A REVIEW OF 3D CONCRETE PRINTING IN CONSTRUCTION

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Abstract

This article contains an overview of global skills in the application of additive knowledge in the construction industry. Concrete 3D printing allows for the implementation of architectural projects of any complexity, lower production waste, less lack of housing stock, and lower labor, material, and energy costs associated with construction. The primary technologies for printing buildings and other structures are covered in the article, along with their unique characteristics. The issue of materials used for the manufacture of building mixtures has also been studied. Particular attention is paid to assessing the current state of 3D printing of concrete in the world. A review of construction companies, equipment manufacturers, and research centers, which are the main market participants, was carried out. The review also discusses ongoing research, emerging trends, and potential future developments in 3D printing concrete technology. Sustainability aspects, environmental impact, and considerations of standardization and regulations within the context of 3D printing concrete in construction are thoroughly examined. As 3D printing of concrete continues to revolutionize the construction landscape, this review serves as a comprehensive resource for researchers, practitioners, and industry stakeholders seeking a deeper understanding of the current state and future directions of this innovative technology.

Keywords: Additive Manufacturing, 3D Concrete Printing, Construction Technology, Material Science, Building Innovation.

I. INTRODUCTION

Historically, the construction industry has assessed the design process using scale models and two-dimensional (2D) drawings. Three-dimensional (3D) modeling in a virtual building information modeling environment is gradually replacing two-dimensional prototypes (Ding et al., 2019). In almost every industry, production automation has grown since the turn of the 20th century. Constructive techniques, a much lower number of finished products than other industries, the economic unattractiveness of expensive

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equipment, and limitations on the materials that can be produced automatically all hindered the growth of automation in the building sector (Di Carlo et al., 2013). The construction industry today is faced with such serious problems as low labor productivity, high statistics of emergencies on construction sites, difficulty in controlling construction procedures, and a lack of qualified workers (Warszawski and Navon, 1998).

The construction industry represents one of the world's greatest consumers of non-renewable resources and natural materials (Ibrahim, 2016). Additive technology have broadened the scope of numerous rapidly emerging manufacturing domains. 3D printing has advanced freshly developed laboratory technologies to the next level. Additive manufacturing is a widely used term for methods that entail producing a product according to a numerical model (or CAD model) by adding material (Zlenko et al., 2013). Layer-by-layer synthesis technologies can be a breakthrough for structures made from cement-based materials

The lack of a national standard for additive manufacturing, specifically on general and special qualifications of materials, designs, technologies, equipment, quality control, property control, and the technique for using additive manufacturing products, is a significant impediment to the widespread adoption of additive technologies in our country. The article review is the concentration and coordination of efforts to provide an integrated approach to the development of additive technologies, including appropriate national standards systems (classification of materials, requirements for the quality of raw materials, design, technology, equipment, and unification of computer model formats).

The application of additive technologies in building necessitates the development and testing of new materials for 3D printing. However, material selection is a challenge that many developers face. The industrial idea's basic linkages (structure, material, and technology) have yet to be integrated into the building sector.

This article discusses global experience in the study and implementation of constructing materials based on concrete mixtures utilized in additive construction technologies, as well as the qualities of these mixtures and individual components. The article also provides an overview of existing 3D printing construction technologies that are currently being explored and deployed around the world.

II. LITERATURE REVIEW

Since more than 20 years ago, the phrase "additive technologies" has been used. A stereolithographic machine was patented in 1986. It prints items in three dimensions (Hull, 1984). Today, additive technologies are used in many manufacturing sectors from mechanical engineering to culinary (Chen et al., 2017, Kablov, 2020, Gálvez et al., 2016, Barazanchi et al., 2017, Kumar and Krishnadas Nair, 2017, Kreiger et al., 2015, Huang et al., 2013). The estimates of the level of development of layer-by-layer production over the past decades are given in the research of numerous investigators (Wong and Hernandez, 2012, Küchler, 2014, Herderick, 2016).

Nowadays, there is a disapproval of widely accepted concepts in the field of construction, and modern developments concentrate particularly on additive constructing technologies (Bos et al., 2016). Many organizations worldwide are conducting scientific research to address the challenges associated with 3D printing in the construction industry. There are plenty of inventions for building mixtures for printers (Tianrong and Qiaoling, 2015, Fu-Cai et al., 2015). In addition to these materials, printers and printing technologies are also patented (Khoshnevis, 2015, Dini, 2012).

Many researchers and engineers began exploring its application in building structures. Pioneering work by **Khoshnevis** introduced the concept of "Contour Crafting," an automated construction method utilizing 3D printing, laying the foundation for subsequent advancements in the field. As the technology matured, researchers focused on refining concrete formulations suitable for 3D printing (Khoshnevis, 2004). **Le et al.** delved into mix design and fresh properties for high-performance printing concrete, a critical aspect of achieving structural integrity (Le et al., 2012).

The significance of 3D printing in concrete lies not only in its potential to revolutionize construction methodologies but also in its versatility across diverse applications. **Bos et al.** discussed the advantages and disadvantages of 3D printing concrete, with a focus on how it may be used to build intricate architectural designs. Because of its versatility, 3D printing technology is being investigated for use in a variety of construction applications, from complex and avant-garde architectural projects to residential buildings (Bos et al., 2016).

