Committee Report : JCI- TC192A

Technical Committee on Construction of Concrete Structures Based on 3D Printing Technologies with Cementitious Materials

Tetsuya ISHIDA [*1], Koji KINOMURA [*2], Yoshikazu ISHIZEKI[*3], Yoji OGAWA [*4], Kaname SAITOH [*5], Minoru KUNIEDA [*6]

Abstract

The technical committee has deployed a wide range of activities focusing on three-dimensional (3D) printing technology for construction, which has been remarkably developed in recent years, with the aim of improving the technological base for development and propagation in Japan and providing information transmission and motivation as a next-generation concrete technology. Specifically, the following aspects were addressed: collection of the latest technical information and utilization cases in Japan and overseas, identification of required performance and research subjects, execution of common tests using 3D printers by various organizations, examinations oriented on the unification of related terminology, holding of workshops and exchanges of opinions, and preparation of a detailed technology development roadmap, etc. This report outlines the results of these activities and describes the prospects of this technology.

Keywords: 3D printing, productivity improvement, application examples, required properties, common test, roadmap

1. Introduction

Technological developments to innovate in the construction and production systems of concrete structures have been vigorously promoted in foreign countries. In this regard, the three-dimensional (3D) printing technology, which has been applied in the construction field, does not require formworks, can directly manufacture various shapes, has the potential to improve productivity with labor saving and shortening of construction periods, rationalize the

*1 Graduate School of Engineering, University of Tokyo, PhD (Engineering) (Regular member)
*2 Taisei Corporation, PhD (Engineering) (Regular member)
*3 Obayashi Corporation, PhD (Engineering) (Regular member)
*4 Taiheiyo Cement Corporation, PhD (Engineering) (Regular member)
*5 Sika Japan, PhD (Engineering) (Regular member)
*6 Gifu University, PhD (Engineering) (regular member)

design and reduce weight through structural optimization, as well as provide high value-added technologies and services to meet diverse needs.

In foreign countries, research and development has been promoted, mainly on RILEM, ACI, etc., and some examples of applications to actual structures have already been reported. However, there are still many technical problems to be solved for full-scale practical application, such as identification of workable material properties, materials development for realizing required performance, and methods for ensuring durability and structural safety.

In response to this situation, there have been concerns about delays in our efforts in Japan. Therefore, to integrate knowledge in the fields of architecture, civil engineering, and materials, and aiming at efficient and systematic technological development and horizontal deployment, the "FS Committee on the Application of 3D Printing to Concrete Structures (Chairman: Tsuyoshi Maruya)" was established in fiscal year 2018 as the predecessor of this technical committee[1)]. The FS committee investigated overseas technological tendencies and performed extensive information gathering by attending international conferences. A workshop was also held on the prospects of 3D printing technology, and a schematic technology development roadmap was prepared based on changes in social needs and the potential of this technology.

This technical committee has deployed more activities based on the results of the FS committee. The member composition is shown in **Table 1**, and an activity outline is shown in **Figure 1**. The diverse member composition and cross-disciplinary activity were features of this technical committee, and the improvement of the technological base, which will become a support for practical application, was promoted, centered on each workgroup activity. In addition, lectures and workshops by outside experts were held with the aim of creating new possibilities

Table 1: Composition of Members

Chairman	:	Tetsuya ISHIDA (University of Tokyo)	Secretary: Koji KINOMURA (Taisei)
Advisor	:	Tsuyoshi MARUYA (Taisei)	
[Other Industries WG]	○	WG secretary	
	○	Yoshikazu ISHIZEKI (Obayashi Corporation)	Manabu KANEMATSU (Tokyo University of Science)
		Atsushi TERAMOTO (Hiroshima University)	Hiroki TAKABAYASHI (aT Robotics)
		Takeshi KINUMURA (Maeda Corporation)	Kazuto TAHARA (Denka)
		Yoshikazu MINOMIYA (Master Builders Solutions)	Hiroya TANAKA (Keio University)

[Materials WG		
	○ Hirotsugu OGAWA (Taiheiyo Cement)	○ Ken SAITO (Sika Japan)
	Hirohisa KOGA (Public Works Research Institute)	Koji TERANISHI (Meijo University)
	Hirokazu KIRIYAMA (Ube Industries)	Satoshi KOBAYASHI (Kajima Corporation)
[Structures WG]		
	○ Minoru KUNIEDA (Gifu University)	Motohiro ONO (University of Tokyo)
	Daiki OGURA (Shimizu Corporation)	Yusuke TANABE (Takenaka Corporation)
	Hirotomo HIGASHI (Aizawa Group)	Koichi MATSUZAWA (Building Research Institute)

