3D concrete printing: review

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Abstract
3D printing technology is an exciting young method that can change the construction industry as we know it. But as with any new change, people are hesitant and worried about it; this paper aims to give a general review of the 3D printing technology concerning the construction industry. The current construction approach requires many expensive labours and formwork that can be dispensed with the 3D printing technology. It is also more harmful to the ecological system and more time-consuming. The 3D printing technology allows the modification of the materials used for printing, which opens the door for trying new mixtures and reduces the impact of construction on the ecological system. The technology is a developing one that you can see different approaches to the way to do it and the missing regulations for testing and designing. The most commonly used material is concrete. However, 3D printed concrete must be pumpable and extrudable while it's still fresh and suitable for building into layers as it reaches the hardening stage.
Keywords: 3D printing technology, 3D concrete printing, extrusion, concrete composition, layer thickness, gap time, pumpability, extrudability
Kulcsszavak: 3D nyomtatási technológia, 3D betonnyomtatás, extrudálás, betonösszetétel, rétegvastagság, hézagidő, szivattyúzhatóság, extrudálhatóság

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1. Introduction

With the global understanding of our planet, the reduction in the carbon footprint has become a common factor in evaluating anything we do. The conventional construction industry has proven a solid and reliable way to construct a great range of structures. With the more knowledge we have, the more complex designs we can do, new technologies have been added to the industry, but the technique of construction has not significantly changed; it remained with a high environmental impact while depending on high labour during labours shortage time, and needs a lot of time and money which lead to higher costs of residential houses to a raising population.

Cutting waste, reducing time on site, and addressing labour shortages. Those are the three main goals that 3D printing technology can try to achieve. 3D printing is a modern technology that can build everything from small structures to whole houses and even varied structures like wind turbines. It is an exciting new way of making buildings, and it has the potential to solve many of the problems we face when trying to find affordable housing.

The 3D printing technology is done by providing a cad file into the system and providing how fast and how much of the material should be extruded. It works in the same way as the brick system; after the completion of the first line of bricks, the second line starts as well does the 3D printing it extrudes a layer of the mixture and repeats the process with a spaced time between the layers called the gap time.

The technology can construct a vast range of structures, but the load bearing of these structures remains not equivalent to what the conventional way can provide. But it allows the creation of a new, more environmental mixture to be used for the new constructions using local materials and with a lower carbon footprint. The mixture has some requirements to keep as it has to go through the pumping phase to the layer phase, thermal performance, and durability.

2. Conventional construction industry

The construction industry is a traditionally conservative industry that had seen no significant modifications in the daily practice at the time that most of the industries have implemented modern technologies to improve the overall method. The traditional building method can be described as expensive, laborious, and time-consuming. Moreover, the construction sector is responsible for high environmental impacts worldwide [1, 2].

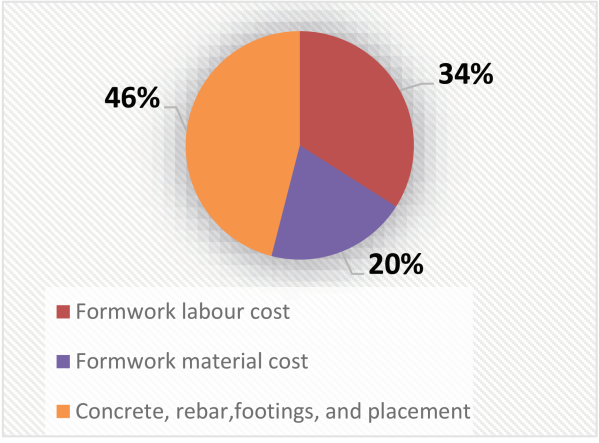

Fig. 1 Cost distribution of a typically constructed project
1. ábra Egy tipikusan épített projekt költségeloszlása

The construction of structural elements in the conventional way is a limiting process that has disadvantages that can be overcome or reduced by the modification of the process itself or by introducing a new way to construct. In the conventional way, the concrete is poured into the formwork and then compacted. The formwork will shape the structural element constructed; this can be a very limiting method for architects as the shapes are confined to the formwork requirements. Moreover, the conventional way has disadvantages such as time and money consumption,

dependency on high manual labour, and a high ecological impact. *Fig. 1* shows the cost distribution and how much formwork affect the cost, from the cost of formwork materials and the part of the labour performing the formwork [3].

The world's population is the main factor that affects the demand for housing and the climate change issues we have. The United Nations (UN) predicts that there will be 10.9 billion people by the end of the century [4]. More recent research from the Institute for Health Metrics and Evaluation (IHME) shows that we would reach a peak in 2064 (9.7B). A total of 8.8 at the end of the century [5], International Institute for Applied Systems Analysis (IIASA) also predicts a lower population than both have expected; the reason for the significant differences between the predictions is in the fertility evaluation in the Sub-Sahara Africa as *Fig. 2* shows [6].