Researchers are working to comprehend the state-of-the-art in concrete 3D printing, and they have made great progress in developing printing materials and technology. **Ma et al.** offered a state-of-the-art review, highlighting the evolving landscape of 3D printing concrete technology in the construction industry (Ma et al., 2018).

II. CONSTRUCTION ADDITIVE TECHNOLOGIES

Currently, additive technologies are drawing more and more investment. They have progressed beyond quick prototyping and 3D printing of models to producing finished goods for a variety of businesses. The increasing demand for additive technologies is because of many reasons, including a high level of production automation, higher quality of products, acceleration of creation techniques, the ability to improve CAD models, and a decrease in production waste (Campbell et al., 2011, Brennan-Craddock et al., 2012, Klammert et al., 2009). These reasons are the basis for a successful transition to the concept of "digital factories" of the future (Horbach et al., 2011, Müller, 2010). This revolution includes additive manufacturing of components and products in general, as well as digital technologies for design, manufacturing, and testing. There are two categories of additive technologies based on how layers are formed: Separate Deposition Methods: Bed and Direct (Chen et al., 2017).

Bed Deposition is a class of technologies in which a layer of powder material is applied to the workspace. The product is created layer by layer with a heat source such as a laser (SLM), electron beam (EBM), light (DLP, SLA), or a secondary material (Binder Jetting), by the present CAD model component. The remaining powder is removed, the working platform is shifted and the process is repeated (Gibson et al., 2021).

Direct Deposition is a forming method in which the material is supplied directly to the construction site in accordance with the CAD model (Gibson et al., 2021). As noted (Nawy, 2008), the production of formwork accounts for 35 to 60% of the total cost of concrete structures. The ability to construct concrete structures without formwork installation is an important advantage in terms of cost reduction, production speed, and architectural freedom, as well as ease of installation of utilities (Lloret et al., 2015). Additive technologies belong to the class of so-called green technologies, as they involve almost waste-free production. High automation and robotization of the process make it possible to implement projects in aggressive environments without endangering the health of personnel (Ramachandran and Gale, 2008).

One of the first to propose the idea of gradual automation of the construction process was Joseph Peña, a professor in the Department of Mechanical Engineering at Stanford University (Pegna, 1992). It was he who proposed the use of cement-based materials for an additive approach to construction (Pegna, 1997). Behrokh Khoshnevis, a professor at the University of Southern California, proposed the idea of implementing construction 3D printing. In the mid-1990s, he proposed the innovative Contour Crafting (CC) technology (Khoshnevis and Dutton, 1998).

Contour Crafting (CC) is one of the additive construction technologies that can be used in the construction of large-scale facilities (Fig. 1) (Khoshnevis and Dutton, 1998). According to Khoshnevis, SS can allow the printing of several buildings per run (Khoshnevis, 2004). The following materials can be used: polymers, ceramic slip, and concrete. During the process of material extrusion, a smooth surface is formed using spatulas installed on the feed nozzle (Hwang et al., 2004). The trowel sizes limit the total height of the layer; moreover, the layer should be chosen so that the lower layers start to solidify and have sufficient strength before the upper layers are laid. By using specialized equipment installed on a frame, it is able to automate the process of placing utilities in wall cavities, thanks to the Contour Crafting technology (Perkins and Skitmore, 2015).

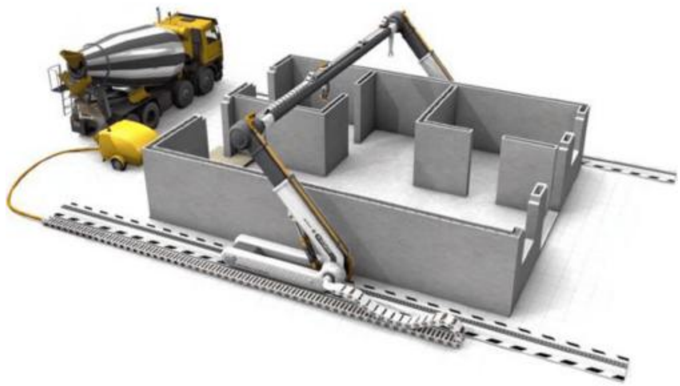

Figure 1. Construction of buildings using 3D-concrete printing (Lesovik et al., 2022)

A while after Behrokh Khoshnevis announced Contour Crafting, Concrete Printing (CP) was the name of the new technology that was made public. Richard Buswell and associates initially introduced this technique in 2009 at Loughborough University to showcase its potential (Gardiner, 2011). Since then, this technology in construction has gained many adherents, and there are reasons for this (Tay et al., 2016). This method is similar to Contour Crafting technology, in that is, it is based on layer-by-layer extrusion of the building mixture. The main difference from CC is that in the CP method, there are no spatulas on the extruder (Fig. 2), which makes it possible to create even more geometrically complex contours (Lim et al., 2011). It is thanks to this feature that this method seems to be the most promising in construction since the creation of buildings and structures of unique shapes is becoming an increasing priority and popular area in this area (Buswell et al., 2007). The downside is that due to the absence of spatulas on the extruder, it becomes necessary to treat the surface of the printed structure (Buswell et al., 2008).

