Аддитивное производство. Обзор исследований, возможностей и проблем

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Информация о статье обзор

Аннотация

3D печать, известная как аддитивное производство, может изменить строительную отрасль в лучшую сторону. Большая структурная эффективность, снижение расходов на материалы, повышенная точность и экономическая выгодность, все эти характеристики присущи к аддитивному производственному процессу. В статье рассказывается о резком увеличении публикаций по теме аддитивного производства в строительстве и о перспективах дальнейшего развития этой технологии. Проблемы с труднодоступностью материалов для печатающих головок строительного принтера были решены путем фильтрации частиц земли, 50% из которых пригодны в использовании в качестве мелкого заполнителя. Также были рассмотрены способы улучшения свойств материалов: прочность, скорость затвердевания защита от влаги и др. Аддитивное производство открывает множество возможностей для строительства, но вместе с этим приносит новые проблемы, связанные с большим акцентом на проверку и нагрузочное тестирование и новым способом проектирования.

Ключевые слова: 3D печать, аддитивное производство, строительная информация, моделирование строительной отрасли, бетон, строительные материалы, исследования, обзор

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1. Introduction

The construction sector plays one of the most important role in the economy of any country. According to a report which published by the World Economic Forum, the construction industry currently accounts for more than 6% of global GDP [1] and is expected to reach more than 14.5% by 2030 [2]. Construction is a strategically important sector for the Russian and European economies due to the participation of a wide range of stakeholders and companies that can provide more than 18 million jobs [3]. A 1% increase in labor productivity around the world can save about $ 100 billion a year in costs [4], which in the long run can contribute to the country's sustainable development [5-7]. Worldwide, more than 200,000 people move to urban areas per day, where they need affordable, sustainable housing and infrastructure [1]. Nevertheless, still relying on traditional methods the perceived image of the construction sector is mainly low-tech, which characterized by poor efficiency, low productivity and unstable build quality [8-11].

For example, Gartner [12] is one of the world's leading companies in the field of information technology, which has named 3D printing as “a rare example of one technology, which in itself has become truly large-scale and destructive,” as well as one of the new technological trends, which are believed by employees, which will significantly affect the construction business in the 2020s. Other industrial sectors, such as the automotive, aeronautics and aerospace industries have already undergone radical changes in the process of introducing digital technologies to improve quality and productivity [17–20]. Metal structural sections and connecting nodes have been built with the help of additive processes. A pedestrian bridge has been built using this technology (fig. 5). According to a survey conducted by Roland Berger, 93% of construction stakeholders agree that digitization will affect every process but less than 6% of construction companies can fully afford digital planning tools [16], because of too long payback periods.

The contouring method is focused on the speed and productivity of printing, therefore, it is a kind of low-resolution printer, which is most often used as the most optimal method and which experts seek to develop further for mass production and construction [21], because of the high printing speed, certain limitations on the strength of the material and the shapes are associated with this method [22].

Additive manufacturing processes based on solid materials include the layered assembly of material in solid form, which takes a lot of time to build. The connection between different layers is achieved using a number of different methods, such as the use of glue-like material [23, 24] or, for example, weaving [13]. Masonry is probably one of the oldest additive building processes based on solid materials [25]. Building a brick wall using mortar for bonding layers was an additive manufacturing process before the development of 3D printers.

The review contains an analysis of the main additive manufacturing technologies that developed for construction in developing countries, subject to the need for maximum use of local materials for the construction of buildings and structures.

The purpose of this study is to identify important problems that limit the introduction of robotics in the construction industry and find the most suitable devices and materials for additive production of all available and proposed at the moment. To achieve these goals, a literature review was given on the types of robotics that perform work by various methods and existing materials that have the necessary conditions and ease of use. Later, a quantitative analysis was given to determine the optimal raw materials and the necessary robotics for implementation in the construction industry.1

2. General situation of additive manufacturing in recent years

Over the past few years, there has been a rapid increase in scientific publications related to terms such as 3D-printer and Additive manufacturing. Charts 1 and 2 show how many publications were found at the request of Construction 3D-printer and Additive manufacturing. This study is based on a cartographic study, which is intended to carry out an objective and more accurate selection of literary sources related to the topic under consideration. The search for the keywords shown in the graphs was carried out in ScienceDirect. According to the graphs, we can conclude that over the past 10 years interest in additive processes has grown more than 10 times, the calculation was performed taking into account the increasing popularity of the magazine.

