GREEN WAY TO 3D PRINT
3D PRINTED CUSTOM BLOCK PAVEMENT AND OBJECTS
INDUSTRIAL CONCRETE PRINTING SOFTWARE
3D PRINTED STAIR MOLDS
3D printed homes for homeless in Austin
Bedroom, bath, kitchen, living room and large porch
The whole world is holding its breath while the Corona pandemic is affecting our private lives and professional work in a completely unprecedented manner. However, we have no choice but to move on and plan for the future. We need to develop creative solutions in order to avoid further standstill as much as possible. During the past weeks and months, countless trade fairs and technical conferences in the construction sector had to be cancelled, and organizers are all facing the same question: should the events be postponed to a later date, or cancelled altogether?

In some instances, both of these choices may be unsuitable, and a more innovative approach has to be considered. The organizers of Digital Concrete 2020, which under normal circumstances would have taken place at the beginning of July at Eindhoven University of Technology in the Netherlands, are setting a good example in this regard. This unique event is an absolute highlight for the global construction printing industry and a cancellation is certainly not an option. However, postponing the event to a later date is also close to impossible, considering that the participants would have to travel from all over the world, which at the moment is very difficult to plan and organize. Consequently, an alternative solution will be implemented, which probably is the only sensible response to the situation: Digital Concrete 2020 will take place as a full online conference.

The organizers simply reverted to modern technology to provide maximum value for their clients and partners. This creative approach is fitting for this cutting-edge technical event, as it perfectly well reflects the developments in 3D construction printing technology. Construction printing is at the forefront of technical innovation, attracts an increasing international attention, and paves the path into the future of construction and manufacturing methods. On all continents, experts are dedicating their professional efforts to this technology and contribute to the translation of an idea into a global trend. In the current edition of CPT Construction Printing Technology, we report on social housing projects in the USA and the construction of medical facilities in China. We hope that you, dear readers, find inspiration in these projects, which were successfully completed with 3D printing technology.

Without doubt, Contour Crafting belongs to the pioneers of concrete printing and we are pleased to present you with a comprehensive account of the company. Also discussed in this edition – a Russian company that is investigating the application of geopolymer concrete in 3D printing. With respect to research and development, we have included interesting technical papers by the Technical University of Dresden and the Danish Technological Institute.

Despite the difficult circumstances faced by us all, we are pleased to have delivered another edition of CPT Construction Printing Technology that is true to its aim of being at the forefront of the industry. Enjoy reading through the journal and stay healthy!

Any further suggestions? Would you possibly like to publish in CPT? Please feel free to contact me anytime at editor@cpt-worldwide.com

Dipl.-Ing. Mark Küppers, editor in chief
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CONTOUR CRAFTING CORPORATION WILL PRINT FOUR LOW-INCOME HOUSING UNITS IN LOS ANGELES

Los Angeles County Development Authority (LACDA) Award

In an open competition, proposal solicitation (RFP NO. LACDA19-125) and selection process, the Los Angeles County Development Authority (LACDA) has awarded Contour Crafting Corporation (CC Corp) a project on using construction 3D printing for affordable housing.

CC Corp, in collaboration with the design firm HDR and the supportive services provider Volunteers of America Los Angeles (VOALA) is tasked with building four low-income housing units at a designated site in the Los Angeles County. This innovative project will showcase the potential of the Contour Crafting technology in addressing the homelessness problem in Los Angeles and worldwide. The freedom in the architectural design and high degree of customization which is possible using CC Corp technologies will be utilized to create a livable, sustainable and vibrant community.

In this project, CC Corp’s engineered printing mixture will be used to print safe and durable houses. Various fresh and hardened properties of the CC Corp’s printing mixtures have been
tested in order to provide conclusive data and assure the satisfactory performance of the material. This mixture includes gravel, and therefore it is classified as concrete as opposed to mortar which is commonly used by many other construction 3D printing systems.

Use of concrete for building these units is advantageous due to numerous technical, economical, and environmental considerations. From a technical standpoint, using gravel can improve the dimensional stability of the hardened material, can reduce the risk of cracking in the structure, and can improve the long-term durability of the printed structure.

From an economical viewpoint, inclusion of large aggregate in CC Corp’s printing mixture has made it possible to reduce the Portland cement content, which is the most expensive ingredient of cementitious mixtures. Consequently, the cost of CC Corp’s printing material is very similar to the cost of traditional concrete which has been used for decades.

The third advantage of inclusion of large aggregates in CC Corp’s printing mixture is reduction in the carbon footprint of the printed units. Production of Portland cement produces significant amount of CO₂. Inclusion of gravel in the printing mixture makes it possible to reduce the Portland cement content, and the result is a more sustainable and eco-friendly construction material. CC Corp is currently investigating the use of supplementary cementitious materials to further reduce the Portland cement content in its engineered printing mixture in order to further improve the sustainability of future printed buildings.

Finally, during this project CC Corp and VOALA will organize a job training program. Multiple workshops and hands-on training sessions will be held to educate local workers and vulnerable population on practical aspects of the CC technology and to engage local workers in different stages of this innovative construction project.

Contour Crafting Corporation
215 South Douglas Street, El Segundo
Los Angeles, CA 90245, USA
www.contourcrafting.com

CC Corp, in collaboration with the design firm HDR and the supportive services provider Volunteers of America Los Angeles (VOALA) is tasked with building four low-income housing units at a designated site in the Los Angeles County.
ADDITIVE MANUFACTURING IN CONSTRUCTION (AMC) – THE CHALLENGE OF LARGE SCALE

DFG funds new CRC/Transregio at Technische Universität Braunschweig in collaboration with Technical University of Munich

Additive Manufacturing (3D printing) is a new manufacturing technology that is now introduced in many industrial sectors. If the potential of this technology is transferred to the large scale of construction, new design possibilities and more efficient, resource-saving construction methods can be created. The aim of the TRR 277, funded by the German Research Foundation (DFG), is to fundamentally investigate Additive Manufacturing in interdisciplinary research for the implementation into construction industry. The DFG is establishing a total of ten new Collaborative Research Centres to strengthen cutting-edge research at universities. Starting on 1 January 2020, they will initially receive a total of around 101 million euros in funding for four years.

The basic principles of Additive Manufacturing are based on digitally controlled layer-by-layer component design, without any mould making or forming processes. “This represents a paradigm shift to the predominantly manual construction techniques, which promote simple element forms and inefficient material utilization,” says the designated spokesperson Professor Harald Kloft of the Institute of Structural Design at the TU Braunschweig. Against the background of the enormous demand for resources in the construction industry with its significant contribution to global CO₂ emissions, this novel technology will provide an efficient use of material.

“Great news – for a project in which scientifically outstanding colleagues are working in an exciting field for research,” says
Professor Anke Kaysser-Pyzalla, President of the TU Braunschweig. “I am proud of the team effort across the borders of TUM and TU Braunschweig and look forward to further cooperation on an issue that is highly relevant to society and the economy”.

“I am particularly pleased with the positive assessment of the transregional project,” said Professor Peter Hecker, Vice President for Research and Young Scientists at the TU Braunschweig. “The SFB/TRR is an award for our research focus ‘City of the Future’ and contributes to raising the profile of civil engineering at the TU Braunschweig”.

