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The construction industry is in an exploration stage to integrate automation and robotics in construction for efficient structures using advanced materials. A limited level of autonomy is being used for manufacture of components in precast plants, but onsite and real-time fabrication of large scale components has not yet been realized. This implementation of automation can significantly reduce cost, improve worker safety, and enhance construction practices. The lower bound on the qualitative aspect of automation is to construct structures that are emulative to conventional construction. The use of ultra-high performance concrete has shown superior material and mechanical properties which can be utilized in additive construction owing to its extrudability and workability. This report synthesizes the current practice related to materials and automated systems suitable for additive construction along with metric evaluation for both materials and automated systems. In addition, this report presents a detailed framework and performance metrics for a new placement method for UHPC using a 3D printing system. The printing system consists of heating plates mounted on a raptor drive which can place continuous additive layers using optimum heat curing. The novel curing methodology using in this study for accelerated extruding can facilitate construction and reduce open time for the material. An extensive material testing was carried out to optimize the open time without compromising the strength of the material. The synergistic combination of heated curing and extruding formwork has promising potential for bringing a paradigm shift in the construction industry.</td></tr>
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Robotics and Automation in ABC Projects: Exploratory Phase

Final Report

May 2021

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CHAPTER 1: INTRODUCTION

1.1. Project Background and Motivation

The automation and robotics advancement in manufacturing industries are much pioneered if compared to the construction industry as shown in Figure 1 **[1]**. The key reasons for such lag in the construction industry are unsuitability of such approach to the current design and construction techniques, lack of standardization in construction industry, and the limitation in 3d-printing materials which are necessary for additive and automated construction.

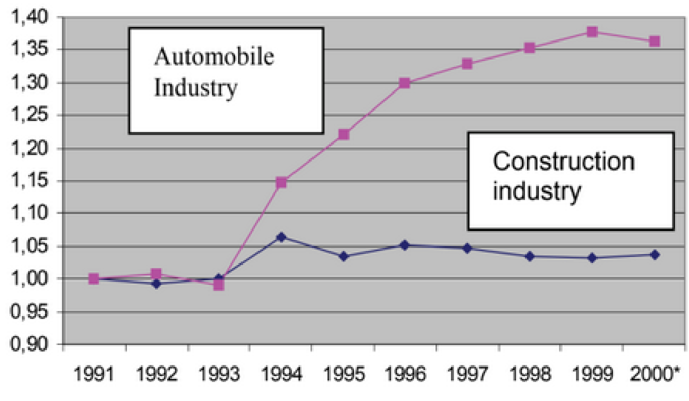

Figure 1 Robotics productivity in automobile and construction industry in EU [1]

Accelerated bridge construction of bridge elements and in-suit connections, and repair of damaged elements are good candidates for automation and robotics application. The use of automation and robotics in ABC projects has numerous advantages including enhanced quality of prefabricated elements, further reduction in construction time and decrease in accident rate at construction sites. It can also lead to the introduction of standardization in the construction industry as researchers and engineers can develop a wide range of structural and bridge elements which can be repeatable, customized and aesthetic and even with complex geometries. Due to the challenges like fatal work injuries and work zone crashes in the construction industry especially in bridge infrastructure sector, the need for automated construction and partial replacement of human activities with robotic activities becomes necessary. According to the U.S. Department of Labor-Bureau of Labor Statistics **[2]**, the number of fatal work injuries exceeded 5,100 for four consecutive years from 2016 to 2019 which represent 35 fatal injuries per million full-time workers. In 2019, there were 5,333 fatal work injuries which represents the largest annual number since 2007. These injuries were categorized as 39.9% due to transportation accidents, 16.6% due to falls, slips, trips, 15.8% due to violence and other injuries caused by persons or animals, 13.8% due to contact with objects and equipment, 12.1% due to exposure to harmful substances, and 1.9% due to fire and explosion. Figure 2 shows a breakdown comparison for the fatal work injuries which happened in 2019.

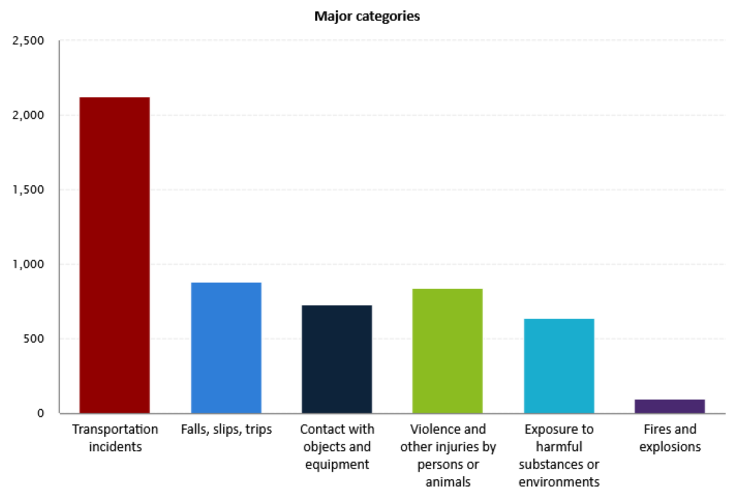

Figure 2 Fatal Work Injuries by Major Event in Year 2019 [2]

The challenge of fatal work injuries is considered unpredictable but the replacement of some of the human activities with robotic activities can help to reduce the number of fatal work injuries significantly. According to the U.S. Department of Transportation-Federal Highway Administration (FHWA), between 2018 and 2019, the fatal crashes in work zone have increased by 11%. There was a total of 842 work zone fatalities which is at the highest level since 2006 **[3]**. The percentage of fatal worker injuries in 2019 also increased 2.5% as if compared to 2018. Figure 3 shows the U.S. national trend in fatal worker injuries at a road construction site from 2011 to 2019 **[4]**.

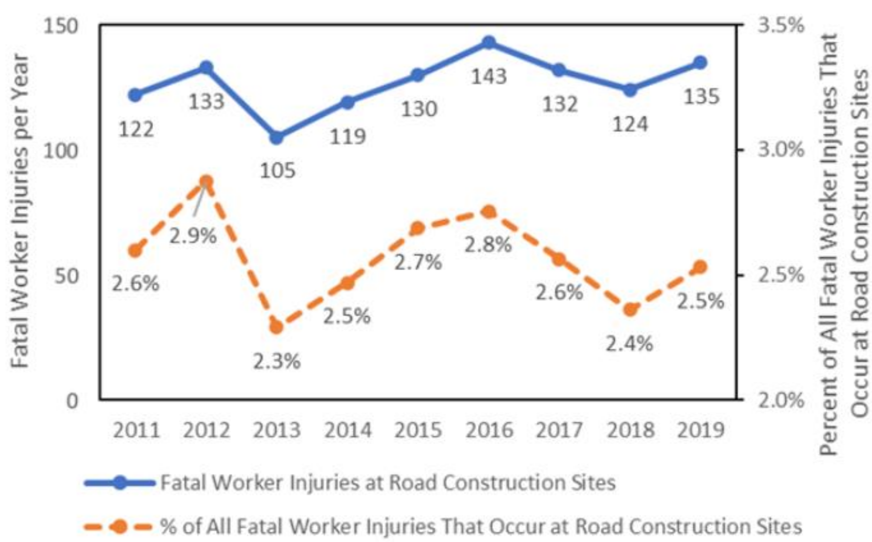

Figure 3 U.S. National trend in fatal worker injuries[4]

The conventional construction methods reached a plateau during the period between 1970 and 2010 after passing innovation and growth stages; however, automated construction is still currently between innovation and growth stages. Figure 4 shows a comparison between conventional and automated construction in stages such as innovation, growth, and maturity **[5]**.

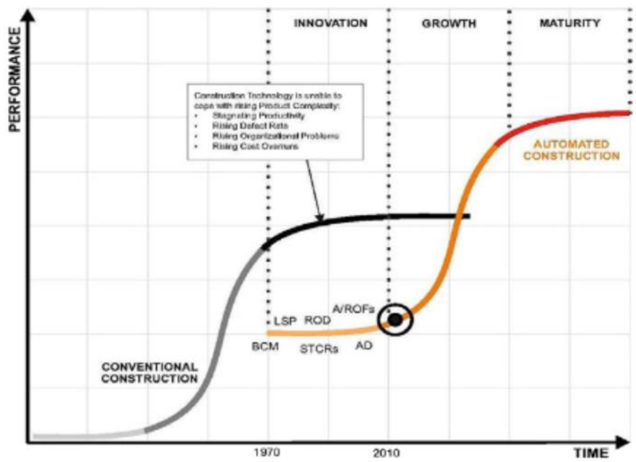

Figure 4 Comparison of innovation, growth and maturity between conventional and automated construction [5]

The use of robotics and automation can impact a project in various ways. It leads the project to accurate estimations and precise scheduling of the project along with quality delivery **[6].** The use of robotics and automation in construction also benefits in saving labor cost, as shown in Figure 5 **[7]**. Furthermore, it can increase project productivity.

