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REVIEW

Prospect and barrier of 3D concrete: a systematic review

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Abstract

This paper aims to explore the current state of the art and potential of 3D concrete printing and its use in large-scale applications. The study analysed 373 academic research, all of which were obtained from the Scopus database. The review conducted on some crucial issues on development of 3D concrete that included materials and their desirable properties, printer nozzle developments, reinforcement in printing, geopolymers as printing materials, and the use of coarse graded aggregates. This study provides researchers and institutions with an in-depth insight into 3D concrete printing and research trends worldwide and assesses the future of 3D concrete printing in large-scale applications. The requirement of more research on the mechanics of 3D printers, standardising a printer nozzle, the automation of reinforcing processes, and use of coarse graded aggregate for large-scale structural application were identified in this review. It also shows how 3D concrete printing has evolved and changed over time and gives an insight into the future of 3D concrete printing—making this scientometric review a framework for future studies.

Keywords 3D concrete · Systematic review · Concrete printer · Printer nozzle

Introduction

The construction industry has a need and desire to become digitalised due to the vast number of benefits, including a saving in costs and a reduction in raw materials used. Construction 4.0 refers to the digitalisation and automation of the industry. The concept of Industry 4.0 came about at the beginning of the last decade. Construction 4.0 is about exploiting the vast number of possibilities created by the mass digitisation of information [25]. 3D concrete printing can address several critical challenges including increasing sustainability and is therefore at the forefront of the automation of the construction industry. It will have a significant social and economic impact in years to come. Governments have initiatives in place promoting automated, sustainable construction, and due to this, companies and universities are working to accelerate the development of 3D concrete printing and other modern construction techniques beneficial to Construction 4.0. The promotion of Construction 4.0 is exemplified by the seventeen projects selected by the UK Research and Innovation (UKRI) to receive £50,000 in seed funding to promote the digitalisation of construction sites and offshore windfarm construction.

3DCP is at the forefront of Construction 4.0 and has the potential to transform the industry. 3D printing in construction is the use of a computer model to transform a thought into a real facility with the least human involvement and a reduction in natural resources[24]. There are two main groups of 3D concrete printing technologies: powder-based and extrusion-based printing.

Powder-based printing is when a binder liquid is deposited onto a power bed such as sand to form structures. However, powder-based printing is not usually suitable for large-scale construction as it is a very slow process and is done off-site. Extrusion-based manufacturing is when a

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cementitious material is extruded layer by layer from a nozzle in an automated system. Traditionally unlike additive manufacturing, wet concrete needs formwork and vibrations to consolidate it. The use of 3D concrete printing reduces labour and material costs, whilst also reducing greenhouse gas (GHG) emissions, material waste, resource demand, construction time as well as the likelihood of human error [12]. 3DCP does not require formwork which can contribute up to 60% of the overall cost when concrete is cast conventionally (Hurd, 2005). This reduction in waste is necessary, as the construction industry generates an estimated 80% of global waste [34]. The elimination of formwork also increases geometrical freedom (Nematollahi et al., 2017). Since powder-based manufacturing is not suitable for large-scale applications, this paper will predominantly focus on extrusion-based manufacturing [72].

Ensure the durability of concrete material science has changed drastically. In the 1960s, concrete only had a compressive strength of 15–20 MPa, whereas ultra-high-strength concrete reaches compressive strengths of up to 150 MPa [17]. The strength of concrete is not the only development. Special concretes have also been developed with enhanced properties, such as low-density structural concrete, self-compacting concrete, and fibre-reinforced concrete [38]. Whilst concrete science has developed and changed, the process of placing concrete has largely remained the same until 3DCP.

Another term commonly used instead of 3D printing is additive manufacturing. Additive manufacturing first developed in the 1980s [65]. The concept of additive or layered construction is not at all new. In the early twentieth century, slip forming techniques were used where typical construction techniques were not applicable. In slip form construction, formwork is mechanised and moves as the material is deposited in layers [60]. All additive manufacturing techniques follow the same process: firstly, computer software is used to create a 3D blueprint. Then, the design is converted to a set of manufacturing instructions specifying where the material is to be deposited and its quantity. Finally, the material is deposited in successive layers. The technology has been steadily progressing and has been used for structural purposes, as, for example, for the cycle bridge in the city of Nijmegen Netherlands, which used a gantry style printer and cable reinforcement [56].

It is becoming more and more common for research metrics and data mining tools to be used to examine existing pieces of literature and determine their importance by the number of times they have been cited by other academic journals. The scientometric analysis is used to map a specific knowledge area and is also able to evaluate how well an article or piece of research is performing [15]. The principal use of scientometric analysis is to measure the impact of countries, articles, authors, and institutions and to understand how each of these interrelates. When used in conjunction with special software, these datasets can be visualised to show how they link with one another.

This research aims to use scientometric techniques and a detailed discussion to give an insight into identifying the research gap and the barriers of 3D-printed concrete in large-scale applications to facilitate the automation of the construction industry and increase sustainability within this sector.

Research methodology

The study used a scientometric-based review [77, 37, 22, 11, 76] and an all-inclusive discussion of current research areas and gaps within the field of 3DCP. A scientometric review shows unbiased and less subjective results than other review methods, whilst also showing the growth of a research field over time. When this type of review process is carried out with the use of datamining tools and visualisation software, it is possible to visualise and map quantitative data showing relations in the chosen research field. The review used the quantitative methodology individuated by [58], which consists of four steps: collection, descriptive analysis, selection of categories, and analysis of the materials collected.

Scientometrics and bibliometrics are related fields used for the investigation of quantitative data found from bibliometric datasets. The use of this type of study allows for fast and efficient results. It also produces precise and objective results [39]. Scientometrics was first defined as ‘a quantitative study of the research on the development of science' by Mulchenko [16]. It is a sub-branch of bibliometrics and measures the impact of research and maps current knowledge for large datasets. The following types of scientometric data analysis were applied to the dataset: co-author analysis, co-citation analysis, co-word analysis, and co-occurrence analysis. When used together, an accurate insight into the field is given.

Data design

When deciding on the database from which the data should be collected, it is essential for a scientometric review that the dataset is reliable and broad. Scopus and Web of Science are the two databases with the most extensive and objective academic literature results [16]. When searching the two databases for 3D concrete printing, Scopus was the database with wider coverage, having 792 document results compared to the 596 documents found in the Web of Science Core Collection. Scopus is Elsevier’s abstract and citation database. Scopus’s larger dataset facilitated the use of scientometric analysis and made it easier for mapping results. The phrase

'3D concrete printing' was searched in all abstracts, keywords, and titles with no set period to obtain the largest possible dataset. The results were then refined by only using documents that had two or more citations.

Data filtering

These papers were further refined by only considering papers written in English. Once this had been done, there were a total of 373 documents left. Their abstracts were then read to ensure that each of the papers was related to the field. The method of filtering is shown in Fig. 1.

Data analyser

To visualise the datasets and quantify how articles linked to one another, VOSviewer was used. Scopus analyser was used to examine research trends and sources with the most articles published. VOSviewer is a free to download software which is used for data mining bibliometric data and then visualising this data in the form of maps showing connections between authors, papers, countries, and institutions [69]. VOSviewer can also be utilised to perform a variety of different scientometric analysis techniques. In particular, this paper used the following: co-occurrence analysis,