The two universities, TU Braunschweig and TUM, have been working together for many years in various fields of engineering disciplines and in particular in the field of Additive Manufacturing. Due to the excellent equipment with large-scale research facilities at both locations, a wide variety of material-process combinations can be investigated right from the beginning.

The TRR 277 promotes the future strategic orientation of both universities. Thus, the CRC/Transregio is integrated into the research focus City of the Future/Future City at TU Braunschweig and strengthens the action agenda TUM.additives of the TUM as part of the “Bavarian Additive Manufacturing Cluster”. The TRR 277 aims to contribute to the development of Additive Manufacturing as a key technology for the digitalization of the construction industry, with increased productivity and an efficient use of resources.

Collaborative Research Centres and Transregional Projects

Collaborative Research Centres enable innovative, challenging and long-term research projects to be carried out in a collaborative effort and are thus intended to serve as focal points and structures for the applicant universities.

Transregional projects (TRR) are a variant of the classical Collaborative Research Centres. This enables universities in Germany to closely network and apply for and carry out research projects on fundamental issues across all locations.

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Digital Concrete 2020

Full online conference

Due to the Corona virus outbreak, the Digital Concrete 2020 Organizing Committee, in close coordination with RILEM, has decided to reshape the conference in a different format.

Digital Concrete 2020 will take place as a full online conference, in the same week as originally planned, starting on July 6. Over the course of 4 days, there will be online sessions of approximately 4 hours, including keynote lectures, parallel sessions, Q&A options, and meet & greet facilities. In addition to the online conference, a shorter on-location multi-day workshop in Eindhoven will be organized in 2021, focusing particularly on interaction within the Digital Concrete-community. This event will include a PhD course, an excursion and site-visits, too.

DigitalConcrete

www.digitalconcrete2020.com
3D concrete printing is particularly suitable both for digital construction on-site and manufacturing of concrete elements in prefabrication. In combination with digital planning, such new technologies can open up the way to Construction Industry 4.0. The digitisation and automation of relevant production processes constitute the most promising approach to introducing urgently needed changes into the practice of construction.

After the successful start last year, the 2nd German Industry Seminar on 3D Concrete Printing and Other Digital Concrete Construction Technologies aims to present once again a comprehensive overview of the most important developments, which will be scrutinized critically and impartially. The seminar will take place on October 28th, 2020 at the TU Dresden, Germany. The organizers are the Institute of Construction Materials, the Endowed Chair of Construction Machinery, and the Institute of Construction Management.

Presentations from industry and science will provide an up-to-date overview of the state of the art, relevant development trends, but also the challenges in dealing with the new production processes.

The seminar offers an exhibition options for national and international companies active in the field of construction printing which should contribute to intensive exchange between participants.

The event venue is the Alte Mensa Event Hall ("Dülfersaal", 1st floor) at the Technische Universität Dresden, Mommsenstrasse 13/15, D-01069 Dresden. The seminar language will be German.

Further information: http://tu-dresden.de/bau/3ds2020
ACCIÓN LAUNCHES GLOBAL 3D PRINTING CENTER IN DUBAI

Culmination of an internal development process

Acciona, a leading company in sustainable infrastructure solutions, inaugurated in Dubai a new global 3D printing center to meet the growing demand for 3D printed infrastructure.

The new facilities feature one of the world’s largest operational 3D printers using powder bed technology. This technology is particularly suitable for generating highly resistant structural parts. In addition, the technique uses concrete as base material, which renders it an ideal solution for architectural, urban and building applications.

The printer, with 6x3x2 meters in size, allows greater efficiency and automation of the construction processes. The 3D technology offers a freedom of architectural and urban design that had previously been unthinkable. It also opens the way to scientifically documenting heritage items and making replicas from their digital copies, which enables the public to contemplate identical reproductions.

Acciona’s new production facility is the culmination of an internal development process in the Innovation area starting in 2016, which has enabled the technology to be fine-tuned for commercial use.

During this process, Acciona achieved milestones such as one of the first walkways in the world made using 3D printing, in Alcobendas (Madrid, Spain), or the architectural piece of cultural heritage made on a real scale using 3D printing on concrete, the Romanesque arch of San Pedro de las Dueñas, in collaboration with the National Archaeological Museum of Spain (MAN).

Acciona has chosen Dubai to install its 3D printing center in order to support the emirate’s commitment to deploying this technology in all economic fields and, specifically, in the construction sector.

The “Dubai 3D Printing Strategy” is integrated into the Emirate’s strategic development plan for cost reduction, productivity and performance improvement of products and environmental impact mitigation. The Strategy aims to make Dubai a world-class 3D printing hub.

Among the concrete initiatives included in the Strategy is the introduction of a new law under which 25% of new buildings’ components must be manufactured with 3D technology by 2025.

UNLOCKING NEW POTENTIAL

New partnership

IRS Robotics and Vertico are partnering to provide world class 3D concrete printing technology solutions to the market.

As an experienced player in the concrete printing market, Vertico has the know-how to provide turn-key, full service concrete printing solutions. IRS Robotics installed a refurbished ABB IRB6640 IRC5 for them on a 6 meter ABB track. Unlocking new potential for the 3D concrete printing market.

Vertico

www.irsrobotics.com
EXCLUSIVELY DESIGNED FURNITURE

More than just an eye catcher

3D concrete provides creative opportunities for architects and planning agencies. The Austrian enterprise 3D Betondruck Solutions has been a pioneer in this innovative technology.

Based on intense development efforts unique solutions for indoor and outdoor use, such as exclusively designed furniture can be realized. Possible re-use as recycled granulate guarantees sustainability. Different surfaces and colouring of the concrete set individual accents.

www.3dbetondrucksolutions.at
CONPrint3D
On-site, large-scale, monolithic 3D concrete printing

The construction industry faces severe problems resulting from low productivity and increasing shortages of skilled labor. The purposeful digitalization and automation of all relevant stages, from design and planning to the actual construction process appears to be the only feasible solution to master these urgent challenges. Additive concrete construction has a high potential to be a key part of the solution. In the first place, technologies are of interest which would enable large-scale, on-site manufacturing of concrete structures in accordance with the demands of contemporary architectural and structural design. The article at hand presents the CONPrint3D concept for on-site, large-scale, monolithic 3D printing as developed at the TU Dresden. This concept is driven by the demands and boundary conditions of construction practice. It complies with common architectural standards, valid design codes, existing concrete classes and typical economic constraints. Furthermore, it targets the use of existing construction machinery to the highest possible extent.

Viktor Mechtcherine, Venkatesh Naidu Nerella, Frank Will, Mathias Näther, Jens Otto, Martin Krause, TU Dresden, Germany

CONPrint3D concept
Most of the known 3D concrete printing approaches are based on layered extrusion and most of them do not comply with the requirement of large-scale, on-site mass construction. The main reason is their focus on high spatial resolution, the use of fine filaments, and the concentration on in-plant-rather than on on-site-fabrication. Apart from high resolution, the use of fine filaments offers additional advantages such as lightweight printheads, which can be of very simple design as well; often a circular, vertically oriented nozzle is sufficient to provide the necessary control of material flow and the precision of material placement. However, fine filaments also mean both low production rates and the need for very fine-grained mortars, which do not comply with existing concrete codes. In contrast, the use of large-size filaments would enable high productivity and use of concrete with coarse aggregates in accordance with valid national and international norms. Since large-scale, on-site mass construction requires rather massive cross-sections of simple geometrical shape, high spatial resolution is not needed. This does not mean, however, making compromises in the geometrical precision of structural elements to be built. A comprehensive state of the art can be found in [1], which also provide more details on the technology presented in this article.

