Project Management Institute. Kingdom of Saudi Arabia

Digital Insights:

UITILIZING 3D CONCRETE PRINTING IN JAFURAH

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ABSTRACT

This paper explores the integration of 3D printing in the construction of buildings, examining its potential to revolutionize the industry by enhancing efficiency, reducing costs, and promoting sustainability. Focusing on Jafurah Gas project (JGP), it outlines the key stages of implementation, from design through material selection and final construction. The paper highlights the benefits of 3D printing, such as the ability to create complex geometries, minimize waste, and reduce labor requirements. It also discusses challenges related to scaling, regulatory standards, and material limitations. By analyzing a case study of 3D printed buildings in Jafurah Gas Project, the paper provides practical insights into the current and future role of additive manufacturing in transforming the architectural and construction landscapes.

Additionally, this paper evaluates the economic and environmental impacts of adopting 3D printing technology in large-scale projects, emphasizing its alignment with global sustainability goals. The paper explores how advancements in material science and robotics contribute to enhancing the durability and efficiency of 3D printing applications. Finally, it discusses the future outlook of 3D printing in construction, considering its contribution to a more resource-efficient and environmentally-conscious built environment, while addressing the broader implications for industry stakeholders and urban development.

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1. INTRODUCTION

The integration of 3D printing technology into large-scale construction projects has emerged as a transformative solution, offering unprecedented opportunities to improve efficiency, reduce costs, and enhance design flexibility. In the context of mega oil and gas projects, characterized by their complex infrastructure needs, challenging environmental conditions, and tight timelines, 3D printing presents a promising avenue for addressing these unique challenges. This paper explores the potential for implementing 3D printing within the construction phases of a major gas and oil project, highlighting its advantages in producing critical components, optimizing material usage, and accelerating construction timelines. By leveraging additive manufacturing, project stakeholders can achieve highly customized, durable, and cost-effective solutions tailored to the specific demands of the energy sector. The paper will examine key aspects such as material selection, logistics, and scalability, as well as the technical and regulatory barriers that must be overcome to successfully incorporate 3D printing into the project. Through this exploration, the paper aims to demonstrate how 3D printing can revolutionize the construction practices of large-scale energy infrastructure, paving the way for a more sustainable, efficient, and innovative approach to future mega-projects in the gas and oil industry.

1.1 HISTORY OF 3D PRINTING IN CONSTRUCTION

The concept of 3D printing, or additive manufacturing, has rapidly evolved from an experimental technology into a viable method for constructing buildings and structures. The history of 3D printing in construction dates back to the early 2000s when researchers and engineers first explored the potential of using this technology beyond its origins in industrial prototyping. In 2004, the first significant steps toward 3D printing in construction were taken when the Dutch company, D-Shape, pioneered the use of a concrete-based printer to build large-scale structures [1]. However, it was in 2013 that 3D printing for buildings gained widespread attention with the debut of the “Vulcan” printer by the company, Winsun, which was capable of printing entire homes using a mixture of industrial waste [2]. Over the following decade, advancements in 3D printing technologies have led to the development of printers capable of using a range of materials, from concrete to plastics to more exotic blends of materials like recycled aggregates and bio-based composites [3]. Notable milestones in 3D printed architecture include the construction of the world’s first 3D-printed office building in Dubai in [4] 2016 and the creation of 3D-printed affordable housing in Mexico in [5] 2020. As 3D printing continues to evolve, it is poised to revolutionize the construction industry, providing solutions to labor shortages, environmental sustainability, and the need for affordable housing. This historical trajectory demonstrates that 3D printing in construction is more than just a theoretical innovation— it is becoming a practical, transformative tool that could reshape the future of architecture and urban planning.

1.1 HISTORY OF 3D PRINTING IN CONSTRUCTION

As part of Aramco's ambitious plan for digitalization and, in particular, implementation of 3D Concrete Printing construction, the company has completed a first 3D-printed concrete industrial building in Hawiyah, marking a significant milestone in its digital innovation journey. This achievement reflects Aramco's commitment to becoming a global leader in digital solutions for the energy sector. Additive manufacturing has proven to be an effective digital approach to meeting the demands of Aramco's capital projects while aligning with the company's de-carbonization goals by optimizing the use of resources. With a modest footprint of 63 square meters and a height of 3.85 meters, this first building demonstrated the applicability of this innovative construction methodology in the heavy industry space. This automated process significantly reduced the risk of errors and delays, enabling continuous printing and cutting delivery times by more than 45% compared to traditional methods. Additionally, the use of 3D printing resulted in cost savings of up to 60% on materials and up to 80% on labor [6].

From this achievement, the company has been seeking additional and incremental opportunities to apply this innovative construction method within its capital program.