a) b) c)

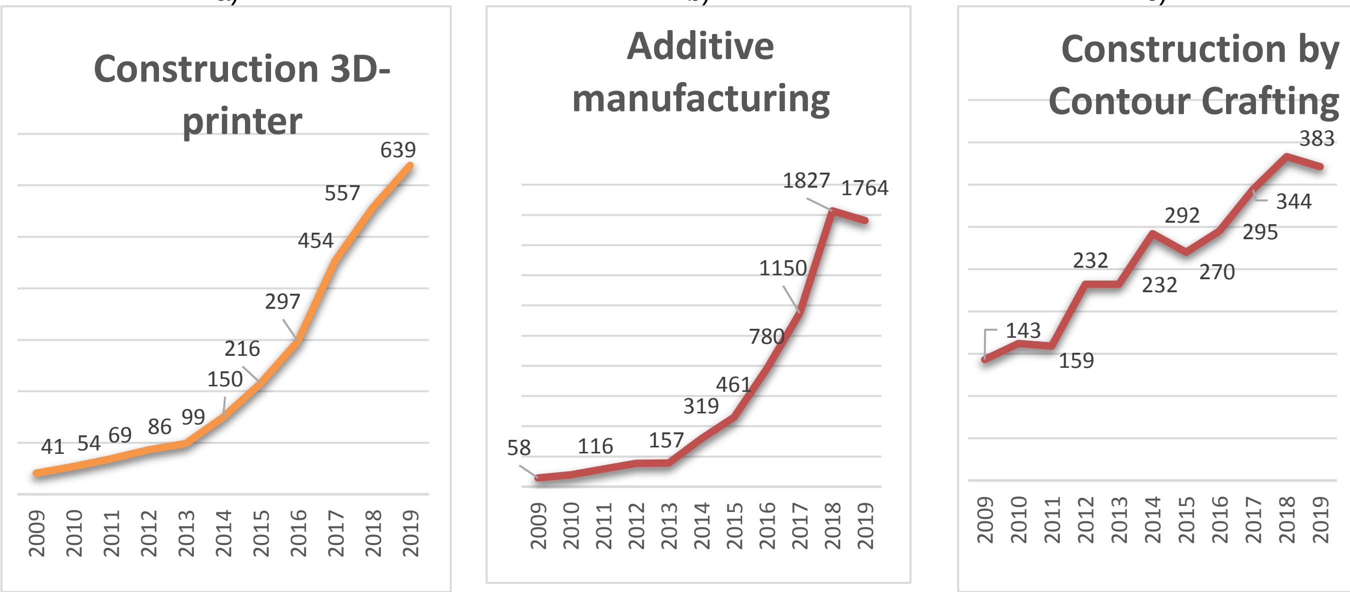

Figure 1. Graphics 1a, 1b, 1c. Keywords used for the initial search.

Petersen et al. [26] describe how to conduct systematic cartographic research using software development and their proposed structure. Later it was implemented in other areas [27]. This study uses similar methods. Searches for the described search method were performed in 3 scientific bases: Scopus, Direct Science and Engineering Village. Searches in only 3 scientific bases do not indicate the absolute accuracy of the studies, but by similar growth indicators you can average the results among other well-known scientific bases. The main keywords used to search for articles set out on graphics 1a, 1b, 1s. The selection was made on August 26th and presented the following results:

- Scopus have 974 publications
- Direct Science have 730 publications
- Engineering Village have 769 publications

12 publications from academic sources and more than 72 web pages were also included in the results of research. All identified keywords were combined in order to develop a high level of understanding of the field of additive production in relation to the construction industry.

Given the fact that robotic and automated systems in the construction field have been developed since the 1960s [28], this technology still has a large number of drawbacks. The development of technology in this industry is limited by the complexity, scale and technology of construction. Research is not enough to address these factors. In [29] all the frameworks that affect the introduction of additive production in Mailazia and Japan were investigated in detail. The complexity of implementation, in addition to all, is also affected by the absence of most studies in the literature [30]. The authors emphasize that despite all the prospects for automation of the construction process, subject-oriented tasks have not been studied yet.

