printed multi-binder geopolymer composites. **Construction and Building Materials**, v. 250, n. 1, 118928, 2020. DOI: https://doi.org/10.1016/j.conbuildmat.2020.118928.

DE SCHUTTER, G.; LESAGE, K.; MECHTCHERINE, V.; NERELLA, V. N.; HABERT, G.; AGUSTÍ-JUAN, I. Vision of 3D printing with concrete: Technical, economic and environmental potentials. **Cement and Concrete Research**, v. 112, n. 1, p. 25-36, 2018. DOI: https://doi.org/10.1016/j.cemconres.2018.06.001.

DEDENIS, M.; ANZIANE, S.; PERROT, A.; AMATO, G. Effect of metakaolin, fly ash and polypropylene fibres on fresh and rheological properties of 3D printing based cement materials. *In*: RILEM INTERNATIONAL CONFERENCE ON CONCRETE AND DIGITAL FABRICATION, 2., 2020, Eindhoven. **Proceedings** […]. Cham: Springer, 2020. p. 206-215. (RILEM Bookseries, v. 28). DOI: https://doi.org/10.1007/978-3-030-49916-7_21.

DIGGS-MCGEE, B. N.; KREIGER, E. L.; KREIGER, M. A.; CASE, M. P. Print time vs. elapsed time: A temporal analysis of a continuous printing operation for additive constructed concrete. **Additive Manufacturing**, v. 28, n. 1, p. 205-214, 2019. DOI: https://doi.org/10.1016/j.addma.2019.04.008.

DING, T.; XIAO, J.; QIN, F.; DUAN, Z. Mechanical behavior of 3D printed mortar with recycled sand at early ages. **Construction and Building Materials**, v. 248, n. 1, 118654, 2020a. DOI: https://doi.org/10.1016/j.conbuildmat.2020.118654.

DING, T.; XIAO, J.; ZOU, S.; WANG, Y. Hardened properties of layered 3D printed concrete with recycled sand. **Cement and Concrete Composites**, v. 113, n. 1, 103724, 2020b. DOI: https://doi.org/10.1016/j.cemconcomp.2020.103724.

EL CHEIKH, K.; RÉMOND, S.; KHALIL, N.; AOUAD, G. Numerical and experimental studies of aggregate blocking in mortar extrusion. **Construction and Building Materials**, v. 145, n. 1, p. 452-463, 2017. DOI: https://doi.org/10.1016/j.conbuildmat.2017.04.032.

FALLIANO, D.; SCIARRONE, A.; DE DOMENICO, D.; MAUGERI, N.; LONGO, P.; GUGLIANDOLO, E.; RICCIARDI, G. Fiber-reinforced lightweight foamed concrete panels suitable for 3D printing applications. **IOP Conference Series: Materials Science and Engineering**, v. 615, 012018, 2019. DOI: https://doi.org/10.1088/1757-899X/615/1/012018.

FIORETTI, M.; KOMPELLA, K. S.; MONTE, F. L.; ESPOSITO, L.; MENNA, C.; MORO, S.; ASPRONE, D.; FERRARA, L. Experimental investigation on the early age tensile strength of fiber reinforced mortar used in 3D concrete printing. *In*: RILEM INTERNATIONAL CONFERENCE ON CONCRETE AND DIGITAL FABRICATION, 2., 2020, Eindhoven. **Proceedings** […]. Cham: Springer, 2020. p. 255-261. (RILEM Bookseries, v. 28). DOI: https://doi.org/10.1007/978-3-030-49916-7_26.

FURET, B.; POULLAIN, P.; GARNIER, S. 3D printing for construction based on a complex wall of polymer-foam and concrete. **Additive Manufacturing**, v. 28, n. 1, p. 58-64, 2019. DOI: https://doi.org/10.1016/j.addma.2019.04.002.