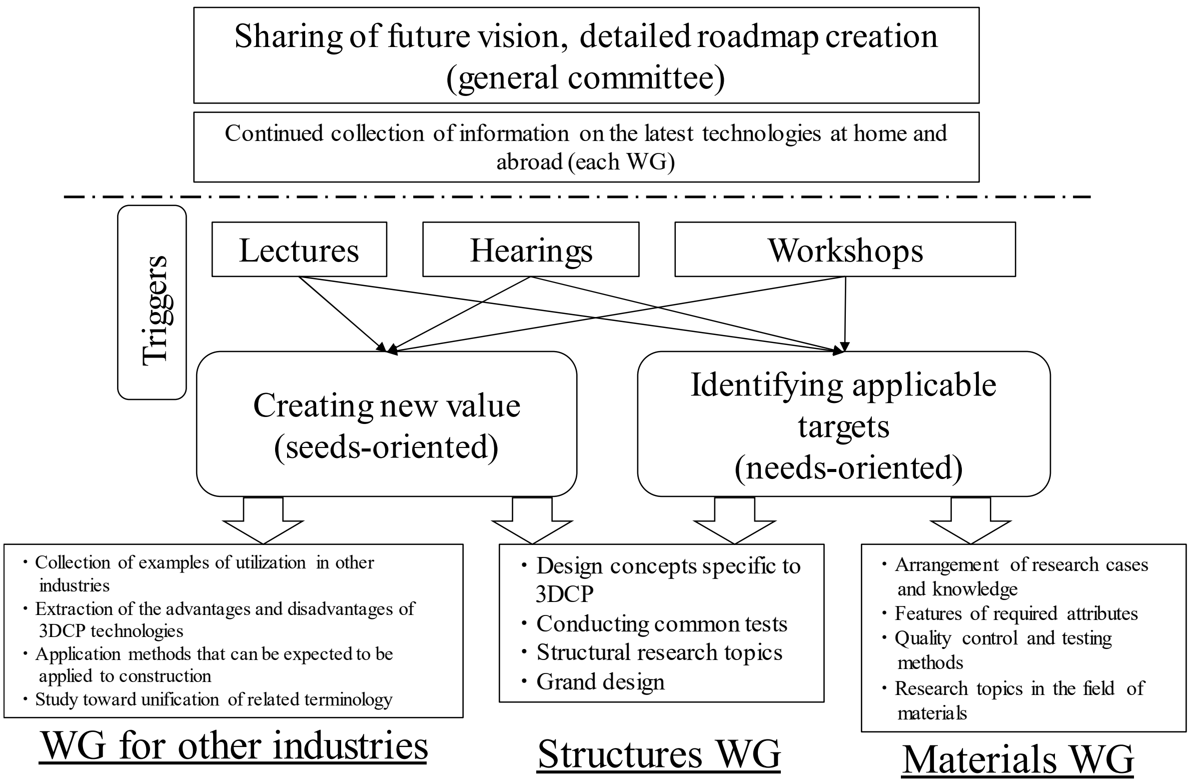

Fig. 1: Outline of Activities (Activity period: April 2019 to June 2021)

free from the frameworks of conventional concrete engineering and providing information dissemination and motivation as a next-generation concrete technology. There were actually approximately 150 participants in the free online "Workshop on the Frontiers and Future Prospects of 3D Printing Technologies for Construction" (held March 2, 2021).

The following is an overview of the results of the activities. For details, please refer to the committee report scheduled to be released this autumn.

2. Overview of 3D Printing Technologies

2.1 Classification of digital fabrication technologies

Digital fabrication technology is a technology to embody shapes based on digital data created by 3D modelers represented by computer aided design through manufacturing processes known as subtractive, forming, and additive, and the main processes are largely classified into these three methods [2)].

Subtractive manufacturing is a method that performs mechanical removal processing on a workpiece, machining it to a predetermined size and shape. It is excellent in terms of productivity, accuracy, processing cost, etc., and is widespread because it enables the production of parts with necessary shapes and characteristics from any materials.

Forming manufacturing is a process of forming a metallic part or an object by mechanical deformation or producing a predetermined shape by casting.

Additive manufacturing is a method of fabricating a predetermined shape by adding a material, and 3D printing using cementitious materials (hereinafter referred to as 3D concrete printing – 3DCP), which is a theme of this technical committee, is included here. In the next section, we will introduce an outline of additive manufacturing methods that have been developed for construction applications.

2.2 Additive manufacturing technologies using cementitious materials

(1) Material-extrusion method

This is a system in which nozzle position and motion speed are accurately and digitally controlled while a material is extruded, and each layer is fabricated step by step. This system is the most adopted in construction applications[3), 4), 5)]. In many cases, the materials are formulated with a high powder content such as to obtain a favorable rheology for lamination. Although it is necessary to quickly resist the upper dead-weight acting during and after lamination, the progress of hydration must be controlled such that the lamination does not form cold joints. Therefore, in the mixture design, rheological change and setting time are controlled by adjusting the combination of constituent materials and admixtures and the respective ratios. This method can make free shapes at a comparatively high speed and is methodologically easy to apply on-site. However, it is difficult to perform reinforcement while laminating, being necessary to combine tensile reinforcement techniques instead of conventional reinforcement.

(2) Particle bed binding method

This includes methods in which a cementitious material is laid in a thin layer and water or a binder is sprayed (injected) from above to be selectively solidified, or methods in which an aggregate such as sand is laid in a thin layer and cement paste is injected[6]. Compared to other methods, it has higher resolution and can produce finer shapes, and the unsolidified powder (the part that is not selectively solidified in fabricating the object) acts as a support material for the upper layer, enabling to fabricate hollow shapes and narrow, complex shapes. However, a large amount of time is required for printing and work is required after printing to remove unconsolidated powder. Therefore, the larger the scale, the lower the economic efficiency. In addition, the difficulty of the combined use of reinforcing materials and the re-use of unconsolidated moisture powder after removal have also become barriers to popularization.

(3) Spray systems (material jetting)

3DCP equipped with a spray system at the end of a robot arm has also been developed. The advantages are fast fabrication speed that can accommodate various shapes and applications. In addition, because the spraying is under pressure, it has higher bulk density and improved compressive and flexural strengths compared to lamination by the material extrusion method. Moreover, it is practical as the anisotropy of the flexural strength is small due to the relationship between the stacking direction and the loading direction[7]. However, to ensure the quality, detailed and appropriate rheological control of the material must be conducted according to the situation in addition to the process controls such as spray motion speed, distance/angle to the object, spray flow rate, etc.. Thus, control management for these is very difficult[8].

2.3 Expected effects and challenges

(1) Expected effect

Figure 2 shows the main effects expected with the introduction of 3DCP in the construction industry[9]. As formworks become unnecessary, fabrication of various shapes can be easily realized. Therefore, the degree of design freedom is improved, and it is possible to embody more rational structures through the inclusion of cavities and curves. This also leads to weight reduction of members and reduction of materials used. In addition, construction waste such as formworks and the use of cementitious materials can be reduced, and environmental benefits such as the control of CO_2 emissions in the construction process can be expected. Improvement of productivity, shortening of construction periods, and

