3D Concrete Printing: Recent Progress, Applications, Challenges, and Role in Achieving Sustainable Development Goals

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Abstract- This work explores the role of 3D concrete printing (3DCP) in achieving the relevant sustainable development goals (SDGs) that were set out by the United Nations. The study focuses on the recent progress and limitations of the three dominant types of cementitious mixtures, ordinary Portland cement (OPC), recycled aggregate-based cement, and geopolymers, and real-world applications for 3DCP. The study reveals that 3DCP has a significant advantage in terms of cost, with a potential to save around 78% and 60% of the costs associated with conventional construction methods and labor, respectively. Moreover, 3DCP consumes less water than conventional construction methods, with a water usage reduction of 20%. Additionally, it was found that 3DCP is on track to reduce the global energy utilization by 5% by the year 2025. Even though 3DCP bears a lower climate change impact, there is still work to be done to improve its sustainability.

Keywords- : 3D printing; cement; applications; challenges and barriers; sustainable development goals.

1. INTRODUCTION

With the rapid population growth and the acceleration of urbanization, existing construction methods are bound to become obsolete [1]. Conventional construction methods lack considerations regarding waste repurposing and environmental protection [2,3], as well as their notorious economic deficiencies, making it difficult for developing countries and low-income communities to provide or sustain affordable housing [4]. Concrete is a conventional mixture used in construction that is composed of various key components such as aggregates, a binding cementitious material, and water. Moreover, 3D concrete printing (3DCP) offers a viable alternative to streamline conventional construction methods [5] and attenuate their everlasting challenges in order to increase the efficiency and reduce the overall cost of construction, all while having a lower environmental impact [6].

Research and development in 3DCP focus on fabricating sustainable materials for a futuristic utilization of this technology [7]. The result is a wide arsenal of materials such as ordinary Portland cement (OPC), recycled aggregate [8], and geopolymer-based cementitious binders [9]. OPC is a type of cement that is used in conventional construction and 3D printing applications. OPC hardens and sets when it is mixed with water, providing desired rheological properties, such as the ability to withstand high pressures, tensile forces, facilitating its resistance to external harsh conditions, as well as fire, rust, and rot resistance, and flexibility in molding and shaping [10]. Aggregates are considered main components in concrete that add volume and bulkiness to the mixture, as well as dictate its overall mechanical properties [11]. On a similar note, recent research is concerned with replacing conventional aggregates with recycled alternatives, to attenuate negative environmental effects and reduce the cost of 3DCP, as well as repurposing waste feedstock. Finally, geopolymers utilize industrial waste, such as fly ash (FA), silica fume (SF), and slag [12], with alkaline activators to produce a cementitious-like mixture, with competitive properties and lower environmental impacts. Through automated robotic arms, these materials are activated (using water) and are printed with a high accuracy and efficiency to build targeted structures that can bear flexible complex designs.

Moreover, 3DCP has the ability to effectively lay the groundwork for achieving some of the 17 sustainable development goals (SDGs) set out by the United Nations [13]. The SDGs are a set of 17 goals that were established to address global issues and challenges, such as poverty, climate change, and inequality [14]. For example, 3DCP is a sought-out technology to tackle goals targeting poverty (SDG1), global health and well-being (SDG3), clean water and sanitation (SDG 6), and climate action (SDG13). This is a result of the diversity of sectors that are affected by the conventional construction industry, with a greener alternative being the salvation from many obstacles. The impact of 3DCP on the SDGs is shown in Figure 1 represents the keyword analysis obtained from the VOS viewer software. Each node in the figure represents a keyword. The size of the node indicates the number of times it has been mentioned in research papers. In this keyword analysis, the most trending topic of 3D printing is 3D concrete printing.

