AN IN-DEPTH ANALYSIS OF MATERIAL ASPECTS IN EXTRUSION-BASED CONCRETE 3D PRINTING: A COMPREHENSIVE REVIEW OF CURRENT ADVANCEMENTS

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Rezumat. *Această lucrare prezintă o analiză detaliată a caracteristicilor materialelor în contextul printării 3D a betonului, bazată pe tehnologia extruziunii, acoperind atât stadiile incipiente (starea proaspătă), cât și aspecte ce țin de performanțele pe termen lung. În prima parte a articolului sunt prezentate progresele recente, relevante pentru înțelegerea comportamentului inițial al betoanelor printate 3D. Caracteristicile din stadiul incipient sunt vitale pentru asigurarea stabilității și preciziei procesului de printare în etapele sale formative. În continuare, se prezintă și se analizează proprietățile mecanice după ce betonul 3D s-a întărit, în contextul metodelor de introducere a armăturilor. În finalul lucrării, sunt indicate perspective și direcții de cercetare viitoare privind strategiile de optimizare a betoanelor printate 3D, cu scopul de a îmbunătăți durabilitatea lor în timp.*

Abstract. *This paper provides an extensive review of the material characteristics in the context of extrusion-based 3D concrete printing (3DCP), encompassing both the initial stages (fresh state) and the long-term performances. In the first part of the paper there are presented the recent advancements, relevant in comprehending the early-stage behavior of 3D printed concrete. The early-stage characteristics are vital for ensuring the stability and precision of the printing process in its formative stages. Subsequently, the mechanical properties, once the 3D concrete has hardened, are presented and discussed in conjunction with various approaches to incorporate reinforcement. Finally, there are indicated valuable insights and future research directions regarding optimization strategies for 3DCP, to enhance its durability over time.*

Keywords: 3D printed concrete, fresh properties, mechanical strength, reinforcements, extrudability.

DOI https://doi.org/10.56082/annalsarscieng.2023.2.83

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1. Introduction

In the evolving landscape of construction technology, Extrusion-Based 3D Concrete Printing (3DCP) has emerged as a transformative technology, promising unparalleled efficiency and innovation in the realm of structural fabrication. 3DCP is an innovative construction technology that utilizes a layer-by-layer additive manufacturing approach to create three-dimensional structures by extruding specially formulated concrete mixes through a nozzle or a printing head. This method is a subset of 3D printing specifically tailored for the construction industry.

As 3DCP garners widespread attention for its potential to revolutionize construction practices, understanding the intricacies of this technology becomes imperative. Notably, the initial sections of this paper unravel recent advancements in 3DCP, shedding light on the diverse types of printers employed and their implications on the early-stage behavior of printed concrete. From gantry systems to robotic arms, the choice of printer significantly influences the precision and intricacy achievable during the formative stages of construction.

Delving deeper into the material aspects, the paper navigates through the myriad materials utilized in 3DCP processes, ranging from traditional concrete mixes to novel formulations incorporating additives and fibers. This exploration extends to the advantages and challenges associated with each material choice, providing a comprehensive understanding of the impact on the final product's properties.

Furthermore, the mechanical properties of 3D printed concrete post-hardening are meticulously examined, with a focus on structural integrity, durability, and load-bearing capacities. The discussion extends to various reinforcement strategies, encompassing mesh reinforcements, fibers, and other innovative approaches.

In elucidating the nuanced landscape of 3DCP, this paper not only captures the current state of the art but also propels the discourse forward by highlighting valuable insights and delineating future research directions. By illuminating the diverse types of printers, materials, and the inherent advantages of 3DCP, this article contributes to the ongoing scientific dialogue, paving the way for a sustainable and transformative future in construction technology.

2. Applications and projects achieved with 3D printed concrete

The progress of research in the 3D printing domain experienced a sluggish pace between 1998 and 2015. Before the year 2012, the annual count of scientific articles did not surpass three publications. However, post-2015, there was a remarkable surge in 3D printing research, marking the onset of the current developmental phase. Presently, Elsevier has published 4609 scientific articles on 3D concrete printing, while MDPI and Taylor & Francis Group have contributed

192 and 3111 papers, respectively. Fueled by heightened interest, the applications of this technology have transcended conceptual prototypes. Consequently, 3D printing technology has made significant inroads into both the manufacturing and construction industries, consistently making headlines for the introduction of pioneering elements or structures. The subsequent sections showcase some of the most noteworthy projects and applications in the realm of 3D concrete printing.

