3D CONCRETE PRINTING

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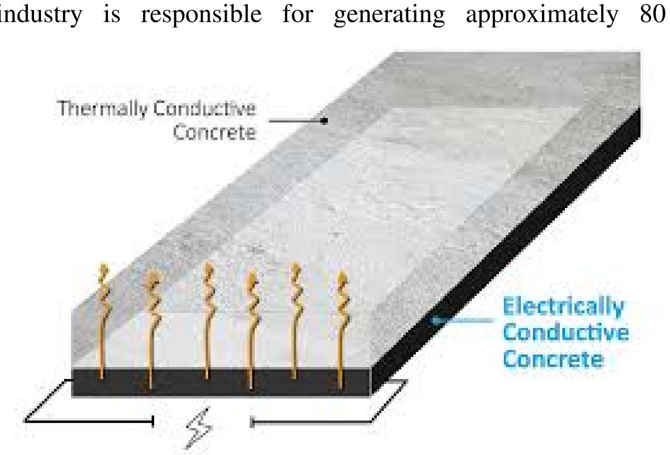
***Abstract*—The construction industry is expected to go through large transformations since construction automation is anticipated to drastically alter standard processing technologies and could lead to possible disrupting technologies such as 3D concrete printing (3DCP). While 3D printing techniques have been successfully applied in a wide range of industries such as aerospace and automotive, its application in concrete construction industry is still in its infancy. 3DCP can allow freeform construction without the use of expensive formwork, which in return offers excellent advantages compared to conventional approach of casting concrete into a formwork. In the last few years, different 3DCP technologies have been developed. This paper presents the current progress of 3DCP technologies. An innovative methodology recently developed by the authors of this study for formulating geopolymer-based material for the requirements and demands of commercially available powder-based 3D printers is also briefly presented.**

***Index Terms*—Additive manufacturing; 3D printing; 3D concrete printing; concrete construction; geopolymer**

I. Introduction

Concrete is the most widely used construction material on this planet. The current concrete construction industry faces several challenges. One of them is the high cost. According to a recent study conducted by Boral Innovation Factory [1], formwork is responsible for about 80

The significant amount of wastage generated in the construction is another challenge. Formwork is a significant source of waste, since all of it is discarded sooner or later, contributing to a generally growing amount of waste in the construction industry. Astonishing data presented in Llatas [2]'s paper showed that the construction industry is responsible for generating approximately 80



Furthermore, the conventional approach of casting concrete into a formwork limits geometrical freedom for the architects to build in various geometries, unless very high costs are paid for bespoke formworks. Rectilinear forms not only limit the creativity of the architects, but they are also structurally weaker than curvilinear forms owing to stress concentration.

A.

Another challenge is the slow speed of construction (i.e. long and hard to control lead time). The concrete construction often comprises many steps including material production, transportation, and in-situ manufacture of formwork, and each step is time consuming. Moreover, the current concrete construction industry is labor intensive and has issues with safety. According to Safe Work Australia's report [3], on average, 35 construction employees per day are seriously injured in Australia. In addition, over one-quarter of construction deaths are caused by falls from a height [3]. This is despite the fact that Australia has one of the highest levels of safety regulations in construction sites in the world. Last but not least, the current construction industry has serious issues with sustainability. In general, the current construction methods and materials are not environmentally friendly. The entire construction process, including off-site manufacturing, transportation of materials, installation and assembly, and on-site construction, emits huge amounts of greenhouse gases and consumes large quantities of energy [4]. In addition, conventional concrete made by ordinary Portland cement (OPC) is not sustainable. Manufacture of OPC is highly energy and carbon intensive [5].

B. Basic Introduction

Application of three-dimensional (3D) printing techniques in concrete construction could solve the aforementioned challenges. 3D printing technology is recently gaining popularity in construction industry. In the last few years, different 3D concrete printing (3DCP) technologies have been explored. This paper presents the current progress of 3DCP technologies. An innovative methodology recently developed by the authors of this study for formulating geopolymer-based material for the requirements and demands of commercially available powder-based 3D printers is also briefly presented. 3D printing, also known as additive manufacturing (AM), is a group of emerging techniques for fabricating 3D structures directly from a digital model in successive layers with less waste material. The American Society for Testing and Materials (ASTM) International Committee F42 on AM technologies defines AM as “the process of joining materials to make objects from 3D model data, usually layer upon layer” [6]. The AM technologies have been initially developed in the 1980s. Currently, AM technologies have become an integral part of modern product development and have been successfully applied in a wide range of industries including aerospace and automotive manufacturing, biomedical, consumer and food [7].