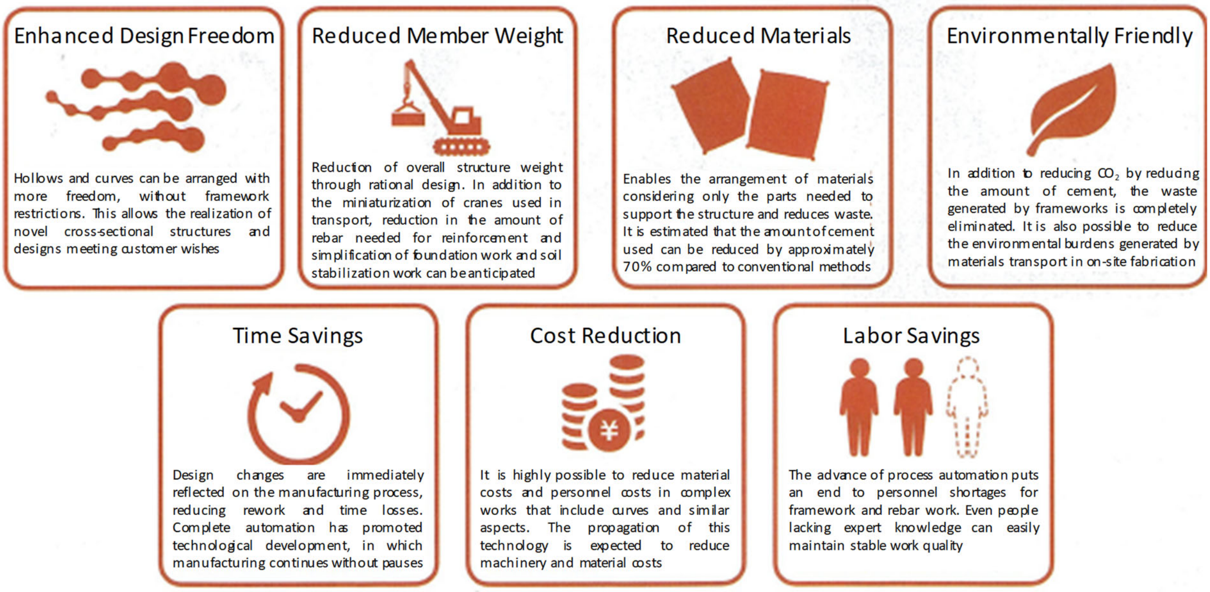

Fig. 2: Expected Introduction Effects (Reproduced from Reference 9)

improvement of safety by labor saving and manpower reductions can also be expected through mechanization. As 3DCP is applicable to various shapes with flexibility, it enables greater cost reduction especially in a construction with complicated shapes, compared to a conventional method with formworks

(2) Challenges

There are also many technical issues to the introduction of 3DCP. In the material aspect, technologies that control rheology and strength evolution in response to environmental conditions such as temperature change are required. Because formworks are not necessary, shrinkage tends to increase after drying in early ages, and autogenous shrinkage is also large because of the high binder quantity. In addition, compaction and curing are difficult, and strength and durability may be reduced compared with those of conventional methods.

At present, research on the structural aspects is very limited in comparison with the material aspects. In the future, it will be indispensable to establish tensile reinforcement methods and design methods. With regard to proof stress and structural behavior, etc., there are concerns about problems of interlayer adhesion, anisotropy, and shape and dimension dependence.

On the construction side, there is also a need to carefully discuss continuous material supply and construction planning, assurance of structural stability, measures to address equipment failure, and emergency countermeasures, etc., given that this is an unprecedented and novel construction method. It is also considered necessary to review related laws and regulations such as the Building Standards Act and to develop various testing methods and standards for social implementation.

3. Use of 3D Printing in Other Industries

The use of 3D printers in other industries is expanding, with applications ranging from consumer products, industry, and medicine to foods, and the materials to realize these are also varied. For example, in automotive applications, application cases were initially introduced in venture companies, but recently, efforts and application cases have been expanding at major manufacturers. This section describes how 3D printers have been applied in many industries based on use cases.

3.1 Examples of utilization

(1) Automotive

A certain truck manufacturer has been fabricating tools and fixtures that are familiar to the manufacturing industry, such as jigs, clamps, and supports, using 3D printers[10)]. Tools and jigs are indispensable in production lines, and they have various shapes matched to the items manufactured and to the assembly line. For example, to assemble a part to another part, each part must be secured. However, the shapes of the parts and the places where they are installed vary, and dedicated fixtures for these are required. Jigs have a similar application, and should be individually designed and custom-made. Therefore, by switching to 3D printers, they have succeeded in reducing the production time from 36 days for design and manufacturing to just 2 days.

Next, 3D printers are used to produce parts for rare classic cars[11)]. For example, only 292 units of a special sports car were produced, and there was no stock of parts. In a study, some parts were fabricated by a 3D printer using the laser melting method. The printed parts passed pressure testing and inspection for internal defects. Finally, they were mounted on a test vehicle and the perfect quality and function of the components were confirmed by field and running tests.

(2) Iron and steel

The steel industry has long been manufacturing products using the lost wax (investment) casting technology. Lost wax casting has a plurality of processes, starting from the preparation of a mold of the product and production of a wax pattern. Thereafter, the wax pattern is covered with a refractory material or the like, the wax inside is melted at a high temperature, and becomes a mold by firing and solidification. Molten metal is poured into this mold and the product is formed. By utilizing 3D printing, the fabrication of dies for fabricating wax patterns, and the wax patterns, can be omitted. Thus, cost reduction and lead time reduction can be realized. In wax patterns produced by hand, the dimensional accuracy can be improved by 3D printers, and it has become possible to realize complicated shapes that were previously difficult to produce.

(3) Electric power and energy

As the combustion temperature of gas turbines is very high and the higher the combustion temperature, the more efficiently power can be generated, a combustor that can withstand higher combustion temperatures is required. By using metal lamination molding, new designs that could not be manufactures by conventional processing methods, have become possible, and this method is effective in improving performance and reducing the number of parts. In the development process of gas turbines, prototypes manufactured using presses and metalworking processes have been manufactured using 3D printers, thereby considerably reducing development times.

(4) Aviation and military

Features of metallic 3D printers have been utilized in the development of fuel nozzles for new aircraft engines. When manufacturing with laser-type metallic 3D printers started, it was possible to turn 20 parts into one. Durability was drastically improved compared to before due to its integrality, as the parts were composed of the same material. The introduction of 3D printers to the production of fuel nozzles enabled a 30% reduction in price due to the drastic decrease in the number of components[12)], and a savings of $1.6 million per year in fuel costs per aircraft were achieved due to a reduction in weight and improved fuel efficiencies[13)].

The budget reductions in the United States (U.S.) military led to difficulties when procuring special components for fighter jets etc., regarding component replacement and maintenance of F-22s, which had finished production due to the extremely high cost of procurement by conventional manufacturing methods. To address this issue, the U.S. military has focused on the use of 3D printing technology to application to F-22 fighter jets[14)]. The U.S. Air Force is aiming to reduce the downtime required to repair fighter aircraft by speeding up the replacement of damaged titanium components in aircraft through the use of 3D printers[15)]. The U.S. Army "Apache" and "Black Hawk" helicopters have successfully tested the newest 3D printing engine in compliance with the Improved Turbine Engine Program (ITEP) and it is moving to the next step toward practical deployment.