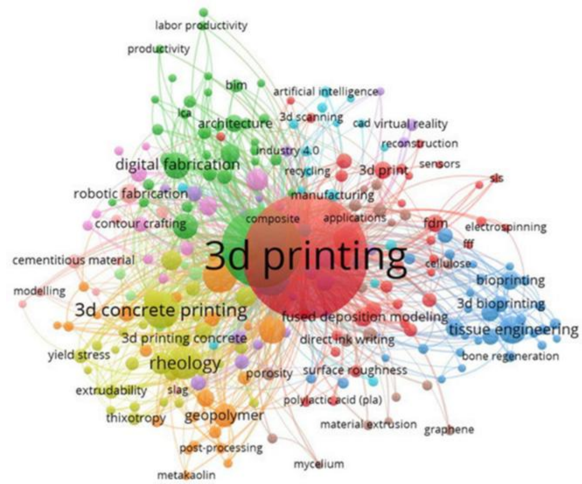


Figure . A demonstration of the keyword analysis conducted via VOS viewer software.

2. 3D CONCRETE PRINTING

3D concrete printing (3DCP) is an increasingly engaging topic in the context of the future of sustainability, given the combined precision and speed of the 3D printing process, with competitive advantages in terms of durability and strength. 3DCP has the potential to revolutionize the construction industry and facilitate the emergence of large-scale complex structures, with a lucrative building efficiency and low overall costs. Moreover, this industry has a wide potential in repurposing industrial waste through the different building mixtures that are currently under research and development. For instance, Portland cement is the most commonly used cement mixture in construction worldwide. Current research is directed towards decreasing the environmental impact of Portland cement by replacing some of the components in cement mixtures with cheaper and more abundant materials in order to optimize the 3DCP process, which is where alternatives that use recycled aggregates, as well as geopolymers, come into play. In this section the concept and recent progress of ordinary Portland cement, recycled aggregate-based concrete, and geopolymers-based 3DCP are discussed.

2.1. Ordinary Portland Cement (OPC) 3D Printing

For 3D printing applications specifically, OPC is mixed with other additives to allow for a printable material that can be extruded. A 3D-ready OPC is fed through a nozzle into the printer and is layered onto the desired area to construct the end structure. Moreover, 3D printing allows the construction of complex shapes that would otherwise be difficult to achieve via conventional techniques. However, there are challenges to be overcome in terms of 3DCP due to the high abrasive nature of the printed material.

There are three main parameters to be considered when dealing with 3DCP materials which are the workability, printability, and buildability. The workability of a cement 3D printing mixtures is determined by the open time available when the cement is in contact with water. The printability is the ability of the material to pass through a printing nozzle with minimal adverse effects on the printing mechanism and the properties of the material. Finally, the buildability of a material is limited by the ability of layering the material over a base, or the material itself. The current research is focused on different additives that are utilized to fine-tune these parameters for an optimized 3D printing process.

Souza et al. [15] demonstrated the effects of adding setting retarders (sucrose $C_{12}H_{22}O_{11}$), accelerators (calcium nitrate-based, and calcium chloride dihydrate), and superplasticizers (third-generation polycarboxylate ether-based) in the process of 3DCP. The setting retarders and superplasticizers showed an enhancement in the open time for the cement mixture, while the accelerators increased the structuration rate of the cement mixtures. Moreover, the need for additives such as the previously utilized accelerators is emphasized by studies, such as the one conducted by Reales et al. [16], where nanosilica particles were used to study the effect of the fresh state properties of OPC paste, and compared them to those of conventional microparticles such as microsilica, metakaolin, and nanoclay. The nanosilica addition was observed to have enhanced the initial yield stress and the thixotropic build up rate of the paste (the degree of viscosity under the effect of stirring); however, a limitation constrained by the maximum and minimum printing velocities arose and could be attenuated with the use of accelerator additives. Additionally, binder/water mixing ratios are also essential in determining the operation of 3DCP as well as curing time. Chaiyotha et al. [17] determined an optimum binder/water mixing ratio of 0.35 (which is a common ratio even with other cementitious pastes) and a limewater-based curing process for a period of 7, 14, and 28 days, with a 12.36 MPa strength achieved.