C. Contributions

The first attempt to adopt AM in construction using cementitious materials was made by Pegna [8]. An intermediate process was used to glue sand layers together with a Portland cement paste [8]. Unlike the conventional approach of casting concrete into a formwork, 3DCP will combine digital technology and new insights from materials technology to allow freeform construction without the use of expensive formwork. The freeform construction would enhance architectural expression, where the cost of producing a structural component will be independent of the shape, providing the much needed freedom from the rectilinear designs. When compared with conventional construction processes, the application of 3D printing techniques in concrete construction may offer excellent advantages incluidng:

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1.Reduction of construction costs by eliminating formwork;

E.

2.Reduction of injury rates by eliminating dangerous jobs (e.g., working at heights), which would result in an increased level of safety in construction;

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3.Creation of high-end-technology-based jobs; Reduction of on-site construction time by operating at a constant rate;

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4.Minimizing the chance of errors by highly precise material deposition;

H.

5.Increasing sustainability in construction by reducing wastages of formwork,

I.

6.Increasing architectural freedom, which would enable more sophisticated designs for structural

and aesthetic purposes; and

J.

7.Enabling potential of multifunctionality for structural/architectural elements by taking advantege of the complex geometry [9,10].

K.

CONCRETE PRINTING: Concrete Printing technology has been developed by a team at Loughborough University in the United Kingdom. This technology also uses the extrusion-based technique and to some extent is similar to the CC technology. However, the Concrete Printing technology has been developed to retain 3D freedom and has a smaller resolution of deposition, which allows for greater control of internal and external geometries [12]. In addition, the material used in Concrete Printing is a high performance fiber-reinforced fine-aggregate concrete, resulting in superior material properties to

those obtained in the CC technology [12]. shows a full scale bench fabricated using Concrete Printing. The bench was 2 m long, 0.9 m maximum width and 0.8 m high and comprised of 128 layers of 6 mm thickness. The bench includes 12 voids that minimize weight, and could be utilized as acoustic structure, thermal insulation, and/or path for other building services. The bench also demonstrates a reinforcement strategy where carefully designed voids form conduits for post placement of reinforcement [12].

A full scale bench fabricated by the Concrete Printing with functional voids and post- tensioned reinforcement [12] Concrete Printing requires additional support to create overhangs and other freeform features. It uses a second material, in a similar manner to the FDM method. The disadvantage of this process is that an additional deposition device is needed for the second material resulting in more maintenance, cleaning and control instructions and the secondary structure must be cleaned away in a post processing operation [12]. Gosselin et al. [10] reported the following drawbacks in regards to the Concrete Printing technology: (1) the trade-off necessary for maintaining its dimensional accuracy makes the process quite slow with regards to the envisioned industrial application, (2) although the technology initially aimed at the generation of 3D topologies rather than 2.5D, the use of second material to support overhangs reduces the efficiency and flexibility of the process while increasing its material cost, and (3) dimensions and possibilities in terms of shape-design are limited by the dimensions of the printing frame. Current Examples of Extrusion-based 3DCP Elements/Structures In 2014, the Chinese Winsun company claimed to have built 10 basic houses in less than a day, with the area and cost of each one being about 195 m2 and US$4'800, respectively. The company used a large extrusion-based 3D printer to manufacture the basic house components separately off-site before they were transported and assembled on site [14]. In 2015, the company also built a 5-story apartment building, with the area of about 1'100 m2, being [illegible] claimed to h[illegible] alone concrete villa with interior fittings for a cost of about US$160'000. The company claimed to 3D print the walls and other components of the structure offsite and then assembled them together on-site [15]. The Chinese Huashang Tengda company in Beijing has recently claimed to 3D print an entire 400 m2 two- story villa ‘on-site’ in 45 days (see Figure 6-a). Unlike the Winsun company, the Huashang Tengda company uses a unique process allowing to print an ‘entire house’ ‘on-site’ in ‘one go’. The frame of the house inclding conventioinal steel reinforcements and plumbing pipes were first erected. Then, ordinary Class C30 concrete containg coarse aggregates was extruded over the frame and around the rebars through the use of a novel nozzle design and their gigantic 3D printer [16]. The Huashang Tengda project seemingly eliminated one of the major challenges of 3DCP which is incorporation of conventional steel reinforcements if structural concrete is to be 3D printed. The company claimed that the two- story villa is durable enough to withstand an earthquake measuring 8.0 on the Richter scale. Their giant 3D printer has a sort of forked nozzle that simultaneously lays concrete on both sides of the rebars, swallowing it up and encasing it securely within the walls [16].

The two-story villa printed by Huashang Tengda company and (b): the novel nozzle of the giant 3D printer [16] The researchers at the University Federico II of Naples, Italy used a 4 m high BIGDELTA WASP (World’s Advanced Saving Project) printer to build the first modular reinforced concrete beam of about 3 m long . With this WASP printer, the researchers have developed a system to produce concrete elements that can be assembled with steel bars and beams or can compose pillars in reinforced concrete [17].