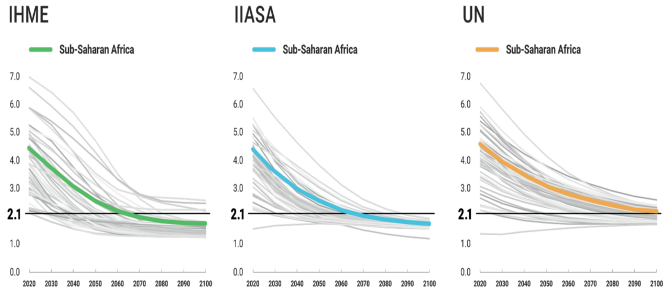

Fig. 2 Fertility rates in the Sub-Sahara Africa for (IHEM, IIASA, and UN) ertility rates in the Sub-Sahara Africa for (IHEM, IIASA, and UN)
2. ábra A szubszaharai Afrika termékenységi rátái (IHEM, IIASA és ENSZ) a szubszaharai Afrikában (IHEM, IIASA és ENSZ)

The larger the population, the worse the issue of housing and climate change (the greenhouse effect of CO_2 emissions). Globally there has been a rise in the cost of constructing residential buildings for the rising world population. With the increasing awareness of the environmental effect we are causing on the ecological system, carbon footprint reduction is becoming a primary concern for evaluating the methods used.

The current construction industry method is highly dependent on manual labour, which is in increasing quantitative shortage caused by significant excess demand with insufficient workers, which caused the rise of unskilled labour's salaries, thus the overall cost of the structure. Moreover, slow supply for the development requirement and a dependency on foreign labour. An example is the EU increasing international and cross-border mobility as a solution while avoiding brain drain [7]. With the reliance on manual labour, human error stays a significant factor in the waste of materials and time among projects.

All the mentioned raised the necessitates for the minimisation of the quantities used, the total cost, and the time needed, which has made it the task of researchers to find, develop and apply modern technologies.

3. 3D printing technology

There have been uses for technology implementation in the industry, but 3D printing has redefined the way we do things, the properties needed for the material used, and even the overall material used, as we can reduce the use of concrete for other mixtures suitable for the case. The technology is vast and new and thus lacks tests, and a clear perspectives chapter is going to lay out some aspects of the technology of 3D printing concerning the construction industry.

3D printing can construct a building in just a few days. 3D printing also offers a significant amount of design freedom, allowing architects to experiment with shapes and styles that would have been impossible using traditional building methods. Errors on site have been almost completely eradicated, saving time, and wasted material and money. While deceiving for a single building might be modest. It adds up when looking at it on a larger scale for development and the housing industry. 3D printing can be built in any location with a different elevation, as well the printing can be operated in harsh climate conditions with full-day printing without additional costs.

As the technology is relatively young, educating people about 3D printing is a barrier that prevents the technology from moving forward to becoming a widely used method in construction. It is a modern technology for contractors, engineers, and the skilled and unskilled labourers themselves, which causes hesitation in using the technology. So, there are still some mean fears about using this technology. Educating people and securing building certification and permits is a huge step for 3D printing to be treated as a valid replacement method for the conventional way. It will teach us how to cope with this technology and adapt to it rather than be threatened by it. The more people are comfortable using 3D printing, the more it becomes widespread and creates a driving force in the research fields to cover the needed knowledge [8].

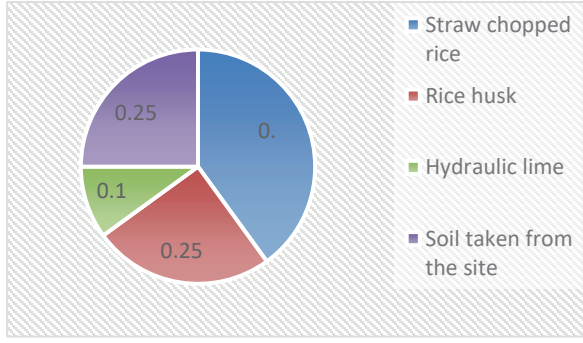

Fig. 3 WASP and RiceHouse mixture components
3. ábra WASP és RiceHouse keverék összetevői

Using 3D printing technology will play a vital role as it allows the possibility of using a good range of materials that can be analysed and assessed to reduce environmental impact. One of the fitting examples can be seen in the Gaia project by the WASP company on using natural materials from the surrounding area, which will be done with a much lower history, footprint, and overall cost. WASP with RiceHouse provided a homogeneous and workable mixture for printing which uses straw chopped rice along with rice husk and hydraulic lime, *Fig. 3* shows the ratios for the components, the soil was made of (30% clay, 30% sand and 40% silt) [9]. Nevertheless, more testing (structural and thermal) must be done [10].