2. IMPLEMENTING 3D PRINTING IN JGP

Leveraging on the first 3D concrete printing construction experience, subsequent projects aim to the optimization of the method and scaling up its usage. This innovative approach not only addresses many of the challenges in traditional construction but also provides an opportunity to explore its full potential across diverse applications. Moreover, as it is true with any disruptive technology, documenting learnings from early deployments are crucial to achieve its full potential; thus, JGP capitalized on assessing the outcomes of the previous project and documenting any challenges faced, such as design limitations, equipment logistics, or regulatory hurdles, and devise strategies.

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2.1 DESIGN

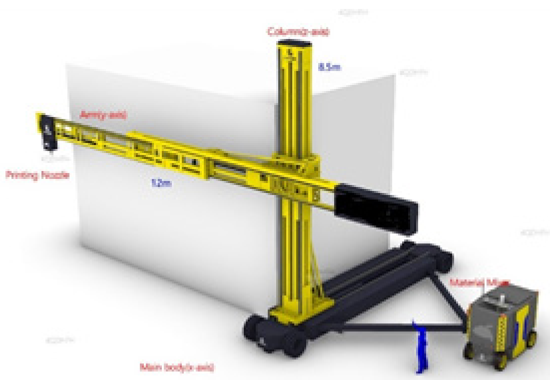
Pushing the boundaries of 3DCP freeform capabilities, the construction in JGP included whimsical wall designs which were achieved by using a 3D printer of latest generation, developed to reach a larger scale. that was designed to reach a larger scale. Motivated to mark a breakthrough improvement in the size of a single 3D concrete printing, the scope of this project included 2 operator shelters and 4 smoking shelters with dimensions as follows in the table below:

BUILDING	LENGTH (M)	WIDTH (M)	HEIGHT (M)
Operator Shelter	12.25	6.00	3.50
Smoking Shelter	5.40	3.00	1.50

1.Buildings Dimensions, Table

3 2.2D PRINTING EQUIPMENT

The 3D printer, or the 3D printing system consists of three main parts: the printer, the mixer and the material input machine.
Firstly, the printer is a single-mast cartesian type, consisting of a self-propelled, automatic folding system of a 12-metre-long arm (Y-axis) and 8.5-meter-high vertical column (Z-axis), resting on a traveling rail integrated to the main body (X-axis).. The second part is an equipment that includes a material hopper, weighting and measuring equipment and a mixer for blending, referred to as “the mixer car”. The mixing car is connected by braces to the printer main body to serve as a counterweight and prevent it from tipping over. Both devices are also equipped with power systems, allowing them to move freely on-site. Additionally, ancillary equipment recently developed to enhance the printing process was used for the first time on this project.



2.3D Printer & Mixer, Figure

An automatic material input system for loading materials into the mixer car’s hopper, which allowed the loading of the dry printing material with ease and reducing the operator’s physical effort Also, an automated fogger was used to ensure the continuity of curing conditions even during off-duty hours.

2.3 PRINTING MATERIAL

The printing material or the mortar used for the 3D printing is a specially formulated construction material used in additive manufacturing for building structures. Unlike traditional mortar, it is designed to flow smoothly through a 3D printer's nozzle while maintaining sufficient viscosity to support subsequent layers.
Various material proportions were used to create the 3D printing material mix design. The table attached in Table.2 in appendix A shows the composition information, the specifications and properties of the material used. Note that the material design and basic information mentioned below were written based on the data sheet provided by the supplier and not all information are disclosed for security reasons.

2.4 MATERIAL TESTING

Although, it was confirmed that the compressive strength of 3DP mortar is more than 35 MPa based on the tests using the material from the supplier abroad. However, when conducting a compressive strength test in Saudi Arabia using the mortar mix ratio and considering the local climate, it was found that the strength was approximately 25 MPa. In light of the above, the 3DP wall is not a concern as it is a non-bearing wall that stands independently, rather than a load-bearing wall. A calculation using the same criteria as the unreinforced masonry wall, resulting in a compressive strength of 10.34 MPa was validated and confirmed its approval since the current strength of 25.0 MPa is higher than the reflected value in the calculation.

2.5 MATERIAL ENHANCEMENT AND LOCALIZATION

Moreover, by enhancing the compressive strength of 3D printing mortar to enable its use in structural elements is a critical step in advancing the construction industry's adoption of additive manufacturing. This can be achieved by optimizing material composition, incorporating innovative additives, and aligning production with localized resources. In this context, a local supplier has provided 2 samples of 3D printing mortar that we did a mock up on and tested for its compressive strength and showed a promising result to start with as shown in a table in table.3 below.