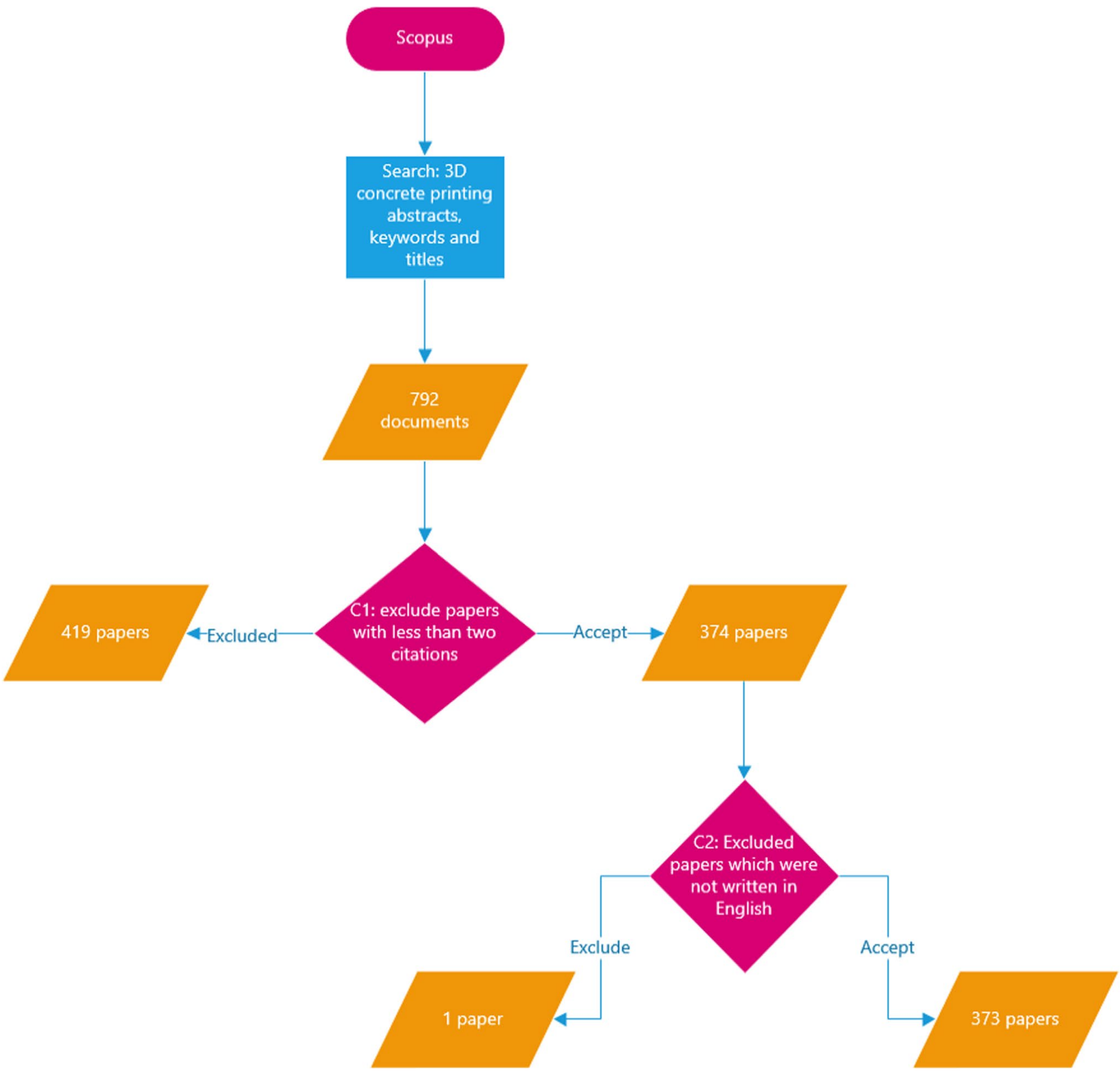

Fig. 1 Method for filtering to obtain the documents for the scientometric review

co-citation analysis, and citation analysis. Co-occurrence analysis is employed to measure the relation of keywords. The relevancy of the items is determined by the number of documents they occur in together. Co-citation analysis determines the relation of references, sources, and authors and is determined by the number of times they are cited together. Citation analysis can determine the relationship between documents, sources, authors, organisations, and countries depending on how often different publications cite one another. According to this method, the greater the frequency of inter-citation, the stronger the relationship [69].

Once the bibliometric data have been loaded into VOSviewer, the relation between pieces of bibliometric data is shown by lines between different nodes: the thicker the line, the stronger the relationship between the line between two nodes the more related the pieces of bibliometric data are. The links and Total Link Strengths are also quantified in table form to show the impact a document, author, country, or research institution has within 3DCP. These visualised datasets can be exported and made into tables showing links and Total Link Strength. Links indicate the relatedness an item has to other items, and Total Link Strength indicates these connections' strength. For example, when looking at the co-authorship links between different authors the number of links indicates how many co-authorships links a researcher has to other researchers in the field. The Total Link Strength shows the total strength of these co-authorship links between researchers. The tables obtained were then examined and sorted with Excel, and the ten articles/authors/countries/sources with the greatest Total Link Strength/links were discussed and displayed in alphabetical order. For author keywords, the twenty-five keywords with the highest Total Link Strength were used. This is because author keywords were used to identify research trends and gaps, meaning a broader dataset was more beneficial. When extracting and exporting data from VOSviewer, the data need to be carefully checked for similar keywords, authors, article titles, and source names to ensure there are no duplicate entries. This type of science mapping showed clusters and interrelatedness of keywords, authors, articles, and institutions, identifying the most recent developments within the field. An overview of the methodology proposed for the study is found in Fig. 2.

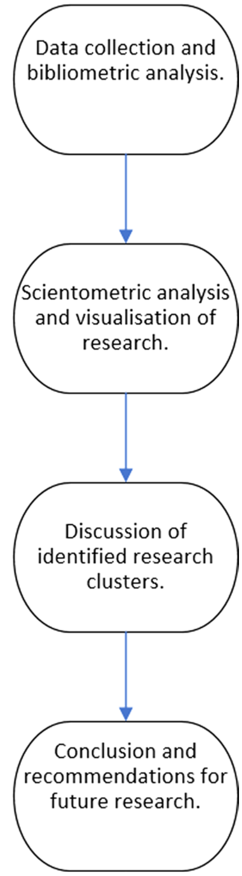

Fig. 2 An overview of the proposed research methodology

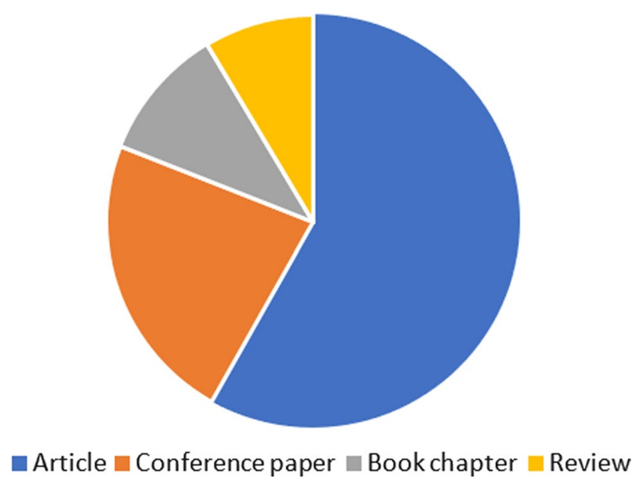

Fig. 3 Type of academic publications collected and analysed in the scientometric review

Scientometric review

Introduction and overview of the documents used in the study

A total of 373 publications were selected whilst searching the Scopus database. The literature sample used shows an increase over time in papers produced in the field of 3D concrete printing. The articles selected can be grouped into different clusters depending on several variables including research aims, problems addressed, and content similarities. Scientometric methods were then used to analyse the selected publications and objectively map the areas of

3DCP and identify research themes and corresponding challenges. Figure 3 shows the types of publications obtained from Scopus, with articles and conference papers making up most of the documents at 58 and 23%, respectively.

Figure 4 shows the distribution of the subject field the papers were created for, with 47% of all papers being Engineering and 27% Material Science showing the two main areas of 3D concrete printing and which subject area publishes the most articles on the topic.

Literature sample according to year the document was published

The first 3D-printed concrete article found on Scopus was in 2010, and from 2015 onwards, there was a sharp increase in research as shown in Fig. 5. The dataset shows a clear trend that researchers are seeing the benefits 3DCP has as an alternative concrete construction method, and it can be expected that this trend is going to continue and the amount of research in the field is only going to increase in years to come.