GIBSON, I.; ROSEN, D. W.; STUCKER, B. **Additive manufacturing technologies**: rapid prototyping to direct digital manufacturing. 2nd. ed. New York: Springer, 2009.

HAMEED, R.; PAPON, A.; PERROT, A.; RANGEARD, D. Effect of metallic fibers on the print quality and strength of 3D printed concrete. *In*: RILEM INTERNATIONAL CONFERENCE ON CONCRETE AND DIGITAL FABRICATION, 2., 2020, Eindhoven. **Proceedings** […]. Cham: Springer, 2020. p. 439-448. (RILEM Bookseries, v. 28). DOI: https://doi.org/10.1007/978-3-030-49916-7_45.

HOSSEINI, E.; ZAKERTABRIZI, M.; KORAYEM, A. H.; XU, G. A novel method to enhance the interlayer bonding of 3D printing concrete: An experimental and computational investigation. **Cement and Concrete Composites**, v. 99, n. 1, p. 112-119, 2019. DOI: https://doi.org/10.1016/j.cemconcomp.2019.03.008.

HUBS. **3D printing trends 2020**: Industry highlights and market trends. Chicago: Hubs Manufacturing LLC, 2020. Available at: https://downloads.hubs.com/3D_printing_trends_report_2020.pdf. Accessed on: 21 Sep. 2022.

INGAGLIO, J.; FOX, J.; NAITO, C. J.; BOCCHINI, P. Material characteristics of binder jet 3D printed hydrated CSA cement with the addition of fine aggregates. **Construction**

and Building Materials, v. 206, n. 1, p. 494-503, 2019. DOI: https://doi.org/10.1016/j.conbuildmat.2019.02.065.

INOVAHOUSE3D. **Desenvolvimento de produto em impressão 3D em Brasília**. 2020. Available at: https://www.inovahouse3d.com.br. Accessed on: 7 Oct. 2021. In Portuguese.

KHALIL, N.; AOUAD, G.; EL CHEIKH, K.; RÉMOND, S. Use of calcium sulfoaluminate cements for setting control of 3D-printing mortars. **Construction and Building Materials**, v. 157, n. 1, p. 382-391, 2017. DOI: https://doi.org/10.1016/j.conbuildmat.2017.09.109.

KHAN, M. A. Mix suitable for concrete 3D printing: A review. **Materials Today: Proceedings**, v. 32, part 4, p. 831-837, 2020. DOI: https://doi.org/10.1016/j.matpr.2020.03.825.

KHAN, M. S.; SANCHEZ, F.; ZHOU, H. 3-D printing of concrete: Beyond horizons. **Cement and Concrete Research**, v. 133, 106070, 2020. DOI: https://doi.org/10.1016/j.cemconres.2020.106070.

KHOSHNEVIS, B. **Robotic systems for automated construction**. Depositor: University of Southern California USC. US 7,641,461 B2, Filed: 21 Jan. 2005, Application granted: 5 Jan. 2010. Available at: https://patents.google.com/patent/US7641461B2/en. Accessed on: 10 Oct. 2021.

KRUGER, J.; ZERANKA, S.; ZIJL, G. V. A rheology-based quasi-static shape retention model for digitally fabricated concrete. **Construction and Building Materials**, v. 254, n. 1, 119241, 2020. DOI: https://doi.org/10.1016/j.conbuildmat.2020.119241.

KRUGER, J.; ZERANKA, S.; ZIJL, G. V. An ab initio approach for thixotropy characterisation of (nanoparticle-infused) 3D printable concrete. **Construction and Building Materials**, v. 224, n. 1, p. 372-386, 2019. DOI: https://doi.org/10.1016/j.conbuildmat.2019.07.078.

LAO, W.; LI, M.; WONG, T. N.; TAN, M. J.; TJAHJOWIDODO, T. Improving surface finish quality in extrusion-based 3D concrete printing using machine learning-based extrudate geometry control. **Virtual and Physical Prototyping**, v. 15, n. 2, p. 178-193, 2020. DOI: https://doi.org/10.1080/17452759.2020.1713580.