(5) Shipbuilding

There is a report of the 3D printing of an actual hull[16)]. A 30-ft-long carbon fiber-based 3D printed submersible has been designed based on the Mark 8 Mod 1 SDV (SEAL Delivery Vehicle), a special operations submersible adopted by the U.S. military. Large 3D printers were used to produce the submersible, and the hull was completed in just four weeks. Conventional manufacturing methods require approximately 3 to 5 months per boat and cost 600 to 800 thousand USD, whereas the production of boats with 3D printers results in cost savings of approximately 90%. The hull data for the 3D printing is divided into six units and is mounted in approximately seven days.

(6) Medicine

3D printing is suitable for use in the medical field because it is possible to form a large variety of products of very small quantity at relatively low-cost. However, materials such as metals and plastics, which are often used in industrial products, cannot be applied, because the products directly touch human skin. Therefore, in addition to formability, prerequisites such as texture and biocompatibility are required[17)]. Examples of applications of 3D printing in the medical field include intraocular lenses and artificial bones implanted in the body, individually-customized prosthetic hands and feet, and organ models that accurately reproduce the locations of blood vessels and tumors to aid in the rationalization of surgical planning[18)].

(7) Apparel and sporting goods

In the field of apparel and sporting goods, there are many cases in which 3D printing technology has been used to manufacture shoes, which are commercially available to general consumers [19,20)].

A major sports manufacturer has partnered with a 3D printing manufacturer to mass-produce running shoes utilizing 3D printing in the production of midsoles[21)]. The product uses a lattice structure completely different from that of conventional midsoles and is designed based on running data collected over the past few years. Although it is a single material, changing the density and thickness of the stereoscopic grid creates a variety of cushioning properties for each part of the foot. Both the shape and performance are difficult to fabricate by conventional techniques, thus the product can only be manufactured by 3D printing. It is also reported that the manufacturing lead time has been reduced by a digital design process centered on 3D printing. The material was photo-cured polyurethane, and a forming system capable of printing with high precision and high speed was adopted.

(8) Aerospace

Lockheed Martin and Stratasys have jointly developed 3D-printed components for the development of spacecraft. For the parts, they adopted Stratasys's Antero^{TM}800NA ESD, which is a PEKK (polyetherketone ketone) material with high rigidity, flame retardance, and antistatic functions[22)].

Application cases can be seen in the components of the Atlas V commercial rocket operated by the U.S., and the rover being developed by NASA for exploration of Mars[23)].

3.2 Advantages and disadvantages of utilizing 3DCP techniques

3D printers enable innovations in design and development processes that are constrained by current manufacturing methods [22)]. In the past, the progress of mechanization has enabled people to have access to several products, being able to focus on knowledge rather than action. The internet is now popularizing a variety of information, and the diversity inherent to mankind is affecting business models. What will happen with the democratization of the manufacturing process? Unlike a monopolar centralized manufacturing process, connecting to a democratized communications infrastructure will expand opportunities for all small businesses, including non-manufacturing, to participate in the production of objects. The entire ecosystem will change beyond the current value chain of manufacturing when people become involved in manufacturing through 3D printers to make personalization-ready products. The digitalization of the value chain across industries will be facilitated and all data will be connected, creating new business opportunities. We see the tendency of change as an opportunity to connect with future generations.

4. Literature Survey on Cementitious Printed Materials and Arrangement of

Knowledge

4.1 Main research cases

In this paper, information on the specific performance required for 3D printing concrete and the necessary materials, mixtures, evaluation methods and standards were collected and organized from the existing literature. This literature survey used the JDREAM-III database and covered a period of 10 years (2010–2019).

With the specific performance required for 3D printing materials as keywords, titles and abstracts were searched, and the papers were further sorted. Based on the knowledge in the FS committee, the following keywords were used for specific performance parameters: buildability, rheology, thixotropy, extrusion, lamination, fluidity, rapid hardening, strength, shrinkage, creep, durability, quality control, and test methods. In keyword correspondences, strength (n=49) was the most numerous, followed by rheology (n=35), extrusion (n=32), and buildability (n=27). Regarding items on fresh properties, there were many correspondences in the order of rheology, extrusion, thixotropy, and fluidity. Buildability, which was considered important as a characteristic property of 3D printing, was detected in a certain number of reports together with lamination.

In terms of strength, reports of interlayer adhesion strength were also found in addition to compression and bending. Literature on quality control and testing methods was detected with eight correspondences each. Examples included reports on mortar flow, robustness, rotating viscometers, yield strength, shear testing (vane, direct), extrusion testing (pressure measurement), shape stability test methods (layer settlement, cylinder stability test), interface (interlayer) adhesive strength, settings, calorimeters, 3D scanners (geometric properties), ultrasonic propagation velocity, fracture energy testing, etc.

There were few correspondences with regard to durability as a hardening characteristic other than strength, and one correspondence on freeze-thaw resistance. The content was a case of internal structural evaluation by CT scanning of a hardened body using a gypsum type material with a binder jet system.

Shrinkage and creep produced only a small number of correspondences, and no reference measurement data were shown in the papers. There are very few reports on physical properties after hardening other than strength, and this has been suggested as a future study subject.

Regarding the characteristics of the materials and mixtures, most of the reported examples were of cement paste and mortar, and no reported examples of concrete mixed with coarse aggregate were found. In addition to cement materials, a number of reported cases using geopolymers and Portland blast furnace slag cement, Portland fly ash cement, and alkali stimulants (such as sodium silicate) as binders were also detected. Fine aggregate was used as the aggregate, and lime sand, silica sand, etc., were used in addition to river sand and natural sand. Maximum dimensions were usually 3 mm or less. Portland fly ash cement, silica fume, limestone fine powder, blast furnace slag fine powder, bentonite, minerals such as calcium aluminates, and expanding materials, etc., were used as admixtures. Admixture agents included water reducers, rheology modifiers, thickeners, curing modifiers (accelerators, retarders), and polymers. In addition, fibrous materials were also used as reinforcing materials and shape-retaining materials. PVA (polyvinyl alcohol), PP (polypropylene), and PBO (polyparaphenylene benzoxazole) were used as organic fibers in addition to carbon, glass, basalt, and steel.