Figure 2. The construction process uses Concrete Printing technology (Bos et al., 2016)

A fundamentally different technology in construction additive manufacturing is the D-shape. D-Shape technology is the invention of Enrico (Dini, 2012)The printing process using this technology is conventionally divided into 3 stages:

1. Creation of a 3D model of the object,
2. Construction of the object,
3. Final processing of the object

The extruder, unlike the techniques mentioned above, applies an adhesive to sand or other powdered material rather than a ready-made building combination. A coating of powder 5-10 mm thick is uniformly added to the printing area when an item is being printed. The glue is then applied to this surface (Perkins and Skitmore, 2015). Following that, another layer of powder with the desired thickness is placed, and the procedure is continued until the printing is complete. Finally, the layer of powder used as a support is removed, and the object's surface is honed and polished. Thus, the procedure is almost equivalent to binder jetting technology (Mahapatra and Panda, 2013). An excellent example of the capabilities of the DShape technology is the sculpture “Radiolaria”, printed back in 2009 (Fig. 3) (Lim et al., 2012). The material for the sculpture was artificial sandstone, and the adhesive was a solution with the addition of magnesium oxide (Le et al., 2012a). The final material was robust enough to withstand the weight of the entire building and was safe for the environment (Vatin et al., 2017).

Figure 3. 3D printed construction elements by D-Shape technology (Nerella and Mechtcherine, 2019)

Since all materials are natural and undergo only minor processing, the final printed product looks very natural (Tibaut et al., 2016). At the moment, the possibility of using this technology for printing from lunar stone regolith is being considered. It is expected that with positive results from research in this area, D-shape technology can be used to print structures in space (Cesaretti et al., 2014).

The primary downside of employing this technology in building is that it only allows you to print little items. This restriction is related to the qualities of sand and other printing materials. Thus, we may infer that this technique is more suited for printing ornamental pieces than for building and erecting structures. It is worth mentioning that one of the major obstacles to broad implementation of Direct Deposition (CC and CP) technologies is a scarcity of materials that fulfill the required specifications.

The whole studies that have been used in this articles are summarized in to a table the these materials used in 3D printing for construction as shown in the table 1.

Table 1 Summary of Materials Used in 3D Printing for Construction in this article

Material	Researcher(s)	Date (year)	Application/Status
Polymers, Ceramics, Concrete	Khoshnevis	2004	Used in Contour Crafting for large-scale facilities; automated construction method.
High-performance Concrete	Le et al.	2012a	Mix design for structural integrity in 3D printing; used in experimental structures.
Sulfur Concrete	Grugel and Toutanji	2008	Proposed as an alternative for construction printing; not widely implemented.
Concrete with Cement, Limestone, Metakaolin	Perrot et al.	2016	Tested for yield strength; useful for extrusion in 3D printing.
Concrete with Sand, Chemically Active Components	Le et al.	2012	Used in Wonder Bench; suitable for 3D printing; strength 95% of normal concrete.
Concrete with Sand, Fly Ash, Micro Silica, Polypropylene Fibers	Le et al.	2012	High-performance mixture for 3D printing; tested for 61 layers with high compressive strength.
Extrudable Concrete Mixture	Vatin et al.	2017	Tested at American University of Beirut; mix shows compressive strength of 42 MPa.
Crazy Magic Stone (with fibers and quartz sand)	Winsun	-	Used by Winsun; abrasion-resistant, strength 4-5 times higher than natural stone.
Glass Fiber-Reinforced Gypsum	Liu et al.	2008	Used in Winsun; enhances mechanical properties and flexibility.
Artificial Sandstone	Lim et al.	2012	Demonstrated in D-Shape technology; used for decorative elements.

The two main 3D printing techniques utilized in the construction industry, Direct Deposition and Bed Deposition, are depicted in the flow diagram. By supplying material directly to the construction site in accordance with the CAD model, the Direct Deposition approach eliminates the need for formwork and increases architectural freedom. Applying a layer of powdered material and then solidifying it with heat sources like lasers or electron beams is known as bed deposition. Excess powder must be removed using this manner after each layer is constructed. These procedures are a part of additive technologies, which allow for waste-free layer-by-layer building as shown in the belo flow diagram (Fig4).