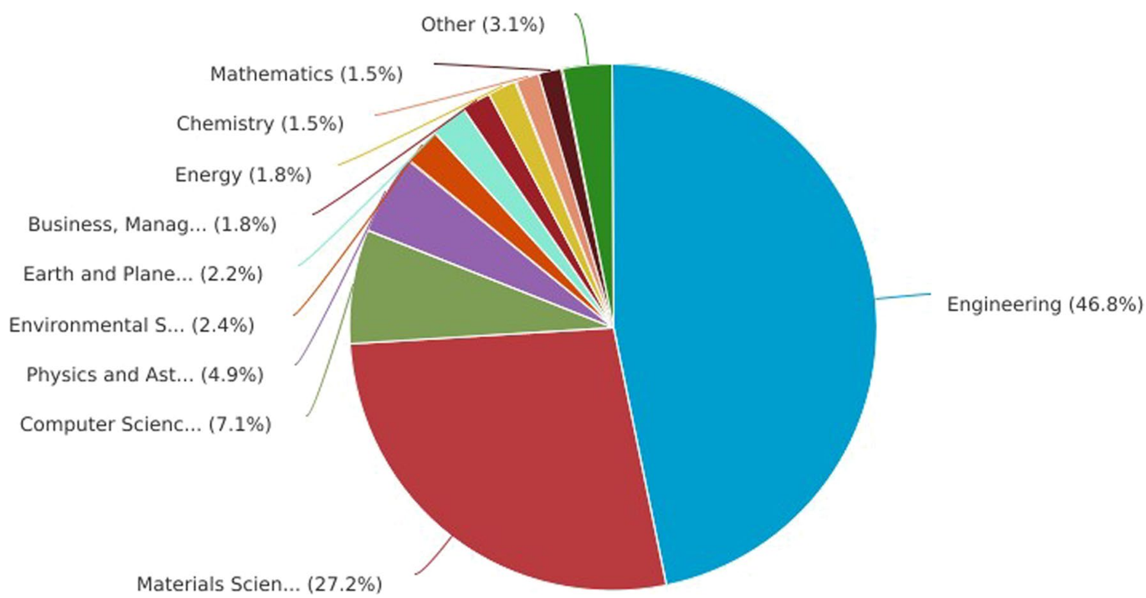

Fig. 4 Documents by subject area

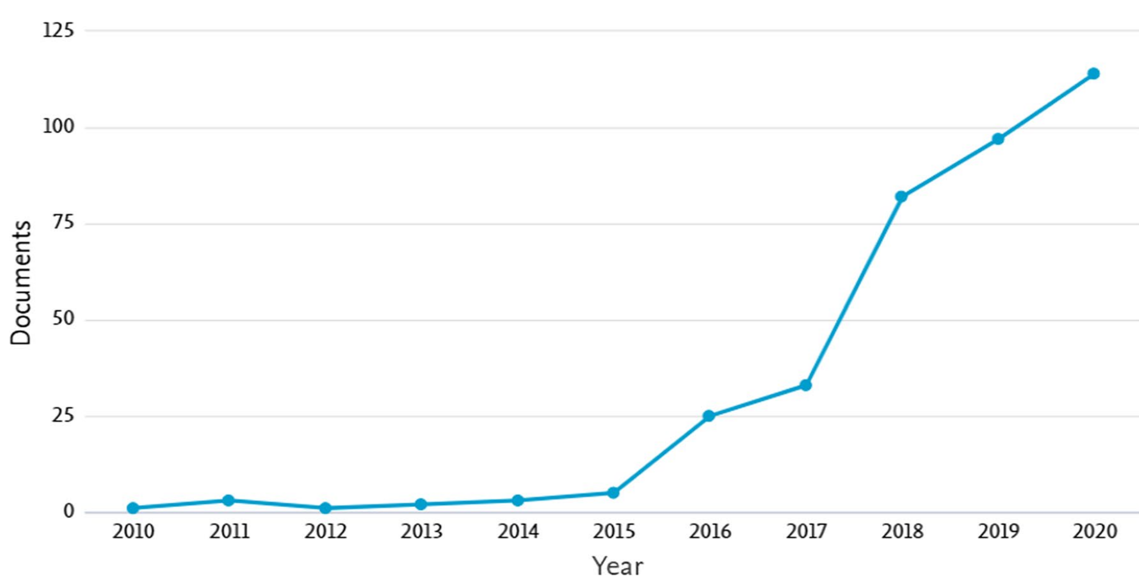

Fig. 5 Historical trend of academic literature in 3DCP obtained from Scopus database

Frequency of documents published per source

Figure 6 shows the number of documents produced by leading academic sources and journals around the globe from 2017 to 2021. This graph was obtained with the use of the data analyst tool on Scopus. It shows how each academic publisher has influenced the field of 3D concrete printing over the years. The two leading academic journals are 'Rilem Bookseries' and 'Construction and Building Materials'. The plot shows a clear positive trend of documents released by all sources over the years as 3D concrete printing develops and becomes viable for large-scale applications.

Most occurring author keywords in the research articles used in the study

Keywords showcase the core content of the published documents and showcase the core areas of research within the topic's boundaries [68]. Table 1 shows the most commonly occurring author keywords in the examined documents. The Total Link Strength and occurrences were obtained with the use of VOSviewer: a bibliometric mining tool.

Figure 7 visualises the network of co-occurring keywords and their connections to one another. The thicker the line connecting two keywords, the stronger the Total Link Strength. The distance between the keywords represents the strength of the relation between the two knowledge domains [49], and for the keywords, this distance is quantifying how often they co-occur. Keywords are representative of the specific research domain and topics [73] thus making them a useful unit of analysis in the field of 3D-printed concrete. The co-occurrence of keywords provides temporal and spatial depictions of the research field [70]. Examining the visualisation of the keywords alongside the table of most occurring keywords and excluding the ones that do not represent a key research area, the most prominent research areas are rheology and geopolymers.

Table 1 Most commonly occurring author keywords and their total link strength in 3DCP

S/N	Keyword	Occurrences	Total link strength
1	3d-printing	12	24
2	Bond strength	9	21
3	Buildability	16	30
4	Cement-based materials	4	13
5	Compressive strength	5	13
6	Concrete	38	82
7	Concrete 3d printing	12	14
8	Construction	14	33
9	Contour crafting	8	14
10	Digital construction	17	40
11	Digital fabrication	14	23
12	Extrudability	9	15
13	Extrusion	15	37
14	Fly ash	5	17
15	Geopolymer	21	53
16	Mechanical properties	16	26
17	Post-processing	5	18
18	Powder-based 3d printing	4	16
19	Reinforcement	16	30
20	Rheology	32	67
21	Selective paste intrusion	5	14
22	Structural build-up	6	14
23	Sustainability	12	24
24	Thixotropy	14	27
25	Yield stress	11	26

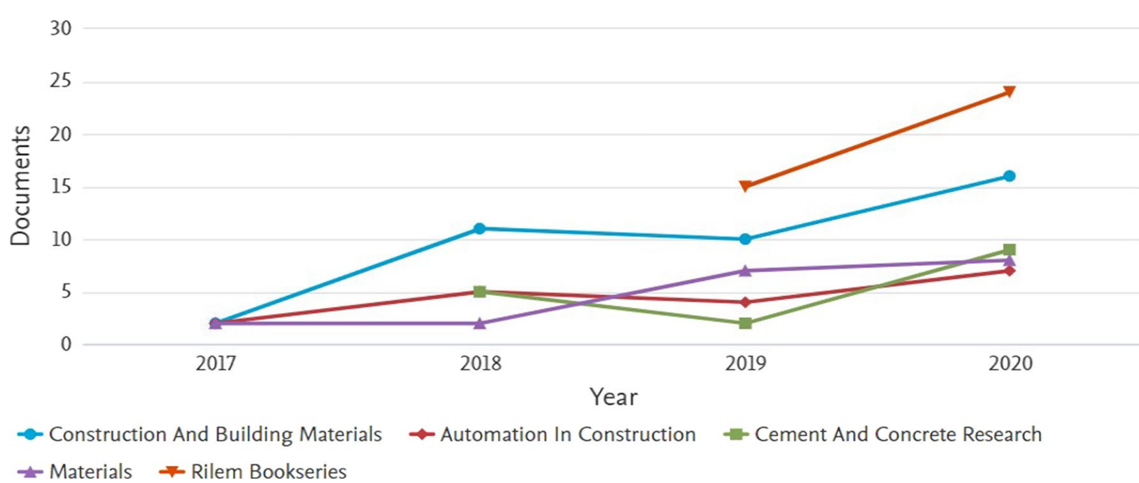

Fig. 6 Number of documents released by leading sources worldwide in 3DCP from 2017 to 2020

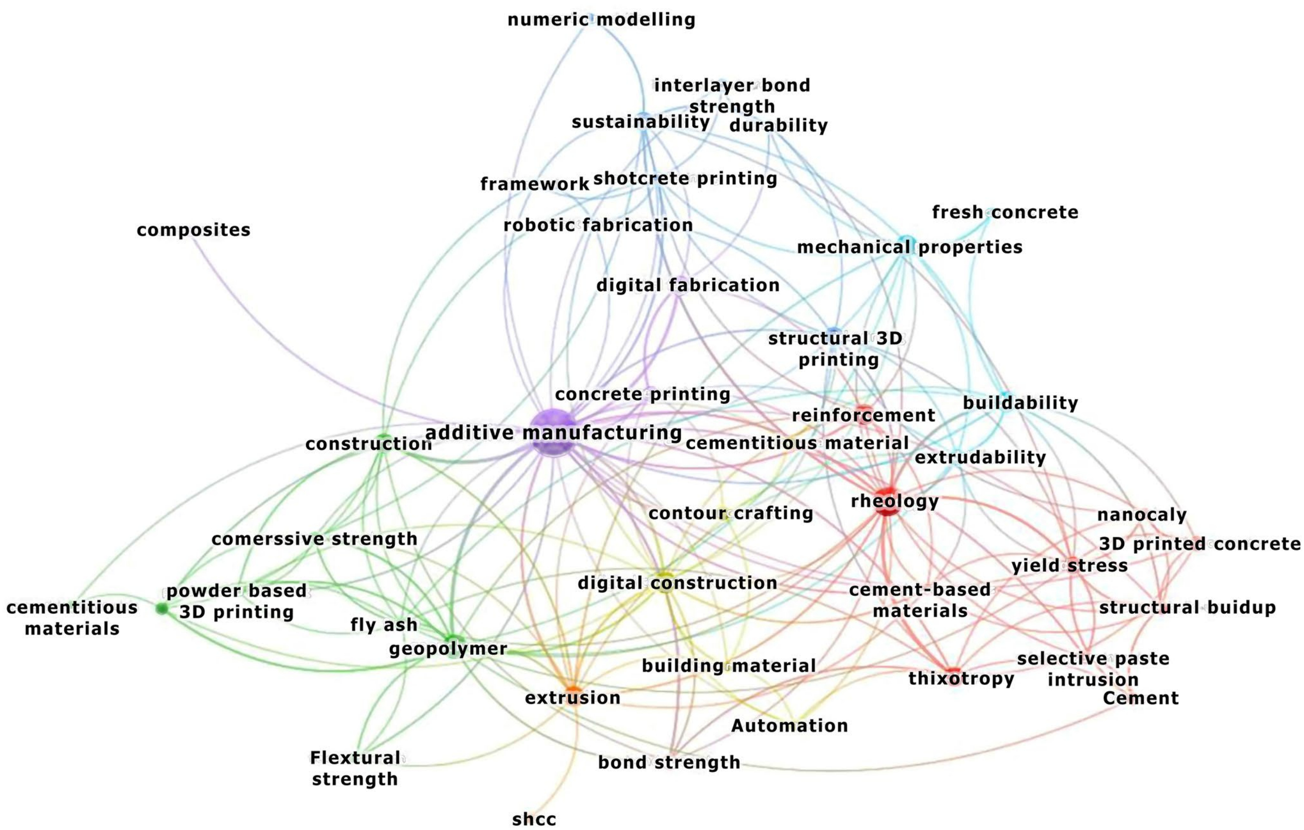

Fig. 7 Visualisation of author keywords and their links between one another

Journals with the highest Total Link Strength are based on the number of times they are co-cited.