The authors started work on the concept of a formwork-free, monolithic construction process using 3D-printing in the framework of the research initiative ZukunftBau of the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR). They named it CONPrint3D®, which stands for large-scale, on-site 3D-printing. The concept was first presented at bauma 2016 (Munich), which is the world’s leading trade fair for construction machinery, and it was granted the ‘Innovation Award’ in the category ‘research’. The corresponding video and description to the concept were published in [2-4], respectively. Since then the researchers continued to develop this approach further toward its deployment in the practice of construction by working closely with various industrial stakeholders.

The CONPrint3D concept should make a time-, labor-, and resource-efficient, advanced construction process possible, but make the new process economically viable while achieving broader acceptance from industry practitioners as well. The main features of the new concept which distinguish it from other approaches are:
Adaptation of concrete-3D-printing to today’s architecture and structural design
Other extrusion-based methods are more suitable for producing filigreed elements with more complex geometries, which currently, however, are used relatively rarely. CONPrint3D is developed for monolithic construction with sharp corners and predominantly straight walls (see Figure 1).

Maximum use of common construction machinery
At present, concrete printers are expensive special machines. For reasons of economy and early deployment into the practice of construction, the maximum use of existing construction machinery, with some necessary upgrading, would be of great advantage. CONPrint3D implies upgrading such machines as a mobile concrete pump for use as a 3D printer, see Figure 2.

Concrete composition and properties of hardened concrete within existing concrete standards
The development of new standards and their eventual implementation are tedious and expensive. Therefore, in the near and medium terms, one should work as far as possible with printable concrete within the existing concrete standards. For CONPrint3D, concrete compositions with maximum aggregate size of 8 mm have been developed. In addition to ordinary and high-performance concrete, foam concrete [13] and fiber reinforced concrete [8] can be printed.

Printheads which enables surface quality and precision / tolerances according to existing standards
At present, printheads are in the main merely simple nozzles. Due to the lack of smoothing post-processing, on the one hand a “sausage look” is created which is...
not always acceptable. On the other hand, total control of the material flow as well as the precision of the material placement and its final shape are often insufficient if simple printheads are utilized. Furthermore, the forming of sharp corners and precise openings is problematic. CONPrint3D printheads are designed to deposit large-scale filaments of defined geometrical shape and surface quality, while enabling manufacturing sharp corners as well as accurate endings and openings.

At the present stage the CONPrint3D concept focuses on replacing masonry walls as a first step. For such applications steel reinforcement is not needed. While the authors have been working on various approaches of introducing reinforcement into the concept (see, e.g., [19-21] and Figure 1), comprehensively presenting this work here would overload this article. Thus, the following deliberations are limited to non-reinforced concrete.

**Printer – Manipulator system**

Most of the known concrete printing projects rely on the use of proven robotics concepts from other industrial applications for moving the printhead. These concepts seem less suitable if they are to be used for large-scale printing of buildings directly on the construction site because there are, in part, completely different conditions:

- rough environment, dirt, weather;
- frequent assembly and disassembly;
- necessity of easy handling for cleaning and maintenance;
- required machine mobility for quick changeover between construction sites;
- frequently untrained personnel and resulting lack of care in the handling of sensitive technology;
- conservative attitude of the construction industry to modern technology.

From the authors’ point of view, it is advisable therefore to search for the concrete printing manipulator in the field of existing construction machinery, which have been specially developed for this harsh working environment and have proven themselves over many years. The truck-mounted concrete pump is particularly interesting for concrete printing. On the one hand, it has the needed concrete convey-or technique on board and, on the other hand, it has a long, foldable boom whose range (total lengths of up to 70 m) is large enough to print multi-story buildings. The CONPrint3D process therefore aims to use a truck-mounted concrete pump as a large-scale manipulator for the printhead; see Figure 2.

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Frank Will is holder of the Endowed Chair of Construction Machinery at Dresden Technical University since 2017. The three major focal topics of the chair are machine automation, construction techniques and drive systems & components. His professional background is based on a PhD in Mechanical Engineering and 20 years of industrial experience from different management positions in machine and plant engineering companies.

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Figure 2: Illustration of CONPrint3D approach depicting a truck-mounted concrete pump as manipulator for on-site concrete printing.
Several years of research work at the TU Dresden have been concerned with the investigation and modification of the boom drive in order to optimize the positioning accuracy of these machines. For example, measurements were carried out to determine the position deviations and mast oscillations of conventional truck-mounted concrete pumps; see Figure 4. With the help of this data, optimized drive components, control algorithms, and control systems can now be developed to reduce the oscillation amplitudes by up to 95 % and positioning accuracy can be increased [4,5,6].

**Printhead for concrete printing**

Contrary to the described concrete printing approaches that mostly print thin layers of fine-grained concrete, the goal of the CONPrint3D technology from TU Dresden is to print massive, monolithic wall structures with concrete containing coarse aggregates. This results in more ambitious requirements for the concrete conveyor and the shaping tools of the printhead with regard to delivery rates, robustness and wear resistance. In addition to the requirement of processing concrete with coarse aggregates, the printhead was designed with respect to the following specifications:

- high output of concrete for economical print speeds;
- high level of automation;
- high level of modularity;
- variable wall cross-sections and smooth wall surfaces;
- minimal weight;
- easy cleaning and handling.

The CONPrint3D method includes the conveying and dosing technology directly at the printhead; see Figure 4a. This allows better control of the concrete flow. In addition, the fresh concrete properties can be determined and adjusted according to the requirements directly before printing. After further development steps, the forming system at the concrete outlet will be able to automatically adapt the nozzle cross-section to the desired layer geometry. Several automatically controlled shaping elements ensure precise shaping of the building-specific wall geometry; see Figure 5.
The currently most frequently used CONPrint3D printhead is designed to print monolithic wall profiles using concrete with an aggregate size of up to 10 mm. It is capable of printing concrete layers with a cross-section of (width x height =) 150 mm x 50 mm at speeds of up to 10 m/min. During the development of the printhead, special attention was given to a modular design. This allows, for example, the use of different conveying mechanisms or the exchange and optimization of particular components. As indicated above, the printhead can also be equipped with different forming systems adjusted to the respective printing principle:

- Simple outlet nozzles with a fixed cross-section for production of test specimens and wall with unvaried thickness; see Figure 4b;
- Complex forming systems with several actuators for printing complex filament shapes and various filament cross-section / wall thicknesses; see e. g. Figure 5;
- Alternative forming systems for printing finer, curved structures.

Through various measurement points, the printhead provides important data for understanding and controlling the printing process, especially during the test phase in the laboratory.

Properties of printable concrete in fresh and hardened states
Extrudability, buildability, workability and open-time are the key requirements for 3D-printable concretes. Printability can be defined as the property of a material to satisfy these requirements without formation of weak layer-to-layer interface bonds [7]. There are no established process-specific material design approaches and test methods for 3D-printable concrete. Thus, various test methods have been developed as part of CONPrint3D research framework, see e. g. [8,9,10] and used for designing 3D-printable concretes in a performance-based approach. A comprehensive overview of these methods is provided in [11]. Note that due to the presence of coarse aggregates in concrete, testing of its rheological properties relevant for...
3D-printing becomes even more challenging when compared to mortar.

