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Cement-Based Composites with Additive Manufacturing Technologies for Sustainable Architecture: A Review

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Abstract
To minimize environmental damage caused by architecture and contribute to sustainability, digital fabrication technologies, which have lower CO_2 emissions and energy consumption compared to traditional production techniques, have been applied. One of the processes of digital fabrication is additive manufacturing (AM). AM technology is becoming increasingly popular due to its ability to give the designer freedom of form and its eco-friendly nature. Considering the cement-based composites applied with AM technologies, CO_2 emissions can be reduced by approximately 32%. This paper aims to systematically summarize the content, improved properties, and environmental advantages of cement-based composite materials applied with AM technology and to determine the distribution of the number of studies by year. It has been observed that the studies have started to increase significantly since 2017. This indicates that cement used in architectural applications through various reinforcements and, AM technology for environmental sustainability has become more and more widespread.
Keywords: Digital fabrication; additive manufacturing; cement-based composites; sustainability, fiber-reinforced cement.

1. Introduction

In recent years, environmental pollution, global warming, overpopulation, problems in recycling, inefficient and excessive consumption of resources and the effects of increased consumption of fossil energy on the environment have been on the world agenda (Lányi, 2008). As a result of excessive energy consumption and the consequent significant increase in man-made CO_2 emissions, an environmental crisis is occurring (Afara et al., 2024; Amen et al., 2024). To avoid this crisis and reduce ecological damage, according to The European Green Deal, energy-intensive industries need to decarbonize (Locmelis et al., 2021). Looking at energy-intensive industries, it is known that the construction sector is responsible for almost 40% of total energy consumption (Yang et al., 2014). In addition, traditional raw materials used by the construction sector, such as steel and concrete, cause around 40% of CO_2 emissions, while 8% comes from the use of cement (Sippach et al., 2020).

Cement is used as a binder in concrete and various cement-based materials in the construction industry. It is generally divided into two polymer-based organic cement and inorganic cement (Portland cement). Organic cement is a material that binds aggregates together by hardening them from their plastic state. However, its cost is very high. Because of this, inorganic cement is widely preferred in the construction sector rather than the organic one. In inorganic cement, plastic paste is mixed with water to form and make it rigid. Over time, the compressive strength value increases due to the chemical reaction with water (G. C. Bye, 1999). Due to its widespread availability and low cost, cement has become one of the most widely used materials worldwide (Scrivener, 2014) and its production has reached 3.9 billion tons. Although it is one of the most used materials in the construction sector, the clinkerization process used in its production causes 2 billion tons of CO_2 emissions annually and has a negative environmental impact (Bouchenafa et al., 2022). Although cement is essential for economic development (Uwasu et al., 2014) it is necessary to reduce its environmental damage. It is known that studies have been carried out to make cement more eco-friendly by reducing its environmental damage. These are known to be the use of cement with materials such as fly ash and limestone (Amran et al., 2021; Bhatia Jain Subodh PG, 2016; de Matos et al., 2020; Prakash et al., 2019; Yum et al., 2018), offering different fuel alternatives during the production phase (Scrivener, 2014), and capturing and storing the emitted carbon (Schneider et al., 2011). These methods are based on minimizing CO_2 emissions during the cement production phase, and it is thought that a full environmental benefit cannot be achieved without making the application phase more eco-friendly.