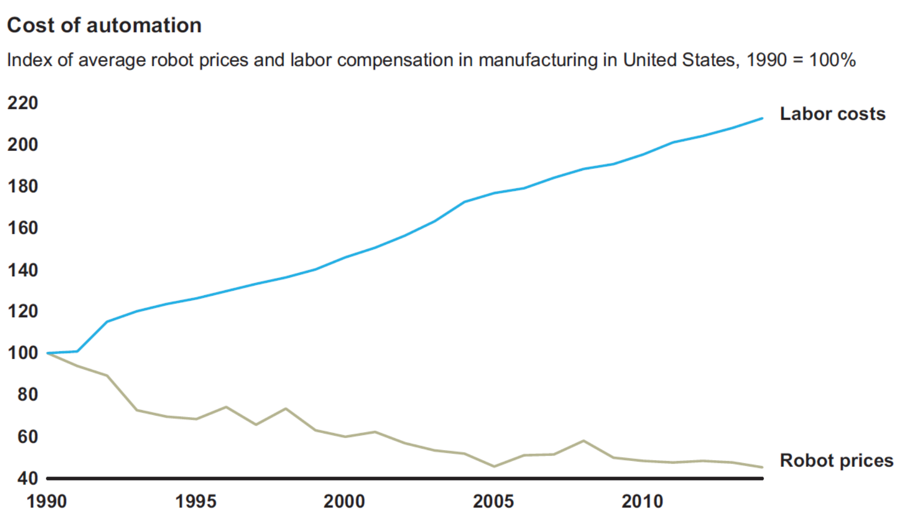

Figure 5 Decrease in automation prices over the years [7]

1.2. Problem Statement

The majority of bridge elements (such as full-depth deck panels, superstructure girders, bent caps, and columns) are prefabricated in a controlled environment. The construction of these substructure components (footing, columns, and bent cap) off-site saved over 80% of in-suit construction time over the conventional cast-in-situ practice by prefabricating the bridge columns and bent caps with only cure time needed for concrete in the footing and grout between the precast columns and bent caps **[8]**. Thousands of ABC projects had been already constructed including different prefabricated elements such as full or partial depth deck panels with closure joints, prefabricated bent caps, prefabricated columns, prefabricated bridge foundation, and prefabricated abutment. Therefore, they are qualified to be constructed through an automated process such as 3D-printing or additive construction using stationary systems or mobile robots. In addition, in-suit construction activities associated with ABC (such as connections between prefabricated elements, repairing damaged elements, and upgrading existing substructure elements) are candidates for automated construction through the use of mobile robots.

The advances in robotics and automation in construction industry is not comparable to the other sectors such as automobile, aircraft, electronics, etc. because the current conventional construction and design approaches are not suitable for automation; a lower ratio of production of final projects as compared to other industries; and limitation in materials that could be employed by automation **[9]**. Since ABC projects utilize prefabricated elements and in-suit connections between prefabricated elements through nozzle injection and employed materials, advances in automation and robotics are suited for ABC. This report suggests feasibility studies for types of robots and systems, suitable for ABC along with identifying the suitable materials, ABC elements and connections which are used in automation processes. Several advantages can be achieved by integrating automation and robotics with ABC techniques including increasing construction quality and reducing accident rate at construction sites **[9]** and steps could be taken for provision of standards for automated construction in the industry. This study is limited to feasibility investigation with proof of concept experimental work.

1.3. Research, Objectives, and Tasks

The primary objectives of this research project are the following:

1. Conduct a comprehensive search to identify the application of robotic in construction worldwide.
2. Identifying the list of robots, materials, ABC elements, and ABC in-suit connections that are suitable to be used in the automation of ABC projects.
3. Develop a roadmap for the application of robotic in ABC.

This project provides a roadmap for the use of robotics and automation in bridge construction especially topics related to ABC. Automation in construction industries is still undergoing innovation and growth, this project targets the gaps in automation and robotics for construction of ABC projects.

These objectives were accomplished through the following research tasks.

- **Task 1 – Worldwide Literature Search**
  Under this task, a comprehensive literature search was conducted to comprehend the application of automation and robotics in construction.

- **Task 2 – Feasibility Study on Application of Automation and Robotics in ABC**
  In this task, a comprehensive feasibility study are carried out to review the current development of automation and robotics techniques feasible for ABC. Different techniques of additive construction (3D-Printing) are identified before the start of this project with different techniques such as blinder Jetting, contour crafting (CC) and stick dispenser **[10]**. Part of the feasibility study includes a review of state-of-the-art findings of using additive

construction in mobile robots **[11]** by using multiple synchronized mobile robots for 3D-printing of large single-piece of concrete structure.

- **Task 3 – Identification of List of Robots Suitable for ABC**
  In this task, a comprehensive review of the current types of robots were conducted. The purpose of this task is to identify more types of robots that are suitable for ABC projects.

- **Task 4 – Identification of List of Materials Suitable for Automated Construction using Robots**
  In this task, a comprehensive review of materials that are currently used in automated construction was conducted. The purpose of this task is to identify more suitable materials for automated construction in ABC projects.

- **Task 5 – Identification of Suitable Prefabricated Elements and Systems Suitable for Application of Robotic in ABC**
  Oftentimes, the use of robotics is viewed as simply replacing human with robots. This is a very simplistic view of automation. Under this task, at least one ABC system will be identified that could be constructed using robotics. For this system, different elements of the automation are identified and a roadmap for conducting the actual construction is developed.

- **Task 6 – Development of Scope of Work for Next Phase of the Study**
  Under this investigation, project findings are used to develop a scope of work for the next phase of the study.

CHAPTER 2. RECENT ADVANCES AND CHALLENGES IN MATERIALS FOR AUTOMATED CONSTRUCTION

2.1. Materials

Additive manufacturing (AM) is the technology of building 3D objects using layer-upon-layer techniques. Many materials can be deposited using additive manufacturing such as tissues, plastics, ceramic, metal, fibers, and concrete. The equivalent name for additive manufacturing in construction industry is "Additive Construction". Concrete is the most utilized material in construction industries with isotropic properties and slumps to allow it to fill prefabricated formwork in order to minimize air voids. By adapting concrete to additive construction, many changes are introduced to concrete such as replacing large aggregates with fine components; anisotropic properties (mechanical properties of each direction differ based on direction of loading) unlink the isotropic nature of cast concrete, as shown in Figure 6 **[12]**. In order to facilitate the use of concrete for additive construction, a low water-to-cement ratio should be used to increase the buildability of the printed layer, however, reducing the water-to-cement ratio decreases the material pumpability and workability. Sika$^{@}$ developed few materials suitable for 3D-printing such as "Sika 3D mortars"," Sika accelerators" for designed setting, and "Sika ViscoCrete$^{@}$" **[13]**. Many researchers have developed mixtures for cementitious materials and tested them to explore their suitability for 3D-printing. Table 1 shows different mix compositions for several 3D-printed cementitious materials.

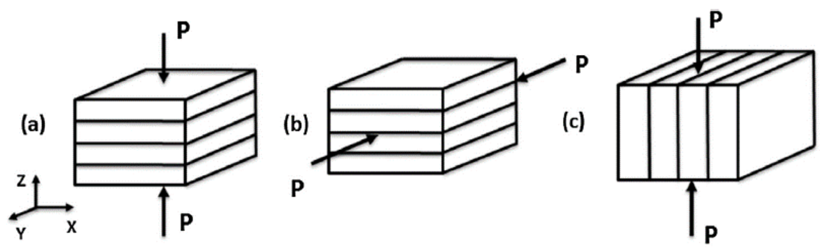

Figure 6 Anisotropic properties of the printed concrete due to additive construction (a) loading perpendicular to the layers, (b) and (c) loading along the layers at each direction [12].

2.2. Evaluation and Testing Criteria of Extruded Materials

In order for cementitious materials to be suitable for additive construction through robotics or 3D-printing systems, the cementitious mixture should meet the rheological criteria described in the following subsections.

2.2.1. Extrudability

Extrudability is generally defined as the ability of the material to be extruded through the printing nozzle and retain the intended shape. Since there is no available standard test for extrudability, researchers developed methods to evaluate it through the success of extruding continuous filaments. Le et al. **[14]** proposed printing of sets of 1-to-5 filaments of 12 inches (300mm) long each using a nozzle of 0.35 inches (9 mm). Ma et al. **[15]** used the same proposed method with different length of filaments of 8 inches (200 mm) and a total of 8 continuous filaments. Figure 7(a) shows an example of a successful extrusion by Ma et al. **[15]**. It should be noticed that the length of filaments and the size of the nozzles vary based on the proposed element, therefore researchers should develop an extrudability method that fits their needs. However, the methods described hereinabove can be utilized as a start point.

2.2.2. Workability

Workability is generally defined as the ability of the mixture to draw a certain level of consistency avoiding being stiff or too loose. Le et al. **[14]** used shear vane test to measure, which was adopted by Austin et al. **[16-18]**, the correlation between the shear strength and workability and it was found that shear strength between 0.073 to 0.087 lbs/in^2 (0.5-0.6 kPa) is sufficient to maintain good workability. Many factors such as the percentage of superplasticizer, retarder dosage, and accelerators dosage affect the mixture workability, for instance, by increasing the percentage of superplasticizer, the workability improved until a limit where the buildability can no longer be maintained. It is the opposite in the case of increasing the dosage of retarder and accelerator. Ma et. al **[15]** used slump tests to quantify the workability of their mixtures as shown in Figure 7(b). Unlike conventional material construction where materials need high slump to fill up a prefabricated wood or steel formwork, the materials in automated construction are usually printed in layers so maintaining the workability within a slump limit should be targeted.

2.2.3. Open Time

Open time is generally defined as the time in minutes in which the mixture can maintain good extrudability without disruptions and loss of workability and buildability (which are described in the next subsection). The open time can be evaluated by performing slump tests over a 15-min period as used in Alhozaimy, 2009 **[19]**. Le et al. **[14]** used the same method vane shear test as mentioned in the previous subsections and concluded that the increase in shear strength from the initial value should not exceed 0.044 lbs/in^2 (0.3 kPa) and the open time was found to be 100 min. in case of the use of 0.5% retarder dosage by weight.

2.2.4. Buildability

Buildability is generally defined as the ability of the printed layer to sustain its shape under the weight of the sequential layers without noticeable layer settlement. Unlike conventional construction material, materials for automated and additive construction are extruded in layers or with a temporary trowel. Le et al. **[14]** quantified the buildability by the number of layers in the filament without noticeable geometrical changes of the initial layers. Ma et al. **[15]** used the same approach to define the buildability of their mixtures. After defining the number of layers sufficient to maintain the buildability, the extruded layers should be left for curing upon the continuation of the process as shown in Figure 7(c).