Within the scope and length of the paper at hand, it is not possible to present results for all process-relevant properties for the newly developed 3D-printable concretes containing coarse aggregates. Thus, only some material parameters will be presented, and this exemplarily for one printable concrete with maximum aggregate size of 8 mm; see Table 1.

A combination of CEM I 52.5 R Portland cement, microsilica (MSS) and fly ash (FA) was used as binder. The 3PC had 43.4 % binder paste by volume. The equivalent water-to-cement ratio \( w/c_{eq} \) was 0.51, calculated in accordance with EN 206-1. Very fine quartz sand (0.06-0.2 mm), two natural river sands (0-1 mm and 0-2 mm) and gravel (2-8 mm), all complying with EN 12620/13139, were used as aggregates. The polycarboxylate-based, high-range water reducing agent was added as superplasticizer (SP).

### Table 1. Composition of printable concrete with maximum aggregate size of 8 mm.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>CEM</th>
<th>FA</th>
<th>MSS</th>
<th>Aggregates [mm]</th>
<th>Water</th>
<th>SP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dosage [kg/m³]</td>
<td>350</td>
<td>140</td>
<td>105</td>
<td>427 0.06-0.2</td>
<td>427 0.1-0.2</td>
<td>325 0.2-0.2</td>
</tr>
</tbody>
</table>

Further information can be obtained under [http://tu-dresden.de/bau/3ds2020](http://tu-dresden.de/bau/3ds2020)
The workability of fresh PC was estimated by means of flow table tests according to EN 12350-5. In view of a spread value of 36 cm at an age of 20 min, the 3PC at hand can be classified into consistency class F3 (plastic) according to the EN 206-1. The extrudability of the composition was proven by printing concrete at various concrete ages up to 90 minutes from water addition using equipment as presented in Figure 4.

Extruded layers had right-angled edges with high surface quality; see Figure 4b. Specimens for mechanical tests were extracted from several printed little walls. The time interval between depositions of subsequent layers was 3 minutes. The compressive and flexural strengths were measured according to EN 1015-11 on cubical specimens (100 mm x 100 mm) and prismatic specimens (160 mm x 40 mm x 40 mm), respectively, cut out of printed wall elements. In addition, compressive strength was measured on prism halves after the flexural tests. To assess possible anisotropy, the specimens were tested in various directions with respect to the layer-to-layer interface; see Figure 6. In addition, reference specimens were cast and tested to assess the influence of the printing process on the hardened-state properties. All specimens were tested at an age of 10 days, under consideration of the anticipated high speed of digital construction.

Table 2 shows the results of mechanical tests performed on the hardened concrete. The compressive strengths of the cast and printed specimens (both for cubes and prisms’ halves) are nearly the same, when printed specimens are tested in the parallel case. In contrast, the printed specimens exhibit about 20 % lower strength values than the cast specimens when tested in the perpendicular case; see Table 2. An explanation can be found in [12]. The flexural strengths of printed specimens in all cases except Par3, are not significantly different from cast specimens (below 10 %). The critical case Par3, however, showed the least flexural strength: 66 % lower than that of the cast prisms. The large size of layers, horizontal laying (required for such large filaments) instead of vertical pressure-deposition, stiff composition, absence of curing measures and smooth nozzle inner surfaces are the suggested causes for such relatively weak bond. The bond could be significantly enhanced and the anisotropy reduced by adequate preventive measures. This is the subject of ongoing research.

For widespread use of the new technology, a range of printable compositions is needed which are suitable for various application scenarios and machine setups. To meet particular requirements with respect to structural design, construction physics and durability, compositions and properties of 3PCs

![Figure 6: Specimens’ extraction and test setup: a) compression tests and b) bending tests.](image)

<table>
<thead>
<tr>
<th>Test</th>
<th>Cast C-Cubes</th>
<th>Cast C-Prisms</th>
<th>Printed cubes PerpC</th>
<th>Printed cubes ParC</th>
<th>Printed prisms Perp1</th>
<th>Printed prisms Par1</th>
<th>Printed prisms Perp2</th>
<th>Printed prisms Par2</th>
<th>Printed prisms Par3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>57.7 (1.2)</td>
<td>57.3 (2.9)</td>
<td>46.9 (1.0)</td>
<td>56.2 (1.8)</td>
<td>46.8 (3.3)</td>
<td>57.5 (2.9)</td>
<td>48.6 (4.4)</td>
<td>54.7 (2.5)</td>
<td>53.3 (2.6)</td>
</tr>
<tr>
<td>Flexure</td>
<td>X</td>
<td>X</td>
<td>6.70 (0.29)</td>
<td>6.72 (0.37)</td>
<td>6.75 (0.37)</td>
<td>7.45 (0.45)</td>
<td>2.52 (0.93)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
should be versatile. Currently this translates into 3PCs with aggregate sizes ranging from 2 mm to 16 mm and compressive strengths from 1 MPa (foam concrete) to 80 MPa. For example, in the project CONPrint3D Ultralight, the authors developed a series of load-bearing, lightweight printable foam concrete with densities ranging from 600 kg/m$^3$ to 1500 kg/m$^3$ and compressive strengths from 1 to 10 MPa [13]. Reduction of carbon footprint and sustainable construction are a crucial requirement for the seminal construction materials and processes. While the concretes developed for CONPrint3D applications have lower cement content in comparison to the most known examples of printable concrete, see Table 1, further reduction of clinker content in 3PCs is targeted in ongoing research using limestone calcined clay cements and novel binder systems.

**Economic feasibility, market potential and data management**

Concrete work is still considered to be labor-intensive and time-consuming. In particular, the formwork significantly determines the execution time and take at about 25 % to 35 % a high proportion of the total cost of the structural work, even for relatively simple geometrical configurations. There is consensus in science that the introduction of additive manufacturing in construction has significant economic potential [3,14,15].

An essential criterion for a successful market launch of CONPrint3D$^\circledR$ is the economic competitiveness with conventional construction methods. The aim of the first development step is the automated production of unreinforced concrete walls, continuously and reliably, in order to replace manual masonry construction. With 75 % of the total construction volume, traditional masonry construction is still the most commonly used method in residential constructions in Germany. The building materials bricks (about 32 %), sand-lime bricks (about 17 %), cellular concrete (22 %) and lightweight concrete (4 %) are used in residential construction [15]. This already illustrates the high market potential in Germany only. In addition, the process can be certified as highly competitive worldwide for buildings up to five stories. In particular, potentials are seen also in the emerging economies, where there is a high demand for simple, solid constructions. A second development step, reinforced concrete components are to be produced in order to expand the application scenarios successively. In a third development step finally installations of thermal insulation and technical building equipment, such as electricity, water and sewage are to be integrated.