To contribute to sustainability by preventing high energy consumption and CO_2 emissions during the application phase of cement, the need to offer alternatives to traditional production techniques was realized. According to Gebler et al., Additive Manufacturing (AM) technology, has the potential to improve sustainability (Gebler et al., 2014). AM technology, also called 3D printing (3DP), has developed rapidly in the last 20 years. 3DP devices are emission-free as they are completely electrically powered (Perkins & Skitmore, 2015). Production with 3DP does not require coolants, lubricants or other partly environmentally harmful substances (Gebler et al., 2014). Thanks to 3DP, it is possible to improve the carbon footprint by reducing the embodied and operating energy of buildings (Khan et al., 2021). AM is defined by ASTM as the process of producing a 3D digital model as a physical object layer by layer. In the first step, the digital model is created using Computer Aided Design (CAD) software or a 3D scanner and converted into STL (OBJ, 3MF, etc.) format. Then, the digital model in STL format is made ready for printing using slicing software compatible with the 3D printer to be used. 3D printer printing parameters such as printing temperature, speed, number and thickness of layers, and bed temperature can also be intervened with this slicing software. The model, whose printing parameters are defined and sliced, is usually saved in g-code format to be printed on a 3D printer (Cruz et al., 2023). According to ISO-ASTM 52,900, there are seven types of 3D printing technologies. These are Material Extrusion (ME), Powder Bed Fusion (PBF), Vat Polymerization (VP), Material Jetting (MJ), Binder Jetting (BJ), Directed Energy Deposition (DED), and Sheet Lamination (SL) (Cruz et al., 2023). Although 3D printers generally have material extrusion and powder bed, movement types include gantry, crane and robotic arm. The printing area can be on-site or off-site (pre-fabrication). The printed part of the structure can be a load-bearing structural element or a formwork. Prefabricating any component of an architectural structure off-site with 3DP is more profitable in terms of time and cost than traditional cast-in-place building and construction methods (Cruz et al., 2023). Compared with traditional manufacturing techniques, 3D printing reduces production time by almost 70% (Marijnissen & Van Der Zee, 2017), reduces the use of raw materials by 70% and waste materials by 60% (Siddika et al., 2020). Also with 3D printing, only a small team of 3-5 individuals are required to finish the project so, cutting down on human labor can lower the total project cost by 50-70%. Most importantly, saving 35-60% of the total project cost by eliminating human-made errors (Ahmed, 2023).

The process of applying cement-based materials or concrete with 3DP devices is known as 3D concrete printing (3DCP). The application of cement with 3D printers has gradually increased in recent years, and it is predicted that there will be a revolutionary increase in this field in the coming years (Ahmed, 2023). Advances in 3DCP technology are enabling high efficiency, flexibility and environmental benefits in both complex geometric forms and ordinary-shaped structures. Thanks to these advantages and its wide adaptation to the construction industry, large-scale 3DCP is used in 3D printing elements (pre-cast), 3D printing formworks (cast) and monolithic 3DCP on-site applications (Xiao, Ji, et al., 2021). Looking at the construction industry, it is known that companies such as CyBe, Apis Cor, and Winsum have 3DPC construction projects in Asia and Europe (Khan et al., 2021). In addition, in the literature, there are various studies on the application of cement-based materials with 3D printers.

Based on the information obtained from the literature, it is seen that AM technology is more advantageous than traditional production techniques in terms of time, cost and most importantly environmental sustainability. To observe the contribution of 3D printer use to environmental sustainability in construction applications, it should be questioned whether 3DPC technology is becoming more widespread. Within the scope of this paper, aims to investigate the development of 3D printer technology in the construction sector and to make predictions for the coming years. Using the SLR technique, the development of the use of cement-based materials with 3D printers in the last 10 years has been investigated by examining the material content and developed/improved properties.

2. Methodology

A Systematic Literature Review (SLR) was conducted to identify studies on 3D-printed cement-based materials in the literature. As the first step of SLR, the research questions were identified. The research questions are,

- What are the cement-based materials?
- Which cement-based materials have been produced/developed for use in 3D printers?
- Which properties of these produced/developed materials were examined?
- Which properties of materials are intended to be improved?

In the second step of SLR, included and excluded criteria were determined. Table 1. Shows the included and excluded criteria of the research scope. The criteria were determined according to the purpose of the study and research questions. Since the study aims to question the development in the use of cement-based materials in 3d printers in the last 10 years, the year limitation was made between 2014-2024. The language restriction was set as English. The material limitation was determined as 3d printed cement or cement-containing composite materials. The production method is limited to 3D printers and studies using other production methods are excluded. When it comes to the improved properties to be examined, the properties required for the optimum application of the material with the 3D printer have been determined to limit the scope. It is known that for high-quality 3D printing, the material must successfully transition from the liquid stage to the solidification process. That is, the fresh material flowing from the print head must be able to transform smoothly into a self-supporting, layered and rigid material. This depends on the rheological properties of the material. For cement-based materials to be printed on a 3D printer, in addition to the basic rheological parameters of viscosity and yield stress, complex behavior such as thixotropy should also be investigated (De Schutter et al., 2018). For this reason, the requirement of rheological behavior studies has been included among the developed properties of cement-based materials printed in 3D printers The mechanical properties of the material, which will ensure its applicability in various structural or semi-structural building applications, depend on the quality of the interlayer adhesion obtained as a result of the AM process. Interlayer adhesion also can be questioned on a micro and macro scale (Ghaffar et al., 2018a). For this reason, to determine the improvement of interlayer adhesion, both the limitation of mechanical properties were determined as tensile, flexural compressive and shear and microstructural behavior were included in the scope.