Table 2 shows the most cited and linked sources extracted from the Scopus database with the use of datamining tools. To obtain these results document co-citation analysis was performed. This sort of scientometric analysis shows the number of documents released by publications and the authority of their references cited by these publications [37].

Figure 8 visualises a network of co-citations to show the relationship of co-citations at an individual level, showing how different academic journals are linked to one another. It is clear that there is little to no centrality of the co-cited documents excluding 'Materials'. The node size represents the number of co-citations, examining Table 2 and Fig. 8 simultaneously. 'Construction and Building Materials' has the most significant impact on the field with the largest node size and a Total Link Strength of 175,243,

Table 2 Leading academic journals in terms of co-citations

S/N	Source	Citations	Total link strength
1	ACI materials journal	76	10,218
2	Automation in construction	296	5699
3	Cement and concrete composites	202	85,333
4	Cement concrete research	295	90,203
5	Construction and building materials	533	175,243
6	Journal of cleaner production	180	66,808
7	Journal of materials in civil engineering	71	29,458
8	Materials and design	146	15,852
9	Material structures	248	24,470
10	Materials	182	16,329

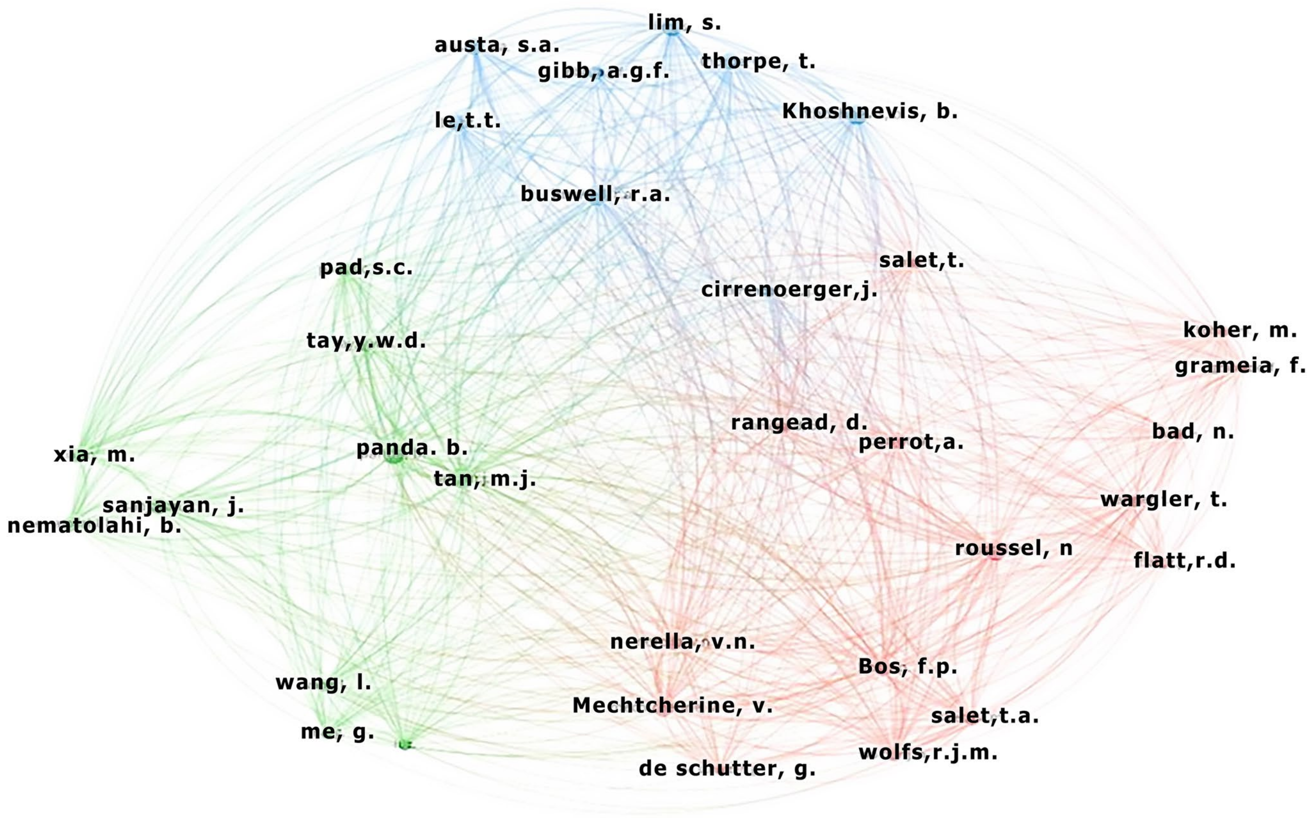

Fig. 8 Visualisation of author co-citation analysis and their links

although it is not placed centrally. Each link between journals represents the co-citation relationship between corresponding sources. The large spread of the sources in Fig. 8 shows the little relationship academic journals have with one another.

Authors with the highest citations and total link strength

Author co-citation analysis was performed with the use of VOSviewer. It gives an insight into relationships between authors who have been cited in the same publications and thus helps identify and analyse how the research field is developing. Table 3 shows the most cited authors and the Total Link Strength of each author. The most cited authors include Tan (501), Panda (470), and Khoshnevis (456).

Research institutions with the highest citations and total link strength

Table 4 shows the leading research institutions which have the greatest impact on the study of 3D-printed concrete. Eindhoven in the Netherlands and Nanyang in Singapore are the two leading institutions in terms of the number of times they have been cited. The Total Link Strength is based on citation analysis on VOSviewer, which is the number of times each institution cites one another.

Figure 9 shows a visualisation of the leading research institutions and their relation. The visualisation highlights the impact Nanyang Technological University, Singapore, and the Eindhoven University of Technology, Eindhoven, Netherlands, have on 3D concrete printing.

Table 3 Most commonly co-cited authors and their Total Link Strength

S/N	Author	Citations	Total link strength
1	Bos, f.p	323	302.64
2	Buswell, r.a	430	410.4
3	Khoshnevis, b	456	378.18
4	Le, t.t	326	315.41
5	Lim, s	403	384.35
6	Mechtcherine, v	403	362.75
7	Panda, b	470	433.51
8	Roussel, n	456	395.02
9	Tan, m.j	501	459.15
10	Thorpe, t	325	313.22

Table 4 Impact of research institutions determined by the number of times they are cited and their total link strength to one another

S/N	Institution	Citations	Total link strength
1	Beijing University of Technology, China	74	52
2	Delft University of Technology, Netherlands	20	42
3	Eindhoven University of Technology, Eindhoven, Netherlands	809	121
4	Hebei University of Technology, China	126	98
5	Nanyang Technological University, Singapore	585	120
6	Swinburne University of Technology, Australia	81	27
7	Technische Universität Dresden, Germany	116	29
8	The University of Western Australia	179	64
9	Tongji University, Shanghai, China	46	28
10	Beijing University of Mining and Technology, China	52	32

Figure 10 shows the research institutions with most documents released on the topic of 3DCP. It shows that although Eindhoven has the greatest Total Link Strength, it is only fourth in publications released on the topic of 3D concrete printing, showing how large an impact this institution is having on the field.

Countries with the highest citations and total link strength

Table 5 shows the leading ten countries globally in which most of the research in the field of 3D concrete printing takes place. The country with the highest impact is the Netherlands with a Total Link Strength of 704, which is to be expected with two of the leading research institutions for 3D concrete being situated there in Eindhoven and Delft. In terms of most documents released in the field, the USA leads with 62 documents and 3309 citations. The Total Link Strength shows the impact documents from each country have had on countries around the globe.

Figure 11 shows the interrelatedness of the leading countries determined with the use of citation analysis. The five most connected countries are the USA, Singapore, Netherlands, Germany, and Australia, showing their impact on the field.