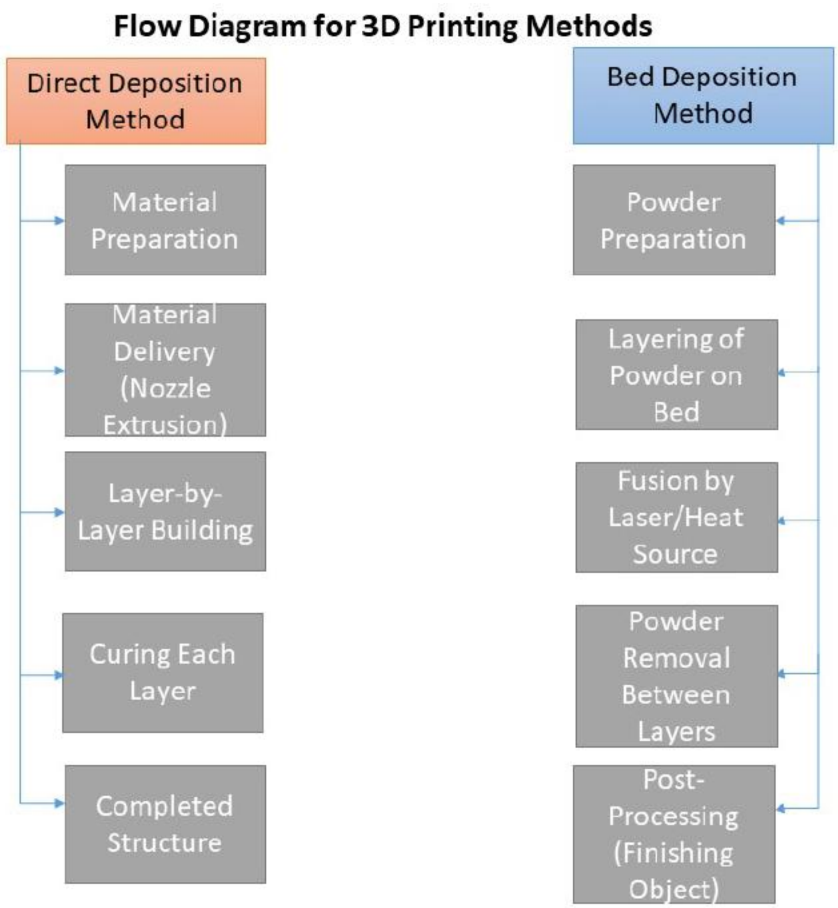

Figure 4 Process Flow Diagram for 3D Printing Methods: Direct Deposition vs. Bed Deposition

III. ANALYSIS OF THE COMPOSITIONS USED

Nowadays, a broad range of materials are employed for additive technologies: a variety of polymers and steel powders, rubbers, titanium, nickel, aluminum, and alloys of copper, in addition to instrumental and structural ceramics, compatible with life and nano-strengthened composites. Most of these materials are used in mechanical engineering, the automotive and aircraft industries, the production of consumer items, and medicinal applications. We need to pay close attention to the advances made by 3-D printing technology in the production of exoskeletons and endoprostheses. However, as additive technologies are still in the early stages of development, the materials used are still at this development stage.

A team of researchers from Chattanooga, Tennessee, is utilizing Branch's technology: a quick robot that constructs scaffolding from carbon fiber-reinforced ABS plastic. The structure may have a sophisticated architectural design. After being brought to the construction site, it is supplemented with traditional building supplies such as concrete, plaster, and foam using the same tools that construction workers use today. However, this technique has yet to enable the building of load-bearing walls and critical structures.

Cement compositions that harden for an extended period are unable to meet the quality requirements of three-dimensional printing. The mixture needs to be thixotropic, meaning that when subjected to mechanical stress, it should become less viscous and more viscous at rest. Sulfur concrete, a composite material composed of sulfur and aggregate, represents a possible solution for construction printing. The combination is heated to temperatures above the melting point of sulfur. Concrete does not require permanent hardening to reach the desired strength after cooling (Grugel and Toutanji, 2008).

The standards for building materials needed for 3D printing are not met by regular cement made from concrete (Hager et al., 2016). To maximize the process of 3D printing, two criteria must be taken into consideration. First, as the time intervals between layers increase, the adhesive strength between layers decreases (Lloret et al., 2015). Second, the material needs to harden enough to withstand the weight of later-placed layers without deformation. Building construction will be slowed down by the requirement to cure previously printed layers. The combination of these two limitations leads to the puzzle of print speed optimization. The time gap between two deposited layers must be both sufficiently long to produce the required strength and sufficiently short to provide good adhesion between the layers (Le et al., 2012).

The capacity of deposited layers to support their weight is directly related to yield strength (Le et al., 2012a, Perrot et al., 2016). While building a wall layer by layer, the first deposited layer bears the greatest load. To maintain wall stability throughout this procedure, the yield strength must be sufficient to support this load. However, the mixture needs to be sufficiently fluid to allow for extrusion. To construct the structure, adequate fluidity throughout extrusion and stability after applying the layer is required. The yield strength of cement-based materials improves with time at rest (Perrot et al., 2012, Lowke et al., 2010, Wallevik, 2009)

A group of French scientists (Perrot et al., 2016) proved that the variation in yield strength is linear (Rousselle model) (Roussel, 2006) through the initial 40 minutes; for a longer period, the increase in yield is well defined by the model of Perrault et al. (Perrot et al., 2015). The scientists adopted the following mixture for the experiments: 50% cement, 25% limestone, and 25% metakaolin. The proportion of water to cement was 0.41. As a superplasticizer, polycarboxylate was utilized; its mass percentage in cement is equal to 0.3%. It was discovered that the material's initial yield strength was 4 kPa, which is within the range of the yield strength of the material created at the University of Southern California for the Contour Crafting technique. This yield strength was quite high (Khoshnevis et al., 2006, Zhang and Khoshnevis, 2013).

For concrete extrusion, in particular, the use of limestone as a filler enhances the material's workability, flexural strength, and compressive strength (Alhozaimy, 2009, Bederina et al., 2011).