In economic feasibility studies, the execution time and construction costs of CONPrint3D were investigated. Using the example of one floor of a detached house, a comparison was made between CONPrint3D and conventional masonry construction. As a result, cost savings potential of 25 % and four to six times shorter execution times were estimated. The wall-printing of a floor with a space of approximately 130 m$^2$ can be realized in about one day [15]. The currently conceivable printing speed is 150 mm/s with layer heights of 50 mm. This enables a printing performance of approximately 1,9 m$^3$/h taking into account some delays for wall connections [16]. Two workers are scheduled for the printing process: A specially trained machine operator and a professional skilled worker. Further information to economic prospects of 3D concrete printing can be found in [16].

Compared to conventional construction methods, the number of qualified skilled workers is significantly reduced. On the one hand, this has a positive effect on the construction costs. On the other hand, in Central Europe the trend is being recognized that fewer and fewer workers are available for skilled manual labor. In less developed countries, there is usually enough affordable labor. But often the workers are not sufficiently qualified to build high-quality concrete structures.

To be able to produce building structures autonomously with concrete 3D-printing, the demanding boundary conditions of the construction processes must be mastered by the machine. For this purpose, the construction machine must be controlled by means of specially prepared data structures and sophisticated data management. The basis is a Building Information Model (BIM) containing geometric and material-specific information. The digital structure required for the concrete 3D printing process has to be extracted from the BIM model, then sliced, and after that converted into a machine-readable G-Code. Therefore, an integrated digital process chain must be developed. This topic is addressed in detail in [17,18].

**Summary and outlook**

The article at hand elaborated the necessity of developing digitized, fully automatic technology for large-scale concrete construction. Against this background the authors presented their concept CONPrint3D for on-site, monolithic 3D-printing. The concept is based on layered extrusion as the most existent approaches. The main features of the new concept which distinguish it from other approaches are:

- adaptation of concrete-3D-printing to today’s architecture and structural design (sharp corners, straight-line geometries, wide monolithic cross-sections);
- maximum use of the common construction machinery, such as truck-mounted concrete pumps;
- concrete composition and properties of hardened concrete within the existing concrete standards;
- printhead which enables surface quality and precision according to existing standards.

While introducing CONPrint3D, various perspectives were presented, namely those of mechanical engineering, concrete technology, and construction management. At the present stage the main challenge in applying truck-mounted concrete pumps as on-site 3D-printer is the insufficient positioning accuracy of the printhead. Currently optimized drive components as well as measurement and control systems are being implemented to considerably improve the movement precision of the pump mast.
Concrete compositions for large-size filament printing were developed. While the mechanical performance of the printed specimens was nearly identical to that of the cast specimens made of the same concrete mixture, testing of the printed concrete in various directions yielded a certain extent of anisotropy resulting primarily from the quality of the interlayer bond. Another challenge the authors deal with is enhancing robustness of the mixtures specifically with respect to on-site applications.

In its present form, CONPrint3D technology is designed as an alternative to manual erection of masonry walls. The market shares and economic viability of this alternative have been explained. The use of large-size filaments for printing massive walls requires particular printing strategies and purposeful adaptation of the data from digital planning.

**Acknowledgements**

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**References**


The number of extrusion-based 3D Concrete Printing (3DCP) applications has increased rapidly over the past few years. This indicates an industrial strive to explore new construction methods, aiming at boosting productivity and obtaining new architectural designs; thus, shifting building methods into a manufacturing process. To enable that, it is necessary to create a seamless link between design, materials, and processes in construction. This calls for research on material development, process monitoring, and material characterisation methods [1]. To address such need, while generating new knowledge to the construction industry, the Danish Technological Institute—in collaboration with key players from the Danish construction industry—started the project “Next Generation 3D-printed Concrete Structures” (N3XTCON).

The N3XTCON project aims at developing technologies that bring 3D Concrete Printing (3DCP) to an industrial scale—with a clear focus on sustainability and new architectural designs. Its scope includes both on-site and prefabrication applications based on extrusion-based 3DCP, including the production of large-scale reinforced concrete structures as well as residential buildings. The project is funded by the Innovation Fund Denmark and runs until 2022.

The developments covered in the project range from material characterisation to numerical modelling and process control as illustrated in the diagram shown in Figure 1. Whereas Figure 2 depicts some of the initial project results; specifically: a Finite Element Model describing the failure of printed elements, a Computational Fluid Dynamics model describing the shape of extruded layers depending on 3DCP process parameters, and a Digital Image Correlation (DIC) characterisation method used to monitor layer deformation on printed elements.

In this publication, we present the results of a N3XTCON case study related to the fabrication of a concrete column using a novel cement type developed by Cementir Holding N.V. and

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Figure 1: Development steps covered in the N3XTCON project.
an in-line mixing nozzle that is currently under development at the Danish Technological Institute. Through this case study, we cover the key aspects in the design-to-fabrication workflow; namely, architectural design, material development, 3DCP process setup, and fabrication of a concrete element.

Design to fabrication – case study

Architectural design

Extrusion-based 3DCP has revealed new architectural design opportunities that differ significantly from what is possible with the use of formworks. Some of these opportunities have been explored in the design and fabrication of a column. Specifically, one characteristic enabled by 3DCP is the possibility to make freeform cavities that normally would encapsulate or lock the formwork inside the concrete, i.e. it is not likely possible to remove the formwork in one piece after casting.

Designing with freeform cavities gives new expressions to concrete structures and – together with the characteristic layered surface resulting from extrusion-based 3DCP – adds a design language that refers to the digital fabrication method. In other words, the surface and geometrical features of the concrete element become the "fingerprint" of the digital fabrication method used to produce such element. It is not likely possible to remove the formwork in one piece after casting.

The so-called “twisted column” in the case study featured in this article results from a parametrically designed geometry using a combination of the 3D-modelling software Rhinoceros and the visual programming plugin Grasshopper. The design originates from a baseline curve that gives the base cross-section of the column – including free-form cavities. The baseline curve was then rotated 2 degrees per each printed layer, ending up in a 360 degrees twist at 180 layers. The combination of the gradual rotation and shape of the baseline curve results in a design where the geometry varies the expression of the elevation from top to bottom. In addition, the rotation pushes the limits of the material properties by introducing a twisted...
cantilever towards the inner hollow of the column. The final geometry of the “twisted column” as well as the section that has been printed are shown in Figure 3.

**Material development**

From a material outlook, extrusion-based 3DCP requires fine control of the concrete structural build up – ranging from a material that is initially fluid to a stiff material as the printing process evolves. At first, the material needs to maintain its workability to enable pumping. Next, it must sustain its shape after extrusion and then exhibit enough structural build-up to prevent collapse. The latter relates to a characteristic referred to as buildability.

The so-called material buildability is strongly related to its early-age structural build-up. Figure 4 depicts the required structural build-up after extrusion and the failure mechanism of printed elements suggested in [4]. A thorough review of the mechanisms responsible for structural build-up can be found in [5]; while [6] offers a comprehensive overview of the underlying physics relevant to extrusion-based 3DCP.

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Concrete’s structural build-up can be tuned in many ways, e.g. with viscosity modifying agents and shotcrete accelerators. The former fails to provide enough strength at very-early age, so printed elements cannot be moved shortly after printing; whereas the latter has a rather fast effect, thus hindering operation. Conversely, blended binder systems, e.g. a blend of Ordinary Portland Cement (OPC), Calcium Aluminate Cement (CAC), and Calcium Sulphate (CS), offer a more promising and robust alternative, since CAC combined with CS can modulate the system’s structuration and reactivity; in other words, it can control both stiffening during the printing phase and hardening post printing. The structural build-up scenarios provided by using blended binder systems in combination with hydration retarding admixtures are shown in Figure 5.