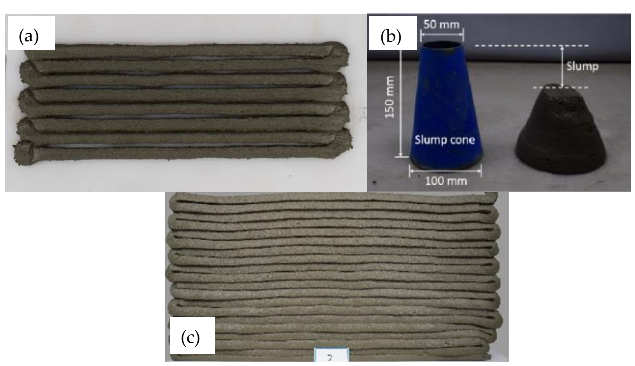

Figure 7 Evaluation Criteria of extruded materials. (a) Extrudability, (b) Workability, (c) Buildability [15]

2.2.5. Mechanical Properties

Mechanical properties in which the 3D-printed material should achieve good compressive strength, tensile strength, bond strength, and modulus of elasticity, among others, compared to materials that are constructed using conventional methods. Each mechanical property should be measured in three directions as shown in Figure 6 due to the anisotropic nature of the extruded layers.

2.3. Cementitious Material Mixtures

Zhang et al. **[20]** designed two materials to facilitate the 3D-printing using team mobile robots by meeting rheological printing requirement yield stresses and velocity. The first mixture was for ordinary concrete as shown in Table 1 using ordinary Portland cement (OPC), ASTM Type 1 cement, Class F Fly Ash, Unidentified Elkem for Silica fume, water, and river sands. However, second mixture represented fiber reinforced concrete developed by Weng et al. **[21]** but modified because of the use of different mixing equipment and hose length of the robot. Each mixture was used to cast half of a 6 feet (length) x 1.5 feet (width) x 0.43 feet (height) curved, truss beam as shown in Figure 8(a). Researchers reported no issues during the printing using a 10-mm print nozzle. The researchers did not report the compressive strength. Both mixtures were 3D-printed successfully, however, more research is needed to examine the mechanical properties of the printed specimens to ensure their use as material for 3D-printed structural elements.

Liu et al. **[22]** developed different mix designs by studying the rheological properties of the mixtures using static yield stress (i.e. the critical stresses for the printed material allowing steady-state flow) and dynamic yield stress (i.e. final stresses applied before complete stoppage of the material). Researchers have tested 22 different mix designs by varying the mix composition (cement sand, fly ash, silica fume, and water) in order to optimize the rheological properties by achieving high cementitious material static yield stress and low dynamic yield stress. The mix composition was based on the volume so certain material was replaced by the other materials to maintain the total volume of the mixture. The researchers concluded that cement, sand, and fly ash did not affect the static and dynamic yield stresses, however, higher water content produces lower static and dynamic yield stresses and higher silica fume produces higher static and dynamic yield stresses as silica fume absorb water. The optimized mix composition by volume was 0.15, 0.22, 0.26, 0.33, 0.04 for cement, sand, fly ash, water, and silica fume respectively. The optimized mix decomposition by weight is listed in Table 1. The optimized mix design was successfully used to 3D-print 25 layers of a spiral structure as shown in Figure 8(b). The mixture was 3D-printed successfully, however, more research is needed to examine the mechanical properties of the printed specimens to ensure its use as material for 3D-printed structural elements.

Tay et al. **[23]** studied the bond strength between the printed cementitious material layers and the influence of the time gap between the printed layers. The mixture design met pumpability requirement and included Ordinary Portland Cement, undensified Elkem based Silica Fume, Class F Fly Ash, river sand, and water. The mixture design composition is listed in Table 1. The researchers concluded that by increasing the time gaps between the printed layers, the bond strength between the layer dropped due to void formation at the top of the first layer which weakens the bond with the sequent layer logarithmically. Researchers only reported the bond strength results with respect to the time gaps between the printed layer without reporting other mechanical properties, therefore more research is needed to examine the mechanical properties of the printed specimens to ensure their use as material for 3D-printed structural elements.

Kazemian et al. **[24]** proposed four different cementitious mixtures as shown in Table 1. The base mixture (Mix 5 in Table 1) contains cement, sand, water, and high-range water reducing (HRWR) admixture. The second mixture (Mix 6 in Table 1) differs from the base mixture by replacing a portion of cement with Silica Fume and increasing the percentage of (HRWR). The third mixture (Mix 7 in Table 1) differs from the base mixture by adding 1.2 kg/m^3 of polypropylene fiber of 6 mm length and 60 ksi tensile strength. The last Mixture (Mix 8 in Table 1) differs from the base mixture by adding nano-clay by 0.3% of the mass and increasing the percentage of (HRWR). The researchers quantified unit weight, flow, and compressive strength at 28-day age for each mixture and compressive strength ranges from 6.4 ksi to 7.25 ksi as shown in Table 1. The researchers performed multiple trials to print the base mixture with no gap time (time between printing two layers) due to discontinuity and tearing of the printed layers due to high mixture stiffness and uniform width of the printed layers. The time gap was increased to 19 min which led to a successful print with 0.06 inches (1.5 mm) layer settlement. Three other mixture (Mix 6 to Mix 8) were printed successfully with no time gap but with more than 0.063 inches (1.6 mm) layer settlement, however, layer settlement was eliminated when increasing the time gap to 19 min. for those mixtures.

Le et al. **[14]** designed five mixtures with different sand/dry mixture proportions (dry mixture includes, sand, cement, silica fume, and fly ash). The sand-to-dry mixture ranges from 75% to 55% with 5% increment whereas binder-to-dry mixture ranges from 25% to 45% with 5% increment. Binder content contains (70% cement, 20% fly ash, 10% silica fume), in addition, water-to-binder ratio was 0.28 to achieve 14.5 ksi and over. Table 1 shows the mix composition by weight for all mixtures (Mix 9 to Mix 13). It was concluded that the best mixture has 60% sand to 40% binder ratio, 0.075 lbs/ft^3 polypropylene fibers, 1% superplasticizer, and 0.5% retarder to maintain workability, open time of 100 minutes, and buildability. Cubes of 4 inches (100 mm) were tested to obtain compressive strength of the optimum mixture (Mix 12), the results showed that the optimum mixture achieved 15.95 ksi and 18.13 ksi at 28-day and 56-day, respectively. Figure 8(c) shows the ability of the optimum mixture to be printed in five filaments with 25 layers prior to collapse.

Paul et al. **[12]** proposed two cementitious mixtures after testing different mix proportional and chose two optimum mixtures as listed in Table 1. The optimum mixtures were chosen based on slump value, pumpability, and constructability. The first mixture contains cement, fly ash, sand, and water with 0.44 lbs/ft^3, however, the second mixtures includes 0.84 lbs/ft^3 of glass fiber. The average compressive strength of the mixtures was determined to be 7.25 ksi. Figure 8(d) shows the deposition of the mixtures using an autonomous robot. It can be noticed that even with the successful 3D-printing of the mixture, the mixtures were a mortar based material and may not be the best choice for bridge elements.

Weng et al. **[21]** designed a cementitious material that contains ordinary Portland cement, natural river sand, fly ash, silica fume, water, and superplasticizer as shown in Table 1. The rheological performance of different samples of the same mixture was evaluated by measuring static torque, flow resistance, torque viscosity, static yield stress, dynamic yield stress, and plastic viscosity. The 3D-printed cylinder specimen was printed in 42 layers prior to collapse while printing the 43rd layer as shown in Figure 8(e). The compressive and flexural strengths were determined as 7.21 ksi and 0.54 ksi respectively at age of 28-days.

Ma et al. **[15]** proposed six mixtures as listed in Table 1. All mixture includes the same ratio by weight for the binder (cement, fly ash, and silica fume), water, HWRW and polypropylene fibers. The difference in the mixtures is due to replacing a portion of sand by tailings. The base mixture (Mix. 17) include zero tailings. The percentage of sand replacement increased from 10% (for Mix 18) to 50% (for Mix 22) with 10% increments for Mix 19 to Mix 21). The different mixtures were evaluated by extrudability, buildability, open time, flowability, and structural build-up behavior. For extrudability, all mixtures were extruded without tearing or disruption. The mixtures up to 30% sand replacement (Mix 17 to Mix 20) performed well under buildability criterion of 3D-printing 20 layers, however, mixtures with high percentage of sand replacement suffered with high layer settlement, for example, the height of final print of 20 layers of Mix 22 (50% of sand replacement) was half the height of Mix 18 (10% sand replacement) of the same number of layers, therefore both Mix 21 and Mix 22 were not suitable for 3D-printing. For mixture open time, it was concluded that 70 minutes is the effective time for 3D-printing. Compressive strengths were determined by testing cubes of each mixture and range from 6.38 ksi to 7.69 ksi as shown in Table 1. It was concluded that a mixture with 30% sand replacement (Mix. 20) performed the best among all other mixtures.

Arunothayan et al. **[25]** developed a 3D-printable ultra-high performance fiber-reinforced concrete mix using viscosity modifying agent (VMA) along with high-range water reducing (HRWR) admixture. They performed several trials with different proportions of HRWR and VMA to fulfill workability, extrudability and buildability properties of the material for 3D-printable material though which they printed a curvilinear bench. The compressive strength, modulus of rupture (MOR) and flexural toughness of the developed material was evaluated and it was concluded that with the presence of steel fibers, the workability of the mix reduces, the porosity in the specimen increases but it helps gaining a better shape retention. Binrong Zhu et al. **[26]** developed cementitious composites with ultra-high tensile ductility for digital printing using hydroxypropyl methylcellulose (HPMC) and different proportions of polyethylene fibers. The fresh and hardened properties of the material along-with its microstructure was evaluated and it was concluded that the prepared mix exhibit strong strain-hardening, tensile strength and tensile strain capacity. Table 1 shows different mix compositions for several 3D-printed cementitious materials proposed by the above-mentioned researchers.