COMPRESSIVE STRENGTH TEST	SAMPLE (1)	SAMPLE (2)
At 1 Day	11.30 MPa	16.50 MPa
At 2 Days	19.80 MPa	16.50 MPa
At 3 Days	26.60 MPa	31.10 MPa

3.Local Material Compressive strength, Table

The tests for the two material samples have been successful in a laboratory and a field mixing stage. However, in pumping and printing stages at the site, it has a little bit different result. The material sample 1 is printable but it needs improvement for flowability, consistency and reducing water ratio to ensure more stable printing performance. For sample 2, additional tests are required to verify printing performance. In addition, the number of samples provided from the local cement company are insufficient to print a larger structure. For printing a large structure, it is necessary to additionally verify the behaviors such shape stability, settlement and crack propagation during curing stage.

3. CONSTRUCTION WORK FLOW

3.1 OVERALL PLAN

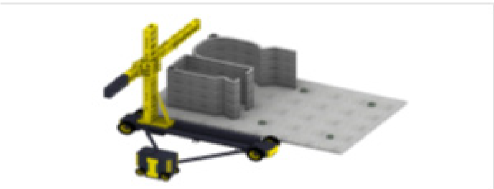
The construction of 3D Printing Buildings is consisting of 4 major works. Foundation work, 3D Printing wall, reinforced concrete columns and Precast Roof work / Roof topping concrete Work. A conventionally constructed foundation with dowel bar shall be installed prior to the 3D construction. 3D Printing machine starts extruding the outer wall and columns and the reinforced concrete is installed inside columns. Precast roof is installed once the walls and reinforced columns have reached the required strength.

3.2 CONSTRUCTION SEQUENCE

First step of constructing the building is by casting the building foundation with dowel bars at the column's locations so that the column rebars can be connected by a coupler in the foundation with 50mm apron for 3D printing. 3D Printer is located by itself on a flat area which is composed of main body with material supplying machine. 3D printer automatically will unfold the Y and Z axes to prepare for printing.

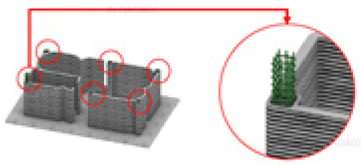
3.Foundation and Printer positioning, Figure

The Building is printed in 2 blocks as shown in the figure below with at least 1000mm extra space should be reserved for maintenance area of 3D printer. Dividing the process into two parts was required to accommodate the larger building footprint within the printing boundaries of the printer. The 3D printer and the material supplying machine then is then re-located and re-installed to print the next block of the building.



4.Printing First Block, Figure

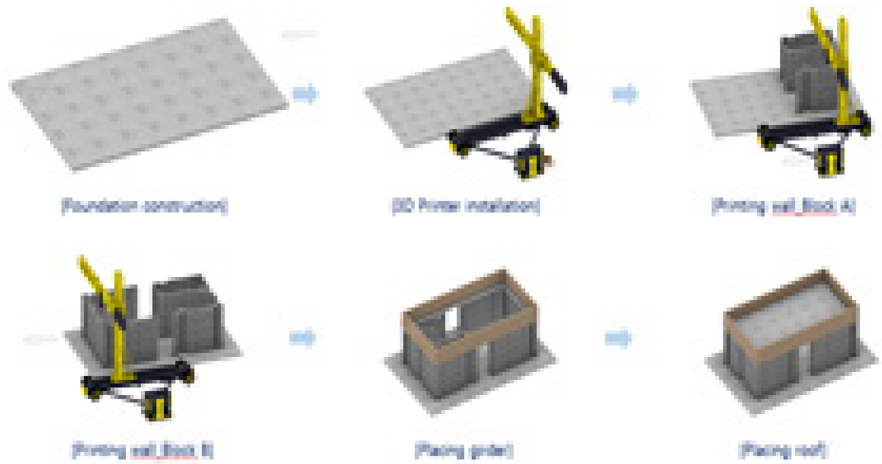
The rebar installation for the columns is done in a segmental fashion, following the printing of approximately 1meter height of column and wall. Mechanical couplers were used to connect dowels to the reinforcement cage.



5.Column Rebar Installation Figure

Concrete for structural elements then is poured into the printed columns and cured. After curing, Precast beams and roof slabs are installed on the 3D printed building after casting completion. The precast parts are connected to the dowel bars in the casted columns.

First step of constructing the building is by casting the building foundation with dowel bars at the column's locations so that the column rebars can be connected by a coupler in the foundation with 50mm apron for 3D printing. 3D Printer is located by itself on a flat area which is composed of main body with material supplying machine. 3D printer automatically will unfold the Y and Z axes to prepare for printing.