The activation strategy Type C (Figure 5) is the one adopted in the study presented in this article. Specifically, a CAC slurry is used as the triggering agent in retarded mortars (OPC-based) via a delayed slurry addition in a custom-designed in-line mixing nozzle. Details on the nozzle as well as dosing and mixing systems are described along with the 3DCP setup in the following section.

In addition to enabling a proper structural build up using CAC, there exists costs and sustainability aspects to be considered in the development of 3DCP mix when compared to conventional concrete compositions. After all, in most cases, custom-designed 3DCP mixes comprise high cement content. To overcome that, the first alternative is to replace the most used white or grey CEM I (that comprise clinker content from 95% up to 100% and with overall CO2 emissions ranging from 860 to 1235 kg CO2/t cement, respectively [7]) with blended binder systems comprised of CEM I and supplementary cementitious materials, e.g. fly ash and limestone filler.

Another most recent alternative is the FutureCEM, i.e. a CEM II/B-M(Q-LL) 52.5 N cement with a low clinker content, where clinker is replaced with a blend of calcined clay and limestone filler. This Portland-composite cement has been gaining momentum in the cement industry due to a combination of factors such as fly ash shortage in some markets, e.g. in Denmark, as well as raised concerns on the sustainability aspects of cement and concrete production.

FutureCEM was under development at Cementir Holding N.V as a result of the SCM and Green Concrete II projects [8,9]. The composition figures related to one of the FutureCEM batches produced at industrial scale trials is summarized in Table 1. These values are presented along with the equivalent values for a White CEM I – also used for 3DCP in previous experiments at the Danish Technological Institute.

To access the feasibility of using FutureCEM for 3DCP, while keeping the same structural build-up activation strategy, i.e. CAC slurries injected and mixed in the nozzle, we utilized needle penetration tests. Such test allows for accessing the evolution of yield stress – computed based on the penetration load

<table>
<thead>
<tr>
<th>Parameter</th>
<th>White CEM I 52.5 R SR5</th>
<th>EN 197-1 requirements</th>
<th>FutureCEM CEM II/B-M(Q-LL) 52.5 N</th>
<th>EN 197-1 requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clinker content (%)</td>
<td>100</td>
<td>95-100</td>
<td>69</td>
<td>65 -79</td>
</tr>
<tr>
<td>Calcined clay &amp; limestone contents (%)</td>
<td>–</td>
<td>–</td>
<td>31</td>
<td>21 - 35</td>
</tr>
<tr>
<td>$f_{c,2d}$ (MPa)</td>
<td>44</td>
<td>≥ 30</td>
<td>28</td>
<td>≥ 20</td>
</tr>
<tr>
<td>$f_{c,28}$ (MPa)</td>
<td>72</td>
<td>≥ 52.5</td>
<td>61</td>
<td>≥ 52.5</td>
</tr>
<tr>
<td>Initial setting time (min)</td>
<td>145</td>
<td>≥ 45</td>
<td>155</td>
<td>≥ 45</td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>3130</td>
<td>–</td>
<td>3000</td>
<td>–</td>
</tr>
</tbody>
</table>
over time as suggested in [12]. Note that, in order to capture the evolution of yield stress from the first minutes of activation up until one hour, we utilized an adapted penetration tip; specifically, a hemispherical tip with radius equal to 10mm. At this stage, the analysis of results was rather straightforward, i.e. we carried out penetration tests to access whether a mix comprising FutureCEM activated with 10% CAC by weight (bwoc) would exhibit the same structural build up behavior as the one comprising White CEM I and activated with the same CAC dosage. The latter corresponds to a mix design that has been successfully used in our 3DCP setup [13] at a vertical build up rate of 1.67 m/h – one example is depicted in Figure 6. This mix comprises White CEM I (CEM I 52.5 R SR5), limestone filler, fine sand (> 0.5mm), water, and a hydration retarder dosage of 0.50% bwoc to maintain a long open time during printing. Moreover, the mix has a water-to-binder ratio of 0.39, 0.10% of PCE-based plasticizer, and 0.10% of viscosity modifying agent bwoc. In the tested mix, we replaced the equivalent volume of White CEM I with FutureCEM. The obtained evolution of yield stress for White CEM I and FutureCEM mixes, including a FutureCEM-based mix without CAC, is shown in Figure 7.
The results in Figure 7 show that the FutureCEM base mix (without CAC) exhibited a steady yield stress value during the monitoring period, i.e. the retarded base mix will remain workable during the printing time. Next, when comparing the results of the CAC-activated systems, we observed a good match in the yield stress evolution. In other words, the FutureCEM-based mix is expected to be buildable (without collapse) at the same vertical build-up rate tested in previous studies with the CEM I-based mix, e.g. in [13]. Note that the equivalent dosage of CAC in both systems is not the same, since the clinker content in CEM I and FutureCEM differs. In particular, FutureCEM has a greater CAC dosage by weight of clinker (bwok) when compared to White CEM I. The actual dosages are 10% CAC bwoc and 10.5% CAC bwok for the White CEM I mix, and 10% bwoc and 13.1% bwok for the FutureCEM mix.

3D Concrete printing setup
The 3DCP installations from the High-Tech Concrete Lab at The Danish Technological Institute served as basis for the printing experiments. An overview of the 3DCP setup is shown in Figure 8. Basically, the setup comprises a 6-axis industrial robot (Fanuc R-2000iC/165F), two progressive cavity pumps (NETZSCH) equipped with a frequency inverter. The first pump, namely “mortar pump”, is used to pump the mortar at flow rate up to 100 dm³/h; whereas the second, namely “dosing pump”, pumps the activating slurry at a flow rate up to 3.6 dm³/h. The flow ratio between these pumps depends on the slurry dosage and solid-content set in the mix design as well as printing process parameters.
In addition, the setup includes a 3.0m long steel-wire rubber hose (Ø32mm), and a custom-designed round nozzle with Ø20mm equipped with a mixing shaft developed at the Danish Technological Institute. The latter is Ø32mm and 200mm long shaft that is equipped with mixing blades controlled by a motor. In this shaft, the base mortar is continuously mixed with the CAC slurry at a given volumetric ratio and mixing speed.

For the printing process parameters used in our case study, the residence time of the material in the mixing shaft is 10.2s (i.e. mixing shaft volume / mortar flow rate). Such short residence time proved enough to activate the White OPC-based mortar using a CAC slurry and black pigment. The scenario, resulting from an empirical study in our 3DCP setup, is shown in Figure 9. This figure depicts the result obtained from varying several parameters, e.g. mixing energy as well as flow rates of the mortar and dosing pumps. As such, Figure 9 is merely presented to illustrate the outcome of the in-line mixing nozzle, without necessarily leading to conclusions on whether the current configuration is optimal. To evaluate that, complementary studies on mixing quality, residence time, and washout function of the in-line mixing nozzle are to be performed in the N3XTCON project.

Prior to any printing task, the pump hopper, hose, and extrusion nozzle were primed with a thin limestone filler paste. Also, a pneumatic vibrator was attached to the hopper of the “mortar pump” to ease concrete pumping, since agitation reduces the internal particle friction and, thus, lowers the effective viscosity of the material. Also, an impeller was added to the hopper of the “dosing pump” to prevent any slurry segregation during the process.