Table 1. Criteria of the research scope (Developed by Author).

Included Criteria:	Excluded criteria:
Studies on natural cement-based materials were published between 2014-2024.	Studies published outside the years of 2014-2024.
Articles published in English.	Articles published in a language other than English.
Concretes, cement-containing earth-based composites, recycled sand, geopolymers, lime-based mortars, strain-hardened cementitious composites, gypsum, flexible FRP textiles, kaolinite, aggregate composites	Studies involving other materials
Studies using the 3D printer production method	Studies using other production methods
Papers studied rheological behaviour (viscosity, yield stress, thixotropy), mechanical properties (tensile, flexural, compressive, shear), and microstructural behaviours.	Papers that are not studied on rheological behaviour (viscosity, yield stress, thixotropy) and, papers studied on mechanical properties other than tensile, flexural, compressive and shear strengths.

67 articles within the scope of the inclusion and exclusion criteria shown in Table 1 were examined, and the answers given to the research questions determined according to the articles reviewed were examined under the following headings.

2.1. SLR Findings

As a result of the systematic literature research, 67 articles were found between 2014 and 2024 that meet the research criteria determined within the scope of the study. 57 of these articles are accessed via ScienceDirect and, 10 of them were accessed via Springer. Figure 1 shows in which journals the articles accessed through ScienceDirect were published and how many of them there are. It is seen that the articles that meet the specified criteria are mostly published in the journal 'Construction and Building Materials'. 'Journal of Building Engineering' and 'Automation in Construction' come in second and third place.

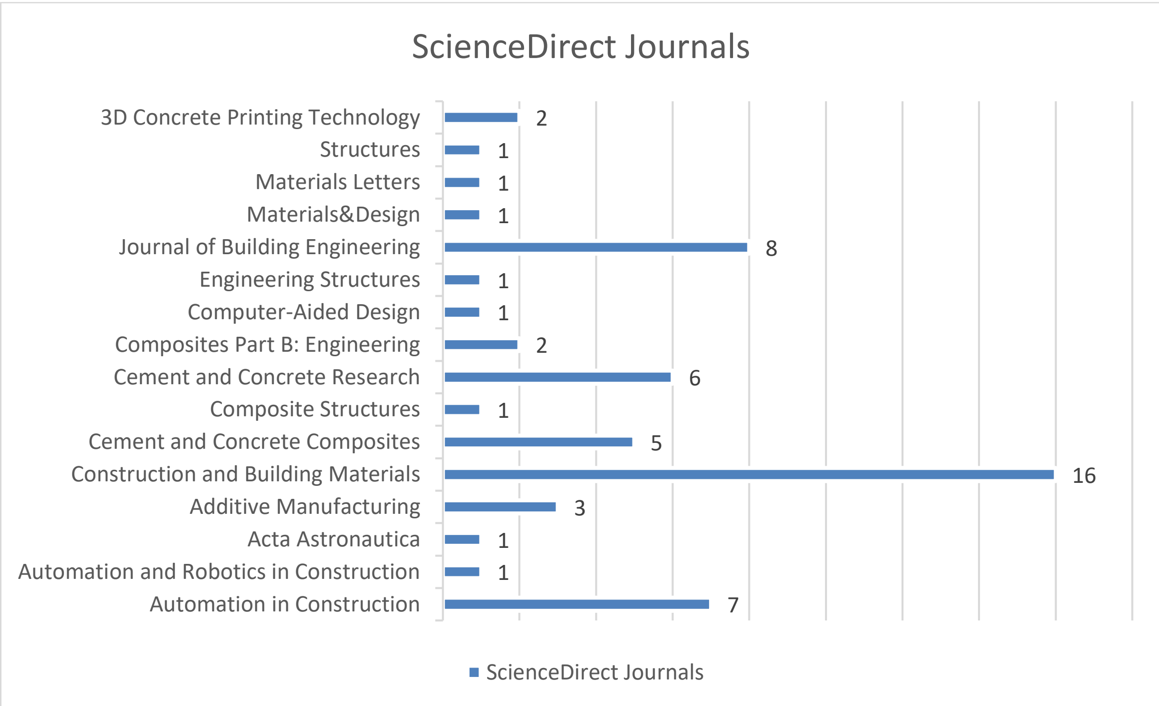


Figure 1. Distribution of articles accessed through ScienceDirect journals (Developed by Author).