The first 3D printed modular reinforced concrete beam of about 3 m long [17] As a result of a collaboration between Supermachine Studio and the Siam Cement Group (SCG), recently a 3 m tall cave structure called the “Y-Box Pavilion, 21st- century Cave” was built in Thailand using the 4 m high BIGDELTA WASP printer . The components of the pavilion was 3D printed off-site at the SCG factory and then all the components were assembled together. The cost of manufacture of the pavilion was reported to be about US$28'000$ [18].

The 3 m tall cave structure [18]

On-site’ 3D printed house by Apis Core (a): Construction using a ‘mobile’ 3D concrete printer, (b): House exterior [19]

II. Preliminaries

The problem statement for 3D concrete printing can vary depending on the specific application or use case. However, some common challenges and goals in the field of 3D concrete printing include:

A. Problem Statement

Speed and efficiency: 3D concrete printing has the potential to revolutionize the construction industry by allowing for faster and more efficient building processes. However, current printing technologies are often slow and can only produce small structures. Improving speed and efficiency will be critical for widespread adoption.

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Material properties: The properties of concrete used in 3D printing can impact the strength, durability, and overall quality of printed structures. Developing concrete mixtures that are optimized for 3D printing, and that meet or exceed traditional construction standards, is an ongoing challenge.

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Design flexibility: One of the advantages of 3D printing is the ability to create complex, custom shapes that are difficult or impossible to achieve with traditional construction methods. However, the software and design tools used for 3D printing can be limiting or difficult to use, especially for non-experts. Improving design flexibility and ease of use will be critical for widespread adoption.

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Cost effectiveness: While 3D printing has the potential to reduce construction costs over the long term, the upfront costs of equipment, materials, and training can be significant. Finding ways to make 3D concrete printing more cost-effective will be important for its widespread adoption.

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Sustainability: Concrete is a major source of greenhouse gas emissions, and the construction industry is a significant contributor to global carbon emissions. Developing more sustainable concrete mixtures, and finding ways to reduce waste and environmental impact in 3D printing processes, will be important for the future of the industry.

B. Models

There are several different models of 3D concrete printing that are currently being developed and used in research and industry. Here are a few examples:

Extrusion-based printing: This is the most common method of 3D concrete printing, in which a concrete mixture is extruded through a nozzle or print head to create a 3D structure layer by layer. Extrusion-based printers can be either gantry-style (where the print head is mounted on a moving frame) or robotic (where the print head is mounted on a robotic arm).

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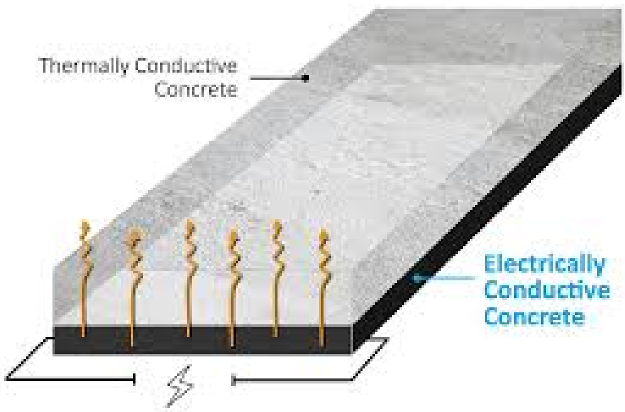

Powder bed printing: In this method, a layer of dry concrete powder is spread over a build platform, and a print head selectively sprays a liquid binder onto the powder to solidify it in the desired shape. The platform is then lowered, and the process is repeated layer by layer.

Inkjet-based printing: In this method, a concrete mixture is loaded into an inkjet printer and sprayed onto a build platform in droplets, which solidify to form the desired shape. Inkjet-based printers can be more precise than extrusion-based printers, but they are typically slower and can only print small structures.

Continuous printing: Some 3D concrete printers are designed to print continuously, without the need for layer-by-layer construction. These printers can create long, seamless structures like walls or beams.

Mobile printing: Mobile 3D concrete printers are designed to be transported to a construction site and print structures on site, rather than printing off-site and transporting them. This can reduce transportation costs and improve construction speed.

Hybrid printing: Some 3D concrete printers combine multiple printing methods (such as extrusion-based and powder bed printing) to achieve the desired properties and precision in the printed structure.

Each of these models has its own strengths and limitations, and researchers and industry professionals are continually exploring new ways to improve and advance 3D concrete printing technology.