2.2. Recycled Aggregates in Conventional Concrete

Aggregates can be defined as inert geological materials, such as gravel, sand, and rocks, that are added to a concrete mixture in order to add bulkiness and volume (making up 60% to 75% of its volume [18]) and enhance its mechanical properties. Furthermore, strength is an important aspect of any concrete mixture and is heavily influenced by its aggregate content, as it helps to evenly distribute any load or stress applied on its final form. Additionally, the more aggregate content added to a concrete mixture, the less it costs to produce it, given how easily obtainable aggregates are. Moreover, the coarse structure of the utilized grains impacts the end texture of the concrete mixture, which can be altered to obtain specific finishes. Although it is worth noting that the coarse nature of a concrete mixture dictates the processing and the 3D printing applicability, given that different printing techniques adhere to specific coarse aggregates requirements [19].

Recycled aggregates, such as recycled concrete, glass, sand, and fine aggregates harbor the previously discussed merits with the addition of providing numerous environmental benefits which are manifested in the reduction of raw conventional aggregate production such as gravel, given that in some geographic locations gravel has been deemed scarce, which means that turning to artificially produced or recycled aggregates is economically and socially more feasible. Moreover, recycled aggregates repurpose waste materials thus reducing potential greenhouse gas emissions that are associated with virgin aggregate production. Additionally, recycled aggregates can be used to achieve various sustainable development goals, such as SDGs 7, 12, and 13, set out by the United Nations given their high environmental sustainability.

Ding et al. [20] investigated the addition of recycled sand sourced from old, crushed concrete, in concrete mixtures for 3D printing purposes. Recycled sand is a conventional byproduct of construction and demolition waste, which means that employing recycled sand will improve the sustainability of the 3D printed concrete structures. Their study reported the effects on the parameters such as the curing age, nozzle height for 3D printing, tensile splitting strength, and flexural strength. The utilized sand particles were up to 0.90 mm, which were obtained from 100% waste concrete and used as the fine aggregate. It was noted that the water requirement for the concrete mixture increased with increasing the recycled sand content. Moreover, the compressive strength decreased by increasing the recycled sand content with reduction percentages reaching 31%. A similar behavior was witnessed for the tensile splitting strength. However, the flexural strength increased up to a recycled sand content of 25% and decreased above that threshold. Having this property, concrete with recycled sand can be used for applications that require materials that withstand high loads, given how they can counter bending and deformation.

Liu et al. [21] investigated the addition of recycled coarse aggregate (RCA) which, similar to recycled sand, comes from demolition and construction waste, in concrete mixtures for 3D printing. Their recycled coarse aggregate was similar to a baseline natural coarse aggregate (NCA), which was sourced from natural gravel, in terms of density at an apparent density of ~2500–2700 kg/m3 for RCA and NCA, respectively. However, the water absorption for RCA was higher at 7.29 vs. 1.1 for NCA, which led to an increase in the total amount of cement relative to the water content. Moreover, the increased surface roughness of RCA increases its bonding with the existing mortar matrix. Finally, given these two factors, the mechanical strength of the 3D-printed RCA-containing concrete to have favorable mechanical strength properties, not far from those containing NCA, while bearing less effects on the environment and being more economically feasible.

Heidi et al. [22] utilized recycled brick aggregate (RBA) by replacing 64% of the natural aggregate present in an existing 3D printable concrete mixture. Incorporating RBA into the concrete mixture increased the water requirements due to the porous nature of the utilized bricks and their high-water absorption ability, which can negatively impact SDG 6 (clean water and sanitation). Moreover, optimizing the %RBA in the mix can potentially aid in reaching a desired packing density. Although the resulting concrete mixture had low compressive cube strength, and low interlayer and low 3D printed compressive strength, it showed good printability and high repeatability.

Zou et al. [23] studied the addition of recycled fine aggregate (RFA) in 3D printing mixtures with RFA contents of 0%, 50%, and 100% in place of conventional concrete aggregate. It was noted that increasing the RFA content increased the water requirement given the increased water absorption in comparison to the initial aggregate source. The shear stress and viscosity increased over time with increasing RFA%. Moreover, Hao et al. [24] utilized RFA as a support material for a parafilm wax phase change material (PCM) to alter the thermal conductivity of 3D-printed concrete; it was found that the thermal conductivity of PCM-impregnated RFA cement was close to 31% lower than that of mold-casted concrete which can affect the number of printing layers, path, and extrusion rate. Table 1 shows a comparison of different recycled aggregates that were utilized in concrete mixtures with their advantages and disadvantages.