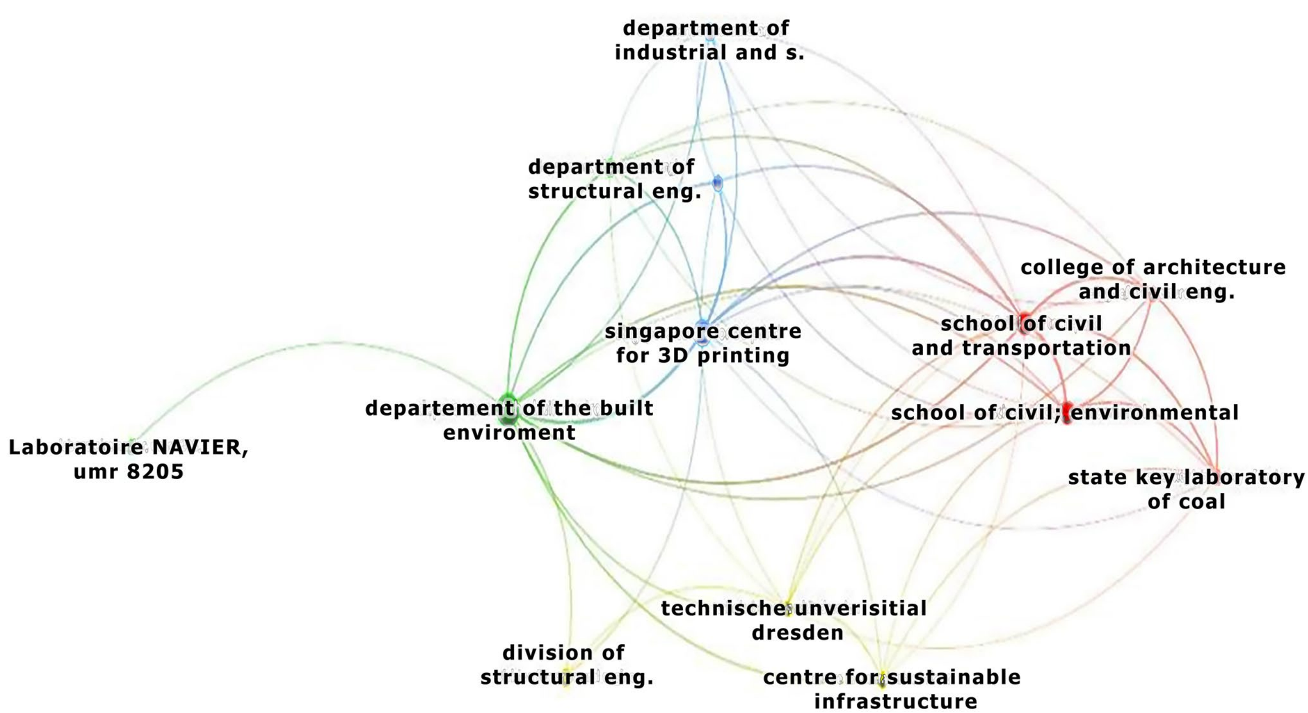

Fig. 9 Visualisation of research institutions based on citations

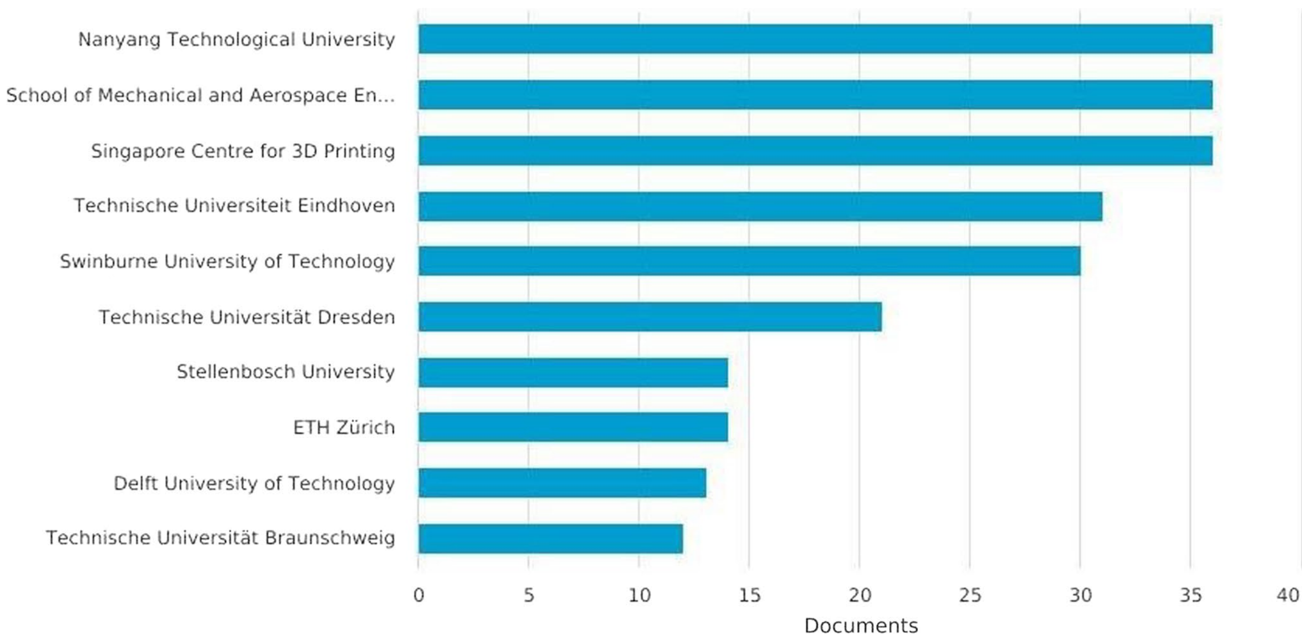

Fig. 10 Leading research institutions globally in 3DCP based on the number of documents produced

Documents with the highest citations and their citation links to one another

Table 6 shows the most cited articles in 3D concrete printing obtained from the Scopus database and their number of links. The most cited article is the 2018 article by Tuan D.Ngo called 'Additive manufacturing (3D printing): A review of materials, methods, applications and challenges'. The article itself has 1393 citations alone on the Scopus database showing how impactful it is in the field. The Total Link Strength between these most cited articles is low, suggesting that there is no collaborative work between these authors to produce them.

Table 5 Most cited and impactful countries globally and their total link strength

S/N	Country	Documents	Citations	Total link strength
1	Australia	57	2535	619
2	Belgium	15	287	288
3	China	57	1065	549
4	France	28	1303	639
5	Germany	44	933	575
6	Netherlands	44	1423	704
7	Singapore	41	1638	663
8	Switzerland	15	526	269
9	United Kingdom	15	616	262
10	USA	62	3309	551

Figure 12 visualises these most cited documents and how they link with one another. From the visualisation obtained with the use of VOSviewer, it is clear to see Freek Bos's article 'Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing' links many articles which are shown by its total links as well as its centrality.

Analysis and discussion

In comparison with traditional construction techniques of concrete, 3D concrete printing is still in its infancy, but the existing literature and studies clearly show the great potential this technology has and the impact it is likely to have on the construction industry. Despite the rapidly growing interest in 3DCP as demonstrated by the increasing number of scientific publications (Fig. 5), there is still a gap between research and its everyday use in large-scale applications. Furthermore, several studies have highlighted barriers to 3D-printed concrete [7, 32, 20], including issues linked to reinforcing and printing using coarse aggregates. The clusters found in the scientometric review can be grouped into materials and their desirable properties, barriers, new technologies, printer nozzles, reinforcements, geopolymers, and the use of coarse graded aggregates in 3D concrete printing.