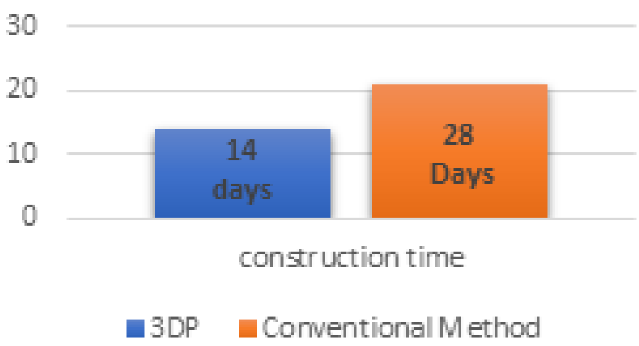
6.Complete Construction Sequence, Figure

The complete 3D printing of 2 operator shelters and 4 smoking shelters with total printed area of 179.4 m2 took approximately 11 weeks including construction time, preparation and transferring equipment and materials from and to the several locations.

4. COMPARISON

3D printing in construction offers advantages such as rapid construction speeds, high design flexibility for complex shapes, and reduced material waste, making it a potentially eco-friendly option. However, it comes with disadvantages, including high initial costs, limited scalability due to printer size, and the need for specialized training and equipment. 3D printed buildings, while innovative and efficient are generally not blast-proof due to material limitations, structural weaknesses, and the nature of additive construction method which make it one of the major limitations of this technology in operational facilities. On the other hand, conventional concrete construction is suitable for projects of any size or complexity, provides proven durability and structural strength, and is widely accessible and understood. Nonetheless, it is time-consuming, labor-intensive, prone to human errors, and generates significant material waste, contributing to environmental concerns. A more detailed comparison Table.4 in appendix A elaborates more on multiple comparison aspects.

The chart below highlights the clear difference in the time consumed and construction speed between 3D printing and the conventional construction method of the operator shelter in which the schedule impact is reduced.



1.Construction Time Comparison, Chart

5. CONCLUSION

The integration of 3D printing technology in Jafurah Gas Project represents a significant advancement in construction methods within the oil and gas industry. This study highlights the numerous benefits of 3D printing, including enhanced efficiency, reduced material waste, and greater design flexibility. The successful implementation of 3D-printed operator and smoking shelters demonstrates the feasibility of this technology for large-scale industrial applications.

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APPENDIX A

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5.Column Rebar Installation Figure

CHEMICAL COMPOSITION	
CaO	54.28%
SiO2	10.72%
Al2O3	4.75%
Fe2O3	2.18%
MgO	0.50%
K2O	1.35%
SO3	1.02%
TiO2	0.13%
Na2O	0.28%
P2O5	0.05%
Loss on Ignition	24.73%

PHYSICAL PROPERTIES	
Compressive Strength	
at 1 Day	20.8 MPa
at 7 Days	36.8 Mpa
at 28 Days	40.6 Mpa
Flexural Strength	> 7 MPa
Flow Table Test (at 10 drop)	60-40 %
Penetration of Conical Plunger	60-40 mm
Density	2200 kg/ m3
Dry Shrinkage at 28 days	0.06%

5.Column Rebar Installation Figure

ASPECT	3DP	CONVENTIONAL CONSTRUCTION
Speed of Construction	Faster, due to automation and continuous operations. 14 days were enough time to complete the operator shelter.	Slower; involves multiple manual processes like mixing, pouring, and curing. It would've taken over 28 days to complete the same building.
Cost	Lower for customized or repetitive designs; fewer labor costs.	Higher due to labor, material wastage, and prolonged timelines.
Labor Requirements	Minimal; requires skilled technicians to operate the printer.	High; involves diverse workforce for various tasks.
Material Efficiency	Highly efficient; uses only the required material with minimal waste.	More wasteful; excess material often discarded.
Design Flexibility	High; capable of creating complex, customized, and organic shapes with ease.	Limited; constrained by formwork, tools, and labor skills.
Environmental Impact	Reduced carbon footprint; less material usage and potential to use sustainable materials.	Higher carbon footprint; relies on traditional cement, contributing to emissions.
Structural Strength	Dependent on the 3D printing material and process; may require reinforcement.	Proven strength; heavily relies on traditional reinforcement techniques.
Quality Control	Consistent quality due to automation, but defects can occur if printing is not properly calibrated.	Requires constant manual monitoring, prone to human error.
Scalability	Limited to specific project sizes and types due to printer size and logistics.	Easily scalable for large, high-rise, or complex projects.
Initial Investment	High initial costs for equipment and setup.	Lower initial investment; uses conventional tools and materials.
Manpower	A crew of 10 people was required.	A crew of 15 to 20 people is required for the same building size.