An illustrative instance showcasing substantial time and cost savings achieved through 3D Concrete Printing (3DCP) is the construction of the world's largest 3D-printed structures [1]. This noteworthy initiative involved a collaboration between the German Technical University, CEMEX, and COBOD to establish the largest 3D-printed buildings in Oman. These impressive edifices, spanning an area of 195 square meters, were erected in an exceptionally brief timeframe of just five days. The architectural design of these residences encompasses three bedrooms, a spacious living area, a fully-equipped kitchen, three bathrooms, and a reception zone (Figure 1).

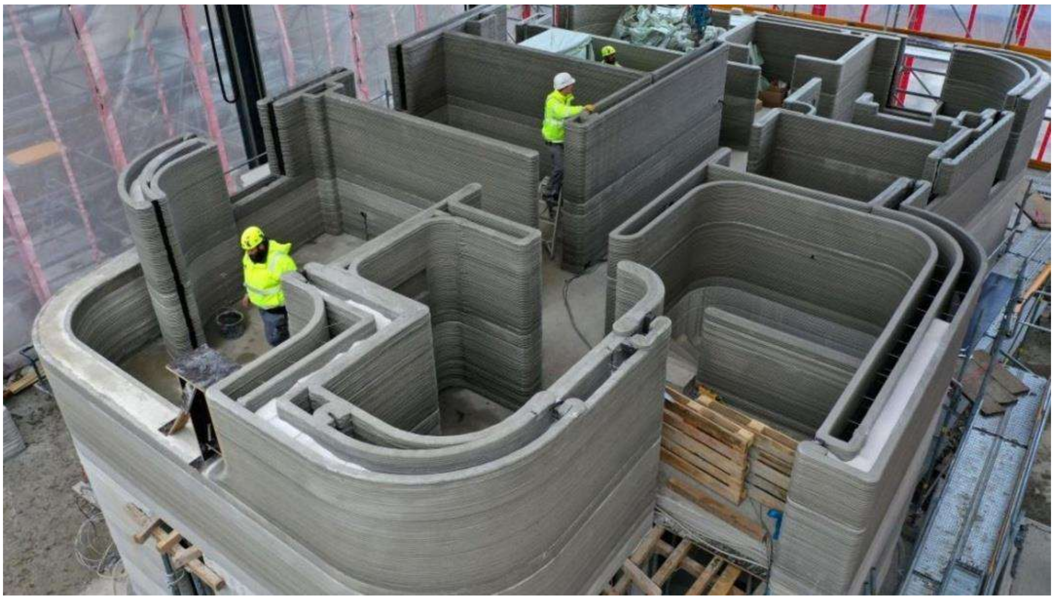

Fig. 1. The world's largest 3D-printed structures in Oman.

The "Office of the Future" in the United Arab Emirates (Figure 2), conceived as the headquarters for the Dubai Futures Foundation under the United Arab Emirates National Committee, stands as the pioneering 3D-printed office building [2]. Crafted from a unique concrete mix, the structure was meticulously built layer by layer, with the entire printing process completed in just 17 days [3]. This initiative was a key component of Prime Minister Mohammed bin Rashid Al Maktoum’s vision to 3D print 25% of Dubai’s buildings by 2030.

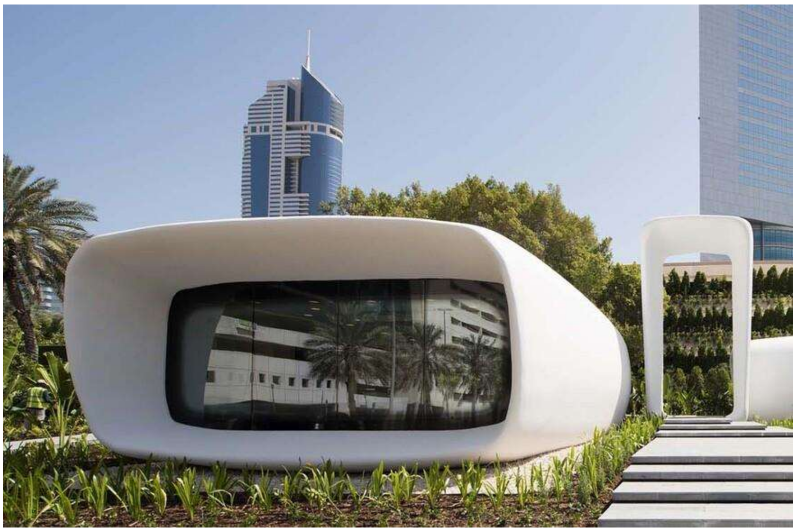

Fig. 2. The "Office of the Future" in the United Arab Emirates [3]