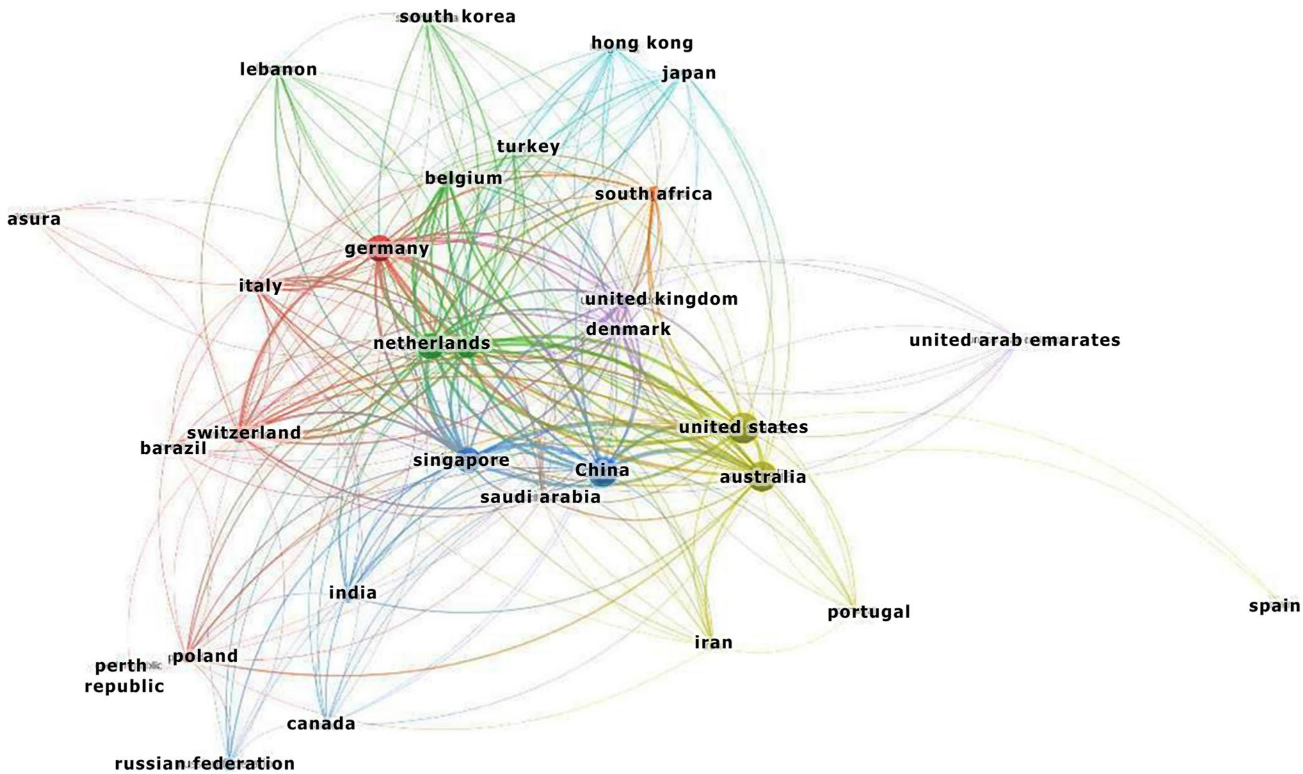

Fig. 11 Visualisation of the most cited countries

Table 6 Most cited documents in 3DCP and their links to one another

S/N	Document	Citations	Links
1	Bos f. (2016)	309	8
2	Buswell r.a. (2018)	263	8
3	Gosselin c. (2016)	300	9
4	Kazemian a. (2017)	184	5
5	Ngo t.d. (2018)	1393	0
6	Oztemel e. (2020)	182	0
7	Perrot a. (2016)	263	6
8	Stansbury j.w. (2016)	573	0
9	Tay y.w.d. (2017)	199	6
10	Wolfs r.j.m. (2018)	172	8

Materials and their desirable properties

The majority of the twenty-five author keywords with the highest Total Link Strength related to materials and their desirable properties, including buildability, extrudability, and thixotropy. To ensure 3D concrete has the correct hardened properties, the fresh properties need to be carefully controlled. Unlike conventional concrete, 3D printing of cement-based materials does not use formwork. Formwork is used as a form of temporary support for cast-in-place concrete. This means it is imperative that 3DCP holds its shape whilst also supporting other extruded layers, therefore, meaning the formulation must have little or no slump. In traditionally placed concrete, vibration is used for consolidation and compaction. Vibration cannot be used due to the concrete being printed and a lack of formwork. As these processes cannot be used, the printed material presents anisotropic properties. To obtain the desired properties, chemical admixtures, mineral admixtures, supplementary cementing materials (S.C.M.s), and reinforcing fibres are used.

The four main properties examined in 3D concrete in a fresh state are flowability, buildability, extrudability, and open time [64, 27, 29]. To obtain these properties, 3D-printed concrete should be thixotropic [18].

Thixotropy refers to the property of a fluid material reducing its viscosity under shear and increasing its viscosity again when the shear stress is removed. Thixotropy is a commonly occurring keyword in the scientometric review. Thixotropic rheology of the wet concrete mixture used in 3D printing is critical: it determines the flowability, extrudability, and buildability. The flowability and extrudability of the fresh concrete are used to evaluate how the material flows during not only pumping but also extrusion. Extrudability refers to the ability of a material to exit the 3D concrete printer's nozzle with the correct shape, size, and consistency. Flowability refers to the concrete mixture's ability to move

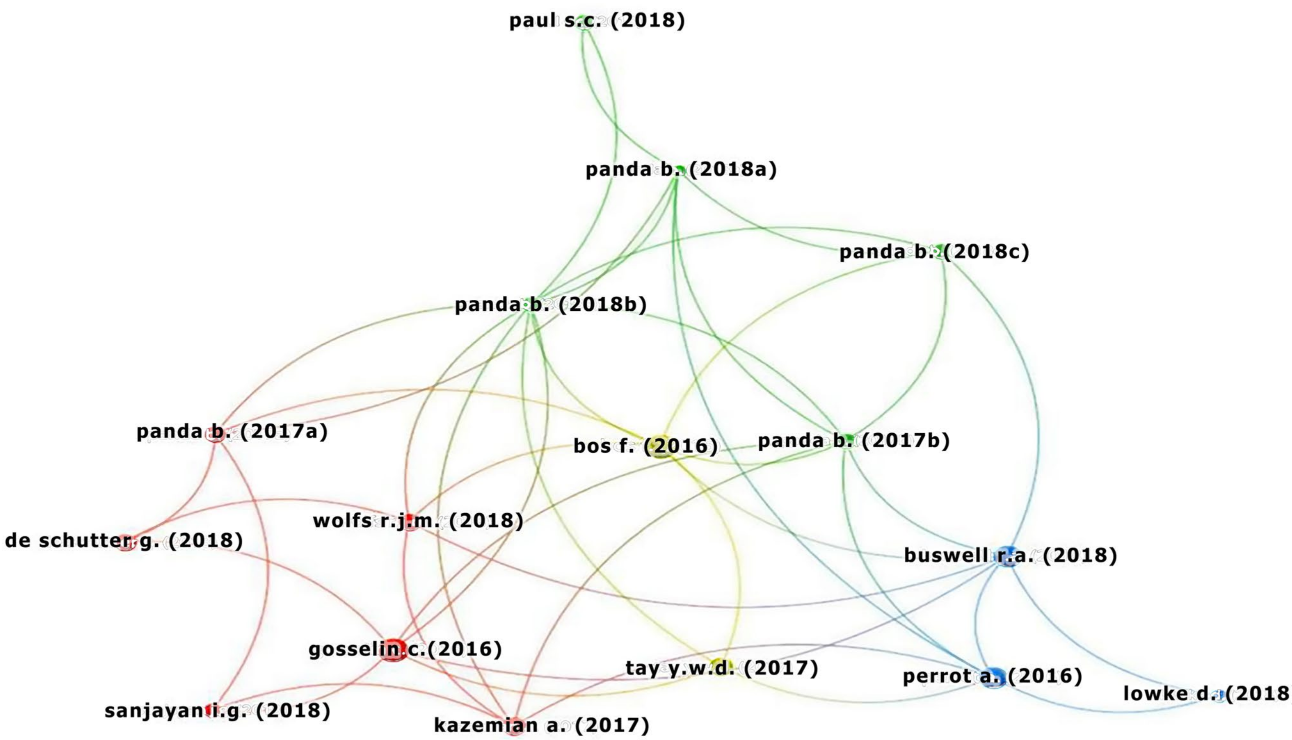

Fig. 12 Visualisation of most cited publications

from the mixer of the printer to the printer nozzle. Buildability is important as it indicates whether a printed filament can not only retain its extruded shape but also be able to allow other layers to be printed on top of it [33]. Finally, open times refer to the length of time the 3D concrete mix maintains the same viscosity allowing the materials to be pumped, transported, and extruded. In existing pieces of literature, there are disagreements regarding flowability and workability. For example, Le et al. [28] regard the flow of materials as workability instead of flowability, whereas other papers such as [33] believe it is unsuitable to describe flow behaviour as workability. In the traditional concrete casting process, workability describes the fresh properties of the concrete, whereas workability in additive manufacturing is the property determining the printable performance of the material.

The main properties examined in 3D concrete in a hardened state are compressive strength, density, tensile bond strength, flexural strength, shrinkage, and cracking. As discussed above compaction of the extruded, still uncured 3DCP through vibration is not possible (thixotropic paste would start to flow again under vibration). There is therefore an increased likelihood of small linear voids forming and resulting in anisotropic behaviour [45]. Small linear voids can be detrimental to the printed structure having an adverse effect on the hardened concrete. Density is the measure of mass per unit volume and is important as it gives an insight into the compaction of concrete**.**

Compressive strength is the capacity of a material or structure to withstand loads under compression [4]. The material's ability to not deform under a load is known as flexural strength [3]. Tensile bond strength refers to how well the materials are bonded to one another and the strength of these bonds. Shrinkage is the contraction in the concrete caused by moisture loss, and cracking is a result of this. Shrinkage of concrete is caused by moisture loss from the drying concrete leading to a contraction. Depending on the degree of shrinkage, this can compromise the dimensional stability leading to cracks in the structure. As outlined earlier, 3DCP is limited by the size of aggregate which can be used in the printing process. A lack of coarse aggregates in the mixture compounds the issue of shrinkage in 3DCP.

To achieve these desired hardened and fresh properties, the materials used, and the proportions of these materials need to be carefully considered. The mix design needs to meet the performance requirements for both fresh and hardened concrete. For the 3D concrete to have an 'optimal' mix design, it should meet certain targets that differ depending on whether the mix is optimised for workability or compressive strength. For compressive strength, the flowability and speed of concrete setting are maximised, whereas for workability, buildability is maximised upon pouring and an appropriate setting rate is maintained [36]. Although there is no standard mix design for 3D-printed concrete, most mix designs use a combination of cement, sand, a combination of geopolymers, a superplasticiser, a retarder, S.C.M.s, and other additives to maintain a sufficient open time, as well as an accelerator when being pumped [28, 34].