2.4. Challenges

Many challenges should be addressed to encourage bridge owners and contractors to start the implementation of automated construction. The challenges in materials are as follow:

- The lack of standard tests to quantify the rheological properties of the extruded layers including extrudability, workability, open time, and buildability. Even that many researchers have investigated methods of quantification for successful 3D-printing of materials, the construction community would demand standard specifications to gain confidence in the proposed results.
- The interrelation between the rheological properties of the mixtures could lead to the failure of meeting all rheological requirements. For examples, increasing the percentage of superplasticizer to enhance extrudability and workability is beneficial however it may adversely affect the buildability of the 3D-printed elements.
- The unavailability of commercial, proprietary, and premix for the most common materials applicable for automated construction such as normal concrete (NC), polymer concrete (PC), high-performance concrete (HPC), ultra-high performance concrete (UHPC), and

grout. Once commercial and premix materials are available, a huge step toward the implementation of automated construction will take place elsewhere.

Table 1 Different mix composition by unit weight for 3D-printed cementitious materials

Mix No.	Reference	Cement	Fly ash	Silica Fume	Sand	Water	HRWR (SP)	Fiber (lb/yd^3)	HPMC	SN RP	f'c (ksi)
1	Zhang et al. [20]	0.288	0.135	0.027	0.360	0.189	0	0	0	0	na
2		0.196	0.196	0.294	0.201	0.113	○	0	0	0	na
3	Liu et al. [22]	0.238	0.234	0.019	0.291	0.218	0	0	0	0	na
4	Tay et al. [23]	0.263	0.075	0.038	0.451	0.173	0	0	0	0	na
5	Kazemian et al. [24]	0.268	0	0	0.616	0.116	0.0005	0	0	0	6.48
6		0.243	0	0.027	0.611	0.117	0.0018	0	0	0	7.24
7		0.268	0	0	0.615	0.116	0.0006	2.02	0	0	6.54
8		0.268	0	0	0.615	0.116	0.0017	0	0	0	6.66
9	Le et al. [14]	0.164	0.047	0.023	0.701	0.065	0	0	0	0	na
10		0.194	0.055	0.028	0.646	0.077	0	0	0	0	na
11		0.223	0.064	0.032	0.592	0.089	0	0	0	0	na
12		0.251	0.072	0.036	0.538	0.094	0.01	2.02	0	0	15.95
13		0.280	0.080	0.040	0.488	0.112	0	0	0	0	na
14	Paul et. al [12]	0.131	0.126	0.066	0.548	0.129	0	0	0	0	7.54
15		0.130	0.125	0.065	0.545	0.128	0	22.75	0	0	6.96
16	Weng et. al [21]	0.345	0.345	0.035	0.172	0.103	◊	0	0	0	7.21
17	Ma et al. [15]	0.283	0.081	0.040	0.485	0.109	0.0012	2.02	0	0	6.38
18		0.283	0.081	0.040	0.437	0.109	0.0012	2.02	0	0.049	6.67
19		0.283	0.081	0.040	0.388	0.109	0.0012	2.02	0	0.097	6.67
20		0.283	0.081	0.040	0.340	0.109	0.0012	2.02	0	0.146	6.96
21		0.283	0.081	0.040	0.291	0.109	0.0012	2.02	0	0.194	7.69
22		0.283	0.081	0.040	0.243	0.109	0.0012	2.02	0	0.243	6.38
23	Arunothayan et al. [25]	0.321	0	0.138	0.459	0.073	*	■	0	0	18.19
24	Binrong Zhu et al. [26]	0.255	0.338	0	0.240	0.166	□	■	0.0006	0	8.09
25		0.255	0.338	0	0.240	0.166	□	♦	0.0006	0	7.66
26		0.255	0.338	0	0.240	0.166	□	●	0.0006	0	7.43

Note: HRWR = high range water reducer; SP = super plasticizer; HPMC = hydroxypropyl methylcellulose; SN RP = sand replacement; VMA = viscosity modifying agent; na = not applicable

* 0.069 HRWR + 0.0014 VMA

○ 2.36lbs/yd^3 ◊ 0.58lbs/yd^3 □ 0.012lbs/yd^3

● 1% added by volume ♦ 1.5% added by volume ■ 2% added by volume

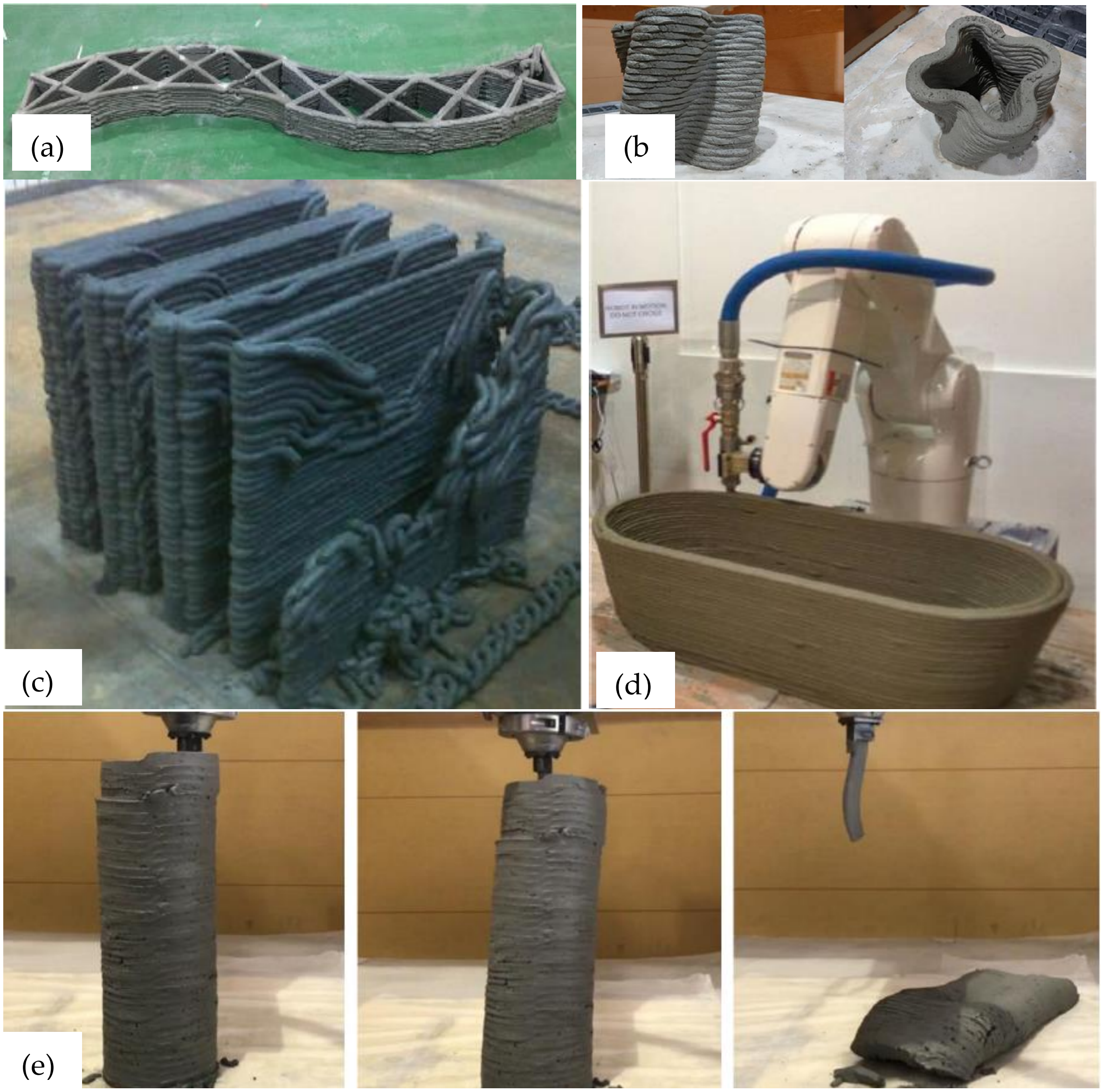

Figure 8 Different 3D-printed elements from different cementitious material mixtures. (a) Truss beam [20], (b) spiral shape elements [22], (c) five filaments element [14], (d) bath-tub shape element [12], (e) cylindrical element [21].

CHAPTER 3. RECENT ADVANCES AND CHALLENGES IN ROBOTICS AND 3D-PRINTING FOR AUTOMATED CONSTRUCTION

Building and Infrastructure construction industry fall behind other industries such as electronics, aerospace, automobile, etc. in implementing robotics within construction activities. Balaguer and Abderrahim **[27]** pointed out some real robot activities in construction such as semi-autonomous paver and compactor **[28]**, automated excavator **[29]**, and 6-degree-of-freedom robot for brick assembly **[30]**. Most of the robotic activities were implemented for roadway and building industries; however, Sutter et al. **[31]** developed a semi-autonomous mobile robot for bridge inspection.

Recently there has been an interest in implementing robotics and automation to construct bridge components. To achieve a robust 3D-printing system, the following criteria should be evaluated:

Mobility: The ability of the 3D-printing system to move freely and easily (being portable) and perform the intended operation properly.

Scalability: The ability of the system to scale up the 3D-printing operation to build large-scale elements.