2.3. Geopolymers

Geopolymers are a type of material that have been recently implemented and grasped a great deal of attention in 3DCP applications. To put it in simple terms, geopolymers are created by mixing industrial waste such as fly ash (FA), slag, and silica fume (SF), known as aluminosilicate precursors, with an alkaline activator to make up a cementitious material. The first step is the preparation of the aluminosilicate precursor, which is done by grinding the precursor to achieve a workable particle size, which is then subsequently dried to remove any residual moisture. Then, the alkaline activator, which is usually a mixture between an alkali metal silicate, such as sodium silicate or potassium silicate, and an alkali metal hydroxide, such as sodium hydroxide or potassium hydroxide. The geopolymer paste is finally formed after mixing in the dried aluminosilicate precursor with the alkaline activator. The geopolymer paste can then be used in an arsenal of applications such as casting, molding, or in this specific case, 3D printing.

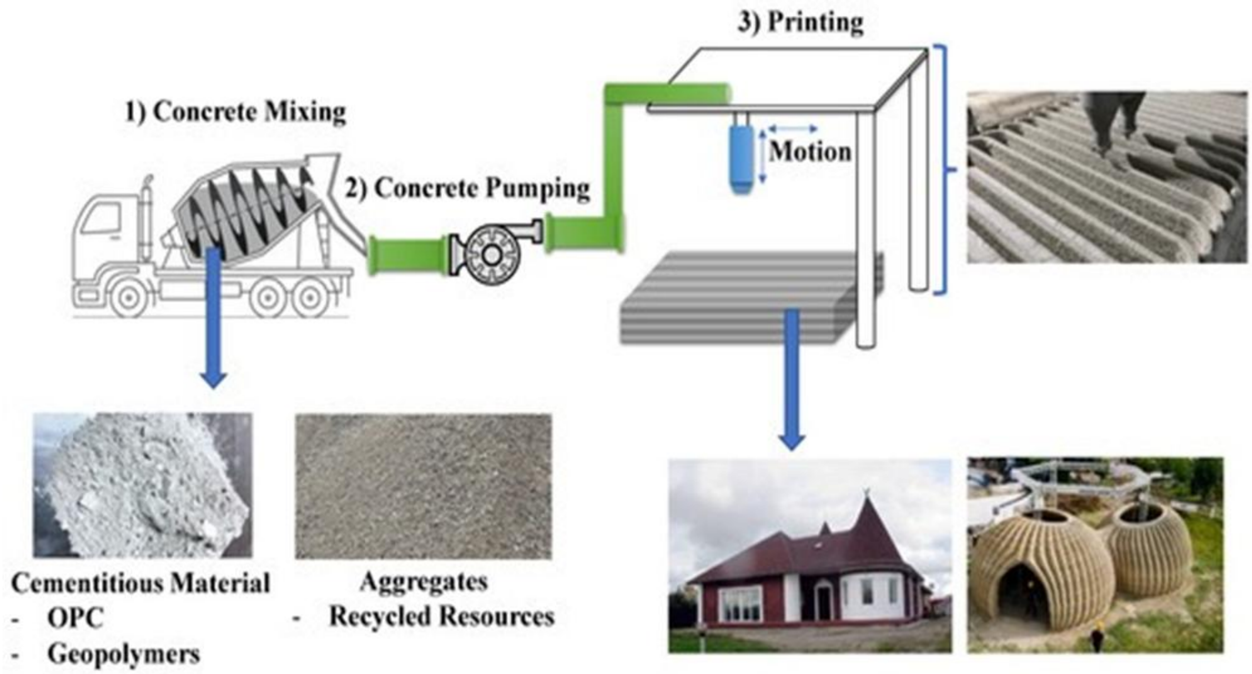
The grand motive behind transitioning into geopolymers in 3D printing is the reduced environmental impact of the end buildings, contrary to traditional ones. Geopolymers repurpose industrial waste into workable cement-like pastes for 3D printing, and thus reducing the amount of waste that goes into landfills. Furthermore, geopolymers utilize less energy during their manufacturing process, leading to an overall reduced carbon footprint for buildings that are based off their derived materials. Additionally, geopolymers are flexible and can be tuned in order to achieve specific requirements for different applications. Finally, geopolymers can revolutionize the construction industry, given how feasible geopolymers are in comparison to conventional ordinary Portland cement OPC. In addition, geopolymers and OPC share similar characteristics, such as high compressive strength, fire resistance, and chemical, mechanical, and thermal stabilities.