D. Assumptions

Assumptions are made when developing any new technology, including 3D concrete printing. Here are some common assumptions made in the field of 3D concrete printing:

Material properties: One assumption is that the properties of 3D printed concrete will be similar to traditionally cast concrete. This includes strength, durability, and other mechanical properties. However, this assumption needs to be verified through testing, as the printing process can affect the microstructure and properties of the material.

Printing time: Another assumption is that 3D concrete printing can reduce construction time compared to traditional construction methods. However, this assumes that the printing process can be done quickly and efficiently, and that the printed structure will be structurally sound and meet all necessary building codes.

Cost effectiveness: 3D concrete printing is assumed to be cost-effective in the long term, as it can reduce labor costs and waste. However, this assumes that the upfront costs of equipment and materials are manageable and that the printing process can be scaled up to larger structures.

Design flexibility: 3D concrete printing is assumed to provide greater design flexibility than traditional construction methods. However, this assumes that the software and design tools used for 3D printing can handle complex designs and that the printed structure will be structurally sound and meet all necessary building codes.

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Sustainability: 3D concrete printing is assumed to be more sustainable than traditional construction methods, as it can reduce waste and use less material. However, this assumes that the environmental impact of producing the equipment and materials needed for printing is taken into account, and that the printing process itself is optimized for sustainability.

It is important to recognize that these assumptions are not necessarily guaranteed and need to be tested and verified through research and development.

III. Overall Algorithms

A. Algorithm

The design and mathematical calculations involved in 3D concrete printing can be complex and depend on the specific application and printer being used. However, here is a general flow chart of the design and mathematical calculation process for 3D concrete printing:

Design requirements: Determine the requirements for the printed structure, such as dimensions, shape, strength, and durability. This will inform the design process and the selection of the printing technology and materials.

Digital design: Create a digital design of the structure using computer-aided design (CAD) software. This will allow for precise control of the shape and dimensions of the structure.

Slicing: Use slicing software to divide the digital design into layers that the 3D printer can print. The thickness of each layer will depend on the printer and the desired resolution of the final structure.

Material selection: Select the appropriate concrete mixture for the printer and the structure. This will depend on factors such as strength, viscosity, and setting time.

Printing parameters: Determine the printing parameters, such as the print speed, nozzle diameter, and layer height. These parameters will affect the final properties of the printed structure.

Simulation: Use simulation software to verify the structural integrity of the printed design and ensure that it meets building codes and safety requirements. This may involve finite element analysis or other methods to model the behavior of the structure under various loads and conditions.

Printing: Set up the printer and load the digital design and printing parameters. Begin the printing process, monitoring the progress and making adjustments as necessary.

Post-processing: After the printing is complete, remove any supports or excess material and allow the structure to cure. This may involve post-processing steps such as sanding or surface treatment to improve the final appearance and properties of the structure.

Testing and validation: Test the printed structure to verify that it meets the design requirements and building codes. This may involve mechanical testing, such as compression or tensile strength testing, as well as visual inspection and other quality control measures.

Iteration and improvement: Use the results of the testing and validation process to inform future designs and printing processes, making improvements as necessary to achieve better performance and efficiency.

B. Details about how where assumptions are used

3D concrete printing technology involves the use of specialized hardware and software to create three-dimensional objects made of concrete. Here is an overview of the hardware and software commonly used in 3D concrete printing: Hardware:

3D Printer: A large-scale 3D printer is the primary hardware used in 3D concrete printing. It consists of a robotic arm or gantry system that moves along an x, y, and z-axis, depositing layers of concrete to form the desired shape.

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Concrete Mixer: A concrete mixer is used to mix the concrete that is used in the printing process. The mixer can be either a batch mixer or a continuous mixer, depending on the printer's design.

Concrete Pump: A concrete pump is used to transport the mixed concrete from the mixer to the printing nozzle.

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Printing Nozzle: The printing nozzle is where the concrete is extruded from the printer onto the printing surface. The nozzle's design can vary depending on the printer, but it is usually a large diameter tube or a series of smaller nozzles.

E.

Printing Bed: The printing bed is the surface on which the concrete is deposited. It is usually a flat surface that can move along the x and y-axes to accommodate the printer's movements.

Software:

CAD Software: Computer-Aided Design (CAD) software is used to create 3D models of the object to be printed. The software can also be used to modify and optimize the model for printing.

Slicing Software: Slicing software is used to convert the 3D model into a series of layers that the printer can understand. The software also generates the printer's toolpath, which tells the printer where to deposit the concrete.

Printer Control Software: Printer control software is used to control the printer's movements and the flow of concrete through the printing nozzle. It is responsible for coordinating the movement of the printing bed, the mixer, the pump, and the nozzle.