Flexibility: The ability of the system to 3D-print different shapes of elements.

Synchronization: It is the ability of the system to work simultaneously with another system to 3D-print large specimens to reduce the printing time.

Adaptation of Reinforcement: It is the ability of the 3D-printing system to incorporate fibers and reinforcement in the 3D-printing operation.

3.1. Robots and 3D-Printing Systems

Zhang et al. **[20]** proposed the use of a team of mobile robots to construct a truss beam shown in Figure 9(a). The printed truss beam was 73.2 inches x 5.1inches x 0.02 inches (1860 mm x 0.46 mm x 130 mm) and was 3D-printed using two robots simultaneously. Each robot was erected over a holonomic platform to allow robot mobility. The concrete mixer was connected to a pump that pumps the mixture through a pipe to the print nozzle at the end of the robot, the robot end has 6-axis robotic manipulator as shown in Figure 9(a). Each robot moved to the printing location and stop in the desired coordinate, then the robot arm starts to extend to print the desired shape. Many advantages can be achieved over other systems including flexibility if compared to the gantry-based system, mobility over the stationary printer, scalability over the use of one robot. However, coordination and synchronization between the team of robots on 3D-printing one element could be challenging in addition to the difficulty of utilizing the 3D-printing of reinforced steel concrete elements. Table 2 evaluates the team of mobile robots along with other systems.

Minibuilders **[32]**, A group of researchers at the Institute of Advanced Architecture of Catalonia (Iaac) developed a concept of a community of small robots which are able to build big structures. Foundation robot with side nozzle was able to 3D-Print up to 5.9 inches (150 mm) or hollow-cylindrical structure, then a gripping robot was used to clamp the 3D-printed cylindrical structure to use it as a platform for printing the rest of the structure as shown in Figure 9(b). The proposed system of a small mobile robot works concurrently allows the construction of many complex structures and enhances mobility, flexibility, and scalability. The proposed system has challenges related to 3D-printing of reinforced steel concrete elements. Table 2 evaluates the Minibuilder system along with other systems.

KUKA **[33]** offers many solutions for different industries such as automotive, electronics, energy, healthcare, and metal. The robot products can be stationary or mobile as shown in Figure 9(c), however, an integrated system with a material delivery system should be implemented with the robot to allow the delivery and printability of the mixtures. None of KUKA robots is implemented or used in construction industries but they have a potential for expansion within the industry. Table 2 evaluates the KUKA robots along with other systems.

Apis Cor **[34]** is the first company to develops specialized 3D-Printing equipment in construction which allows the construction of entire buildings on-site. Apis Cor team with SEArch placed in first place for NASA's 3D-Printed Habitat Challenge **[35]**. The challenge purpose to develop large scale systems which can 3D-print large scale structures for the Moon and Mars colonization. The competition was divided into three phases. In the first phase which was completed in 2015, each team was asked to submit the architectural concept and rendering. In the second phase which was completed in 2017, teams focused on material technology to allow the 3D-printing of their structure. In the third phase which was completed in 2019, the on-site competition took place for each team to fabricate sub-scale of their structures in both three actual construction levels and two virtual levels using Building Information Modelling (BIM) software. The team of Apis Cor and SEArch winning project in Phase 3-Level 3 was a 3D-printed water tank structure that was tested for hydrostatic leak testing as shown in Figure 9(d) **[35]**. The same team won the Phase 3-Level 2 for 3D-printing a foundation which was subjected to various type of loading including dropping a shotput on it to simulate a meteor as shown in Figure 9(e) **[35]**. Table 2 evaluates the Apis Cor system along with other systems.

Mudbots **[36]** developed a commercial 3D-Printer as shown in Figure 9(f). The 3D-Printer is stationary and can print elements within the printer frame. There are many models that cover different areas and heights. Most of the printed elements are segmental due to the space limitation unless the printer is repositioned. Walls, signs, fountains, sheds and other non-structural components were 3D-Printed using the Mudbots system. Table 2 evaluates the Mudbots system along with other systems. Mudbots 3D-printers are stationary therefore mobility of the system is not an option.

Table 2 Evaluation of various construction robots and 3D-printing systems

Robotics and 3D-Printing Systems	Mobility	Scalability	Flexibility	Synchronization	Adaptation of Reinforcement
Zhang et al. [20]	✓	✓	✓	=	✕
Minibuilders [32]	✓	✓	✓	=	✕
KUKA [33]	✕	✓	✕	✓	✕
Apis Cor [34]	✕	✓	✕	✓	✕
Mudbots [36]	✕	✕	✕	✓	✕

✔ Possible
= challenging
✖ Not possible

Figure 9 Robotics and 3D-printing system suitable of automated bridge construction. (a) team of mobile robots [20], (b) Minibuilders [32], (c) KUKA construction robot [33], (d) Winner of Phase 3-Level 3 NASA Habitat Challenge, Apis Cor and SEArch [35] (e) Winner of Phase 3-Level 2 NASA Habitat Challenge, Apis Cor and SEArch [35] (f) Mudbots 3D-Printer [36].

3.2. Challenges

Many challenges are associated with the use of robotics and 3D-printing systems in the construction industry such as:

- Each innovative 3D-printing system and robot is capable of constructing a specific task. There is no generic 3D-printing system or robot that capable of constructing various types of structural elements given different geometry and complexity.
- As shown in Table 2, most of the recent innovations in robotics and 3D-printing systems are limited in terms of adaptation of reinforced steel. The use of steel reinforcement such as wires, reinforcing bars, stirrups, ties, spirals, prestressing strands is mandatory in bridge elements. Several attempts to incorporate reinforcement were conducted and summarized in **[37]** such as placement of reinforcement between 3D-printed layers, extruding metal cables concurrently with 3D-printed layers, enveloping concrete around reinforcement, and 3D-printing of structural elements with voids and cavities for later post-tensioning.
- The operation of the 3D-printing system and robots needs skilled labor with good background and knowledge of operation and Building Information Systems (BIM).
- The layer-by-layer mechanism of 3D-printing system and robots creates cold joints which cause the intervention of liquids and salts that causes corrosion for reinforcement and affects the durability of the 3D-printed elements. Minibuilders **[32]** proposed a partial solution for such an issue by the development of vacuum robot which is used to cover the cold joints between the printed layer using foundation and grip robots (described in Section 3.1). The vacuum robot attaches onto the 3D-printed surface using a vacuum generator and a suction cup, the robot steers on two tracks while the vacuum inside the suction cup holds the robot on the surface.

CHAPTER 4. PROPOSED FRAMEWORK AND 3D-PRINTING SYSTEM FOR AUTOMATED CONSTRUCTION

A flowchart is proposed for researchers and the bridge industry to investigate the implementation of robotics and automation in accelerated bridge construction, as shown in Figure 10. Researchers should conduct a detailed feasibility study to decide whether a certain bridge element is suitable for automated construction or not, given the recent advancements in automation and robotic construction. If the selected element is suitable for automated construction, a mix design should be selected from available 3D-printing proven mixtures that can also fulfill testing criteria of automated construction such as extrudability, workability, open time, buildability, and mechanical properties. If the mixture is not suitable, another mixture should be evaluated until a suitable mixture is selected.