3D printed houses are the current most favourable option mathematically speaking, as they can provide opportunities with much lower costs, which come from lower material consumption than conventional designs use, waste of materials on-site from the human errors and the complexity of cutting the waste and following up with everything going with each aspect in the conventional process, reduction of the labour costs needed as the digital system can use as low as 2-3 people to do almost half of the construction (the printing part of the house), and of course the reduction of time needed which is a considerable cost reduction, it only takes around 48 hours to set up the machine, the building speed (250-1000 mm/s) vary based on the layout, number of robotic arms, type of the robotic arm used and the material used that controls the time gap, the exact numbers vary from place to another on how much the actual reduction of the overall cost is as the materials availability plays a factor, Nevertheless, reduction of some of the issues is being observed.

3D printing construction companies are riding the wave of 3D printing technology. Houses with even three levels using a 3D printed base are getting permitted. Other companies are using multiple printing robotic arms to facilitate and speed up the process even more for spacious structures. Not all companies print on-site; fixed printers can be used to build the pieces. They will then be transported to the building site, such as Mighty buildings, where their printers use a thermoset composite material called light stone materials; it will harden under exposure to UV light [11].

The hopes of becoming a multi-planet species have been surfacing again. The 3D printing technology is being tested to be used to build the first home for humans on another planet. ICON company is working on two technologies with NASA, including the Olympus project, where the focus is to find a suitable construction system to support future exploration of the moon [12], and the Mars Dune Alpha where a simulation for the mars habitat has been done to prepare for a long-duration human mission to Mars [13].

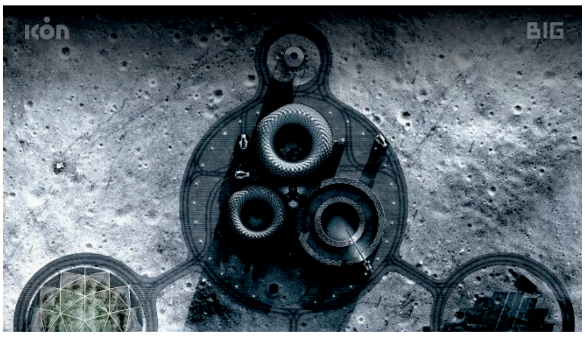

Fig. 4 Olympus project a futuristic vision
4. ábra Az Olympus futurisztikus jövőképet vetít előre

The printing technology have factors must be considered when thinking of specific project with known printing robotics.

- Arm movement (the printing speed of the robotic technology used, gap time between two consecutive layers).
- Tube capacity and nozzle used (diameter and nature of end), printing continuity, and constant layer thickness.
- Reinforcement of the structure (deferent approaches exist on how to reinforce the 3D printed structure. This is still under early studies and needs more data on whether the reinforcing of the concrete will be done manually or by robotics technology.
- Material used: the mixture of the material chosen have the mechanical properties needed.

The technology itself is moving with the research as well. BOD2, a second-generation, was released; BOD2 can print with speeds of up to 100 cm/second – the fastest printer yet, the company COBOD claims [14]. There is a need to systemise and regulate tests to check and adapt to the study and analysis of the mixture and more studies on the effect of the composition of the mix.

The robotics field has advanced the process in many sectors, and 3D printing was the construction industry's share. The current system is expensive, time-consuming, requires sizeable manual labour and environmentally has a more significant impact. The technology is still young but promising.

The leading candidate to be used for the 3D printing technology is concrete. Thus, we will narrow the paper to the concrete and discuss what to consider while dealing with concrete as the material to be printed.

4. Concrete as the printing material

3D concrete printing technology has made a significant impact by introducing a revolutionary way to build. The contradicting properties needed for the mixture in the printing stage and after printing opened the door to many questions, basically how to follow the technology's needs and adapt within these needs to provide the engineering requirements needed for the structure.

When choosing the material to used attention must be given to the mechanical properties of the final mixture. As the mechanical properties represent the material ability to be built using this technology. The material that will be printed has to have good rheological behaviour that is, the mixture is easy to mix and extruded through the printing arm's nozzle and to be able to keep a shape without deformation till the material starts to gain strength.

The 3D printed concrete goes through two stages; in the first stage (fresh concrete), when it is still mixable and easy to be handled, we can generalise the required properties for fresh concrete into two main properties [15, 16]:

- Pumpability: the ability of the mixture to be easily mixed and remain stable while it is being pumped and without losing the fresh mixed properties as the pressure needed to pump the concrete will tend to segregate the mixture.
- Extrudability: as the mixture reaches the end of the pump and approaches the nozzle, it will be extruded into layers without formwork or temporary supports; thus, there is a need to make sure that the mixture will be able to withstand the yield stresses at that stage and remains in the wanted shape without any deformations.