Material Management Software: Material management software is used to manage the materials used in the printing process, such as the concrete mix, the reinforcement fibers, and the additives. It tracks the amount of material used and can adjust the printer's settings accordingly.

Overall, the hardware and software used in 3D concrete printing must work together seamlessly to create high-quality, complex structures with precision and accuracy.

IV. Evaluation

A. Experiment

There have been numerous experiments done in 3D concrete printing over the past few years, with researchers and engineers exploring different printing techniques, materials, and applications. Here are a few examples of experiments done in 3D concrete printing:

Design Optimization: Researchers have used 3D concrete printing to optimize the design of concrete structures. By printing complex shapes and intricate geometries, researchers can test the strength and durability of different designs to find the most efficient and effective structures.

Disaster Relief Housing: 3D concrete printing has been used to create low-cost, quick-to-build housing for disaster relief efforts. Researchers have printed entire houses using a 3D printer, which can be assembled on-site in a matter of hours.

Sustainable Construction: Researchers have experimented with using sustainable materials in 3D concrete printing, such as recycled concrete and natural fibers. These materials can reduce the environmental impact of construction and make the final product more sustainable.

Structural Repairs: 3D concrete printing has been used to repair and reinforce existing concrete structures. By printing concrete directly onto damaged areas, researchers can create a strong and durable repair without the need for extensive demolition and reconstruction.

Art and Sculpture: 3D concrete printing has also been used as a tool for artists and designers, allowing them to create intricate and unique sculptures and architectural elements that would be impossible to make using traditional construction methods.

These are just a few examples of the many experiments being done in 3D concrete printing. As the technology continues to evolve, we can expect to see more innovative applications and groundbreaking research in the field.

B. Result

The results of experiments in 3D concrete printing have been promising, with researchers and engineers achieving significant advancements in the field. Here are a few examples of the results of experiments in 3D concrete printing:

Increased Design Freedom: 3D concrete printing has allowed designers and architects to create complex shapes and geometries that were previously impossible using traditional construction methods. This has led to the development of innovative and efficient building designs.

Faster Construction: 3D concrete printing can significantly reduce construction time, particularly for complex structures. By automating the construction process, 3D printing can reduce the need for labor and speed up the construction process.

Reduced Waste: 3D concrete printing can reduce waste by optimizing the amount of material used and eliminating the need for excess construction materials. This can significantly reduce the environmental impact of construction.

Improved Structural Performance: By printing concrete in layers, researchers have been able to create structures with improved strength and durability. This can lead to longer-lasting and more resilient buildings.

Customization: 3D concrete printing allows for customization on a level that was previously impossible with traditional construction methods. This can lead to buildings and structures that are better suited to the specific needs of the end user.

These are just a few examples of the positive results of experiments in 3D concrete printing. As the technology continues to develop, we can expect to see even more significant advancements in the field.

V. Applications

A.

MATERIALS FOR IN SITU CONSTRUCTION ON MARS : Abstract: A significant step in space exploration during the 21st century will be human settlement on Mars. Instead of transporting all the construction materials from Earth to the red planet with incredibly high cost, using Martian soil to construct a site on Mars is a superior choice. Knowing that Mars has long been considered a “sulfur-rich planet”, a new construction material composed of simulated Martian soil and molten sulfur is developed. In addition to the raw material availability for producing sulfur concrete and a strength reaching similar or higher levels of conventional cementitious concrete, fast curing, low temperature sustainability, acid and salt environment resistance, 100of the developed Martian Concrete. In this study, different percentages of sulfur are investigated to obtain the optimal mixing proportions. Three point bending, unconfined compression and splitting tests were conducted to determine strength development, strength variability, and failure mechanisms. The test results show that the strength of Martian Concrete doubles that of sulfur concrete utilizing regular sand. It is also shown that the particle size distribution plays an important role in the mixture’s final strength. Furthermore, since Martian soil is metal rich, sulfates and, potentially, polysulfates are also formed during high temperature mixing, which might contribute to the high strength. The optimal mix developed as Martian Concrete has an unconfined compressive strength of above 50 MPa. The formulated Martian Concrete is simulated by the Lattice Discrete Particle Model (LDPM), which exhibits excellent ability in modeling the material response under various loading conditions.

B.