Among the formulations, the water/binder ratios (W/B) were 0.30–0.55, and 0.35–0.45 were particularly numerous. The sand/binder ratios (S/B) were up to approximately 1.25–3.40, but 1.4–1.7 tended to be particularly numerous.

4.2 Organization of findings on specific items

(1) Fresh properties and buildability

There is a close relation between fresh properties and buildability of 3D-printed concrete. In addition, when constructing the structure, it is crucial to understand whether the fresh properties of the laminated material are suitable for 3D printing or not, and the relation of the fresh properties and buildability over time.

As required performance properties of 3D printing materials, the fresh properties are divided into the delivery phase and the deposition phase, and these are systematically arranged in the report. In addition, the relationship between the fresh properties and the lamination properties are arranged according to the literature.

(2) Relationship between characteristics of materials and formulations with required performance properties such as strength

In the report, a list of materials and mix proportions was prepared based on the information obtained from the literature survey.

Physical property values related to strength

Compressive strength, flexural strength, and tensile strength testing were conducted using test specimens produced by printing and casting, and the effect of lamination on the strength and the anisotropy of the strength were confirmed by varying the loading direction relative to the layering direction.

The strength varied depending on the formulation and the cement and admixtures (agents) used. The compressive strength was 25 MPa for low strength and 100 MPa for high strength. Although few cases have been examined for flexural strength and tensile strength, there are reports in which the flexural strength was approximately 9 MPa and the tensile strength was approximately 5 MPa. The interlayer adhesion depends on the time between lifts; generally, the longer the time between lifts, the lower the interlayer adhesion strength. To ensure interlayer adhesion, a study in which a paste was applied between layers was also conducted. As a special examination, there is a case in which the effect of the print pass on the strength was ascertained, and the difference between a case in which the print was made in a spiral shape and a case in which it was made into a lattice shape was evaluated.

Strength test conditions

As the condition of the strength testing, testing is first conducted according to the test standards of each country. However, in case a specimen with dimensions conforming to the standard cannot be manufactured due to the nozzle shape and the properties of the material, the test is currently conducted with the possible dimensions. Basically, a slightly larger specimen is produced by printing, and the specimen is sampled by cutting it out. Cast specimens are taken directly after mixing with a mixer and do not include the changes in properties caused by pumping. Testing with cast specimens is only used to compare with the test specimens produced by printing, not from the viewpoint of quality control.

Relationship between material/mix design and required performance

Although similar materials are used in all studies, except for geopolymers, the methods to improve viscosity and self-sustaining properties are diverse, ranging from thickeners and fibers to high early strength cements and similar agents, and researchers have selected them according to their own concepts. In addition, as the mixers, pumps, 3D printers, nozzle shapes, etc., to be used differ, it is necessary to make the mix design match the equipment.

Furthermore, it is considered that the mix designs differ even if the materials to be used are similar, depending on the mix design concept of the researcher.

Although the strength differs as the mix design differs, there is basically no major issue if the design standard strength of general concrete is ensured. It is considered that high strength is also required if added value such as high flexural strength, tensile strength, and even higher durability are imparted to the fabricated product by 3D printing.

In any case, there is a required performance of strength at present, but the mix design is based on the required performance of the fresh properties, which can be produced by each 3D printer, and the required strength is obtained as a result.

(3) Relationship between quality control/test methods and evaluation standards

Few of the quality attributes in 3DCP are currently clearly defined when the required quality or performance is unclear. In literature surveys, most of the materials development studies at the laboratory level evaluated the quality of the laminate at the time of printing by rheological tests. However, it is considered difficult to apply rheological testing at the construction site. In contrast, the slump value at the time of mortar flow testing has been examined as an index of simple pumpability and buildability, but it cannot be said that it has been established as a quality test method for materials.

In the report, the items to be inspected for quality control in 3D printing are arranged in a comparison table, with reference to the concepts of Japan Society of Civil Engineers sprayed concrete guidelines (draft).

4.3 Research topics on cementitious printed materials

Technological problems are arranged based on the above content. Test methods for evaluating fresh properties, rheometers, rotational viscometers, vane tests, flow tests, etc., have been attempted many times, but it is necessary to further clarify the relationship with the required performance.

Anisotropy of strength is an issue unique to 3D printing. It is necessary to accumulate data, including how it should be considered in design, which is also a problem considering shrinkage and creep characteristics.

Furthermore, to ensure the accuracy of the finished form in manufacturing members without formworks, not only the relation between the quality of concrete and the lamination performance over time, and the condition of the concrete at the tip of the nozzle, but also the interlayer quality, which is a discontinuity, are mentioned as future topics.

5. Literature and Conceptual Studies on Structural Design

5.1 Main research cases

This paper summarizes the past study cases on structural bodies formed by 3DCP and corresponding design methods. Google Scholar was mainly used for the literature survey. First, the papers were searched by the keywords 3D printing, additive manufacturing, concrete, cement, application, and review, and 17 reviewed papers were selected, centering on the papers with many citations from the retrieval results of approximately 18,800 papers. The main selection criterion was that they received more than 10 citations per year on average post-publication, but a review paper focusing particularly on structure, design, and application examples, and characteristic review papers summarizing points of interest different from others were also included in the subjects. Next, the investigation was extended to individual papers cited in respect of structure, design, and application examples in each review paper.

From the survey results, it was recognized that various structures were shaped using several 3DCP methods such as the slip foam method, Mesh Mould, particle bed binding method, etc., in addition to the material extrusion system. In addition to the previous pavilions and monuments, application examples have spread to structures such as bridges and offices. In the report, these cases were summarized by listing in a table.

It was also found that reinforcement methods for tensile strength are one of the main technical problems toward the construction of structures by 3DCP, and that many study cases have been reported. Various reinforcing methods using short fibers, steel wires, reinforcing bars, outer cables, bolts, and pre-stressing, etc., have been attempted so far.

In addition, many studies have been conducted to apply phase optimization techniques (topological optimization) to 3DCP because of the benefits of 3D printing in improving the degree of forming freedom. There is an effort to enhance an elementary method of phase optimization by considering a single material as a linear elastic body and to apply it to concrete, which is an elasto-plastic composite material. To date, techniques to simultaneously optimize the arrangement of concrete and reinforcement and techniques to optimize the phase of anisotropic materials have been developed. In addition, optimization techniques considering the constraints in construction such as shaping angle in material extrusion lamination systems have also been proposed. Moreover, there are research cases in which structural performance and thermal insulation performance were simultaneously improved, and the application of phase optimization techniques has spread to more advanced multi-objective optimization.