Metakaolin improves the properties of mortar and concrete. A more homogeneous microstructure is produced and water separation is decreased by the paste-like structure that is created in the composition by the tiny particles that may be put in between the cement grains. Metakaolin increases the strength and durability of cement (Kocak, 2020). Moreover, the pore volume is decreased when metakaolin partially replaces cement in cement mortar and concrete (Duan et al., 2013), which enhances tolerance to frost (Steenberg et al., 2011).

The duration of the plasticizing action of polycarboxylates is increased by 3-4 times when compared with sulfomelanine, sulfonaphthalene formaldehydes, or lignosulfonates (Izotov and Sokolova, 2006). This enables the concrete mixture to be more adaptable in the beginning and to be maintained for a longer amount of duration (Ghosal and Chakraborty, 2022), this increases the amount of time the mixture may be fed through the extruder beneficially.

Currently, researchers at Loughborough University have focused particularly on the selection and examination of concrete mixture qualities for 3D printing (Le et al., 2012a, Le et al., 2012b, Lim et al., 2012). The team of researchers demonstrated a full-scale structure measuring 1 x 2 x 0.8 m called the Wonder Bench. For the bench, a concrete mixture that could be readily pumped and extruded was created; the completed construction had to be strong enough to support the weight. Although the exact composition of the combination is unknown, it consists of 54% sand, 36% chemically active cement components, and 10% water by mass. The ultimate material's strength, the researchers saw, was 95% that of regular concrete (Lim et al., 2012).

Additionally, British scientists experimented with creating a composition of concrete that would be appropriate for high-performance printing. It specifies the ideal composition, which contains sand and binder in a 3:2 ratio, with the latter consisting of 70% cement, 20% fly ash, and 10% micro silica, with an additional 1.2 kg of polypropylene fibers per 1 m^3 (Le et al., 2012a). The cement-to-water ratio is 0.26. Superplasticizer and retarder were included in the amounts of 1 and 0.5%, respectively, by weight.

The addition of micro silica to concrete results in a more densely packed concrete structure, higher bending strength, and reduced permeability (Abdou and Abuseda, 2016). The beneficial interactions between the polypropylene fibers and fly ash lead to low drying shrinkage of concrete. Nevertheless, polypropylene fiber makes concrete harder to work with (Karahan and Atiş, 2011), However, the superplasticizer makes the mixture sufficiently plastic for extrusion.

Using a 9 mm nozzle, the combination in question was printed in 61 consecutive layers in a single session without the bottom layers experiencing any discernible deformation. The combination can survive for one hundred minutes. Concrete's compressive strength at 28 days of age is 110 MPa, which is more than anticipated (Le et al., 2012).

Researchers at the American University of Beirut in Lebanon have found a highly extrudable combination that has the strength required for construction businesses to use 3D printing to create things. After experimenting with other combinations, the optimal combination to get the required result was 125 g cement, 80 g sand, and 160 g fine aggregate with a water-cement ratio of 0.39. Add 0.625 ml retarder and 1 ml superplasticizer to enhance print performance. The compressive strength of such a combination is around 42 MPa (Vatin et al., 2017).

The Chinese company Winsun, which holds a prominent position in the 3D printing industry, effectively employs Crazy Magic Stone, an abrasion-resistant composition with a strength that is (4-5) times higher than that of natural stone. Special fiber and treated quartz sand are the reasons for the high mechanical properties. Glass fiber-reinforced gypsum is also extensively used in Winsun. Fiber with a diameter of 5.8 to 100 microns and a length of 1 to 13 cm makes up 3-25% of the fiber in GFRG. The range of the water-to-gypsum ratio is 0.25 to 0.60 (Baehr and Izard, 1981, Liu et al., 2008). It is easier to lay and more flexible since fiberglass strengthens the composition's resistance to breaking. The tensile and bending resistance of composite materials made with glass fiber is significantly increased because the fiber absorbs tensile stresses (Kim et al., 2008, Chandramouli et al., 2010, Yi, 2014).

The importance of the topic under review is reinforced by the continued interest in the issue of 3D printing compositions; in many countries, advancements are already underway that make it possible to employ 3D printing for the construction of buildings and structures. To date, a lot of companies have achieved some success.

The comparision of 3D printing technology and material quality for construction application have been summarized as shown in the table 2.

Table 2 Comparison of 3D Printing Technologies and Material Qualities for Construction Applications

Material Type	Description	Key Qualities
Sulfur Concrete	Composite of sulfur and aggregate, heated to high temperatures for molding.	No need for permanent hardening, quick setting after cooling, suitable for 3D printing.
Metakaolin	Additive in cement to improve strength and durability.	Enhances strength, reduces water separation, improves frost tolerance.
Polycarboxylates	Superplasticizers used to increase workability of concrete.	Extended plasticizing action, improves mixture adaptability for extrusion.
Crazy Magic Stone	Abrasion-resistant composition with high mechanical properties.	Strength 4-5 times higher than natural stone, fiber and treated quartz sand enhance properties.
Glass Fiber-Reinforced Gypsum (GFRG)	Gypsum mixed with glass fibers for improved flexibility and strength.	Increased tensile and bending resistance, reduces cracking.