3. Additive manufacturing in construction

Additive Manufacturing (AM), according to the American Society for Testing Materials, is “the process of combining materials to create objects from three-dimensional model data, usually layer by layer, as opposed to subtractive manufacturing methodologies such as traditional machining.” At present, the production technologies for toys and furniture, the automotive and aerospace industries, which are also undergoing changes, are becoming more and more productive [31, 32]. The increasing industrial use of AM processes is due to their unique characteristics [33-36], such as: a computer model is first formed using the CAD system (surface model), being mosaic and reformatted to the standard STL format, which is later cut into several cross sections, after of this, all parts are sent to the AM system [35,37-40]. The model in the CAD program must be a three-dimensional solid using the solid-state model (CSG) or the boundary representation (B-Rep). The STL file format is easy to create, but has some problems associated with its size and numerical accuracy [41]. It is also impossible to control the properties of the material, therefore, the manufacture of multi-material components requires the use of several STL files (Fig. 1), which is an important drawback and greatly complicates the task, since AM has a high potential for obtaining functionally graded structures.

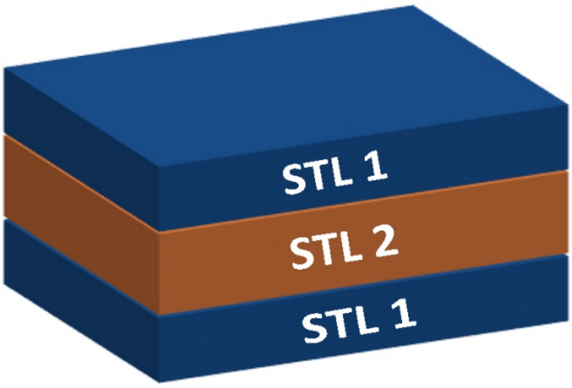

Fig. 1. STL files for multi-material components.

Presentation of these materials requires both geometric modeling and material modeling [42, 43]. Modeling heterogeneous objects includes manifold solids, non-manifold solids, r-sets, s-sets, selective geometric complex (CGC), constructive irregular geometry (CNRG) and discrete representations [43–47]. To solve this drawback, several generalized methods were proposed, including a common layer interface (CLI), an ASCII layer exchange format (sheet) and a piece format (SLC) [48-50]. The creation process can be controlled on the basis of vectors (movement in straight lines; curves close to segments) or a raster (individual points, like a monotonous raster image). Due to the uniqueness of each technology and the type of materials and the size of the building elements, the AM processes used in the construction sector are in most cases extrusion and bonding inkjet processes for off-site and local applications, including the manufacture of modern building elements, houses or structural repairs. In other words, such processes are called contouring processes.

Contour Crafting is an additive manufacturing technology that is controlled by computer programs to use the capabilities of surface formation and create smooth and accurate flat and free surfaces [51], which in the future will allow robots to cope not only with the masonry itself, but also with the form of the solution (connecting material), which should be even and smooth. An important feature of this method is the use of two machines designed for mashing, which operate as two continuous flat surfaces. They were created with the aim of creating surfaces on the fabricated object, which are extremely smooth and accurate [51]. This process is one of the first AM methods proposed for the construction industry, which was developed by Khoshnevis [54]. This technology of deposition of several materials combines the processes of extrusion and filling [51, 52]. The contouring process was used to extrude concrete materials through a 3D printhead mounted on an overhead crane [52]. Support structures create overhangs, and the surface roughness of printed structures becomes smooth without the need for a spatula or other leveling tools. The method of contour crafting was applied in practice by building small-scale structures and walls of the case [54] and successfully manufactured wall elements more than 2 m high with a width of approximately 13.5 cm at a speed of 1 square meter per hour [53.55–57].

There are other methods similar to contour crafting for commercial or academic purposes developed by various companies or research groups, such as TotalKustom (USA) [58], CONPrint3D (Germany) [60], BetAbram (Slovakia) [59], HuaShang Tengda (China) [61], China State Construction Engineering Corporation [62], Specavia (Russia) [63] and ICON (USA) [64]. Some examples of buildings using AM are shown in Figures 2-5.