5.2 Design and evaluation concepts unique to 3D printing

(1) Design concepts

Regardless of the printing method used, it can be said that design for additive manufacturing (DfAM) is indispensable in designing structures that adopt 3D printing. DfAM refers to a design concept tailored to maximize the properties of 3D printing. Within this, manufacturing constraints arising from manufacturing technical requirements for 3D printing are incorporated into the shapes of structures. In addition, performance improvement by realizing shapes that are difficult to fabricate by conventional methods and productivity improvement in accordance with the manufacturing constraints of 3D printing are the key factors in DfAM.

For example, when determining the shape of the structure to be constructed in the structural plan, it is always necessary to examine whether the shape can be fabricated by 3D printing (extruded layer by layer). Using 3DCP, it is not possible to create any free shape, and it is necessary to design a shape that has been optimized for layered extrusion by determining a shape considering restrictions such as single strokes or overhang angles. That is, the shape of structures and members should be decided by repeating structural planning and DfAM.

In addition, the structures produced by 3D printing differ from usual concrete structures in that the interfaces (lamination surfaces) of each printed layer exist, and the adhesion strength of these lamination surfaces may be below that of the base material, such that consideration of mechanical anisotropy is required. If these lamination surfaces are not sufficiently integrated, the durability may be affected. Furthermore, as the surface texture is changed according to the lamination direction, it also affects the design. Therefore, it is necessary to plan and design the lamination path based on these items beforehand, because these are items to be considered in the performance requirements of safety and durability and in the aesthetic design. Incidentally, there is a design example of later introducing pre-stress via steel bars/wires and the like in a direction perpendicular to the lamination surfaces to reinforce the lamination surfaces, and such reinforcing methods are also considered as necessary.

In the case of material extrusion type or material injection type, the outline of the shape to be produced can be made with only one or with multiple lines, and it is possible to produce more complicated shapes than ordinary concrete structures, shapes incorporating optimization, and shapes having hollow structures on the inside. When making a design that proactively incorporates these, care must be taken as the member thickness tends to be thin, and the effects of shrinkage and creep may be large. In the case of shapes that incorporate techniques such as topology optimization, attention should also be given to the accuracy of printing. As a result of printing, when a dimensional error occurs between the actual shape and the design drawing, that is, when it deviates from the topology-optimized shape that was originally assumed, it may exhibit a dynamic behavior that was not assumed in the actual design. It is desirable to optimize the design by considering in advance the accuracy of printing and the dispersion of shape dimensions.

(2) Structural performance prediction

Performance checks of structures using 3D printing, as with ordinary concrete, are similar in setting limit conditions for durability, safety, usability, and seismic resistance, and confirming that structures or structural members do not surpass the limit conditions, but there are many parts that must consider the features unique to 3D printing.

For example, in verifying safety, attention should be given to lamination paths and anisotropy to predict the structural performance of the printed structures. As described above, as the characteristics of the lamination surface are different from the base material, the structural performance may change if the lamination path is different, even in the same shape. It is important to know how to consider them. For verification, it is possible to measure the adhesion strength of the lamination surfaces in advance and incorporate the anisotropy into the model, but the specific modeling methods are a future issue.

In the case of structural members with complicated shapes and shapes incorporating optimization, the application of three-dimensional numerical analysis techniques (finite element method (FEM) analysis, etc.) becomes a premise for structural performance prediction. For the improvement of prediction, it is desirable to have data such as shrinkage and creep characteristics. In the modeling of the verification stage, it is also important to consider the variation of the shape beforehand, as well as the accuracy of printing. In inspection, it is also important to quantify the initial shape irregularity by examining whether the printing structure and member can be manufactured according to the design drawing. If FEM analyses, etc., are conducted by modeling including the shape error, the structural performance can also be evaluated after the fact. In the case of free-form curved surface shapes produced by 3D printing, shape measurement by rulers, etc., is difficult, but there are also methods such as obtaining point cloud data of shapes with 3D scanners, etc.

5.3 Outline of common tests

To popularize 3DCP, it is necessary to deliver the design value used from the material side into the design. When measuring various strengths of members constructed by 3DCP, common tests have been conducted having arranged concepts on, for example, preparation methods of specimens, core-drilling methods, etc. Strength as an object was assumed to be compressive strength, flexural strength, splitting tensile strength, and interlayer adhesion strength, and the strength determined from the cylindrical specimen core-drawn from the laminated structure was compared with the strength of a specimen in which the material was driven into the mold. There were seven participating organizations, all of which printed by the material extrusion method. **Table 2** shows the average values of the compressive strength of the materials packed in the mold and the average values of the compressive strength of the specimens core-drawn from the hardened laminated body. It can be seen that the strength ranged from 46 to 107 N/mm^2, and that the strength was larger than that of concrete used in ordinary concrete structures. Furthermore, as for the ratio of the strength of the core test piece to the strength of the molded test piece, it can be said that all the organizations could ensure values of 90% or more. In the future, it will be necessary to continue the examination including the degree of variance, etc.

Table 2: Examples of Compressive Strength Obtained from Laminated Structures

Engine	Molded specimen	Core specimen	Core/Mold
A	67.0 (n=3)	67.6 (n=3)	1.00
B	107 (n=5)	95.6 (n=5)	0.89
C	42.1 (n=6)	40.8 (n=6)	0.97
D	72.5 (n=5)	68.1 (n=5)	0.94

E	46.3 (n=3)	43.4 (n=3)	0.94
F	68.0 (n=4)	72.0 (n=4)	1.06
G	52.9 (n=3)	48.5 (n=3)	0.92

※Number of specimens in parentheses

5.4 Research topics on structural design

To actually construct a structure, dead weight, earthquake, wind, fire, etc., should be considered regarding safety, and it is necessary to conduct structural design such as to satisfy the performance. This also applies to buildings built by 3D printing. However, as structures made by 3D printing differ from ordinary concrete structures in terms of materials, composition, and construction, these aspects must be considered even during design.

(1) Research topics on design values and design criteria

Design values and design criteria must be set to design structures, and complete data is necessary. **Table 3** shows an example of the problem.