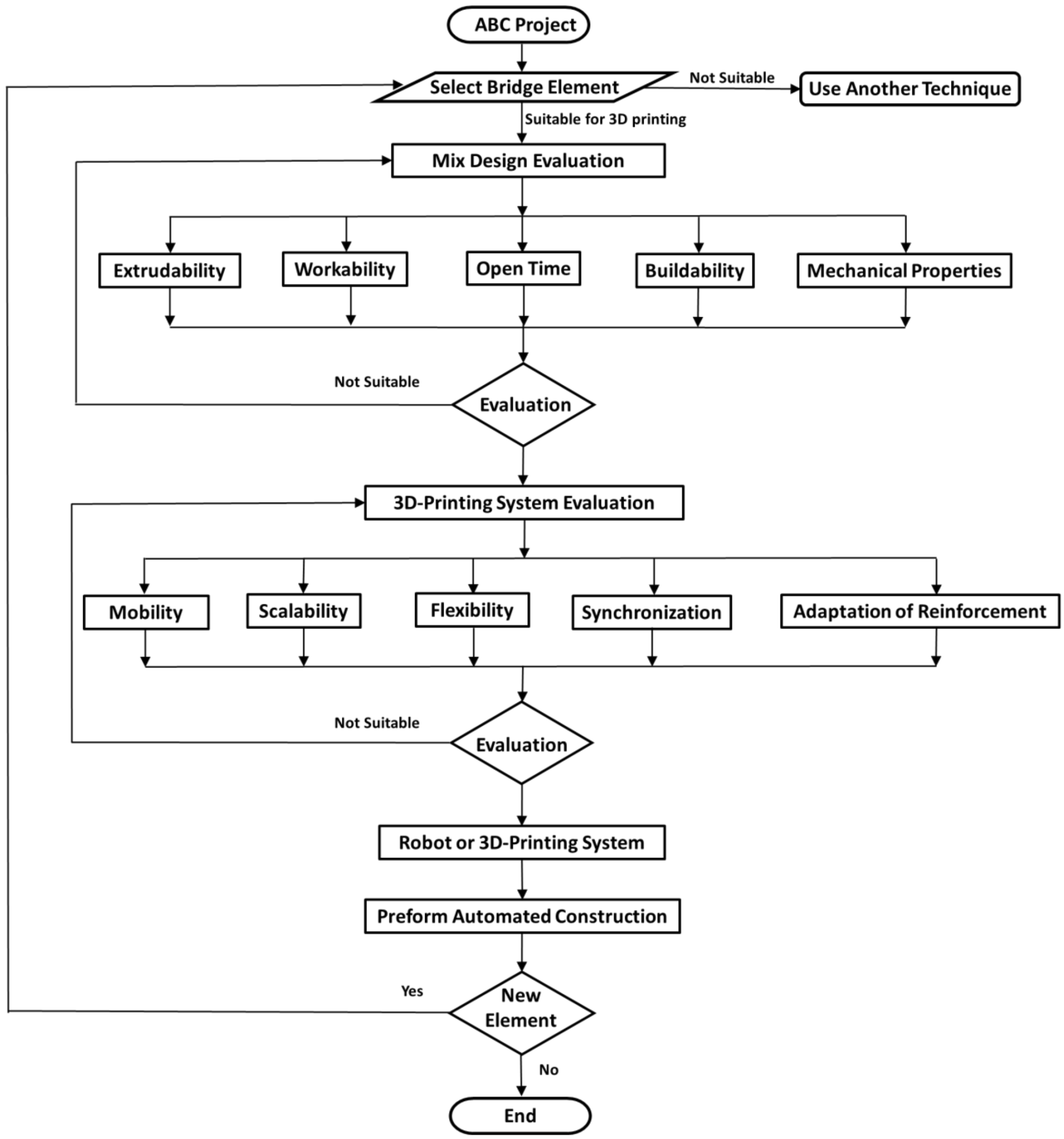

Figure 10 Proposed framework for 3D-printing for robotics bridge construction

After the selection of a suitable mixture, an automated construction system should be selected through the use of robots or 3D-printing systems. Each commercially available robot or 3D-printing system should be evaluated based on the selected element. The evaluation criteria shall include mobility, scalability, flexibility, synchronization if using multiple systems or team of robots concurrently, and adaptation of reinforcement. If the selected robot or 3D-printing is not suitable, another robot or 3D-printing system shall be selected and evaluated until a suitable robot or 3D-printing system is selected. After the selection of bridge element, suitable mixture, and suitable robot or 3D-printing system, automated construction of the selected element should be performed.

An automated concept for 3D-printing is also proposed as part of a research initiative at Accelerated Bridge Construction-University Transportation Center (ABC-UTC) which can be used for 3D-printing and prefabrication of different bridge components using ultra-high-performance concrete (UHPC) especially UHPC shells which act as stay-in-place formwork for bridge columns and beams **[38-39]**. The process to assemble such a 3D-printer is shown in Figure 11. The proposed system for 3D-printing of UHPC utilizes accelerated curing by applying heat curing to the material. The proposed system is also evaluated, hereinafter, based on the framework proposed in Figure 10 for both material testing criteria and 3D-printing system criteria.

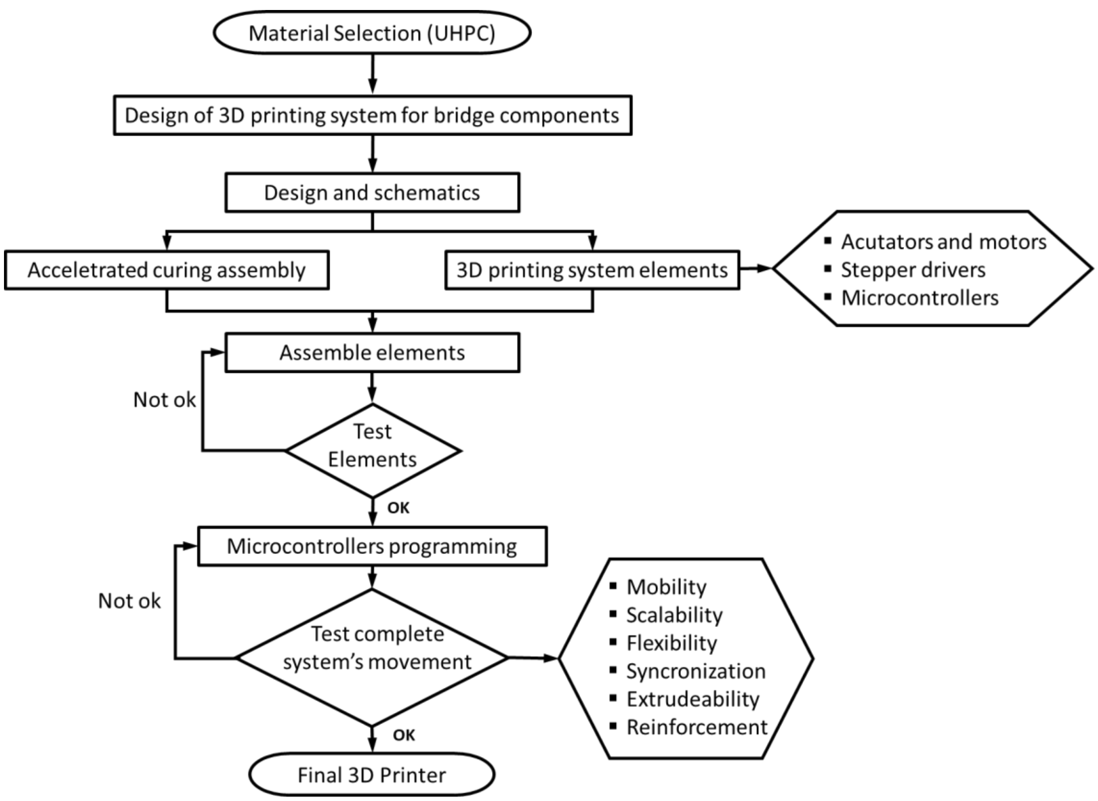

Figure 11 Proposed 3D Printing System for UHPC

4.1. Material for 3D-printing

Several ultra-high-performance concrete (UHPC) mixes were used and tested to obtain proper workability and flowability for 3D-printing including regular and fast setting mixes. Since UHPC is composed of different constituents, the following combination of constituents was used to obtain proper workability and flowability for the material. The proportion of these constituents is shown in Figure 12.

- Ductal® JS1000 premix = 88.0% by weight
- Super plasticizer = 1.0% by weight
- Water = 4.8% by weight
- Steel fiber = 6.2% by weight

The workability of the mixture is measured in terms of flowability according to ASTM C1437 test **[40]**. The selected mix has a flow of 9 inches as shown in Figure 13 (b). A flowability of 7-10 inches showed good properties for workability and material delivery to the printing nozzle in additive construction, as shown in Figure 13 (c).

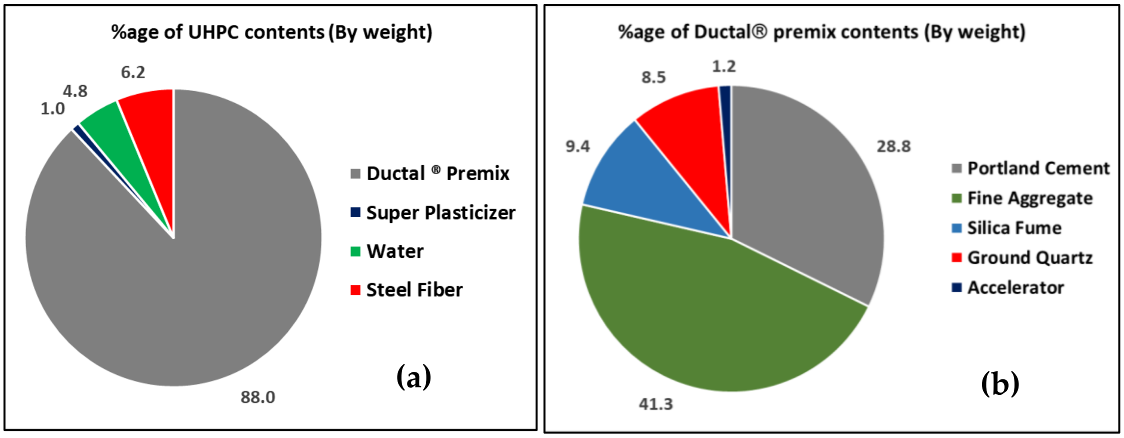

Figure 12(a) UHPC constituents by weight percentage (b) Ductal ® premix constituents by weight percentage Proposed 3D Printing System for UHPC

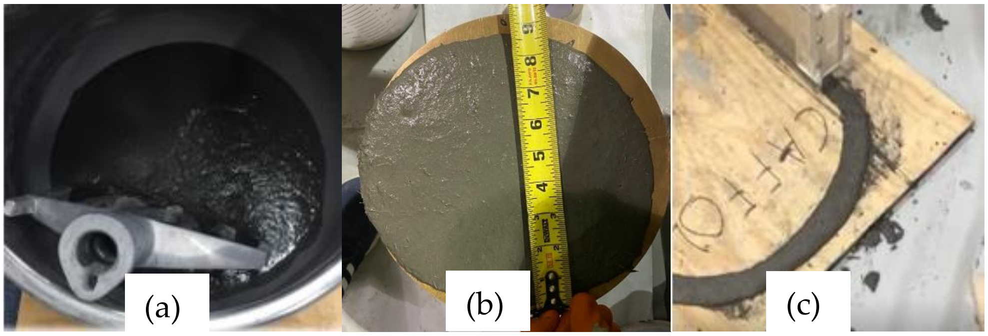

Figure 13 (a) Prepared mix (b) Flowability test (c) Workability of material

4.2. Optimum heating time for accelerated curing

Since UHPC is flowable material with self-consolidation characteristics, to overcome such an issue, 3D printing of UHPC can be conducted by adjusting material rheology to improve layer buildability or by techniques that can make UHPC layer gaining buildability faster. An ideal 3D-printing system should have the ability to print UHPC layer faster to suit the material open time for 3D-printing in layers, therefore, accelerated curing was proposed by heat-curing UHPC using strip heaters, as shown in Figure 14. The resistant thermometer detector (RTD) probe sensor was attached to the heater to sense the temperature which was further controlled using precision programmable temperature controller PID to set the required temperature for the 3D-printer head. The optimum time of heating at different temperatures was obtained by hit and trial method based on shape retention. The final temperature and heating time values for shape retention as given in Table 3 was obtained by removing the nozzle at a particular temperature with several different heating time values and checking the shape of the layer, then one value was selected as optimum value as presented in Table 3.