Figure 2 shows in which journals the articles accessed through Springer were published and how many of them there are. It is seen that the articles that meet the specified criteria are mostly published in the journal 'Materials and Structures'. 'High Tech Concrete: Where Technology and Engineering Meet' and 'Archives of Civil and Mechanical Engineering' come in second place.

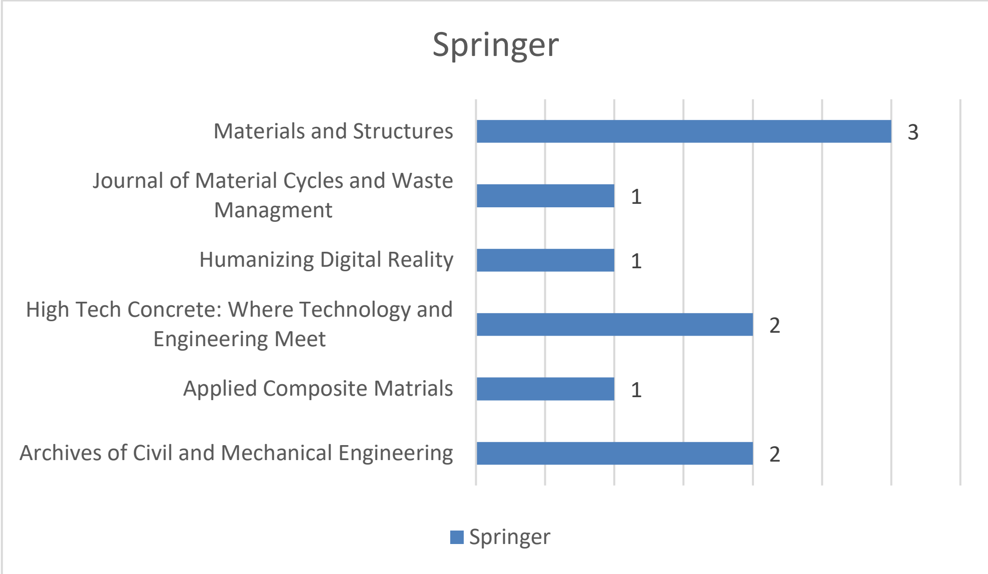


Figure 2. Distribution of articles accessed through Springer journals (Developed by Author).

3. Results and Discussion

3.1. 3D Printed Cement-Based Materials

The types of cement-containing materials applied with a 3D printer and their distribution by years are given in Table 2. Within the scope of the study, 3D printed materials are divided into two main headings, the first of which is 'Cement-based materials' and the second is 'Fiber Reinforced Cements'. Cement-based materials are summarized as 'concrete' and 'other than concrete' since concrete is the material in which cement is most frequently used as a binder. Other than concrete materials include earth-based composites, recycled sand, geopolymers, lime-based mortars, strain-hardened cementitious composites, gypsum and cement mortars, flexible FRP textiles, kaolinite, aggregate and cement composite. Fiber-reinforced cement is divided into two synthetic and natural fibers. Under the title of synthetic fibers, there are mostly studies on polymer fibers, but steel and basalt fibers have also been reported. Under the title of natural fiber-reinforced cement, 3D-printed plant-based fiber-reinforced cement is included. The literature search found no cement reinforced with animal or mineral fibers for use in 3D printers.

Table 2. 3D-printed cement-based materials (Developed by Author).

Year	3D Printed Materials			
	Cement-Based Materials		Fiber Reinforced Cements	
	Concrete	Other than concrete*	Synthetic fiber-reinforced cement	Natural fiber-reinforced cement
2014		(Cesaretti et al., 2014)		
2015	(Lloret et al., 2015)			
2016	(Gosselin et al., 2016; Perrot, Rangeard, & Pierre, 2016a)	(Perrot, Rangeard, & Levigneur, 2016; Perrot, Rangeard, & Pierre, 2016b)	(Labonnote et al., 2016)	
2017	(Lecompte & Perrot, 2017; Nematollahi et al., 2017; Schach R et al., 2017; Zareiyan & Khoshnevis, 2017b, 2017a)	(Lecompte & Perrot, 2017)	(Hambach & Volkmer, 2017a, 2017b; Panda et al., 2017)	
2018	(Bos et al., 2018; Buswell et al., 2018; Duballet et al., 2018; Ghaffar et al., 2018b; Martens et al., 2018; Mechtcherine et al., 2018; Roussel, 2018; Wolfs et al., 2018)	(Al-Qutaifi et al., 2018; Perrot et al., 2018; Weng et al., 2018)		