Finally, the design-to-production framework is based on a custom algorithm developed in Rhino and Grasshopper. This algorithm translates toolpath designs into GCode files, i.e. point coordinates and associated orientation vectors.
required for the robot end-effector to follow a specified path. The generated files are then sent to the robot via RoboDK®, which computes the toolpath through inverse-kinematics.

Fabrication of the “twisted column”
For the “twisted column” fabrication, we prepared 45 dm³ of the base mortar and 2.5 dm³ of the CAC slurry. These two components were processed in our 3DCP setup based on the process parameters listed in Table 2.

Table 2: 3DCP process parameters for the “twisted column” fabrication.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print speed [mm/s]</td>
<td>50.0</td>
</tr>
<tr>
<td>Layer height [mm]</td>
<td>10.0</td>
</tr>
<tr>
<td>Contour length [m/layer]</td>
<td>1.29</td>
</tr>
<tr>
<td>Vertical build rate [m/h]</td>
<td>1.39</td>
</tr>
<tr>
<td>Time per layer [s]</td>
<td>25.8</td>
</tr>
<tr>
<td>Mortar pump flow rate [dm³/min]</td>
<td>0.95</td>
</tr>
<tr>
<td>Dosing pump flow rate [ml/min]</td>
<td>56.2</td>
</tr>
</tbody>
</table>
In total, 72 layers were printed – the printed element is depicted in Figure 10 at different time steps. While this represents about half of the height the original geometry (Figure 3), the obtained results prove the main aspects considered in this case study. Specifically, our focus was on validating the feasibility of using FutureCEM for 3DCP applications while highlighting the key aspects related to architectural design, material development, 3DCP process setup, and fabrication of a concrete element. These aspects were briefly presented in this publication and the readers are welcome to contact the N3XTCON project to discuss any further details that were not covered in this article.

Final considerations
The presented N3XTCON case study showcases that 3DCP calls for a holistic design-to-production strategy, and that it has a great potential to change the way we build. The case study outcome, in the form of a “twisted column”, provides insights on digital fabrication using 3DCP; specifically:

- the mix design and process parameters are discussed and serve as guide for future applications, let alone the further development of numerical models describing 3DCP process,
- FutureCEM serves as a sustainable alternative binder to the typical CEM I in 3DPC applications,
- inline mixing of CAC slurry proved useful to modulate the materials’ early-age structural build-up, and
- penetration tests proved suitable to map the structural build-up in highly reactive binder systems.

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References
4. N. Roussel. Rheological requirements for printable concretes. Cement and Concrete Research, 112: 70-85, 2018
8. SCM – Manufacturing of highly reactive Supplementary Cementitious Materials for low CO\textsubscript{2} cement. Højejktologikfonden (095-2010-1)
9. Green Concrete II - Green transition of cement and concrete production in Denmark. Available at: http://www.gronbeton.dk/
10. Aalborg Portland RAPID® cement CEM I 52,5 N (LA) - Environmental Product Declaration. Available at: https://www.epd-norge.no/sement/ aalborg-portland-rapid-cement-cem-i-52-5-n-la-article1654-324.html
11. AALBORG WHITE cement CEM I 52.5 R – SRS (EA) - Environmental Product Declaration. Available at: https://grishon4.environdec.com/system/data/files/6/1/3911/5/P-01276%20Aalborg%20White%20Cement.pdf

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French chemist and professor Joseph Davidovits coined the term “geopolymer” in 1978. Geopolymers are inorganic materials with a polymeric structure of molecules. They possess high strength and a range of specific properties. They are named geopolymers because the raw materials used for their production are mainly minerals of geological origin. They possess high strength and a range of specific properties. Geopolymer cement and geopolymer concrete represent just one of the many possible applications of geopolymer materials. Companies use geopolymer technology for the production of low-temperature ceramics, fire-proof and heat-resistant composites, and toxic and radioactive waste encapsulation.

Examples of geopolymer cement used in construction can be found in Australia, Ireland, the United States, and Russia, to name a few. For instance, in 2014, an entire airport in Brisbane, Australia, was built with a geopolymer-based concrete. In the United States, special high strength geopolymer concretes have been used for airfield and road repairs. Metropolitan tubings and elements of load-bearing structures are also produced. In 2019, Renca invented a unique geopolymer concrete to build a pedestrian bridge in Skolkovo, Russia.

In Russia, there is a rich history of the development of alkali-activated materials that started in the 1950s. The research was conducted by the Kyiv Institution of Civil Engineering, guided by Glukhovskiy V.D. Various objects were built, including the ones in civil and industrial construction. Examples include a residential house in Lipetsk, part of the railroad concrete ties in Moscow, a motorway in Magnitogorsk, and surfacing of the tank training battlefield near Chelyabinsk.

But one should not mix geopolymers and alkali-activated materials and the terms.
Geopolymers are not alkali-activated materials

The similarity of the raw materials applied in both technologies has led to significant misconceptions about the term geopolymer. In fact, many scientists and civil engineers, to this day, use the terms interchangeably, without understanding what they really are.

Firstly, alkali-activated materials (AAM) are not polymers, so they cannot be called geo-polymers. Geopolymers are not a subset to AAM because they are not a calcium hydrate alternative, the main component of AAM, and Portland cement production. In contrast, a geopolymer has a three-dimensional polymeric framework of chemically-bonded atoms of silicon and aluminum.

Main benefits of geopolymer concrete

Geopolymer concrete is manufactured using 90% less CO₂ compared to traditional Portland cement. Depending on mix composition, it can be stronger, chemically inert to a range of aggressive substances, and remain sturdy even in severe climates. Geopolymer concrete has in some studies been shown superior results in strength, durability, freeze-thaw resistance, fire resistance, heat insulation, corrosion, and aggressive substance resistance, including some types of acids.

Geopolymer cement can also be formulated to reuse a multitude of industrial by-products, including plastics.

In 3D printing, geopolymer mortar can be superior in both performance and also cost compared to Portland cement-based products. Geopolymer is designed as a final product, for example a repair mortar, or a 3D printing mortar. In addition, geopolymer concrete has particular chemical features that are far more beneficial for 3D printing technology. The adhesion of geopolymer concrete is so strong because it is a chemical bond. Its unique properties solve the concerns with interlayer building in 3D printing. Namely, that Portland cement layers can be rife with cold joints if not managed properly. This will never happen with geopolymer concrete because it chemically bonds to itself. You can stop printing today and continue the next day without special treatment of the surface and without risking the formation of a cold joint. The second feature is its natural, rapid-strength development. This makes it perfect for mobile 3D printing.

About Renca

Marina and Andrey Dudnikov (co-founders of Renca) started out working for an innovative department of a construction company in their home city. They were developing new materials and alkali-activated concretes, and their application in real construction. Marina’s father had his Ph.D. in alkali-activated materials from Kyiv Institute, where the technology was born more than 30 years ago, so they had a near first-hand source of information.

**Main Properties**

Geobeton exceeds the properties of natural stone

- **Chemical Resistance**
  Geopolymer concrete is high resistance to various acids and aggressive substances, as well as high sulfur resistance due to the absence of calcium compounds in its structure.