Fig. 2. 3D printed office in Dubai [65]

Fig. 3. The Europe Building (The Netherlands) [66]

Fig. 4. Apis Cor 3D printed house [67]

Fig. 5. Pedestrian bridge. 3D-Shape technology [68]

One of the most important features of contour crafting is the ability to create various shapes. For example, Bosscher et al. [69] proposed a contoured craft platform with the ability to move, driven by a robot suspended on a cable. A system called Cable-Suspended Contour-Crafting (C4) Robot includes extrusion technology for laying concrete balls, as well as computer-controlled spatulas for forming balls as they are laid. The system uses cable robots, which are relatively inexpensive easily transported, also disassembled and reassembled. The authors indicated that this system was created in order to build large structures with lower costs and greater ease of use (see Fig. 6, 7). The C4 robot consists of a rigid frame and an end effector suspended on twelve cables, grouped into four upper and eight lower cables. The lower ones are further divided into four pairs of parallel cables. The cable arrangement was obtained from a cable robot developed by the first two authors [70].

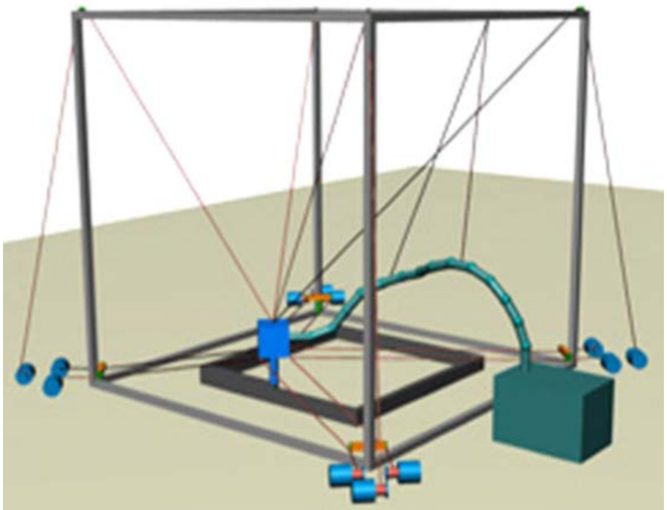

Fig. 6. The contour crafting Cartesian robot

Craveiro et al. [71-77] studied the concept of screw / auxiliary printheads for creating concrete, clay and multi-component structures. First, a system was developed called Rapid Construction, which included a building platform, a linear displacement system and two extrusion heads, each with a screw design that allows processing of various materials. The controller can control 4 axes (3 axes with linear x-y-z movement and rotation of the extrusion head), controlling its movement through each encoder (see Fig. 8, 9). The first extrusion head is capable of producing contour tracks, that smooth the material on the side surfaces through parallel guide vanes. The second head used to create composite meshes has neither freedom of rotation nor side guides.

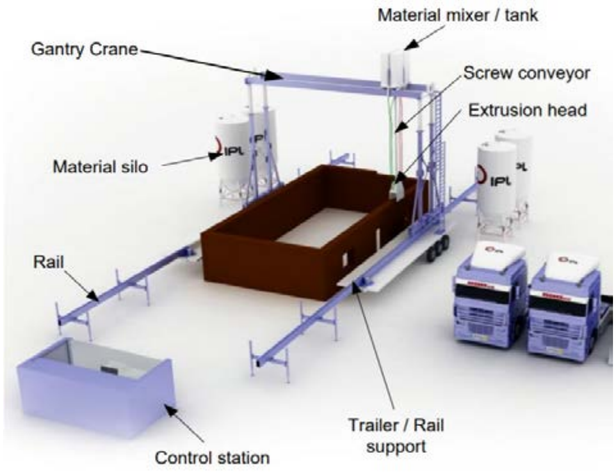

Fig. 8. Representation of the automatic building system

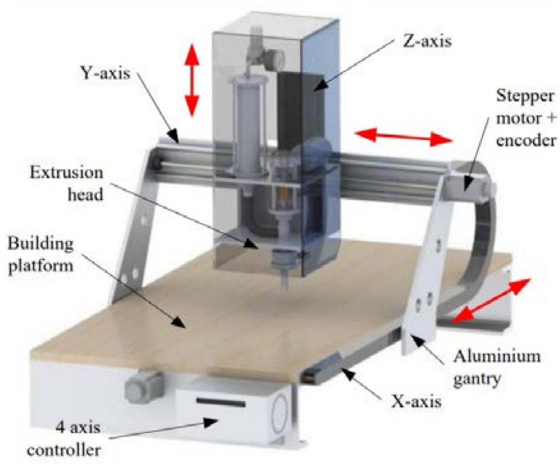

Fig. 9. Equipment for the automatic construction of contour paths.