Fly ash (FA) is a waste product of coal power plants, that is essentially a fine powder with a propensity to become airborne and cause respiratory health issues. However, combining FA with an alkaline activator can aid in remedying this, by producing a workable paste for 3DCP. Moreover, silica fume (microsilica) is a fine powder that harbors a lot of silicon dioxide, which makes for a good aluminosilicate precursor component. Slag is used as a supplementary cementitious material (SCM) instead of conventional aggregate and is employed in geopolymers to fine tune its mechanical properties. Finally, metakaolin is a good precursor for geopolymer production due to the ease of the Si/Al content tuning; however, it is rather rare and expensive, which gives the other alternatives an edge over it.

Markzyk et al. [12] investigated geopolymers comprising of fly ash (FA) and metakaolin (MK) KM60. The FA was collected from the combined heat and power plant in Skawina, Poland. The aluminosilicate precursors were mixed in with sand at a 1:1 ratio and activated with 10M NaOH, where the ratio of NaOH to water was fixed at 1:2.5. It was noted that the increased Si-O-Si bonds within FA promoted better mechanical properties, such as compressive and flexural strength, after 28 days of curing, due to the residual silica acting as reinforcement. Moreover, Guo et al. [25] investigated the addition of slag and silica powder as additives to an FA-based geopolymer. The utilized FA comprised mostly silica at 53% and Al_2O_3 at 28%, while the slag powder mostly consisted of CaO and silica. It was found that the most suitable content of slag powder and silica fume was 10%, where the rheological properties hit a threshold. It was noted that the gel formation at the center of the print was better than the surface, according to SEM observations. Panda et al. [26] studied a relatively similar 3D printing mix, fly ash with ground granulated blast furnace slag (GGBS) (binder), with the addition of sand where the weight ratio (sand/binder) was varied from 1.1 to 1.9. It was noted that the mixture with a sand/binder ratio of 1.5 showed a yield stress in the range of 0.6–1 kPa and a smooth extrusion process. Moreover, the same type of mixture showed a favorable shape orientation (SRF) which is the ability of the cured mixture to retain its shape under its own weight. Additionally, Panda et al. [27] conducted a similar study where they utilized FA, OPC with FA replacements ranging from 50 to 80%, and SF with a fixed water/binder ratio of 0.45 and a sand/binder ratio of 1.35. It was found that further addition of FA after the 50% mark reduced the yield stress and viscosity, which was attributed to the spherical shape of the FA that prevented the friction force between the OPC particles. Moreover, SF addition up to 5% showed an enhancement of the yield stress properties.

3. APPLICATIONS

The implementation of 3DCP in the construction sector has proven to be a viable option for infrastructure, façade elements, modular building support, stairs, outdoor furniture, and complicated wall design applications [28], which can have a significant impact on the different SDGs, especially SDG 11, as will be discussed in the following sections. There are various elements that make up a usable 3DCP system, which the previously mentioned printing materials take up a small part in. A 3DCP setup consists of a concrete mixer, that is connected via pipes to a pump that supplies the material to a printing nozzle, which essentially carries out the operation until the final form of the 3D printed structure is reached. The process is shown in Figure 3.