ICON, a construction technology company based in Austin, USA, designed a portable gantry-style printer utilizing its exclusive concrete mix to construct homes and structures [4]. Marking its initial venture, ICON erected a 32.5 m^2 prototype home directly on-site in Austin, Texas, in March 2018 [4]. This dwelling, granted proper permits and constructed in compliance with International Building Code standards, was successfully completed within approximately 47 hours of total printing time, with a total cost of $10,000 (Figure 3).

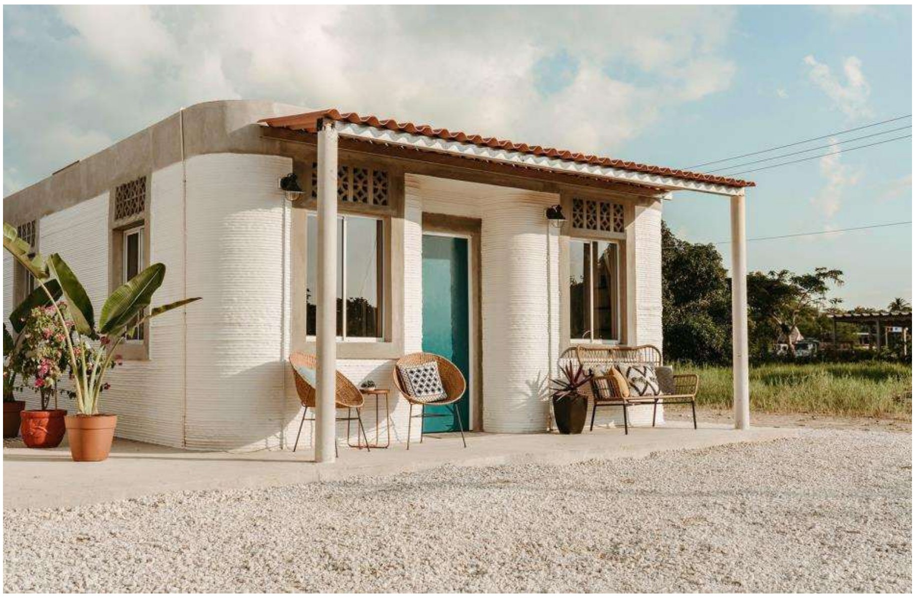

Fig. 3. ICON prototype home [5]

Since May 2016, the ACES research team has accomplished a series of 3D printing projects [4]. These include a military control point, two concrete barracks huts (also referred as the B-huts), a 3D printed concrete bridge spanning 10 m and a military structure designed as a defensive fighting position. The ”B-Hut 1” (Figure 4) stands out as the pioneer 3D printed concrete structure in USA, while the bridge is recognized as the inaugural field-printed structure of its kind in the Americas [6, 7]. Noteworthy for its efficiency, the second barracks hut, B-Hut 2, was completed in 14 hours (Figure 4), [8, 9]. These projects underscore the printers' ability to utilize locally sourced resources and operate effectively in uncontrolled and hard environmental conditions, contributing significantly to the advancement of deployable construction technologies for the U.S. military.