2019	(Keita et al., 2019; Kreiger et al., 2019; Marchment et al., 2019; Rahul et al., 2019; Wolfs et al., 2019; Y. Zhang et al., 2019)	(Z. Liu et al., 2019; Xu & Šavija, 2019)	(Hambach et al., 2019; Ting et al., 2019)	(Kesikidou & Stefanidou, 2019; Silva et al., 2019)
2020	(Baz et al., 2020; Craveiro et al., 2020; Heras Murcia et al., 2020; Wang, Jiang, et al., 2020; Wang, Tian, et al., 2020)	(Z. Li et al., 2020; Shakor et al., 2020; Xiao et al., 2020)	(Ding et al., 2020; Pham et al., 2020)	(Asim et al., 2020)
2021	(Alchaar & Al-Tamimi, 2021; Weng et al., 2021)	(Xu et al., 2021)	(Xiao, Han, et al., 2021; Ye et al., 2021)	
2022	(Nodehi et al., 2022)		(Pham et al., 2022)	
2023	(Harris et al., 2023; Ravula & Gatheeshgar, 2023; Wu et al., 2023)	(C. Liu et al., 2023)	(D. Zhang et al., 2023)	(Choi et al., 2023; Harris et al., 2023)
2024	(Singh et al., 2024)	(Namakiaraghi et al., 2024)	(Hu et al., 2024; Hua et al., 2024)	(H. Li et al., 2024)

In Figure 3, there is a graph showing the distribution of 3D-printed cement-based materials according to years. Figure 3 is derived from the data in Table 2, and it is seen that concrete is the most researched/studied material among 3D-printed cement-based materials. This may be because concrete is a preferred material in many elements in the construction industry, especially in building structures. As a result of the literature research, it is seen that 3D printer technologies are more common in the application of concrete materials compared to other cement-based materials.

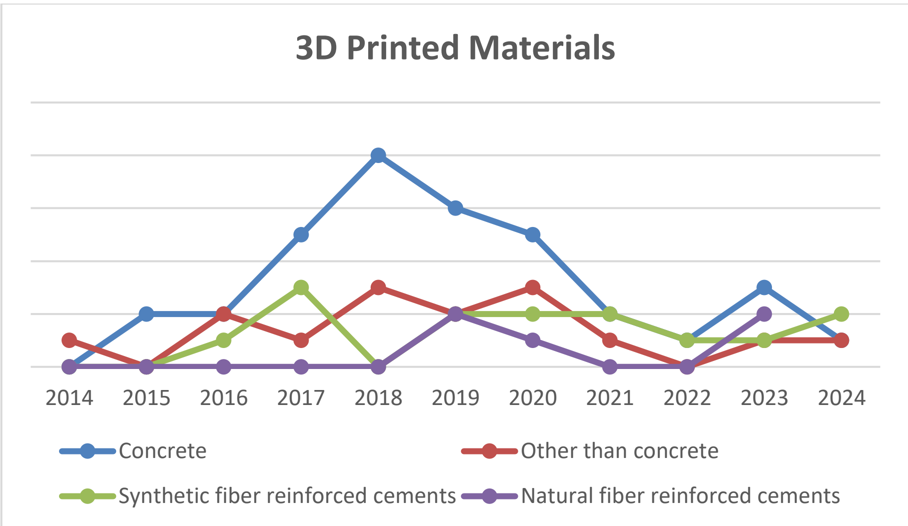


Figure 3. Distribution of cement-containing materials printed on 3D printers according to years (Developed by Author).