IV. CONCLUSION

In conclusion, 3D printing of large-scale construction components remains a newly developed technique and as an alternate construction technique is attracting growing interest. In the industry, additive technologies have already been widely used recently. But when it comes to using 3D concrete printing technology, the construction industry appears traditional and falls behind other industries. A substantial amount of research and development goes into the process of introducing additive technologies into the technique of developing constructions and structures. However, large companies are also developing in this area, whose interest is evident, in addition to educational institutions and scientific groups. 3D concrete printing of buildings has the potential to drastically alter the real estate market and related industries. The main problems, the solution of which will ensure the serious development of additive construction technologies, are:

- absence of a regulatory framework,
- the requirement to develop the market for construction materials for 3D printing,
- The high equipment costs result from the absence of large series.

Although large global institutions and large companies are involved in the research and development of additive construction technologies, there is great potential for scientific research in this area and their application in practice.

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REFERENCES

ABDOU, M. & ABUSEDA, H. 2016. Upgrading offshore pipelines concrete coated by silica fume additive against aggressive mechanical laying and environmental impact. Egyptian Journal of Petroleum, 25, 193-199.

ALHOZAIMY, A. M. 2009. Effect of absorption of limestone aggregates on strength and slump loss of concrete. Cement and Concrete Composites, 31, 470-473.

BAEHR, D. O. & IZARD, D. G. 1981. Method for the production of glass fiber-reinforced gypsum sheets and gypsum board formed therefrom. Google Patents.

BARAZANCHI, A., LI, K. C., AL-AMLEH, B., LYONS, K. & WADDELL, J. N. 2017. Additive technology: update on current materials and applications in dentistry. Journal of Prosthodontics, 26, 156-163.

BEDERINA, M., MAKHLOUFI, Z. & BOUZIANI, T. 2011. Effect of limestone fillers the physic-mechanical properties of limestone concrete. Physics Procedia, 21, 28-34.

BOS, F., WOLFS, R., AHMED, Z. & SALET, T. 2016. Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual and physical prototyping, 11, 209-225.

BRENNAN-CRADDOCK, J., BRACKETT, D., WILDMAN, R. & HAGUE, R. The design of impact absorbing structures for additive manufacture. Journal of Physics: Conference Series, 2012. IOP Publishing, 012042.

BUSWELL, R. A., SOAR, R. C., GIBB, A. G. & THORPE, A. 2007. Freeform construction: mega-scale rapid manufacturing for construction. Automation in construction, 16, 224-231.

BUSWELL, R. A., THORPE, A., SOAR, R. C. & GIBB, A. G. 2008. Design, data and process issues for mega-scale rapid manufacturing machines used for construction. Automation in Construction, 17, 923-929.

CAMPBELL, T., WILLIAMS, C., IVANOVA, O. & GARRETT, B. 2011. Could 3D printing change the world. Technologies, Potential, and Implications of Additive Manufacturing, Atlantic Council, Washington, DC, 3, 1-16.

CESARETTI, G., DINI, E., DE KESTELIER, X., COLLA, V. & PAMBAGUIAN, L. 2014. Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. Acta Astronautica, 93, 430-450.

CHANDRAMOULI, K., SRINIVASA, R., PANNIRSELVAM, N., SESHADRI, S. & SRAVANA, P. 2010. Strength properties of glass fiber concrete. ARPN journal of Engineering and Applied sciences, 5, 1-6.

CHEN, L., HE, Y., YANG, Y., NIU, S. & REN, H. 2017. The research status and development trend of additive manufacturing technology. The International Journal of Advanced Manufacturing Technology, 89, 3651-3660.

DI CARLO, T., KHOSHNEVIS, B. & CARLSON, A. Experimental and numerical techniques to characterize structural properties of fresh concrete. ASME International Mechanical Engineering Congress and Exposition, 2013. American Society of Mechanical Engineers, V009T10A062.

DING, Z., LIU, S., LIAO, L. & ZHANG, L. 2019. A digital construction framework integrating building information modeling and reverse engineering technologies for renovation projects. Automation in Construction, 102, 45-58.

DINI, E. 2012. Method for automatically producing a conglomerate structure and apparatus therefor. Google Patents.

DUAN, P., SHUI, Z., CHEN, W. & SHEN, C. 2013. Enhancing microstructure and durability of concrete from ground granulated blast furnace slag and metakaolin as cement replacement materials. Journal of Materials Research and Technology, 2, 52-59.

FU-CAI, L., YI-YUAN, W., MIN, X., BIN, L., XIN-ZHEN, Z. & MING, H. 2015. High-performance powder concrete for 3D (threedimensional) printing: pat. CN104961411A.

GÁLVEZ, J. A., SIMPAO, A. F., DORI, Y., GRALEWSKI, K., MCGILL, N. H., RIVERA, M. L., DELSO, N., KHAN, H., REHMAN, M. A. & FIADJOE, J. E. 2016. Not just a pretty face: Three-dimensional printed custom airway management devices. 3D Printing and Additive Manufacturing, 3, 160-165.

GARDINER, J. 2011. Exploring the emerging design territory of construction 3D printing-project led architectural research. RMIT University.