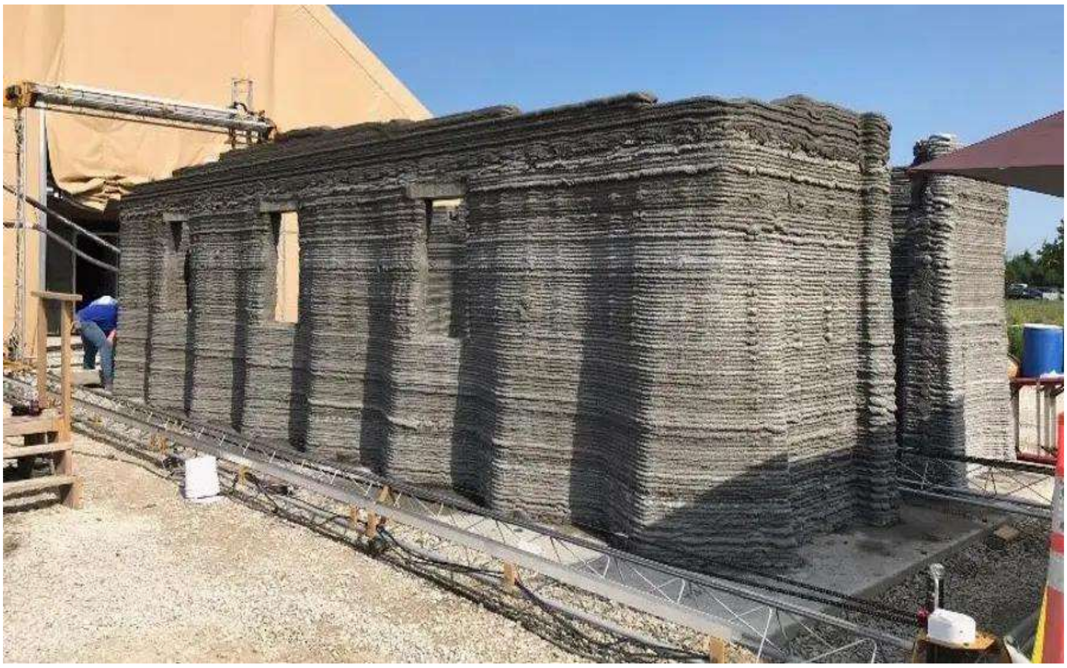

Fig. 4. B-Hut 2 barrack of The Marine Corps, Army and Navy Seabees [9]

The European Space Agency has put forth the concept of establishing a lunar village as the next phase in human space exploration, with the ultimate goal of human colonization of space by the end of this century. This ambitious vision aims to address Earth's depleting resource supplies and the escalating frequency of natural disasters. A study proposed the All-Terrain Hex-Limbed Extra-Terrestrial Explorer robotic system, a solar-powered 3D printer designed to navigate uneven lunar or planetary surfaces (Figure 5), [10, 11]. It utilizes various print heads to stabilize surfaces and create a diverse range of structures, including columns, girders, walls, vaults, domes, shelters, trench walls, hangars, tunnels, paving, landing/launch pads, modular panels and many other components using locally available materials.

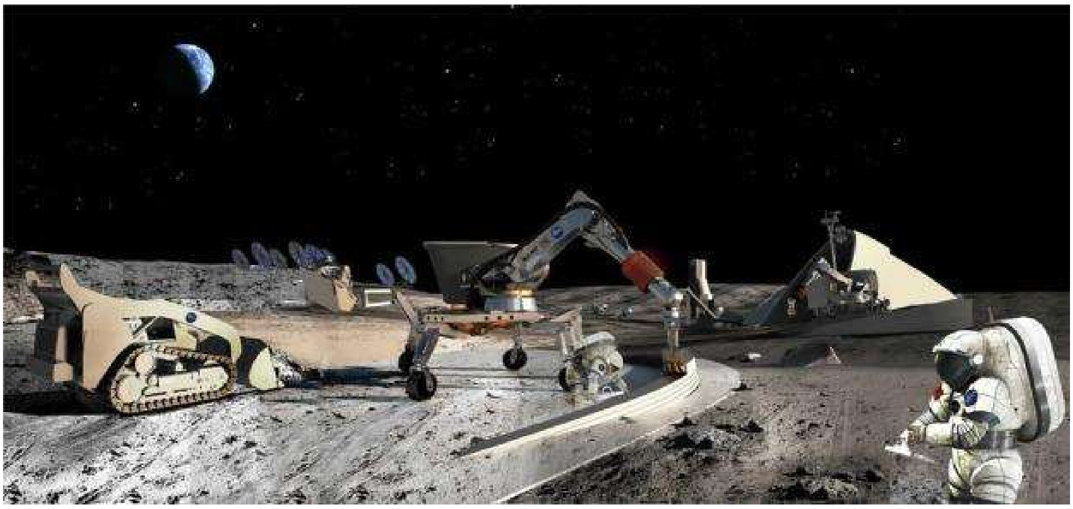

Fig. 5. All-Terrain Hex-Limbed Extra-Terrestrial Explorer robotic 3D printer system [4]