When producing 3D concrete, there is an increased importance of additives and Supplementary Cementing Materials (S.C.M.s). Additives and S.C.M.s are used to enhance the properties of concrete to ensure proper mix design. Examples of S.C.M.s include fly ash and silica fume. S.C.M.s are used in concrete to increase long-term strength and durability. Fly ash and silica fume also have economic advantages since they are cheaper than cement (both are by-products from other industrial processes) [23]. In 3D concrete not only do they improve these properties but are also used to control compressive strength development: an important property, especially as there are difficulties with reinforcement [41 55]. Accelerators, retarders, water-reducing agents, and superplasticisers are all commonly used admixtures. Improving the physical properties of 3DCP using SCMs is important since reinforcements cannot be used in this process. Properties of particular interest affected by additives and admixtures include flowability, stability, and viscosity. To allow for the correct amount of flowability, retarders are used to keep the mixture liquid as well the aforementioned S.C.M.s: silica fume and fly ash (Romagnoli and Bignami, 2006). The stability of the 3D concrete mix is affected by accelerators and how well inter-layer adhesion occurs [36]. The viscosity of the wet concrete is controlled using superplasticisers, and it is also affected by the aggregate blends used and the water/cement ratio. Accelerators are used to accelerate the process of setting. The concentration levels of superplasticisers are generally low ($<1\%$) since excess concentrations can lead to wet and easily deformed mixes (Lediga and Kruger, 2017). A possible area for further research is the use of shrinkage reducing additives (SRAs) in 3DCP since there appears to be little the academic literature on this topic to date.

In large-scale applications, it is imperative that all the aforementioned properties are well monitored and controlled. The fresh material needs to have a homogenous consistency. For large-scale projects, the fresh concrete needs to have an enhanced buildability so that larger loads can be taken as there is an increased self-weight to each layer. The concrete also needs to have different hardened properties to the properties of 3DCP in smaller ornamental projects. In the production of 3DCP, there are large areas of concrete exposed to open air, and therefore, there will be more cracking caused by an increase in evaporation leading to a greater amount of shrinkage and hence cracking. To reduce the likelihood of cracking, the concrete mix needs to use a water-reducing binder, or once printed the open surfaces need to be covered to stop evaporation.

Large-scale applications also need to have increased compressive and flexural strength properties in comparison with smaller ornamental structures. Depending on the desired self-weight of the structure, the density may also have to change. Tensile bond strength will also have to increase in larger structures as there are increased loads. Researchers have a clear understanding of what the properties need to be for concrete in both fresh and hardened states and the materials used in all mix designs are similar. However, a research gap was identified when comparing the material compositions of several concrete mixes. A 2018 study shows that similar materials are used in all the mixes; however, the quantity of each material changed drastically depending on the mix with only sand having a similar quantity in all the studies[48]. There are also large amounts of additives, admixtures, and S.C.M.s used in all mixes. A study examining the effects of different cement additives and S.C.M.s on the durability of large-scale 3DCP structures is currently missing from the scientific literature.

Printer nozzle developments

The author's keywords, extrudability, cement-based materials, and selective paste intrusion were identified as a research cluster all relating to the printer nozzle of 3D concrete printers. The main types of extrusion 3D concrete printers are Gantry style printers and robotic arm printers. Gantry style printers use a frame which supports a printer head that can move on the X/Y axis. Robotic arm printers are not restricted to a frame and are moved by an arm on the X/Y/Z axis. Gantry style printers are easier to scale up, meaning that they are more applicable to large-scale applications. However, Gantry style printers have significant limitations, the main being that they are limited to vertical extrusion. Robotic arms have a greater degree of freedom meaning more complex tasks can be performed which are not achievable with a 4-axis gantry printer [6].To extrude the concrete, 3D printers are equipped with an extrusion-type concrete deposition system that extrudes concrete premixes through a nozzle to form the desired shape [5]. As over half of the processes in 3D concrete printing use extrusion [7], the nozzle which extrudes the continuous concrete filament is of great importance. Displacement of concrete layers can occur when the extrusion nozzle design has not been optimised. This will increase the likelihood that the structure will be unstable and collapse [46].

A variety of different shapes and sizes of nozzle have been tested. The use of circular nozzles is preferred when a greater amount of freedom is needed without having to change the angle of printing at corners. However, the use of circular nozzles means smaller contact layers which may affect the buildability and stability of layers [47]. It has also been shown in a 2002 study that investigates the effects of the nozzle shape that for an enhanced surface finish a square-shaped extruder is better than an elliptically shaped nozzle [26]. When it comes to the size of the printer nozzle, a range of 9 × 6 mm to 38 × 15 mm for rectangular-shaped nozzles is used (Le et al., 2012d). Currently, the printer extrudes concrete at a rate of 0.04–0.009L/s; however, with material and printer nozzle developments a target rate of 2 L/s has been set [54].

A research gap identified is the concept of using multiple printer nozzles. The use of multiple nozzles would allow for increased rates of extrusion with an increased degree of freedom as well as printing multiple materials at once. An in-depth study into the best design for multiple nozzle printer heads is recommended. This would improve the understanding of how to print large-scale objects more rapidly and change shapes more easily.

The new technology that will facilitate the use of 3D concrete printing

The research cluster of technology was identified by keywords such as digital construction and digital fabrication. As discussed previously in materials section, new materials are constantly being tested and used in 3D concrete printing to enhance specific properties such as extrudability and buildability [28, 34]. These materials are developed due to issues with the extrusion and pumping of conventional concrete mixtures [55].

Currently, the design of 3D concrete structures is an automated process that uses computer-aided design models. These 3D design models are then split up into 2D layers and the material is then deposited [59]. When multiple printers and nozzles are used in the construction of a structure, the optimal toolpath needs to be established before construction occurs. To allow for this optimal Toolpath, technology has been developed which optimises the nozzle paths ensuring no overlapping occurs [75]. This new tool path technology aids large-scale structures as multiple nozzles can be used safely and efficiently, thus speeding up the construction process as well as reducing the chance of structural failure. A limitation of 3D concrete printing specific to small-scale projects is the precision of printed parts. In small-scale structures, the printer can quite often fail to print at a sufficiently high enough resolution. There are also issues with surface finishes and layer bonding [66].

Sambucci and Valente [57] reported improvement in the print quality of the mixes containing tyre rubber particles as coarse and fine aggregate over the plain mortar in terms of inter-layer adhesion and mechanical isotropy of the hardened material. The particle size of rubber particles influenced in modulating the physical–mechanical behaviour of the printer materials.

Building Information Modelling (BIM) is a 3D model-based process that creates a digital model of a structure and manages information on this structure across its lifecycle [63]. Not only can BIM be used to create 3D drawings of the structure, but it can also be used to collect data when the building is in operation to help its management. The information collected is used by engineers, architects, and construction professionals to optimise their actions, thus making the building more sustainable and safer. The development of BIM will increase the use of digital information and will thus facilitate the use of automated processes, including 3D concrete printing [50]. 3D concrete printing requires the exploitation of information models, and when combined with BIM, this need would be fulfilled allowing 3D concrete printing to be used more commonly in large-scale applications [67].

A research gap identified in 3D concrete printing relating to technology is that the data models currently used are not yet adequate for large-scale construction due to insufficient information on the relationships between materials, processes, and geometry inconsistencies in the structure (Smarsly et al., 2020). If incorporated correctly, BIM would provide adequate information for 3D concrete printers allowing for automation and increased sustainability. There is an in-depth study of how developing and integrating BIM could be done. Such a study could also show the benefits of using data models that can comprehend the relationships between different 3D printer components which would promote the adoption of 3D concrete printing in large-scale applications.

Barriers preventing the use of 3D concrete printing

3DCP as a relatively new technology is still evolving, and there are underlying barriers preventing it from common use in a large-scale application. A key barrier stopping 3D-printed concrete from being used in large-scale applications is deformation under self-weight. As the wet concrete is deposited, the material must go from a liquid in the printer to a solid phase capable of supporting its shape as well as the weight of subsequent layers. Deformation under self-weight causes issues in larger structural applications that must be manufactured in a vertical orientation. As the height of the structure increases, so do the self-weight and hydrostatic pressure of the structure causing the layers to compress. Although this compression often aids adhesion with increased weight and as the distance between the nozzle and the structure increases, the shape of the filament changes having a limiting effect on the layer adhesion [46]. The low bond strength between successive layers is also a barrier to large-scale construction. This issue primarily occurs through the generation of cold joints between layers where the cycle time is too great, thus leading to a reduction in homogeneity and low bond strength [74]. Bond strength further degrades due to excess surface moisture on the existing layer [20]. Speedy structuration occurs as a result of a chemical reaction that occurs during the hydration of concrete. It causes issues with layer bonding and causes a reduction in bond strength, causing a reduction in the shear strength of the structure [53], limiting its use for large-scale applications.

3D-printed concrete does not use formwork thus saving money and natural resources. However, formwork is an important barrier between curing concrete and the surrounding environment. Printed concrete has a larger surface area exposed to air due to the absence of formwork, meaning more evaporation occurs, which in turn leads to cracking of the printed concrete [27]. This process of drying shrinkage is further worsened by the concrete being placed in layers as the shrinkage differs over the layers causing a reduction in tensile strength between layers [40], which is detrimental for large-scale projects. No formwork also makes it more difficult to reinforce the concrete, as reinforcement is often added whilst the formwork is still in place. For 3D concrete printing to move from being primarily used for aesthetic purposes to large-scale structural projects, tensile reinforcements beyond the mortar's capacity are needed to tolerate stresses whilst being lifted and placed (Duballet et al., 2019). This means either increasing the strength of the concrete printed or finding a way of implementing reinforcement.