1.INTRODUCTION: Sulfur has been used as a molten bonding agent for quite a long time in human history. The use of sulfur was mentioned in the literature of ancient India, Greece, China and Egypt [7]. For example, sulfur was one of the raw materials to manufacture gunpowder by ancient Chinese [29]; sulfur was also used to anchor metal in stone during the 17th century [6]. Starting in the 1920s, sulfur concrete has been reported to be utilized as a construction material [24]. Various researchers and engineers studied and succeeded in obtaining high-strength and acid-resistant sulfur concretes [1–3]. In the late 1960s, Dale and Ludwig pointed out the significance of well-graded aggregate in obtaining optimum strength [4,5]. When elemental sulfur and aggregate are hot-mixed, cast, and cooled to prepare sulfur concrete products, the sulfur binder, on cooling from the liquid state, first crystallizes as monoclinic sulfur (Sb) at 238 ”F (114 ”C). On further cooling to below 204 ”F (96 ”C), Sb starts to transform to orthorhombic sulfur (Sa), which is the stable form of sulfur at ambient room temperatures [8]. This transformation is rapid, generally occurring in less than 24 h and resulting in a solid construction material. However, since Sa is much denser than Sb, high stress and cavities can be induced by sulfur shrinkage. Hence, durability of unmodified sulfur concrete is a problem when exposed to humid environment or after immersion in water. In the 1970s, researchers developed techniques to modify the sulfur by reacting it with olefinic hydrocarbon polymers [9,16], dicyclopentadiene (DCPD) [10,12,11,15,17], or other additives and stabilizers [13,14,18] to improve durability of the product. Since then, commercial production and installation of corrosionresistant sulfur concrete has been increasing, either precast or installed directly in industrial plants where portland cement concrete materials fail from acid and salt corrosion

C.

For earth applications, well developed sulfur concrete features (1) improved mechanical performance: high compressive flexural strength, high durability, acid salt water resistant, excellent surface finish and pigmentation, superior freeze/thaw performance; (2) cost benefits: faster setting-solid within hours instead of weeks, increased tolerance to aggregate choice; and (3) environmentally friendly profile: reduced CO2 footprint, no water requirements, easily obtainable sulfur as a byproduct of gasoline production, recyclability via re-casting, compatibility with ecosystem, e.g. for marine applications. Current precast sulfur concrete products include, but are not limited to, flagstones, umbrella stands, counterweights for high voltage lines, and drainage channels [38]. For example, in January 2009, around 80 m sewage pipeline in the United Arab Emirates (UAE) was removed and replaced by sulfur concrete. In the same time period, a total of 215 fish reef blocks made of sulfur concrete (2.2 tons/block) were stacked at a depth of 15 m, 6 km off the coast of UAE [35]. With regular concrete fish reefs, the growth of algae and shells takes time because concrete is alkaline. However, since sulfur concrete is practically neutral in alkalinity, algae and shell growth was observed soon after installation.

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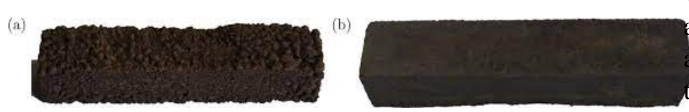


While sulfur concrete found its way into practice as an infrastructure material, it is also a superior choice for space construction considering the very low water availability on the nearby planets and satellites [23]. After mankind stepped on the lunar surface in 1969, space agencies have been planning to go back and build a research center on the moon. Since local material is preferred to reduce expenses, starting in the early 1990s, NASA and collaborative researchers studied and developed lunar concrete using molten sulfur. Around the year 1993, Omar [20] made lunar concrete by mixing lunar soil simulant with different sulfur ratio ranging from 25to reach a compressive strength of 34 MPa. Later he added 2steel fibers to the mixes and increased the optimum strength to 43 MPa. However, lunar concrete has serious sublimation issues because of the near-vacuum environment on the moon.

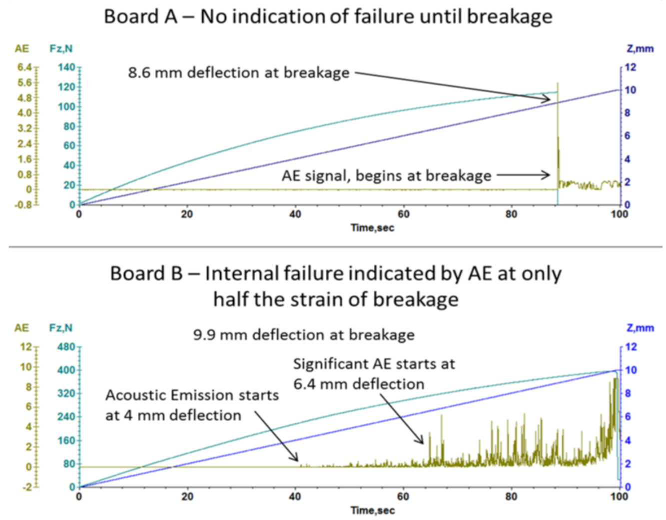
E.