Perrot et al. [78] suggested using a 3D printer from a combination of a 6-axis industrial robot with a load capacity of 195 kg and an electric pump from TPS Giema, capable of creating a pressure of 20 bar at a flow rate of 40 liters per minute, which is necessary for applying the solution and render. A flexible pipe connects the pump to the robot. In the course of research, the authors tested 2 extruder matrices, one of which was a circular cross-section with a diameter of 35 mm and the other had a rectangular cross-section with an aspect ratio of 21X40 mm2 (Fig. 9). The printer was able to print an object, the volume of which was equal to 1 cubic meter. The layer height of this design was limited by the properties of the solution, which was used as raw earth coming from France. This soil was a mixture of quartz, kaolinite, illite and smectite. This soil has excellent ductility index - 21 with a yield strength of 48% and a ductility limit of 27%. Particle distribution took place over particles with sizes less than 10 lm, which for this soil amounted to approximately 60% of all particles. In addition, the amount of sand and gravel was limited (less than 80% of the random packing fraction [79]) in order to avoid frictional behavior and ensure pumpability. An electromagnetic valve was also added to the matrix, which blocks the passage of the solution when the device is turned off. After printing, the samples were able to withstand a temperature of 20 degrees and a humidity of about 50%.

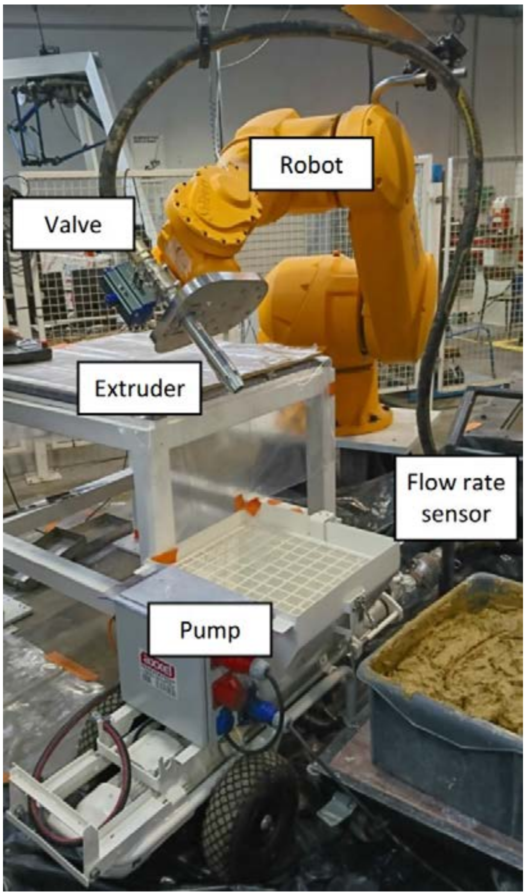

Fig. 9. 3D printer for earth-based material.

4. Requirements for materials, which are used in additive construction

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The requirement for the 3D printing process in terms of material properties can be considered as follows; the raw materials should have a controlled and flexible installation time, a certain level of workability and fluidity to allow the material to flow through the print head, have a proper connection between the different layers (this connection should be uniform in all directions) and high strength in the early stages of filling to ensure maintaining its own weight and the weight of the layers superimposed on top, since in the printing process the lower layers will have to take a load on the entire height of the wall in 2-3 hours.

Over the past 100 years, cement has been considered as the main raw material for construction. The cement used is mainly one of 3 main types: ordinary Portland cement (OPC), calcium aluminate cement (CAC) and sulfate aluminate cement (SAC). Each of the 3 types has different characteristics and different applications. OPC is the most used cement material, which is used as a traditional mortar due to its low cost, high strength and easy availability. The other 2 types provide shorter installation times with high early strength, which makes them more suitable for some engineering tasks, such as high-temperature applications and quick repairs in emergency situations [22, 80-82]. Calcium-aluminum cement was excluded due to its lower final strength [83].