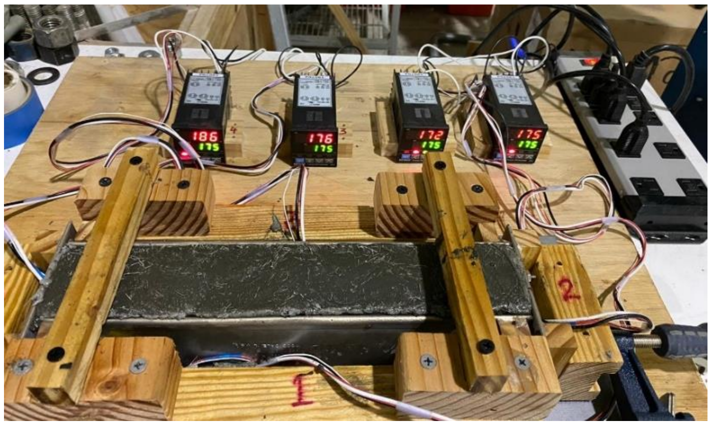

Figure 14 UHPC heating setup using strip heater and PID's

Table 3 Optimum heating time of UHPC for shape retention.

Sr. No.	**Temperature (^{o}F)**	**Heating time (minutes)**
01	100	45
02	125	30
03	150	20
04	175	15
05	200	10
06	225	08
07	250	05

4.3. Optimum heating temperature for accelerated curing

One of the main advantages of heat curing of UHPC is the acceleration of layer printing; however, imposing heat curing could affect mechanical properties which were needed to be studied. The optimum heating temperature was one of the main parameters to obtain proper mechanical properties of the material to fulfill the testing criteria. The optimum heating temperature was decided based on compressive strength of cubical specimens tested at different temperatures for post-printing curing condition in dry (ambient condition) and wet environments. The 2-in cubical specimens were cut as shown in Figure 15(a) from the specimen obtained after cure-heating and then compression tests (ASTM C1856) were conducted to obtain the compressive strength of all samples at different temperatures. Some of the tested samples are shown in Figure 15(b).

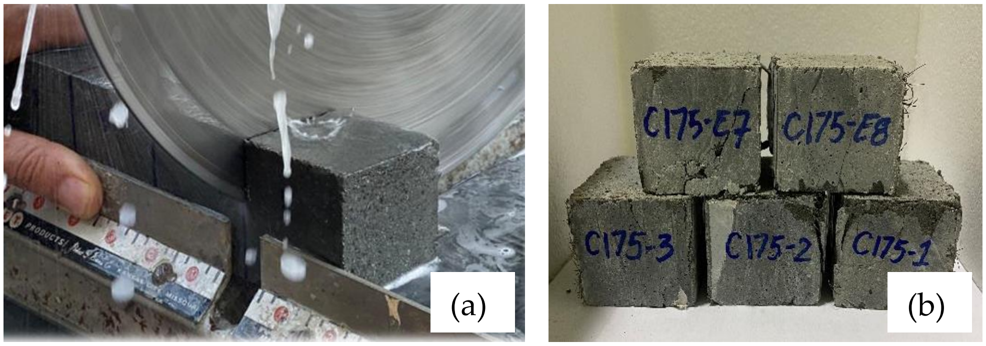

Figure 15 (a) Heated samples preparation (b) Tested sample at 175^{o}F

The average compression strength results of the cubes prepared at different temperatures (for three repetitions per certain temperature) tested after 7 days are shown in Figure 16 and those tested after 14 days are shown in Figure 17. The results indicate that there is a prompt decrease in UHPC strength by heat curing for samples which left in ambient condition (dry condition) after printing but if the cubes are cured in wet conditions after printing, then the UHPC compressive strength is almost the same for temperatures ranging from 125^{o}F to 225^{o}F. Compressive strength of 15 ksi (at 14-days) can be achieved even by heating the material at 225^{o}F which can fulfill strength criteria needed for 3D-printing of bridge components.

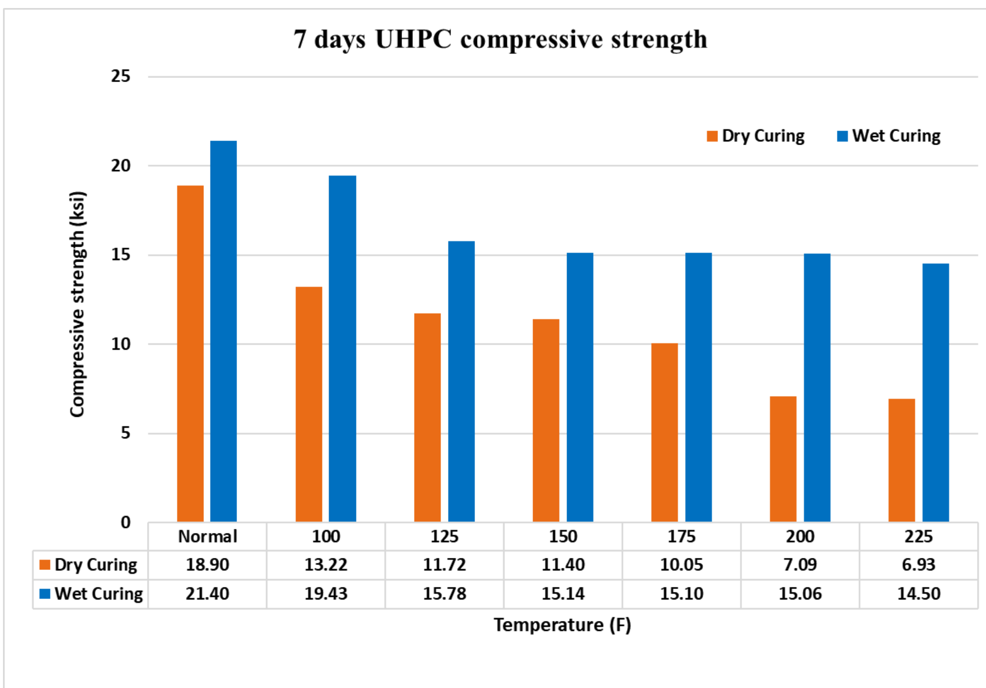

Figure 16 Compressive strength of UHPC at different temperatures from heat curing (7 Days)

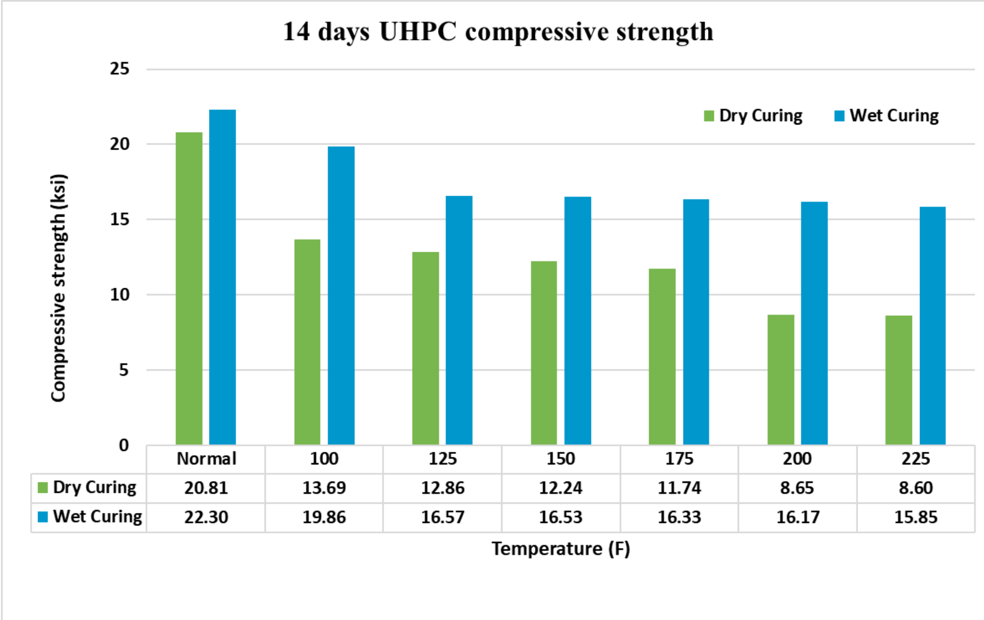

Figure 17 Compressive strength of UHPC at different temperatures from heat curing (14 Days)

4.4. Design of 3D-printer nozzle head

The nozzle head was designed in solid works and then 3D-printed. The nozzle head was designed to print UHPC layer of 12 inch in length, 1.0 inch in thickness and 1.5 inch in height at a given time. The final design of the nozzle includes the following components as shown in Figure 18.