Moreover, 3D-printed structures need to conform to standards; however, due to current standards relating to traditional concrete techniques these are outdated and are difficult to apply to 3DCP. An example of this is that 3D-printed concrete structures do not use formwork, meaning the surface of the structure would have different properties and test results obtained using the surface might be inaccurate. The standards would need to relate to both fresh and hardened properties of the concrete as well as different standards depending on which 3D concrete printing method is used. A study into how current standards need to be adapted to facilitate the common use of 3D concrete printed would be beneficial for the large-scale application's common use. A study into how different test methods and validation techniques could be used to create a new set of standards for 3D-printed concrete assessing its durability as well as its properties would also benefit the construction industry.

The importance of reinforcement in 3D concrete printing

Finding a way to reinforce 3D-printed concrete effectively and safely will allow it to be used more commonly in large-scale applications. A variety of different solutions have been proposed from wire reinforcement to using formwork so that conventional reinforcement techniques can be used. This cluster of research was identified by looking at the author keywords in the scientometric review with reinforcement being directly mentioned as well as compressive strength. The most researched reinforcement techniques with the greatest potential have been identified below.

A reinforcement technique that is currently experimented with consists in adding steel bars horizontally through the back of the extruder (Chua et al., 2016). This process, however, has technical issues due to the layer-by-layer 3DCP process. If implementing vertical reinforcement is to be used commonly, current 3D printing technology needs large amounts of improvement. An example of an improvement is that the route paths technology needs to allow for the steel reinforcement to be implemented accurately and at the correct time, meaning the concrete has not gained too much strength.

Due to steel reinforcement being so hard to implement as the current 3D printing technology is not advanced, enough many researchers are looking at using fibre reinforcement. Fibre reinforcement looks at mixing composite fibres into the concrete, to increase the strength properties of the printed concrete. Different fibres have been tested in 3D-printed cement paste as shown by Hambach et al. [19]. The fibres used in the experiment were carbon fibre (HT C261), glass fibre (AR Force D-6) and basalt fibre (BS 13 0064 12) all of which were added to the paste before the mechanical properties of the paste were tested. The results of this experiment showed that adding 1% of carbon fibres increased the flexural strength of the cement paste to 18.5 MPa, which is 174.5% of standard 3D concrete paste. However, this addition did not drastically increase the compressive strength.

Ideally, a hybrid printing system would be created that can print concrete and lay steel reinforcement. In large-scale projects such as WinSun, steel reinforcement has been manually added (Charron, 2015b). This was done by either adding the reinforcement between the filament layers, between intermediate layers or through printing around a reinforcement cage. Currently, due to the use of manual labour, these processes are not yet fully automated. However, with technological advances this process is set to become fully automated, thus making it more applicable for large-scale applications. Related to reinforcement is the incorporation of other building components such as electricity. Implementing building components and reinforcement would follow similar processes. 3D concrete printing needs to establish how building components and reinforcement can be incorporated into an automated process.

Although several reinforcement solutions are developed worldwide, there is still a lot to be understood in terms of how these reinforcements would affect large-scale structures.

Also, a manufacturing method needs to be developed and implemented that incorporates reinforcement whilst printing. Furthermore, reinforcement techniques need to conform to current construction standards to ensure safety. A study assessing how reinforcements in 3D concrete printing would need to be adapted for large-scale structures would benefit the industry.

The use and importance of geopolymers in 3D concrete printing

After concrete and rheology, geopolymer was the keyword that had the highest link strength, highlighting that it is a key research topic within 3D-printed concrete. Geopolymers are inorganic amorphous polymer materials that can be derived from aluminosilicate-based materials [61]. They have a wide range of applications depending on the geopolymer type. In terms of concrete, geopolymers act as a binder in combination or instead of traditional O.P.C. Since some of the raw materials commonly used in geopolymers are industrial waste products such as blast furnace slags, carbon emissions are reduced. Certain geopolymers can also enhance the mechanical properties of concrete and increase its durability. It is therefore a key area of research for the development of both geopolymer concrete and 3D-printed concrete in which geopolymers are used.

3D-printed concrete's principal challenge is developing a printable mix that is no slump and self-compacting: two properties that usually do not correlate. The use of geopolymers is investigated to overcome this challenge. Silica fume and fly ash have both been used in combination with O.P.C. to increase the yield stress of the mixture [46]. In extrusion-based printing, geopolymer mixes have been developed which can be used in a printer. However, although this mixture regained 70–80% of its viscosity, it must be noted that there is no direct relationship between yield stress, thixotropy, and viscosity properties of 3D concrete materials [44]. This means in layer-by-layer techniques the materials need to still be developed to ensure the stability of structures. As previously mentioned in materials section of the discussion and analysis, geopolymers are commonly used in combination with O.P.C. for 3D-printed concrete. When proportioned correctly, certain geopolymers can increase compressive and tensile strength making them of great interest and use in large-scale applications [2].

There has also been researching into the use of geopolymers in powder-based 3D concrete printing techniques. Powder-based printing uses an aggregate bed with a cementitious liquid binder to harden the layer. Limitations and challenges of normal cementitious materials include the inability to use coarse aggregates and the requirement of additional processing of the powder bed to ensure aggregates are no greater than 20 mm in size [1]. Geopolymers can be used to overcome these limitations. A 2016 study used slab-based polymer with fine sand as the bed as well as a silica-based activator [71]. This yielded positive results due to it having adequate depositability and dimensional accuracy, thus making it applicable for large-scale applications, unusual for powder-based techniques.

A study investigating how geopolymers and 3DCP can be best combined to overcome the current structural limitations of the technique is suggested. This study could also address the financial and sustainability advantages of using geopolymer binders in 3DCP. There is also a lack of geopolymer concrete standards and 3DCP standards which should be investigated.

The use of coarse graded aggregates in 3D-printed concrete

The research area of coarse graded aggregates in 3D-printed concrete was identified due to keywords such as extrusion, rheology, and compressive strength. The printing of coarse aggregates is a limitation of 3D-printed concrete due to the 3D printer's inability to print conventional concrete mixes with a large proportion of coarse aggregates. This is because 3D concrete ink needs to have adequate viscosity so that it can flow through the pump and extrude from the nozzle. Coarse aggregates are important in the production of high strength mixtures as they reduce the price of the mixture due to less cement being used as well as providing additional strength to the concrete [43]. Until recent years, 3DCP had only been used for ornamental structures and a large reason for this is the frequent inability of 3DCP to print coarse aggregates.

According to BS EN 12,620:2013, coarse aggregates are defined as aggregate sizes in the upper sieve greater than 4 mm and the lower sieve is less than or equal to 1 mm. For fine aggregates, the upper sieve size is less than or equal to 4 mm and the lower sieve size is 0 mm [13]. The use of fine aggregates is preferred in 3DCP as coarse aggregates can block the printer.

Coarse aggregates can also increase the amount of bleeding and separation once the concrete has been printed [51]. In the current literature, the maximum particle size of aggregate commonly used in 3DCP is less than 2 mm (Charron, 2015a) [36, 35]. However, coarse aggregates up to 10 mm have been used [55].

For the above reasons, fine aggregate containing concrete mixtures is preferred in 3DCP. However, Rushing looks at how the use of a concrete mixture with traditional materials and coarse aggregates can work in 3D concrete printing [54]. The importance of this study is that if 3D concrete is to be used globally for large-scale projects, conventional materials will have to be used as opposed to synthetic materials. The study attempted to initially use a conventional mix ratio of about 1:2:3, cement, fine aggregate, and coarse aggregate, respectively. However, after modifications due to the printer not being able to extrude this mixture, the final mixture had a mix ratio of cement: fine aggregate: coarse aggregate ratio of about 1:3:1. Importantly, this study shows that coarse aggregates can be used in 3D concrete mixtures with aggregate sizes of up to 10 mm. Although small proportions of coarse aggregates can be used, mixtures with a high percentage of coarse aggregates are not yet suitable. A study into the future of coarse aggregates in 3D concrete printing would benefit the field economically, and the concrete mixture would also benefit.

Conclusion

The systematic review as well as current development in 3D concreting analysis in this study reveals some barriers that focus some specific future research opportunities including 1) research into producing a printer that can print a concrete mix which has the conventional mix ratio, 2) collaborative research to create a standardised mix, 3) how to standardise a printer nozzle that is capable of changing shape and size depending on the structure, 4) an exploration into how 3DCP can work in conjunction with manual processes, 5) the use of BIM for large-scale applications and the implications and benefits of BIM in 3DCP, 6) research into traditional concrete standards and how they need to be adapted for 3D-printed concrete, 7) research into the automation of reinforcing processes, 8) a study examining the effects of using geopolymers and their effects on the structure's durability.

The study also highlighted that materials were the cluster that had received the most attention in 3D concrete printing. Other clusters within 3D concrete printing literature with an increased amount of interest were reinforcement and geopolymers, both of significant importance if 3D concrete printing is to be commonly used in large-scale applications.

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