3.2. 3D Printed Cement-Based Materials and Improved Properties

Unlike materials developed for use in traditional production methods, rheological properties and interlayer bonding due to 3D printing must be improved to be able to apply the 3D printing process. Therefore, it is necessary to quantify how many studies have investigated the rheological behavior, mechanical properties (tensile, flexural, compressive and shear strengths) and microstructural behavior to observe the prevalence and development of 3D printing applications for cement-based materials. Table 3. shows 3D-printed cement-based materials and their improved properties per year. Based on the data obtained from Table 3, it is seen that the number of articles in which only rheological properties, mechanical properties or microstructural behavior are investigated is 13, 26 and 3, respectively. The number of articles in which rheological behavior and mechanical properties were investigated at the same time is 7. While the number of articles in which mechanical properties and microstructural behavior were investigated simultaneously is 3, this number is 1 for rheological and microstructural behaviors.

Table 3. 3D printed cement-based materials and their improved properties (Developed by Author).

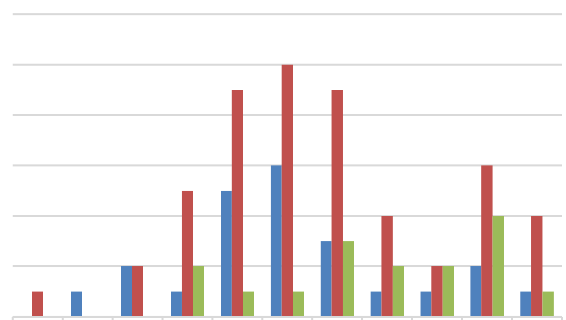
Year	3D Printed Cement-Based Materials Improved Properties					
	Rheological behavior	Mechanical properties				Microstructural behavior
		Tensile	Flexural	Compressive	Shear	
2014		(Cesaretti et al., 2014)	(Cesaretti et al., 2014)	(Cesaretti et al., 2014)		
2015	(Lloret et al., 2015)					
2016	(Perrot, Rangeard, & Levigneur, 2016; Perrot, Rangeard, & Pierre, 2016b)	(Labonnote et al., 2016)	(Gosselin et al., 2016; Labonnote et al., 2016)	(Gosselin et al., 2016; Labonnote et al., 2016)	(Labonnote et al., 2016)	
2017	(Lecompte & Perrot, 2017)	(Zareiyan & Khoshnevis, 2017b)		(Nematollahi et al., 2017; Zareiyan & Khoshnevis, 2017a)	(Zareiyan & Khoshnevis, 2017a)	
2018	(Buswell et al., 2018; Ghaffar et al., 2018b; Perrot et al., 2018; Roussel, 2018; Weng et al., 2018)	(Mechtcherine et al., 2018; Paul et al., 2018)	(Al-Qutaifi et al., 2018; Bos et al., 2018; Paul et al., 2018)	(Duballet et al., 2018; Paul et al., 2018; Perrot et al., 2018; Wolfs et al., 2018)	(Buswell et al., 2018; Martens et al., 2018; Mechtcherine et al., 2018; Wolfs et al., 2018)	(Mechtcherine et al., 2018)
2019	(Keita et al., 2019; Z. Liu et al., 2019; Lu et al., 2019; Rahul et al., 2019; Ting et al., 2019; Y. Zhang et al., 2019)	(Wolfs et al., 2019; Xu & Šavija, 2019)	(Lu et al., 2019; Marchment et al., 2019; Ting et al., 2019; Wolfs et al., 2019; Xu & Šavija, 2019)	(Keita et al., 2019; Kreiger et al., 2019; Lu et al., 2019; Marchment et al., 2019; Wolfs et al., 2019)	(Kreiger et al., 2019; Lu et al., 2019)	
2020	(Baz et al., 2020; Heras Murcia et al., 2020; Wang, Jiang, et al., 2020)	(Z. Li et al., 2020; Wang, Tian, et al., 2020; Xiao et al., 2020)	(Baz et al., 2020; Wang, Jiang, et al., 2020; Xiao et al., 2020)	(Heras Murcia et al., 2020; Z. Li et al., 2020; Xiao et al., 2020)	(Heras Murcia et al., 2020; Z. Li et al., 2020; Wang, Tian, et al., 2020)	(Craveiro et al., 2020; Shakor et al., 2020)
2021	(Weng et al., 2021)	(Xu et al., 2021)	(Alchaar & Al-Tamimi, 2021; Xu et al., 2021)	(Alchaar & Al-Tamimi, 2021)	(Alchaar & Al-Tamimi, 2021)	(Weng et al., 2021)
2022	(Nodehi et al., 2022)	(Nodehi et al., 2022)	(Nodehi et al., 2022)	(Nodehi et al., 2022)	(Nodehi et al., 2022)	(Nodehi et al., 2022)
2023	(Ahmed, 2023)	(Harris et al., 2023; D. Zhang et al., 2023)	(Ahmed, 2023; Harris et al., 2023; C. Liu et al., 2023)	(Ahmed, 2023; Harris et al., 2023; C. Liu et al., 2023; Wu et al., 2023)	(Ahmed, 2023; Wu et al., 2023; D. Zhang et al., 2023)	(Ahmed, 2023; C. Liu et al., 2023; Ravula & Gatheeshgar, 2023; Wu et al., 2023)
2024		(Namakiaraghi et al., 2024)	(Namakiaraghi et al., 2024)	(Namakiaraghi et al., 2024; Singh et al., 2024)		(Namakiaraghi et al., 2024)