Z. Jianchao et al [22] studied and compared setting time (start and end), machinability and durability of CAC and SAC, as well as mechanical compressive and bending strengths. Such comparisons made it possible to determine the applicability of the material in additive manufacturing processes (see table 1).

Varieties	Normal consistency	Setting time/ min		The stability of	Compressive strength /MPa		Flexural strength /MPa	
	/%	Initial setting	Final setting		3d	28d	3d	28d
SAC	27.9	45	73	Qualified	47.6	55.7	7.7	8.6
OPC	28.1	183	237	Qualified	28.4	52.5	5.3	8.1

Table 1. Physical and mechanical properties for the samples.

During the study, the material was submitted through an electric pump, high pressure pipe and nozzle. The minimum diameter in this design is 50 mm. Based on this, the maximum particle size of the solution cannot exceed 5 mm. Numerous experiments have shown that very fine sand, which corresponds to 20-40 or 40-70 quartz sand, is more suitable raw material. Such material is widely available in the regions of the Middle East. This location allows you to get raw materials in large quantities only for the countries of the Middle East, which will complicate the task for countries that are beyond its borders.

The maximum strength of concrete used in multi-storey buildings since 1980 increased from 40 MPa to 130 MPa or more. The strength of concrete is first of all the properties and functions of the gaps between the fine aggregate, which must be filled with a hydration product. In our case, this product is the right amount of water (the ratio of water to cement). The minimum amount of water that can be added to the solution is limited by the need to have workable concrete that can be compacted. To achieve higher concrete strength, only these components are not enough. Chemical additives that improve the fluidity of concrete, plasticizers and superplasticizers are crucial in increasing the strength of concrete [84]. The first generations of cement dispersants were based on natural products. Their disadvantage was poor control over the chemical structure. An important innovation of recent years has been the introduction of plasticizers and superplasticizers based on polycarboxylate ether (PCE). The structure of polymers based on PCE is a comb with a backbone and side branches (see Fig. 10). By changing the length of the chain skeleton, lateral branches and their density, it is possible to increase adhesion, machinability, retention and final strength [85].

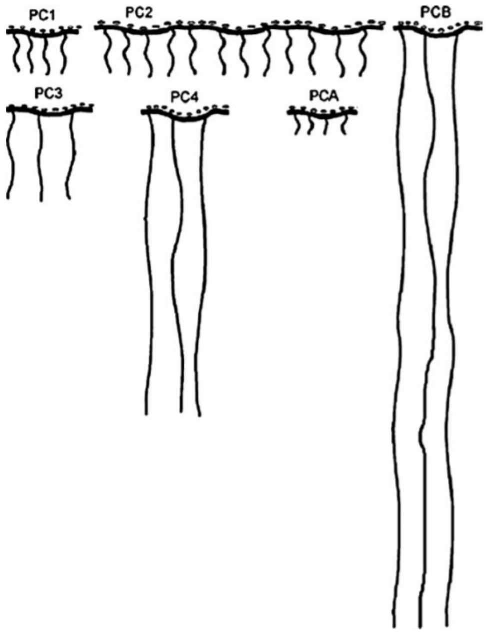

Fig. 10. Illustration of the molecular structure of comb-type copolymers

Productivity can be changed in relation to specific properties such as workability, retention, adhesion, and rate of strength development by manipulating the relative lengths of the chain frame and the side branches and the density of the side branches.

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L.K. Scrivener et. al. [84] proposed the introduction of silica fume. The peculiarity of the additive is due to its small particle size (10-100 times smaller than cement grains), which allows it to fill the space between the grains, increasing the density of concrete. Small particles literally fill the space that remains between the larger ones. However, in concrete made with such a sealing device, particles cannot move, thereby losing fluidity [87].

The distance between the particles (fine aggregate) should be such that the particles do not have the ability to contact each other. Therefore, the authors proposed to increase the proportion of silica to combine high compactness and good workability (Fig. 11a) [86].