GHOSAL, M. & CHAKRABORTY, A. K. 2022. Superplasticizer compatibility with cement properties–A study. Materials Today: Proceedings, 56, 568-573.

GIBSON, I., ROSEN, D. W., STUCKER, B., KHORASANI, M., ROSEN, D., STUCKER, B. & KHORASANI, M. 2021. Additive manufacturing technologies, Springer.

GRUGEL, R. N. & TOUTANJI, H. 2008. Sulfur "concrete" for lunar applications–Sublimation concerns. Advances in Space Research, 41, 103-112.

HAGER, I., GOLONKA, A. & PUTANOWICZ, R. 2016. 3D printing of buildings and building components as the future of sustainable construction? Procedia Engineering, 151, 292-299.

HERDERICK, E. D. 2016. Additive manufacturing in the minerals, metals, and materials community: past, present, and exciting future. Jom, 68, 721-723.

HORBACH, S., ACKERMANN, J., MÜLLER, E. & SCHÜTZE, J. 2011. Building blocks for adaptable factory systems. Robotics and Computer-Integrated Manufacturing, 27, 735-740.

HUANG, S. H., LIU, P., MOKASDAR, A. & HOU, L. 2013. Additive manufacturing and its societal impact: a literature review. The International journal of advanced manufacturing technology, 67, 1191-1203.

HULL, C. W. 1984. Apparatus for production of three-dimensional objects by stereolithography. United States Patent, Appl., No. 638905, Filed.

HWANG, D., KHOSHNEVIS, B. & DANIEL, E. Concrete wall fabrication by contour crafting. 21st international symposium on automation and robotics in construction (ISARC 2004), Jeju, South Korea, 2004. Citeseer, 301-307.

IBRAHIM, M. I. M. 2016. Estimating the sustainability returns of recycling construction waste from building projects. Sustainable Cities and Society, 23, 78-93.

IZOTOV, V. & SOKOLOVA, Y. A. 2006. Chemical additives for concrete modification. M.: Kaz. ACS: Publishing.

KABLOV, E. 2020. New generation materials and technologies for their digital processing. Herald of the Russian Academy of Sciences, 90, 225-228.

KARAHAN, O. & ATIŞ, C. D. 2011. The durability properties of polypropylene fiber reinforced fly ash concrete. Materials & Design, 32, 1044-1049.

KHOSHNEVIS, B. 2004. Automated construction by contour crafting—related robotics and information technologies. Automation in construction, 13, 5-19.

KHOSHNEVIS, B. 2015. Contour crafting extrusion nozzles. Google Patents.

KHOSHNEVIS, B. & DUTTON, R. 1998. Innovative rapid prototyping process makes large sized, smooth surfaced complex shapes in a wide variety of materials. Materials Technology, 13, 53-56.

KHOSHNEVIS, B., HWANG, D., YAO, K.-T. & YEH, Z. 2006. Mega-scale fabrication by contour crafting. International Journal of Industrial and Systems Engineering, 1, 301-320.

KIM, G., PILAKOUTAS, K. & WALDRON, P. 2008. Development of thin FRP reinforced GFRC permanent formwork systems. Construction and building materials, 22, 2250-2259.

KLAMMERT, U., REUTHER, T., JAHN, C., KRASKI, B., KÜBLER, A. & GBURECK, U. 2009. Cytocompatibility of brushite and monetite cell culture scaffolds made by three-dimensional powder printing. Acta Biomaterialia, 5, 727-734.

KOCAK, Y. 2020. Effects of metakaolin on the hydration development of Portland–composite cement. Journal of building engineering, 31, 101419.

KREIGER, M. A., MACALLISTER, B. A., WILHOIT, J. M. & CASE, M. P. The current state of 3D printing for use in construction. The Proceedings of the 2015 Conference on Autonomous and Robotic Construction of Infrastructure. Ames. Iowa, 2015. 149-158.

KÜCHLER, S. 2014. Additive technology and material cognition: a view from anthropology. Journal of cognition and culture, 14, 385-399.

KUMAR, L. J. & KRISHNADAS NAIR, C. 2017. Current trends of additive manufacturing in the aerospace industry. Advances in 3D printing & additive manufacturing technologies, 39-54.

LE, T. T., AUSTIN, S. A., LIM, S., BUSWELL, R. A., GIBB, A. G. & THORPE, T. 2012a. Mix design and fresh properties for high-performance printing concrete. Materials and structures, 45, 1221-1232.

LE, T. T., AUSTIN, S. A., LIM, S., BUSWELL, R. A., LAW, R., GIBB, A. G. & THORPE, T. 2012b. Hardened properties of high-performance printing concrete. Cement and Concrete Research, 42, 558-566.

LESOVIK, V., TOLSTOY, A., FEDIUK, R., AMRAN, M., ALI, M. & DE AZEVEDO, A. R. 2022. Improving the performances of a mortar for 3D printing by mineral modifiers. Buildings, 12, 1181.

LIM, S., BUSWELL, R., LE, T., WACKROW, R., AUSTIN, S. A., GIBB, A. & THORPE, T. 2011. Development of a viable concrete printing process.