Major chemical composition	JSC Mars-1A[1]	P-MRS[2]	S-MRS[3]	MRS07/52[4]
	Wt %	Wt %	Wt %	Wt %
Silicon dioxide (SiO_2)	34.5–44	43.6	30.6	34.6
Aluminum oxide (Al_2O_3)	18.5–23.5	11.9	9.2	14.1
Titanium dioxide (TiO_2)	3–4	0.36	0.05	0.1
Ferric oxide (Fe_2O_3)	9–12	19.6	14.9	20.6
Iron oxide (FeO)	2.5–3.5	–	–	–
Magnesium oxide (MgO)	2.5–3.5	4.52	10.3	3.4
Calcium oxide (CaO)	5–6	4.74	17.8	6.1
Sodium oxide (Na_2O)	2–2.5	0.32	1.09	2.5
Potassium oxide (K_2O)	0.5–0.6	1.04	0.13	0.2
Manganese oxide (MnO)	0.2–0.3	0.16	0.3	–
Diphosphorus pentoxide (P_2O_5)	0.7–0.9	0.55	0.05	–
Sulfur trioxide (SO_3)	–	0.2	9.1	5.1
LOI	–	11.8	5.4	–

2. Experimental study of Martian Concrete: Sulfur concrete products are manufactured by hot-mixing sulfur and aggregate. The sulfur binder first crystalizes as monoclinic sulfur (Sb), and then the mixture cools down while sulfur transforms to the stable orthorhombic polymorph (Sa), achieving a reliable construction material. While sulfur is commercially available, Martian soil simulant JSC Mars-1A [32] was obtained in replacement of Martian soil to develop a feasible Martian Concrete. Table 1 lists the major element composition of the simulant. As seen, the Martian soil simulant, resembling the actual Martian soil [22], is rich with metal element oxides, especially aluminium oxide and ferric oxide. In this study, various percentages of sulfur are mixed with JSC Mars-1A in a heated mixer at above 120 ”C. Temperature measurements are performed during mixing to ensure sulfur melting. Then the mixture is transferred to 25.4 25.4 127 mm (1 1 5 in) aluminum formwork when it reached flowable state or best mixing conditions. Afterwards the material was let to cool down at room temperature, about 20 ”C. Martian soil simulant Mars-1A of maximum 5 mm aggregate size was first used for casting, however the specimens showed many voids and uneven surfaces due to the large aggregate, see Fig. 2a. Sulfur cannot be ensured to fill the large number of big voids or to surround and bind all large aggregates, especially on the specimen surface. Afterwards, only Mars-1A of maximum 1 mm aggregate size was utilized to achieve Martian Concrete (MC) with flat and smooth surfaces, see Fig. 2b. Mechanical tests were conducted after 24 h, and these included unconfined compression, notched and unnotched three-point-bending (TPB), and splitting (Brazilian) tests. Beams of dimensions 25.4 25.4 127 mm (1 1 5 in) are used for TPB tests, which are then cut to 25.4 mm (1 in) cubes for compression and splitting tests.

F.

Three-point-bending fracture test: To complete the mechanical characterization of MC, its fracturing behavior is studied in this section and the next. Beam specimens with nominal dimensions 25.4 25.4 127 mm (1 1 5 in) were cast to perform three-point-bending (TPB) tests. The beam specimens featured a half-depth notch at midspan cut with a diamond coated band-saw machine. Testing notched samples is customary in fracture mechanics to control the fracture onset and to capture post-peak behavior. Dimension and weight measurements were recorded on specifically optimized TPB protocols. Centerline on top of specimen, and support lines at the bottom were premarked then aligned within the servo–hydraulic load frame, which had a capacity of 22.2 kN (5 kip). The adopted TPB test setup is shown in Fig. 9a. The nominal span (distance between bottom supports) was 101.6 mm (4 in). An extensometer sensor was glued to the bottom of the specimens with the notch in between its two feet. After applying a pre-load of up to 5expected peak, the specimens were loaded in crack mouth opening displacement (CMOD) control with a loading rate of 0.0001 mm/s, which was increased in the post-peak section to limit the total testing time while ensuring a fully recorded softening behavior. Typical crack propagation and fracture surface after failure are presented in Fig. 9b and c. The crack starts at the notch tip and develops upward along the ligament. Notched (50sulfur ratio in the range of 40, where P is load, and L; b, and h are span, width, and depth of the specimen respectively; the nominal strain is calculated as ! ¼ CMOD=h. The optimal percentage of sulfur is found to be 50nominal flexural strength of approximately 1.65 MPa, and it agrees with the optimal percentage determined from unconfined compression tests. The highest nominal flexural strength obtained is 2.3 MPa reached by one of the two recast 50shown in Fig. 10a. It must be observed that the nominal flexural strength and flexural nominal stress–strain curves are not material properties, due to the presence of the notch, and they are calculated here only for comparison purposes. The typical material property that can be calculated from TPB test is the fracture energy, defined as the energy per unit area needed to create a unit stress-free fracture area. By adopting the work-of-fracture method [21] the fracture energy is computed by dividing the area under the load vs. stroke curve by the ligament area. The highest average total fracture energy is as well reached by the recast Martian Concrete with 50, as shown in Fig. 10b. When mixed with lower or higher sulfur ratio than 50lower fracture energies. Same as for compressive strength, recast and applying pressure can improve the flexural strength thanks to more compact sulfur bonds.