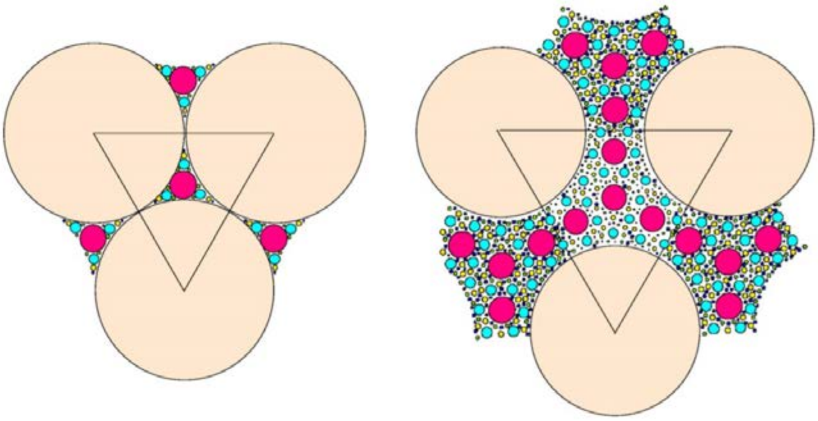

Fig. 11. Schematic model of filling space with small particles

On the microstructure side, the ability of a typical cement material to form bonds and exhibit a yield strength at rest arises from its ability to flocculate between cement grains in its structure formed by cement grains [87]. The following properties apply to cement products:

- After mixing, the cement particles are dispersed
- Cement particles flocculate and form a network by acting colloidal attractive forces. The material continues to rebuild for 2-3 minutes until the configuration of the interacting network of particles is achieved. See fig. 12.

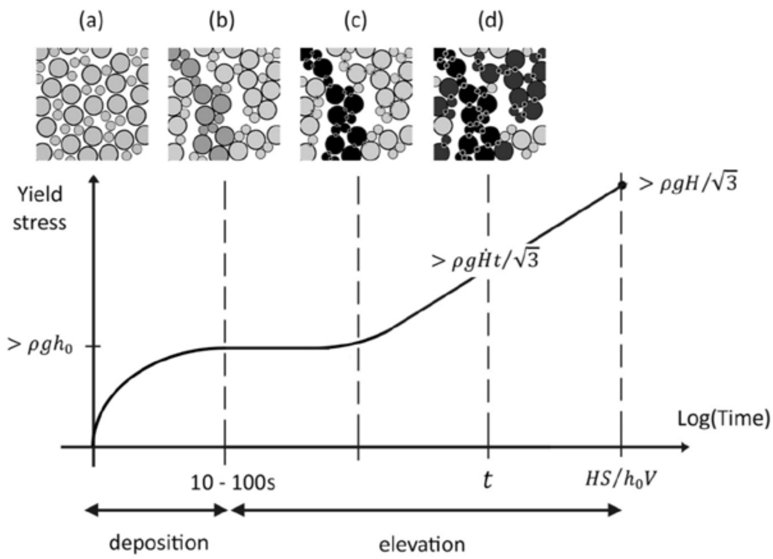

Fig. 12. Network(s) of interacting cement particles along with yield stress evolution and target requirements. h0 is the layer thickness [87]. H is the final object height. S is the contour length. V is the nozzle velocity. ρ is the printed material density.

- In the network of particles, hydrates concurrently with floriculation, despite the fact that the material is at rest. The bond between cement particles is enhanced. As a result, on a macroscopic scale, the modulus of elasticity increases.
- Later, a structuring phase occurs (an increase in the number of hydrated bridges between percolitic cement particles). It can be noted that this reaction creates primary hydration bonds between particles that are not so resistant to shift. They have much less strength than new bonds that appear spontaneously until the stock of the chemical is exhausted.

Most printed materials are based on the acceleration and intensification of flocculation through the use of flocculants and nanoparticles or by enhancing the chemical reaction.

F. Craveiro et. Al [88] suggest, that the properties of concrete can be enhanced either by adjusting the water-binder ratio (cement, fly ash, silica smoke), or by changing the amount and size of additives such as river sand [89], recycled glass [90], or cork [91]. The authors also write that fibers play an important role in the stability of compounds. For construction, the following types of fibers are usually used: linen [92], copper [93], carbon [94], glass [95], steel [96] and polypropylene (PP) [97].