It is worth mentioning that the workability and shelf life of fresh concrete are essential considerations in 3D concrete printing, and the consistency and compactness of fresh

concrete (uncompressed body density and air content) affect the compressive strength and durability of concrete [17].

The durability of the concrete depends on how the fresh concrete can be applied, the consistency, and the air content, so in the case of compaction or shotcrete, the shot has a crucial role in achieving the lowest possible air content. During 3D printing, the correct air content can be ensured by the right consistency and the pressure in the tube. This is usually higher than compacted concrete, so it is important to compensate with a lower w/c ratio.

After the mixture has retained its shape and as time passing, the hardening process starts and speeding up the hardening of the mix after being extruded is a very desirable property of the hardened mixture. The hardened concrete properties can also be generalised into two main properties [18]:

- Buildability: with each layer added, the higher the stresses on the first layer placed (Based layer), and as it is the oldest layer, it had the most time to reach a higher bearing load. The failure in the base layer can be used as failure criteria for the structure [19].
- Interlayer bonding: This part is the most critical part of the process. After adding a layer, if there were no interface bonding between the layers, it would be a poorly printed structure with a high probability of failure as the layers are not acting together as they should.

The composition of concrete also affects the strength, ductility, and durability of concrete, which is mainly influenced by the adhesives of the raw materials and their mixing ratios, as well as between the cement paste, the admixture, and the layers. In addition, the pore content, size, and distribution of the cement paste influence the strength and durability.

For a better 3D printing of concrete, the general approaches for creating a good concrete composition should be easily checked and adapted based on the design needs and robotic printing technology used, considering the following aspects [19-21]:

- Production of suitable base concrete composition and the study of its modifications depending on local raw materials available and the required properties.
- Optimal consistency (appropriate standards and guidelines for testing concrete are not yet available).
- Method of accelerating setting (with cement type and setting accelerator additives) as the cement as a sole binder is highly affected by the time gap between layers.
- Maximum shelf life.
- Adequate stability, ensuring cohesion, proper adhesion, and bonding interface between layers.
- Sufficient compressive strength, ductility, and durability.

When designing the 3D printing concrete, the fresh concrete and hardened concrete properties should be kept in mind for each concrete composition and better identification of the effects of:

- Binder: The binder plays a vital part in the strength of the concrete, the sensitivity to the gap time between layers, intermediate setting time, and adhesion. The effect of the type of the binder.
- Fine sand aggregates: When it comes to the fine sand aggregates, the maximum grain size, grain distribution curve, and the fineness modulus.
- Water: The water-binder factor, water volume, strength, and durability issues
- Additives: The usage of additives is going to improve the concrete as we get to satisfy some of the required properties for the printing concrete, like the use of viscosity modifier (VMA) to achieve the suitable dough-like rheology, the use of stabilisers, the setting accelerator, the shrinkage reduction factors as concrete will shrink due to lack of compaction, the use of sealants, adhesive bridge, hydrophilising agent, and the type and amount of additives effects.
- Fibres: The use of fibres as reinforcement for the 3D printing concrete, the effect of fibres on the workability, viscosity, yield stress, and flexural strength.

The technology of 3D concrete printing is a complex task and attention should be paid to more than the modelling and the recipe, but also a proper operation and execution should be taken into consideration.

- The type of the 3D printing technology used, the nozzle size, the allowed time gap, and tests for the used materials should be developed to ensure the wanted properties were fulfilled.
- Mixing machine type and whether it will be mixed on-site or the mix will be transported to the site of which the compositions are primarily designed for mobile mixing and tests suggested for checking the transported concrete.
- Alignment of the pump machine and the robotics arm to consider the layout, nozzle control speed, discharge rate, wanted layer size and the time gap between layers.
- The operator should be well-trained and have some expertise in dealing with concrete technology problems to notice any issues during the process.

5. Conclusions

The conventional construction is not going anywhere anytime soon, with all the additional costs and ecological impact it is still the known and verified way to design and construct structures under considerable imposed load. On the other hand, 3D printing technology opens a new way for limited types of structures but eliminates some limits on those structures. 3D printing does it faster, more accurate, less labour needed, cheaper, and less ecological impact.

3D printing has requirements for the material to be used, the first part of the materials life is while it is being pumped so the mixture needs to be pumpable and after it is extruded it needs to withstand a shape without formwork, the second part for the material is as it starts to harden, how will the layers are boning, the load bearing, and other properties.

The technology is still developing and there are a lot to be studied, new tests are also needed as the material is needed to have properties for it to be suitable.

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