LE, T. T.; AUSTIN, S. A.; LIM, S.; BUSWELL, R. A.; LAW, R.; GIBB, A. G. F.; THORPE, T. Hardened properties of high-performance printing concrete. **Cement and Concrete Research**, v. 42, n. 3, p. 558-566, 2012. DOI: https://doi.org/10.1016/j.cemconres.2011.12.003.

LI, Z.; WANG, L.; MA, G. Mechanical improvement of continuous steel microcable reinforced geopolymer composites for 3D printing subjected to different loading conditions. **Composites Part B: Engineering**, v. 187, n. 1, 107796, 2020. DOI: https://doi.org/10.1016/j.compositesb.2020.107796.

LONG, W.-J.; TAO, J.-L.; LIN, C.; GU, Y.-C.; MEI, L.; DUAN, H.-B.; XING, F. Rheology and buildability of sustainable cement-based composites containing micro-crystalline cellulose for 3D-printing. **Journal of Cleaner Production**, v. 239, n. 1, 118054, 2019. DOI: https://doi.org/10.1016/j.jclepro.2019.118054.

LOWKE, D.; DINI, E.; PERROT, A.; WEGER, D.; GEHLEN, C.; DILLENBURGER, B. Particle-bed 3D printing in concrete construction: Possibilities and challenges. **Cement and Concrete Research**, v. 112, n. 1, p. 50-65, 2018. DOI: https://doi.org/10.1016/j.cemconres.2018.05.018.

LU, B.; ZHU, W.; WENG, Y.; LIU, Z.; YANG, E.-H.; LEONG, K. F.; TAN, M. J.; WONG, T. N.; QIAN, S. Study of MgO-activated slag as a cementless material for sustainable spray-based 3D printing. **Journal of Cleaner Production**, v. 258, n. 1, 120761, 2020. DOI: https://doi.org/10.1016/j.jclepro.2020.120671.

MA, G.; LI, Y.; WANG, L.; ZHANG, J.; LI, Z. Real-time quantification of fresh and hardened mechanical property for 3D printing material by intellectualization with piezoelectric transducers. **Construction and Building Materials**, v. 241, n. 1, 117982, 2020. DOI: https://doi.org/10.1016/j.conbuildmat.2019.117982.

MANIKANDAN, K.; WI, K.; ZHANG, X.; WANG, K.; QIN, H. Characterizing cement mixtures for concrete 3D printing. **Manufacturing Letters**, v. 24, n. 1, p. 33-37, 2020. DOI: https://doi.org/10.1016/j.mfglet.2020.03.002.

MECHTCHERINE, V.; BOS, F. P.; PERROT, A.; SILVA, W. R. L.; NERELLA, V. N.; FATAEI, S.; WOLFS, R. J. M.; SONEBI, M.; ROUSSEL, N. Extrusion-based additive manufacturing with cement-based materials – Production steps, processes, and their underlying physics: A review. **Cement and Concrete Research**, v. 132, n. 1, 106037, 2020. DOI: https://doi.org/10.1016/j.cemconres.2020.106037.

MECHTCHERINE, V.; NERELLA, V. N.; WILL, F.; NÄTHER, M.; OTTO, J.; KRAUSE, M. Large-scale digital concrete construction: CONPrint3D concept for on-site, monolithic 3D-printing. **Automation in Construction**, v. 107, n. 1, 102933, 2019. DOI: https://doi.org/10.1016/j.autcon.2019.102933.

MOEINI, M. A.; HOSSEINPOOR, M.; YAHIA, A. Effectiveness of the rheometric methods to evaluate the build-up of cementitious mortars used for 3D printing. **Construction and Building Materials**, v. 257, n. 1, 119551, 2020. DOI: https://doi.org/10.1016/j.conbuildmat.2020.119551.