5. Research challenges

In this study, it was considered in which category 3D printing technologies can be successfully applied to the construction of large-scale structures. A systematic cartographic study was later carried out to select publications relevant to the review with a set of criteria. In the process of searching for the necessary publications, the exact number of publications over the past few years has been obtained. After selecting the right material, the additive manufacturing process system was investigated and all the most developed technologies were identified, it was also found that AM has a rapid growth rate in the construction industry, although it lags behind many other areas in terms of implemented technologies and automation.

The extrusion or spraying processes of the binder have been adapted for printing building elements. Additive manufacturing can transform the whole concept of construction and allow engineers and architects to create more complex shapes. All this is possible thanks to the system of extrusion processes. The problem of this method of production is the difficulty of reproducing the work directly on the construction site. All of the above AM technologies are able to work only in specially designated and equipped places. Despite the fact that over the past 10 years, 3D printing technology has reached a whole new level, there is still not enough research in construction that could increase the strength of concrete supplied by the robot, and its mobility. When viewed from the manufacturing side, key challenges include:

- The printing time should be shortened to avoid premature drying of the solution and blocking its supply. This problem can be solved by using two print heads, but in this case they should not interfere with each other.
- The deposition process should be less than the critical limit to ensure good interlayer adhesion, as long as the lower layers will acquire sufficient strength to withstand the upper.
- The print flow of the solution must start and end exactly on time, i.e. be controlled without excess, so that the material is evenly applied over the entire surface of the object.
- In the printing process should be carried out finishing work, as most modern technologies print roughly.
- the printer's human feedback needs to be improved to adjust the appearance of the printed part in a timely manner, thereby improving its quality.

6. Conclusion

Currently, in developing countries, the most suitable robot capable of performing additive manufacturing processes is a 6-axis robot, proposed by Perrot et al. [78], which is capable of printing objects using earth. This greatly eases the problem with the inaccessibility of the material components for printing and their cost. Its major problem is poor mobility. The printer is not able to move on untreated areas, all work is carried out in the room allocated for it.

The last section discussed the material requirements used in additive manufacturing processes. As it turned out, the development of new building materials for AM requires more research in terms of their testing and properties, as well as standardization of construction methods. The raw materials used in additive construction are very rarely characterized in accordance with the specified requirements, such as fire resistance, thermal properties or durability. Thus, it is necessary to study in more detail the possibility of potentially improving the properties of building materials. After the study, it turned out that there is no single optimal system for the use of a certain material in countries that do not have the ability to acquire expensive resources, instead there is a set of solutions, each of which is considered on the basis of such criteria as the type of object that should be produced using AM, the place where the process of creation should take place, the Assembly technology and so on. Each object requires a corresponding material. However, these references are almost always made in terms of end-user benefits, as opposed to a research perspective. Economic efficiency and current technological constraints are key criteria for assessing its future potential.

Gaps in research lead to the following recommendations for further publications on the topic

- Development of innovative processes based on solid and liquid materials for additive construction.

• Study of additive manufacturing processes for heterogeneous materials in order to facilitate the production of universal materials.

• Development of the project to accurately assess the large potential of AM taking into account various performance indicators: cost, quality, safety and construction time.

In conclusion, it should be noted that AM can have a positive impact on the construction industry if accepted by stakeholders in construction. But it must be understood that economic efficiency and current technological constraints are key criteria for assessing its future potential.

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Additive manufacturing. A review of research, opportunities and challenges

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Article info review article

Abstract *3D printing, known as additive manufacturing, can change the construction industry for the better. Greater structural efficiency, lower material costs, increased accuracy and cost-effectiveness, all these characteristics are inherent in the additive manufacturing process. The article talks about a sharp increase in publications on the topic of additive manufacturing. 50% of them are suitable for use as a fine aggregate. They also considered ways to improve the properties of materials: strength, speed, hardening, moisture protection, etc. Additive manufacturing opens up many possibilities for construction, but new problems arise with this, with a greater emphasis on testing and stress testing and new design methods.*

Keywords: 3-D printing, Additive manufacturing, Building Information, Modeling Construction industry, Concrete, Building materials

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