A 3DCP pilot project was commenced in the Dutch city of Eindhoven, which is essentially a commercial housing project that is the fruition of a collaboration between a local construction firm "Houben & Van Mierlo Architecten" and the "Eindhoven University of Technology". One of the houses that was included in the plan is a 95-square-meter, three-room, single-floor house that was said to be followed by multi-story houses [37]. Moreover, the lifetime of this structure is said to be measured in decades. The novel boulder design of this house makes it blend in with the surrounding environment. The house consisted of 24 elements that were printing at the Eindhoven University of Technology, with a total printing time of 120 h, transported to the targeted site, and securely placed on pre-built foundations [38].

Project Virginia, taking place in Virginia, United States, is a 200-house 3D printing project that is planned to take place over the next 5 years. The project will utilize the Black Buffalo 3D' NEXCON printer, that weighs 19,000 kg (19 tons) and can print structures up to three stories high. A test run that included the first 3D-printed house was completed with 28 h of printing time, reducing the gap between prints by a month, and costs by 15% per square foot. These savings were attributed to the reduced labor and lumber requirements. The houses are said to have costs ranging between USD 175 and 350 thousand [39].

Iberdrola, a renewable energy company with more that 1.2 million km of electric transmission and distribution power lines, has initiated a collaboration with "Hyperion Robotics" and "Peikko Group" to apply 3DCP in order to enhance the construction of their transmission lines. Given the shortage of labor and the lack of automation in the current construction industry, the 3DCP solutions offered by Hyperion Robotics propelled the vision of this project, given how 3DCP is cheaper, faster, and safer than conventional construction methods. The transmission structures were printed with a 75% reduced material requirement. Moreover, with implementing recycled materials such as FA, SF, and slag, a 90% reduction of these structures' carbon footprint can be achieved [40].

Researchers from the US Army Corp. of Engineers utilized 3DCP to erect a 9.5 ft-tall concrete wall for a 32 ft × 16 ft barracks, with the ultimate goal of creating structurally safe 3D printed units in the future; they have stated that a structural testing to show the level of safety in the scope of these projects has yet to be done. Additionally, they stated that building temporary housing in disaster areas takes from five to ten days using conventional methods, a timespan that can be brought down to a single day using 3DCP. Moreover, it is said that a single simultaneous crew of three trained workers, with three separate shifts would be required to carry out such an operation [41].

4. COMPRESSIVE STRENGTH OF THE PRINTED COLUMN

The compressive strength of hardened concretes was evaluated on the printed samples. Tests were conducted on printed hollow columns with D = 160 mm and H = 205 ± 10 mm (for each test, three specimens were printed). The width of the layer was assumed as t = 35 ± 5 mm. The side overhangs (Figure 3) of the layers were maintained within the margin of t_{wb} = 3 ± 2 mm. Figure 3 shows the plan and view of the printed structure. Before the printing, a quality assessment test was performed each time in accordance with [26].

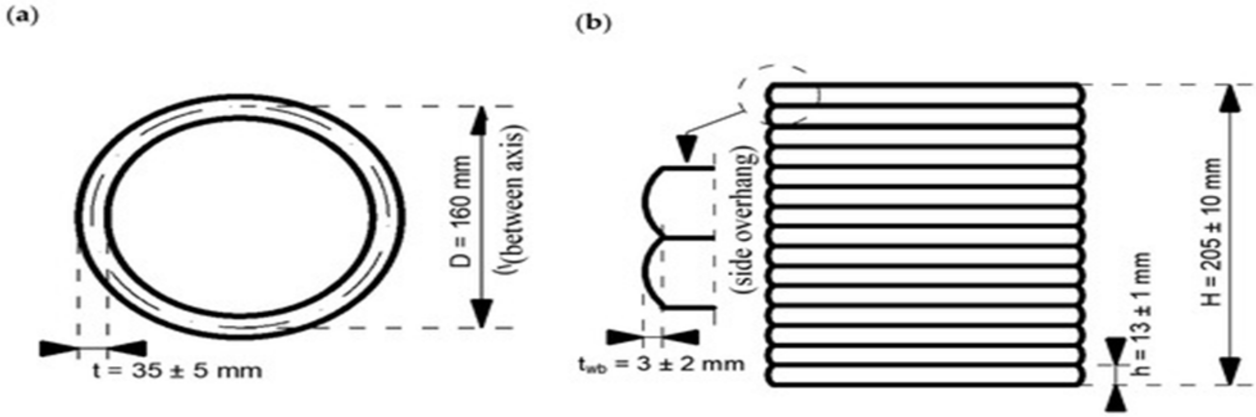


Figure 3. Plan (a) and side view (b) of printed columns.