MOHAN, M. K.; RAHUL, A. V.; DE SCHUTTER, G.; TITTELBOOM, K. V. Extrusion-based concrete 3D printing from a material perspective: A state-of-the-art review. **Cement and Concrete Composites**, v. 115, n. 1, 103855, 2021. DOI: https://doi.org/10.1016/j.cemconcomp.2020.103855.

MOHAN, M. K.; RAHUL, A. V.; TITTELBOOM, K. V.; DE SCHUTTER, G. Evaluating the Influence of Aggregate Content on Pumpability of 3D Printable Concrete. *In*: RILEM INTERNATIONAL CONFERENCE ON CONCRETE AND DIGITAL FABRICATION, 2., 2020, Eindhoven. **Proceedings** […]. Cham: Springer, 2020. p. 333-341. (RILEM Bookseries, v. 28). DOI: https://doi.org/10.1007/978-3-030-49916-7_34.

NERELLA, V. N.; HEMPEL, S.; MECHTCHERINE, V. Effects of layer-interface properties on mechanical performance of concrete elements produced by extrusion-based 3D-printing. **Construction and Building Materials**, v. 205, n. 1, p. 586-601, 2019. DOI: https://doi.org/10.1016/j.conbuildmat.2019.01.235.

PANDA, B.; PAUL, S. C.; MOHAMED, N. A. N.; TAY, Y. W. D.; TAN, M. J. Measurement of tensile bond strength of 3D printed geopolymer mortar. **Measurement**, v. 113, n. 1, p. 108-116, 2018. DOI: https://doi.org/10.1016/j.measurement.2017.08.051.

PANDA, B.; SINGH, G. B.; UNLUER, C.; TAN, M. J. Synthesis and characterization of one-part geopolymers for extrusion based 3D concrete printing. **Journal of Cleaner Production**, v. 220, n. 1, p. 610-619, 2019. DOI: https://doi.org/10.1016/j.jclepro.2019.02.185.

PEGNA, J. Exploratory investigation of layered fabrication applied to construction automation. *In*: ASME DESIGN ENGINEERING TECHNICAL CONFERENCE, 1995, Boston. **Proceedings** […]. Boston: ASME, 1995, p. 219-226. DOI: https://doi.org/10.1115/DETC1995-0029.

RAHUL, A. V.; SANTHANAM, M. Evaluating the printability of concretes containing lightweight coarse aggregates. **Cement and Concrete Composites**, v. 109, n. 1, 103570, 2020. DOI: https://doi.org/10.1016/j.cemconcomp.2020.103570.

SHAKOR, P.; NEJADI, S.; PAUL, G. Investigation into the effect of delays between printed layers on the mechanical strength of inkjet 3DP mortar. **Manufacturing Letters**, v. 23, n. 1, p. 19-22, 2020. DOI: https://doi.org/10.1016/j.mfglet.2019.11.004.

SHAKOR, P.; NEJADI, S.; PAUL, G.; SANJAYAN, J. Dimensional accuracy, flowability, wettability, and porosity in inkjet 3DP for gypsum and cement mortar materials. **Automation in Construction**, v. 110, n. 1, 102964, 2020. DOI: https://doi.org/10.1016/j.autcon.2019.102964.

SHAKOR, P.; NEJADI, S.; PAUL, G.; SANJAYAN, J.; ASLANI, F. Heat curing as a means of postprocessing influence on 3D printed mortar specimens in powderbased 3D printing. **The Indian Concrete Journal**, v. 93, n. 9, p. 65-74, 2019. Available at: http://hdl.handle.net/1959.3/452532. Accessed on: 10 Oct. 2021.

SOLTAN, D. G.; LI, V. C. A self-reinforced cementitious composite for building-scale 3D printing. **Cement and Concrete Composites**, v. 90, n. 1, p. 1-13, 2018. DOI: https://doi.org/10.1016/j.cemconcomp.2018.03.017.