The materials currently used for 3D printers are often optimized for each device, and each material is examined separately. It is often characterized by the fact that coarse aggregate is not used in many cases and that the strength development is rapid. In particular, there is a problem in ascertaining what happens with each item depending on the lamination direction, and how to address the anisotropy in design. The interlocking of aggregates, etc., in the fracture plane may become small between layers, and may be different from conventional concrete. In addition, variations in quality caused by construction with 3D printing are also considered to differ from those of conventional concrete, and the safety margin expected in design also requires engineering evaluation.

Table 3: Design Values and Design Criteria

Design parameters	Aspects to be considered
Rigidity	Young's modulus, Poisson's ratio, stiffness after cracking
Intensity	Compressive, tensile, shear, adhesion, interlayer, and torsional strengths
Durability	Shrinkage, creep, neutralization, water tightness
Fire resistance	Heat capacity, linear expansion coefficient
Safety factor	Variations in construction and quality

(2) Structural characteristics and study topics for 3D-printed structures

3D-printed structures have features differing from conventional structures according to their forming method, and design study subjects corresponding to these features are available.

Table 4 shows examples of such topics. Regarding 3D-printed structures, there is a method in which an embeded formwork is manufactured using a 3D printer, and concrete is filled inside. There are some parts that can be considered as extensions of conventional methods such as masonry and half pre-cast method and in contrast, as an unprecedented manner. At present, it seems that internal concrete is often designed to satisfy the requirement as a structural body only, but it should be rationally evaluated and designed as a composite material in the future.

Effective reinforcement methods for 3D printing, in which it is presently difficult to install reinforcing materials, and their evaluation methods are mentioned as issues. In addition, designs positively incorporating 3D FEM analysis become indispensable for complicated 3D-printed shapes and shapes incorporating optimization. Improved design methods in which both FEM analysis in the elastic region and evaluation as a composite material in nonlinear regions are considered are desired.

In 3D printing, there are also issues with joints, such as areas that cannot be produced with a single stroke, joint construction after hardening, and joining of shaped members.

Finally, in the architectural field, it is necessary to examine the legal treatment such as the Building Standards Act (specifications and regulations regarding designated building materials, rebar arrangement, etc.).

Table 4: Design-related Issues Characteristic of 3D Printer Structures

Features	Design considerations
Embeded formwork	Masonry, half pre-cast, equivalent rigidity, integrity
Complex shapes, optimization	FEM analysis
Reinforcement	Fiber reinforcement, pre-stressing
Junctions	Joints, member joints
Materials, bar arrangement	Legal treatment

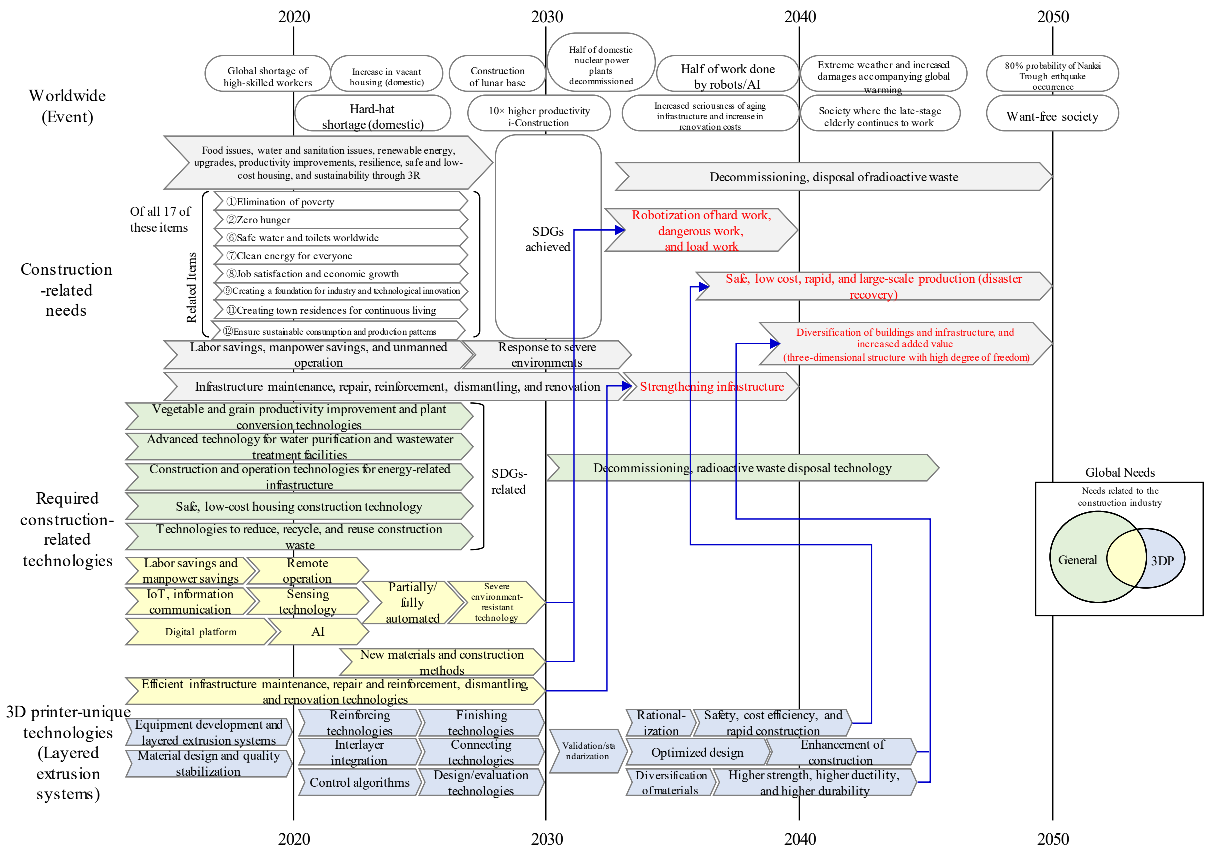

Fig. 3: Schematic Technical Development Roadmap for the 3D Printing (Created by the FS Committee, 2019) [1)]

6. Outline of the Technology Development Roadmap

Our predecessor, the FS Committee, held a workshop on the prospects of 3DCP, and prepared the outline of the technology development roadmap shown in **Figure 3** based on the changes in social needs and the potential of this technology[1)]. This roadmap was prepared after the following three stages of brainstorming: ① advantages of 3DCP, ② issues of the construction industry in which social changes are imagined, and ③ what can be done by 3DCP, and reflected the consensus of the committee members.