The load-bearing capacity of the samples was tested at 10 h after printing (early-age parameters of concrete are crucial in additive manufacturing). The test was performed on a hydraulic press with the use of additional equipment. The test stand consisted of: two LVDT displacement transducers installed on both sides of the sample. The average value of two measurements was taken for final considerations. An additional 500 kN (HMB C6A) force transducer was attached to the hydraulic press (100 kN). The additionally installed force and displacement transducer allowed for simultaneous registration of force and displacement. The results were recorded using the HBM QuantumX and Catman software. The test stand is presented in Figure 4.

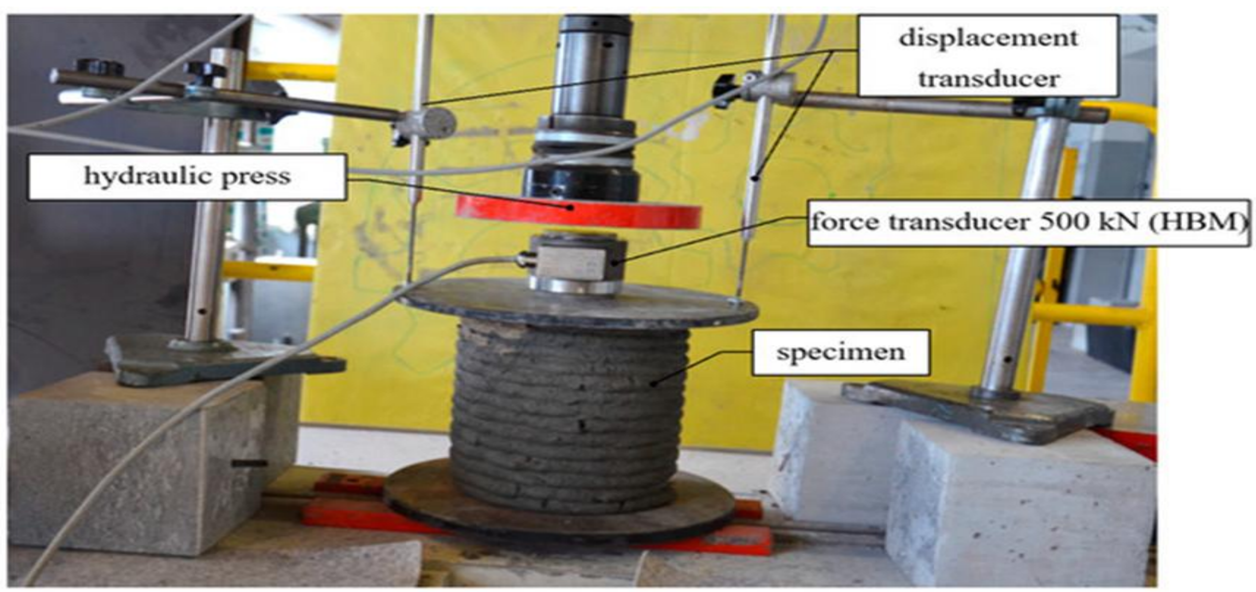


Figure 4. Test stand for compressive strength evaluation of printed structures.