1- Rollers for separation membrane

2- Mounting head with the actuator

3- Strip heater for heating

4- Side plates to control material flow

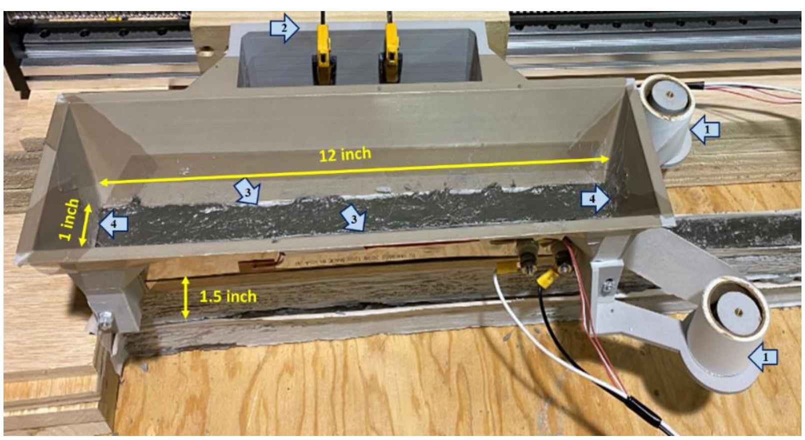

Figure 18 Nozzle head of 3D printer with separation membranes

4.5. Conceptual Design of 3D-Printer

A 3D-printing system, including horizontal and vertical actuators, mounted on a raptor track drive is proposed in this research as shown in Figure 19. Mounting the system on raptor drive provides mobility, scalability and flexibility properties for the 3D-printing. The buildability is achieved through accelerated curing. UHPC has steel fibers and it also has high strength properties which fulfills mechanical testing criteria for 3D-printing. This 3D-printing system is flexible to print different bridge elements such as cap beam shells **[38]** or column shells **[41-42]**.

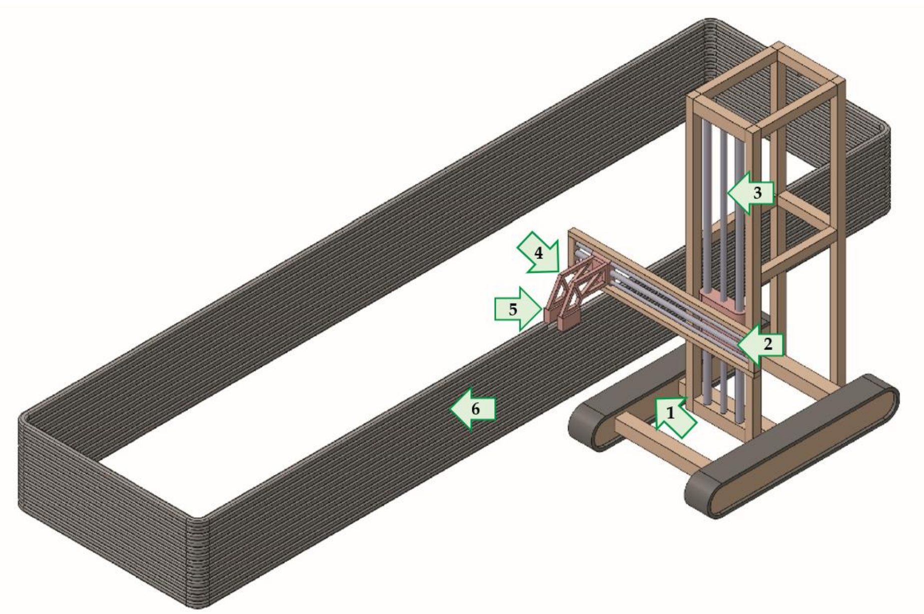

Figure 19 Conceptual design of 3D-printer on mobile platform

4.6. Components of Proposed 3D-Printer

Following items are the main components of the proposed 3D-printer which are also mentioned in Figure 19.

1- Raptor track drive
2- Horizontal actuator
3- Vertical actuator
4- Printing nozzle
5- Heating plates
6- Printed layers

4.7. 3D-Printed Wall

A small 3D-printed sample wall specimen is shown in Figure 20 **[43]**. The wall is printed in the same manner as additive construction using layer-upon-layer and in several segments using small scale stationary frame for proof of concept. The final heating temperature was selected by considering two parameters;

1) reduction in 3D-printing time, and

2) highest compressive strength possible

At 150°F, the material showed good compressive strength (>15ksi) along with a significant reduction in heating time so this temperature was selected to 3D-print the wall shown in Figure 20. The length of each segment was kept 12 inches with a height of 1.5 inches. The wall consisted of 3 segments and four layers resulting in a total length of 36 inches, and a total height of 6 inches. The thickness of the wall was 1 inch. This wall was printed for demonstrative purposes and to observe the efficiency and printing time of the 3D-printing system. Each UHPC segment was printed with heat curing at a temperature of 150°F with a heating time of 20 minutes resulting in 4 hours of printing time which makes it quite a quick process to 3D-print a UHPC wall if compared to other available 3D concrete printers which are discussed hereinbefore. The evaluation of material testing and 3D-printing system for the given wall is discussed hereinafter.

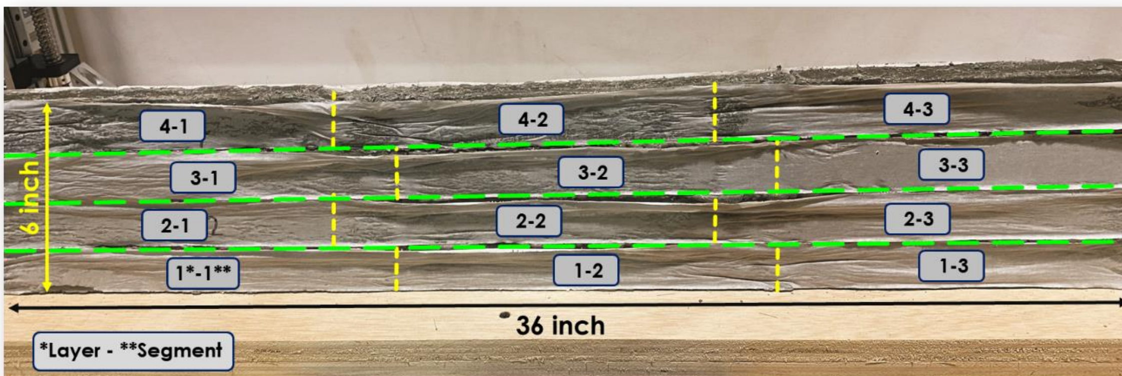

Figure 20 3D-printed wall using the proposed 3d-printing system

4.8. EVALUATING MATERIAL TESTING CRITERIA FOR PROPOSED 3D-PRINTING SYSTEM

Accelerated curing of UHPC is used in this research for 3D-printing of bridge components which provides many advantages in fulfilling material testing criteria for 3D-printing system. Table 4 evaluates all the material testing criteria of UHPC with accelerated curing for automated construction.

1- **Workability:** UHPC is flowable material, as shown in Figure 7(a) which fulfills workability and pumpability requirement for 3D-printing.

2- **Open time:** Heat curing of UHPC maximizes the number of printed layers and segments within the open time of UHPC mix which reduce material wastage. The optimum heating time at different temperatures is listed in Table 3.

3- **Extrudability:** The proposed system is flexible to obtain extrudability by altering the nozzle for the required size.

4- **Buildability:** The buildability is achieved through heat curing in the proposed system. Heat curing increases the buildability of the layers in the proposed system.

5- **Mechanical properties:** sufficient compressive strength of UHPC can be achieved as per requirements of the bridge component by varying the heating temperature but still there is a need for a research study to ensure the highest bond between layers and segments of the printed element which is included in the next phase of this research project.

Table 4 Evaluation of material for the proposed 3D-printing system

UHPC for 3D-Printing System	Workability	Open time	Extrudability	Buildability	Mechanical properties
	✔	✔	✔	✔	=
✔ Possible = Challenging					

4.9. EVALUATING 3D-PRINTING TESTING CRITERIA FOR PROPOSED SYSTEM

The proposed 3D-printing system has several advantages to fulfill the proposed framework for the testing criteria of the 3D-printing system. Table 5 evaluates all the testing criteria of the proposed system.

1- **Mobility:** The proposed system has horizontal and vertical actuators and is mounted on a raptor track drive which provides mobility benefits in any direction. The height of the vertical actuator can be designed to satisfy specimen height.

2- **Scalability:** The proposed system is fully scalable and can print full-scale and scaled bridge elements.

3- **Flexibility:** The proposed system is fully flexible in terms of printing different structural elements.

4- **Synchronization:** There is no requirement of synchronization as the proposed system can operate solely to print different structural elements.

5- **Adaptation of reinforcement:** The proposed system is successfully used to print UHPC wall which includes 2% steel fibers by volume which provides strength benefits. Furthermore, to incorporate typical reinforcement, the system nozzle can be modified as per specific job requirement; however, further research is being conducted in the next phase of this research project .

Table 5 Evaluation of testing criteria of the proposed 3D-printing system

Proposed 3D-Printing System	Mobility	Scalability	Flexibility	Synchronization	Adaptation of Reinforcement
	✔	✔	✔	✔	=
✔ Possible = Challenging					

CHAPTER 5. CONCLUSIONS AND FUTRURE WORK

Many researchers has developed different 3D-printing systems recently and the work is still ongoing but none of the available systems can incorporate all the material testing criteria and the 3D-printing system evaluation criteria which is proposed in this study. The 3D-printing material should have following properties;

- Extrudability
- Workability
- Open time
- Buildability
- Mechanical properties

While the 3D-printing system should have following properties;

- Mobility
- Scalability
- Flexibility
- Synchronization
- Adaptation of reinforcement

The proposed flowchart to develop automated 3D-printing system with UHPC, to fabricate bridge components, has many advantages if compared to the currently available systems. A system developed under these conditions will not only fulfill material testing criteria for automated construction but will also fulfill 3D-printing system evaluation criteria. This proposed framework can be considered a promising step toward the implementation of additive construction and can encourage stakeholders and contractors to implement automated construction in accelerated bridge construction (ABC) projects. Under this framework, the proposed material could be further polished for its utilization in 3d-printing as it fulfills all significant properties like workability, extrudability, buildability and open time. Future work can include studying mechanical properties especially inter-layer bond strength of the material. Furthermore, the large scale 3d-printing could be executed by utilizing the proposed system to evaluate the functioning of printing system itself for the above mentioned properties.

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