1) :

G.

Summary and conclusions: In conclusion, the developed sulfur based Martian Concrete is feasible for construction on Mars for its easy handling, fast curing, high strength, recyclability, and adaptability in dry and cold environments. Sulfur is abundant on Martian surface and Martian regolith simulant is found to have well graded particle size distribution to ensure high strength mix. Both the atmospheric pressure and temperature range on Mars are adequate for hosting sulfur concrete structures.

H. *Future Scope or Substitution*

1) : The future scope of 3D concrete printing is vast, and the technology is expected to revolutionize the construction industry in the coming years. Here are a few potential areas where 3D concrete printing could have a significant impact:

Affordable Housing: 3D concrete printing has the potential to create affordable housing at scale, particularly in developing countries. By automating the construction process, 3D printing can significantly reduce labor costs, material waste, and construction time, making housing more affordable for people in need.

Large-Scale Infrastructure: 3D concrete printing can be used to create large-scale infrastructure, such as bridges, tunnels, and retaining walls. These structures can be designed and printed in sections, significantly reducing construction time and cost.

Disaster Relief: 3D concrete printing can be used to create quick-to-build shelters and temporary housing for people affected by natural disasters. By printing structures on-site, relief agencies can provide shelter quickly and efficiently.

Sustainable Construction: 3D concrete printing can help to reduce the environmental impact of construction by using sustainable materials, optimizing material usage, and reducing waste. This can help to reduce the carbon footprint of the construction industry.

Customized Construction: 3D concrete printing allows for customization on a level that was previously impossible with traditional construction methods. This can lead to buildings and structures that are better suited to the specific needs of the end user.

Overall, the future scope of 3D concrete printing is vast, with numerous potential applications in the construction industry. As the technology continues to develop, we can expect to see more innovative and efficient construction methods emerge, making construction faster, more affordable, and more sustainable.

VI. Conclusions

A.

In conclusion, 3D concrete printing is a rapidly advancing technology that has the potential to revolutionize the construction industry. By automating the construction process, reducing waste, and allowing for customization, 3D printing can significantly improve the efficiency and sustainability of construction projects. Numerous experiments have been conducted in 3D concrete printing, exploring different printing techniques, materials, and applications. The results of these experiments have been promising, with researchers achieving significant advancements in the field, such as increased design freedom, faster construction, improved structural performance, and reduced waste. The future scope of 3D concrete printing is vast, with numerous potential applications in the construction industry, such as affordable housing, large-scale infrastructure, disaster relief, sustainable construction, and customized construction. As the technology continues to develop, we can expect to see even more significant advancements and innovations in the field, paving the way for a more efficient, sustainable, and affordable construction industry. In making of the Martian concrete , there are some of following requirements which are given below :

B.

The best mix for producing Martian Concrete (MC) is 50and 501 mm. The developed MC can reach compressive strength higher than 50 MPa.

C.

The optimum particle size distribution (PSD) of Martian regolith simulant is found to play a role in achieving high strength MC compared to sulfur concrete with regular sand.

D.

The rich metal elements in Martian soil simulant are found to be reactive with sulfur during hot mixing, possibly forming sulfates and polysulfates, which further increases the MC strength. Simultaneously, the particle size distribution of aggregate is shifted to lower ends, resulting in less voids and higher performance of the final mix.

E.

With the advantage of recyclability, recast of MC can further increase the material's overall performance

Acknowledgment

Acknowledgments for 3D concrete printing typically recognize the contributions of individuals, institutions, and organizations that have supported and contributed to research and experimentation in the field. I would like to acknowledge the following individuals and organizations:

Researchers and engineers who have conducted experiments and made significant contributions to the development of 3D concrete printing technology.

Institutions and organizations, such as universities and research labs, that have provided resources and funding for research in the field.

Industry partners and stakeholders who have supported the development and commercialization of 3D concrete printing technology.

Standards organizations and regulatory bodies that have worked to ensure the safety and reliability of 3D concrete printing technology.

Overall, the contributions of these individuals and organizations have been essential in advancing 3D concrete printing technology and making it a viable solution for the construction industry.

F.

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