Two years have passed since this was prepared. The environment and needs surrounding the society have slightly changed, and newly available technologies have also appeared due to the rapid progress of digital technology. Therefore, this technical committee is proceeding with review work of the roadmap by incorporating such new situations, needs, and technologies. In addition, we would like to clarify the application targets of 3DCP and the target timeframes to be applied and include them into the roadmap, and to present indices that can be shared toward social implementation. During the review, new keywords to be considered were suggested, including carbon neutral regulations, carbon recycling in construction materials and construction practices, measures against increasingly severe climate change (national resilience, disaster recovery), promotion and full-scale implementation of digital transformation, creation of compact cities, function application to infrastructure (sensing and monitoring, automated driving assistance, etc.), phase-free, and countermeasures against epidemics, etc.

7. Conclusion

As described above, the technical committee collected the latest technical information and examples of utilization at home and abroad, arranged concepts, performance, and information to be newly considered to the application of the 3D printing technology, and conducted specific common tests using 3D printers. Through these efforts, the committee worked to identify research items that would require future efforts and created a technology development roadmap for the future. As the survey and research progressed, we recognized that many of the studies on 3D printing techniques are still in an exploratory state. Although large advantages and possibilities are indicated in comparison with conventional design and construction technologies, promising technologies and techniques that can become de-facto standards have not been identified at present. Conversely, revolutionary and innovative 3D printing techniques could emerge in the future.

In developing 3D printing technology in the construction field, cooperation not just with the area of concrete engineering, but with other fields such as robotics and information technology, is indispensable. In the future, it will be necessary to meet the challenge of technological development by repeating trial and error while first reducing risks, such as to promote technological development through application to concrete projects as well as "small start" and "agile development." It is also important to value the attempts to create something new, the desire to surprise people, and the playfulness of trying to realize something even more interesting.

We have repeatedly discussed how concrete structures can be made by applying 3D printing techniques, and what type of objects can be made. In addition to these, major changes may also occur in terms of who will make concrete structures or who will be able to make them in the future. 3D printing techniques may create entirely new concepts from non-experts involved in concrete engineering, such that anyone can easily and widely disseminate their own thoughts and talents and attract attention from around the world through social media and video sharing sites. It seems that researchers and engineers involved in concrete engineering should seriously reflect about whether they should regard such "democratization" of concrete engineering due to the progress of digital technology as an opportunity or as a threat.

References

1) T. Maruya and T. Ishida: State of the art and prospects for 3D printing technology applied to concrete, Concrete Journal, Vol. 59, No. 2, pp. 173-180, 2021.2
2) R.A. Buswell, W.R. Leal da Silva, F.P. Bos et al.: A process classification framework for defining and describing Digital Fabrication with Concrete, Cement and Concrete Research, Vol. 134, 2020, 106068
3) T. Wangler, E. Lloret, L. Reiter et al.: Digital concrete: Opportunities and challenges, RILEM Technical Letters, Vol. 1, pp. 67-75, 2016
4) V.N. Nerella, M. Krause, M. Nather, and V. Mechtcherine: Studying printability of fresh concrete for formwork free concrete on-site 3D printing technology (CONPrint3D), 25th Conference on Rheology of Building Materials, 2016, pp. 236-246
5) C. Gosselin, R. Duballet, Ph. Roux et al.: Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders, Materials and Design, Vol. 100, pp. 102-109, 2016
6) D. Lowke, E. Dini, A. Perrot et al.: Particle-bed 3D printing in concrete construction – Possibilities and challenges, Cement and Concrete Research, Vol. 112, pp. 50-65, 2018
7) H. Kloft, H. Krauss, N. Hack et al.: Influence of process parameters on the interlayer bond strength of concrete elements additive manufactured by Shotcrete 3D printing (SC3DP), Cement and Concrete Research, Vol. 134, 106078, 2020
8) I. Dressler, N. Freund, and D. Lowke: Control of strand properties produced with Shotcrete 3D printing by accelerator dosage and process parameters, DC2020, RILEM Book series 28, pp. 42-52, 2020
9) Nikkei BP: Special Feature "Construction 3D Printers to Renovate Design and Construction," Nikkei Construction, July 8, 2019 issue, 28-47
10) Volvo Trucks cuts manufacturing costs by 94% with Stratasys 3D printers, https://i-maker.jp/blog/volvo-3d-print-7259. OOB#OOC, 2019
11) Hard-to-obtain parts are supplied by Porsche for classic models with 3D printers, https://response.jp/article/2018/02/14/306051. html, August 2018
12) The power of 3D printers as seen in GE's practice. https://it.impress.co.jp/articles/-/13829, 2016
13) Giants have begun to move! Innovations brought about by metallic 3D printers (Previous Edition), https://minsaku.com/category02/post254/, 2019
14) U.S. Air Force installs 3D-printed titanium components on F-22 raptor fighter aircraft, https://idarts.co.jp/3dp/f-22-raptor-3d-printed-titanium-part/, 2019

15) GE Aviation has developed a modern military helicopter engine utilizing metal 3D-printing technology. https:// idarts.co. jp/3dp/ge-t901-turboshaft-engine, 2017
16) US Navy and ORNL-sponsored research team develops submersible using large 3D printer BAAM; https://idarts.co.jp/ 3d p/us_navy_ornl-3d-printed-submarine, 2017
17) I. Mitra et al.: 3D Printing in alloy design to improve biocompatibility in metallic implants, Materials Today, (in Press)
18) H. Sasaki, M. Kawakami, H. Yoshikawa: Designable Materials Science for Medical and Welfare Pioneered by 3D Gel Printer, Materia Japan, Vol. 57, No. 4, pp. 159-163, 2018
19) Nike, Nike Flyprint is the first performance 3D printed textile upper, https://news.nike.com/news/nike-flyprint-3d-printed-textile, accessed March 20, 2021
20) New Balance, New Balance launches a premium 3D printing platform, https://newbalance.newsmarket.com/product-news/performance/new-balance-launches-a-premium-3d-printing-platform/s/5c2b466a-13b7-4218-a18a-61d2889e6adc, accessed March 20, 2021
21) Adidas, 4D, https://news.adidas.com/4d, accessed March 20, 2021
22) Technical Information Institute, Development of materials for 3D printers and enhancement of precision of molded products, June 2020
23) NASA lab uses 11 3D-printed metal parts for Mars Perseverance rover, https://idarts.co.jp/3dp/nasa-mars-rover-perseverance/, 2020