TAO, Y.; LESAGE, K.; TITTELBOOM, K. V.; YUAN, Y.; DE SCHUTTER, G. Effect of limestone powder substitution on fresh and hardened properties of 3D printable mortar. *In*: RILEM INTERNATIONAL CONFERENCE ON CONCRETE AND DIGITAL FABRICATION, 2., 2020, Eindhoven. **Proceedings** […]. Cham: Springer, 2020. p. 135-143. (RILEM Bookseries, v. 28). DOI: https://doi.org/10.1007/978-3-030-49916-7_14.

TAY, Y. W. D.; LI, M. Y.; TAN, M. J. Effect of printing parameters in 3D concrete printing: Printing region and support structures. **Journal of Materials Processing Technology**, v. 271, n. 1, p. 261-270, 2019. DOI: https://doi.org/10.1016/j.jmatprotec.2019.04.007.

TAY, Y. W. D.; TING, G. H. A.; QIAN, Y.; PANDA, B.; HE, L.; TAN, M. J. Time gap effect on bond strength of 3D-printed concrete. **Virtual and Physical Prototyping**, v. 14, n. 1, p. 104-113, 2019. DOI: https://doi.org/10.1080/17452759.2018.1500420.

WU, P.; WANG, J.; WANG, X. A critical review of the use of 3-D printing in the construction industry. **Automation in Construction**, v. 68, n. 1, p. 21-31, 2016. DOI: https://doi.org/10.1016/j.autcon.2016.04.005.

XU, J.; BUSWELL, R. A.; KINNELL, P.; BIRO, I.; HODGSON, J.; KONSTANTINIDIS, N.; DING, L. Inspecting manufacturing precision of 3D printed concrete parts based on geometric dimensioning and tolerancing. **Automation in Construction**, v. 117, n. 1, 103233, 2020. DOI: https://doi.org/10.1016/j.autcon.2020.103233.

XU, Y.; ŠAVIJA, B. Development of strain hardening cementitious composite (SHCC) reinforced with 3D printed polymeric reinforcement: Mechanical properties. **Composites Part B: Engineering**, v. 174, n. 1, 107011, 2019. DOI: https://doi.org/10.1016/j.compositesb.2019.107011.

YU, S.; DU, H.; SANJAYAN, J. Aggregate-bed 3D concrete printing with cement paste binder. **Cement and Concrete Research**, v. 136, n. 1, 106169, 2020. DOI: https://doi.org/10.1016/j.cemconres.2020.106169.

ZAREIYAN, B.; KHOSHNEVIS, B. Effects of interlocking on interlayer adhesion and strength of structures in 3D printing of concrete. **Automation in Construction**, v. 83, n. 1, p. 212-221, 2017a. DOI: https://doi.org/10.1016/j.autcon.2017.08.019.

ZAREIYAN, B.; KHOSHNEVIS, B. Interlayer adhesion and strength of structures in Contour Crafting - Effects of aggregate size, extrusion rate, and layer thickness. **Automation in Construction**, v. 81, n. 1, p. 112-121, 2017b. DOI: https://doi.org/10.1016/j.autcon.2017.06.013.

ZHANG, Y.; ZHANG, Y.; SHE, W.; YANG, L.; LIU, G.; YANG, Y. Rheological and harden properties of the high-thixotropy 3D printing concrete. **Construction and Building Materials**, v. 201, n. 1, p. 278-285, 2019. DOI: https://doi.org/10.1016/j.conbuildmat.2018.12.061.

ZHU, B.; PAN, J.; NEMATOLLAHI, B.; ZHOU, Z.; ZHANG, Y.; SANJAYAN, J. Development of 3D printable engineered cementitious composites with ultra-high tensile ductility for digital construction. **Materials & Design**, v. 181, n. 1, 108088, 2019. DOI: https://doi.org/10.1016/j.matdes.2019.108088.