Table 4. shows 3D printed fiber-reinforced cement-based materials and their improved properties per year. Based on the data obtained from Table 3, only rheological properties were studied in one article, while only mechanical properties were studied in three articles. Only one article was found in which rheological behavior and mechanical properties were investigated at the same time. The number of articles in which mechanical properties and microstructural behavior were investigated at the same time was nine. The reason why these results are different from cement-based materials can be explained by the fact that the distribution of fibers in the matrix material has a direct effect on mechanical and microstructural properties.

Table 4. 3D printed fiber-reinforced cement-based materials and their improved properties (Developed by Author).

Year	3D Printed Fiber Reinforced Cement Materials Improved Properties					
	Rheological behaviour	Mechanical properties				Microstructural behaviour
		Tensile	Flexural	Compressive	Shear	
2014						
2015						
2016						
2017		(Panda et al., 2017)	(Hambach & Volkmer, 2017b; Panda et al., 2017)	(Hambach & Volkmer, 2017b; Panda et al., 2017)		(Hambach & Volkmer, 2017b; Panda et al., 2017)
2018						
2019			(Hambach et al., 2019; Kesikidou & Stefanidou, 2019)	(Hambach et al., 2019; Kesikidou & Stefanidou, 2019)	(Silva et al., 2019)	(Kesikidou & Stefanidou, 2019)
2020		(Ding et al., 2020)	(Ding et al., 2020; Pham et al., 2020)	(Asim et al., 2020)		(Asim et al., 2020; Ding et al., 2020; Pham et al., 2020)
2021		(Ye et al., 2021)	(Xiao, Han, et al., 2021; Ye et al., 2021)	(Xiao, Han, et al., 2021; Ye et al., 2021)		(Ye et al., 2021)
2022			(Pham et al., 2022)	(Pham et al., 2022)		(Pham et al., 2022)
2023	(Choi et al., 2023)					
2024	(H. Li et al., 2024)	(H. Li et al., 2024)	(Hua et al., 2024)	(H. Li et al., 2024)		(Hua et al., 2024)

Figure 4. shows the distribution of the improved properties of the materials by years. It is seen that the research and development of mechanical properties for 3D-printed cement-based composites has always been studied more than other properties.



	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Rheological Behavior	0	1	2	1	5	6	3	1	1	2	1
Mechanical Properties	1	0	2	5	9	10	9	4	2	6	4
Microstructural Behavior	0	0	0	2	1	1	3	2	2	4	1

Figure 4. Improved properties per year (Developed by Author).

4. Conclusion

As a result of the research conducted within the scope of the study, it is generally seen that the use of 3DPC technology in the construction sector has become increasingly widespread after 2017. The most researched cement-based material is concrete. The most researched/developed properties are mechanical properties, followed by rheological behavior, which determines the fluidity properties in 3DP production. While it is more common for rheological behavior and mechanical properties to be researched/developed at the same time in cement-based materials, it is mechanical properties and microstructural behavior for fiber-reinforced cement materials. This can be explained by the fact that the distribution of fibers in the matrix material has a direct effect on mechanical and microstructural properties. Since 2017, an increase has been observed in the number of studies on fiber-reinforced cement. As a result of the literature research conducted within the scope of the study, it is seen that studies on 3D printed concrete decreased in 2021-2022. But it remains widespread in general. This indicates that cement used in architectural applications through various reinforcements and, AM technology for environmental sustainability has become increasingly widespread. The widespread use of 3D printing technology with cement-based materials in the construction industry is predicted to provide a great environmental benefit.

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Conflict of Interests
The Author(s) declare(s) that there is no conflict of interest.

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