LIM, S., BUSWELL, R. A., LE, T. T., AUSTIN, S. A., GIBB, A. G. & THORPE, T. 2012. Developments in construction-scale additive manufacturing processes. Automation in construction, 21, 262-268.

LIU, K., WU, Y.-F. & JIANG, X.-L. 2008. Shear strength of concrete filled glass fiber reinforced gypsum walls. Materials and Structures, 41, 649-662.

LLORET, E., SHAHAB, A. R., LINUS, M., FLATT, R. J., GRAMAZIO, F., KOHLER, M. & LANGENBERG, S. 2015. Complex concrete structures: Merging existing casting techniques with digital fabrication. Computer-Aided Design, 60, 40-49.

LOWKE, D., KRÄNKEL, T., GEHLEN, C. & SCHIEßL, P. Effect of cement on superplasticizer adsorption, yield stress, thixotropy and segregation resistance. Design, Production and Placement of Self-Consolidating Concrete: Proceedings of SCC2010, Montreal, Canada, September 26-29, 2010, 2010. Springer, 91-101.

MA, G., WANG, L. & JU, Y. 2018. State-of-the-art of 3D printing technology of cementitious material—An emerging technique for construction. Science China Technological Sciences, 61, 475-495.

MAHAPATRA, S. S. & PANDA, B. N. 2013. Benchmarking of rapid prototyping systems using grey relational analysis. International Journal of Services and Operations Management, 16, 460-477.

MÜLLER, E. Building blocks as an approach for the planning of adaptable production systems. International Heinz Nixdorf Symposium, 2010. Springer, 37-45.

NAWY, E. G. 2008. Concrete construction engineering handbook, CRC press.

NERELLA, V. N. & MECHTCHERINE, V. 2019. Studying the printability of fresh concrete for formwork-free concrete onsite 3D printing technology (CONPrint3D). 3D Concrete Printing Technology. Elsevier.

PEGNA, J. 1992. Construction automation: Are we solving the wrong problem. RPI. RDRC Technical Report 92010.

PEGNA, J. 1997. Exploratory investigation of solid freeform construction. Automation in construction, 5, 427-437.

PERKINS, I. & SKITMORE, M. 2015. Three-dimensional printing in the construction industry: A review. International Journal of Construction Management, 15, 1-9.

PERROT, A., MÉLINGE, Y., RANGEARD, D., MICAELLI, F., ESTELLÉ, P. & LANOS, C. 2012. Use of ram extruder as a combined rheo-tribometer to study the behaviour of high yield stress fluids at low strain rate. Rheologica acta, 51, 743-754.

PERROT, A., PIERRE, A., VITALONI, S. & PICANDET, V. 2015. Prediction of lateral form pressure exerted by concrete at low casting rates. Materials and Structures, 48, 2315-2322.

PERROT, A., RANGEARD, D. & PIERRE, A. 2016. Structural built-up of cement-based materials used for 3D-printing extrusion techniques. Materials and Structures, 49, 1213-1220.

RAMACHANDRAN, N. & GALE, A. 2008. Space colonization. Aerospace America, 46, 77.

ROUSSEL, N. 2006. A thixotropy model for fresh fluid concretes: Theory, validation and applications. Cement and concrete research, 36, 1797-1806.

STEENBERG, M., HERFORT, D., POULSEN, S., SKIBSTED, J. & DAMTOFT, J. Composite cement based on Portland cement clinker, limestone and calcined clay. Proceedings of the XIII International Congress on the Chemistry of Cement, 2011. 97.

TAY, Y. W., PANDA, B., PAUL, S. C., TAN, M. J., QIAN, S. Z., LEONG, K. F. & CHUA, C. K. Processing and properties of construction materials for 3D printing. Materials Science Forum, 2016. Trans Tech Publ, 177-181.

TIANRONG, Y. & QIAOLING, L. 2015. 3D printing cement-based material and preparation method thereof: пат. CN104891891A.

TIBAUT, A., REBOLJ, D. & NEKREP PERC, M. 2016. Interoperability requirements for automated manufacturing systems in construction. Journal of intelligent manufacturing, 27, 251-262.

VATIN, N., CHUMADOVA, L., GONCHAROV, I., ZYKOVA, V., KARPENYA, A., KIM, A. & FINASHENKOV, E. 2017. 3D printing in construction. Stroitel'stvo Unikal'nyh Zdanij i Sooruzenij, 27.

WALLEVIK, J. E. 2009. Rheological properties of cement paste: Thixotropic behavior and structural breakdown. Cement and Concrete Research, 39, 14-29.

WARSZAWSKI, A. & NAVON, R. 1998. Implementation of robotics in building: Current status and future prospects. Journal of Construction Engineering and Management, 124, 31-41.

WONG, K. V. & HERNANDEZ, A. 2012. A review of additive manufacturing. International scholarly research notices, 2012.

YI, M. 2014. 3D (Three-Dimensional) printing high-strength composite board: пат. CN 104328890 A.

ZHANG, J. & KHOSHNEVIS, B. 2013. Optimal machine operation planning for construction by Contour Crafting. Automation in Construction, 29, 50-67.

ZLENKO, M., POPOVICH, A. & MUTYLINA, I. 2013. Additivnye tekhnologii v mashinostroenii [Additive technologies in machine industry].