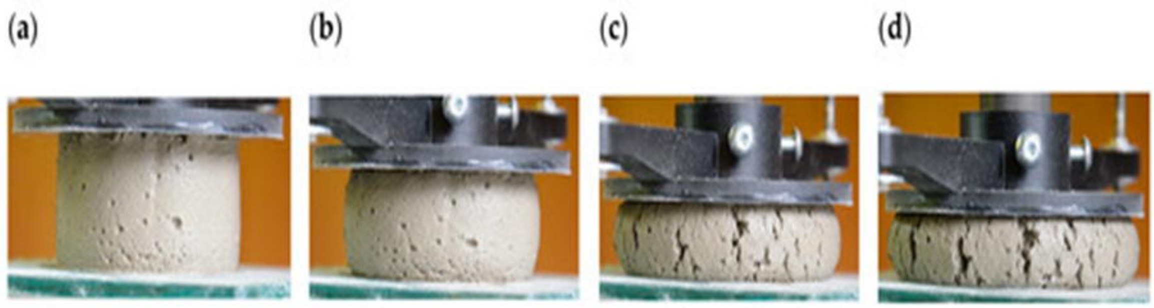


Figure 11. Analysis of specimen failure during the squeezing test—example 1.

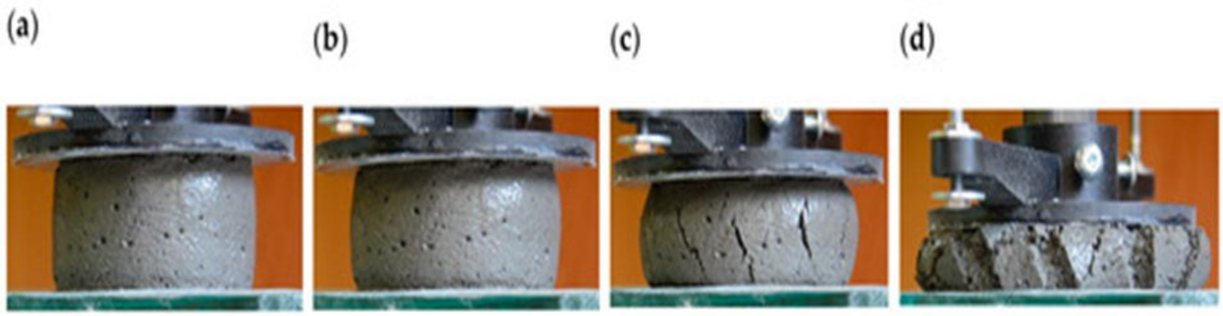


Figure 12. Analysis of specimen failure during the squeezing test—example 2.

Presents the cross sections of printed columns.

Figure 21. Cross sections of printed column: (a) B840/SF/FA/LP; (b) B640/SF/FA/LP; (c) B640/SF/FA.

5. CONCLUSIONS

This study highlights the potential of 3D concrete printing (3DCP) to revolutionize the construction industry and contribute towards achieving the relevant sustainable development goals (SDGs) set out by the United Nations. The research reveals that 3DCP offers significant advantages over conventional construction methods in terms of cost and water consumption, with a potential to save up to 78% and 60% of the associated costs with conventional construction and labor, respectively. By exploring the recent progress and limitations of the three dominant types of cementitious mixtures, this study provided insights into the potential of 3DCP to contribute towards achieving the SDGs. Therefore, continued research and development of 3DCP technology are necessary to overcome its limitations and unlock its full potential for the construction industry. Overall, this study emphasized the importance of adopting innovative and sustainable approaches to construction, such as 3DCP, to address global sustainability challenges and achieve the SDGs.

The study was conducted on eight mixes. The mixes were designed to allow for determining the influence of the binder amount and type of mineral additive on their suitability for 3D printing. In addition, their environmental impact was evaluated.

The mixes were divided into two groups, one with high binder content (840 kg/m^3) and one with low binder content (640 kg/m^3). The binder in designed mixes was either cement (B840, B640, B840/LP, B640/LP) or cement with mineral additives: silica fume (SF), fly ash (FA) as a partial replacement (B840/SF/FA, B840/SF/FA/LP, B640/SF/FA, B640/SF/FA/LP). The influence of limestone powder (LP) was also determined (B840/LP, B640/LP, B840/SF/FA/LP, B640/SF/FA/LP).

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