3. Fresh and hardened properties of 3D printable concrete

In the technique of extrusion-based printing, a printable material (mortar, concrete, clay, etc.) is extruded through a nozzle. The latter movement direction is governed by a computer, which translates the input 3D model into 2D slices thus, the 3D element is constructed by layering these slices. To facilitate continuous construction, the fresh mixtures must possess pumpability, ensuring easy pumping from the mixer to the nozzle. Subsequently, the mixtures must be consistently extruded through the nozzle, demonstrating extrudability. Ultimately, the extruded filaments must have the capacity to bear the weight of superior layers, maintain their shape in the fresh state, and stack up securely layer over layer without evident deformation – a quality referred to as buildability [12, 13].

To fulfill the above-mentioned criteria, researchers incorporated thixotropic additives to enhance the printability of cementitious materials, including substances like nano clay, polymers, bentonite and others. Additionally, it is essential to note that the fresh properties of printable materials are intricately tied to the "open time," denoting the duration from the preparation of the mixture to its extrusion from the printing nozzle [14].

In addition to addressing the fresh properties, there are more significant challenges associated with the mechanical properties of 3D printed concrete in its hardened state. A primary challenge is the inherent brittleness of the material.

Traditional concrete is notably vulnerable in terms of tensile strength and deformability, necessitating heavy reliance on longitudinal continuous reinforcement in practical construction. To tackle this limitation, researchers have explored the incorporation of high-strength fibers as reinforcement into concrete. This exploration has given rise to various types of fiber-reinforced concretes (FRCs), including but not limited to: polypropylene fiber-reinforced concrete [15], microcable-reinforced concrete [16], basalt fiber-reinforced concrete [17] and many more.

However, the tensile strain capacity of the aforementioned 3D printed reinforced concrete solution typically falls below 2%, which is notably insufficient for a structural material that can function independently without relying on steel continuous reinforcement. More recent, a distinct category of FRCs, known as engineered cementitious composites (ECC), has been developed, exhibiting exceptional tensile capacity [18, 19]. ECC boasts a tensile strain capacity of up to 12% and a tensile strength of 15 MPa [20, 21]. Studies have demonstrated that ECC has the potential to be employed in concrete structures without the need for longitudinal continuous reinforcement [21]. Hence, it is also referred to as ”ultra-high ductile concrete” (UHDC). The latter presents a novel option for the application of 3DCP, even in seismic prone areas.

Conclusions

This study presents a comprehensive review that delves into the intricate material aspects of extrusion-based 3D concrete printing (3DCP), covering both its so called ”nascent stages” and long-term performance. The initial exploration highlights recent advancements crucial for understanding the early-stage behavior of 3D printed concrete, emphasizing the vital role of early-stage characteristics in ensuring stability and precision during the formative phases of the printing process.

As the technological landscape of construction evolves, the review underscores the significant strides made in 3DCP applications. From the construction of the world's largest 3D-printed structures in Oman to the innovative "Office of the Future" in the United Arab Emirates and portable gantry-style printers developed by ICON, these projects exemplify the transformative potential of 3DCP in reshaping construction practices.

Moreover, the study sheds light on the applications within the U.S. military, showcasing the efficiency of 3DCP in creating deployable structures in challenging environmental conditions. The emergence of a lunar village concept proposed by the European Space Agency further extends the potential of 3DCP beyond Earth, presenting new horizons for construction technology in space exploration.

Moving beyond the fresh properties, the paper navigates through the formidable challenges in the mechanical properties of 3D printed concrete in its hardened state. While the existing fiber-reinforced concretes (FRCs) show promise, the review emphasizes their limitations, particularly in achieving sufficient tensile strain capacity for structural independence. A noteworthy breakthrough in addressing these limitations comes in the form of engineered cementitious composites (ECC), exemplifying exceptional tensile capacity.

By contributing to the ongoing scientific dialogue, this review anticipates a transformative future for 3DCP in construction technology, offering sustainable and innovative solutions to the challenges of the built environment.

Acknowledgment

This paper was realized with the support of the COMPETE 2.0 project nr.27PFE/2021, financed by the Romanian Government, Minister of Research, Innovation and Digitalization.

and

AOSR-TEAMS II EDIȚIA 2023-2024 *Transformarea Digitală în Științe* - Soluție integrată pentru printarea 3D a elementelor specifice arhitecturii ecleziastice și clădirilor monument

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