- **Superior Waterproof Properties**
  Excellent waterproof properties are achieved thanks to its inherent mesoporous structure. Big molecules like water can’t enter the geopolymer matrix even if they are pushed using external forces.

- **Thermal Resistance**
  Geopolymer concrete is resistant both to high temperatures over 1000 °C (1832 °F) and to low temperatures due to a high level of freeze-thaw resistance.

- **Fire Resistance**
  Unlike ordinary portland cement-based concretes, water in geopolymer concretes easily evaporates (not bound on a molecular level) and does not explode the concrete from inside.

- **Thermal Insulation Properties**
  Materials and plasters using high-quality aggregates and geopolymer cement have superior thermal insulation.

- **Fast Strength Development**
  Geopolymer concrete develops about 50% of its strength in the first three days. This feature increases the construction speed.
What bothered them was that after more than ten years of experience in alkali-activated concretes, they still found its properties to be unstable and, in most cases - unpredictable. Andrey and Marina started to do more research and got acquainted with geopolymer technology. In 2015 they went to Geopolymer Camp in Saint-Quentin, France, where they learned from Professor Davidovits and met their business partner, geologist-mineralogist Alex Reggiani. In 2016, they formed Renca and began extensive research and development of various applications of geopolymer technology in the construction industry.

The first trials with 3D printed geopolymer concrete were made in severe Siberia, where there, for the first time, successfully tested geopolymer concrete for a mobile 3D printer was made by the company Apis Cor. The experience was unique. Both technologies were at the early start of entering the construction market. They were pioneers in construction 3D printing and believed that the future was in eco-friendly construction.

Once an ideal consistency for 3D printing was reached, the tests confirmed the high efficiency of geopolymer concrete. The natural rapid strength development shortened the time of construction with a consistently high mechanical strength (compressive strength reached 92 MPa (13300 psi)). In addition, the elaborated formula of geopolymer 3D printer ink was highly suitable for the technology of 3D printing due to a higher thixotropy, fluidity, and an ability to adjust the setting time.

2017
Renca was a part of Dubai Future Accelerators in UAE and signed an MOU with Dubai Municipality for developing a geopolymer mortar based exclusively on local raw materials for 3D construction printing.

2018
Renca successfully applied geopolymer mortar for 3D construction printing in the harsh climate of Northern Russia for a project with Gazprom Neft, an oil and gas company. The mobile robotic arm 3D printer was used for this project.

Renca awarded the first prize in Katerva Awards, in the Materials, Resources & Water category. RENCA was named one of the top 100 innovative, disruptive construction companies according to Disruptor Daily, and became one of the Top-50 companies, offering solutions for smart-buildings.
Renca, in collaboration with 3D-printing companies and universities, extensively tested geopolymer 3D ink on different 3D construction printers. Based on these tests, the industrial production of geopolymer 3D ink started in 2020.

Renca geopolymer 3D mortar is now a part of the Material Connexion library in New York as one of the most innovative materials not only for 3D printing but for the construction industry in general.

The plans for the future
Renca’s production facilities are located in Russia and Italy, and the products can be shipped worldwide. In 2020 Renca will begin industrial production for the US market.

Renca, in collaboration with its partners, can offer a complete, all-in-one solution, including 3D printers, mortars, mixing machines. They work together with suppliers of industrial robots for robotic arm solutions, and gantry-type 3D printer. It is estimated that less than $100,000 can get you a working solution for the construction of houses. This provides real affordable housing and speeds up the development and spread of 3D construction printing technology.

Since 2016, Renca have tested and adjusted geopolymer mortar for 3D printing on most existing types of 3D construction printers. Renca knows what their clients need and how to adjust the recipe according to their specific requirements.

“I believe that in the near future, 3D printers will become another instrument for the construction industry, as common as hammers or concrete mixers - one may even be able to buy it in a local hardware store” — Marina Dudnikova, Business Development Director, Renca

Renca deliver all-in-one solutions including 3D printers and automatic mixing system for concrete

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PARTNERSHIP TO DEVELOP PRINTABLE CONCRETE

Specially formulated concrete

The Quikrete Companies and the U.S. Department of Energy’s (DOE) Oak Ridge National Laboratory (ORNL) recently entered a cooperative research and development agreement to design next-generation concrete for use in the production of large-scale structures through a 3D printing process.

Using additive manufacturing system developed by ORNL, the collaboration with Quikrete will deliver specially-formulated concrete that establishes new construction capabilities. In alignment with the DOE’s Advanced Manufacturing Office’s Multi-Year Program Plan, Quikrete and ORNL are developing a concrete mix with the strength, curing time, and durability to construct buildings, energy installations, transportation infrastructures and other large-scale structures faster, more affordably and with less energy consumption.

Designed as a pumpable, low- or zero-slump material that sets quickly and gains strength rapidly, this new concrete will be ideal for printable construction projects. In addition, the one-of-a-kind concrete will meet tensile strength, compressive strength, ductility and other structural performance characteristics required as a viable building material.

“Oak Ridge National Laboratory is one of the most advanced players on the global additive technology stage. Quikrete is not only a leader in concrete technology, but also second-to-none in construction materials manufacturing and logistics. Working together, Quikrete and ORNL can quickly develop advanced and economical “concrete inks” to supply all varieties of 3D concrete printers. We are optimistic that this technology will be a game changer for the concrete industry and revolutionize the construction practice,” said Chuck Corman, Chief Technology Officer at The Quikrete Companies.

“We look forward to working with Quikrete, developing a novel material for large-scale construction, and we anticipate this project will have significant industry impact,” said Brian Post, R&D Scientist at ORNL. “As a leader in advanced manufacturing, DOE’s Manufacturing Demonstration Facility at ORNL is uniquely suited to advance this technology.”

The partnership will leverage ORNL’s scientific expertise and its unique facilities along with Quikrete’s robust experience in the plastic and hardened properties of cement-based building materials. The two-phased collaboration, which is the first between Quikrete and ORNL, concludes in two years.

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Software support for 3D concrete printing hardware has been almost unavailable. Where research and development departments rely heavily on the flexibility of skilled CAD modelers and Grasshopper specialists to quickly test new hardware features, manufacturers that are looking for consistent, reliable and easy to use software have found themselves without any good options.

From the experience in robotic manufacturing software and a three-year development process for a custom printing application for Bruil Prefab Printing, Dutch software vendor RAP Technologies has now consolidated its knowledge in a product for a wider audience: RAPCAM Concrete.

**For Industrial 3D Concrete Printers**
Where many companies are still relying on software that has been built for DIY plastic printers, the RAPCAM Concrete software package is an industrial manufacturing software completely dedicated to the high volume production of large scale concrete printed objects. To deliver on this promise RAPCAM offers its users much more than just a slicer.

**Utilizing cloud-based standards**
One of the most fundamental architectural features is the cloud-based Project Management Environment. Although common in any cloud storage provider like Google Drive or Dropbox, keeping track of files, versions, machine instructions and log files isn’t just a nice-to-have anymore. For reliable manufacturing it has become essential.

RAPCAM allows its users to manage tasks and files across projects, and processes them in a standardized, controlled fashion. At any moment in the process users can quit and their progress will be stored in the task they were working on.
Minimizing mistakes with a structured workflow
The RAPCAM concrete workflow consist of three easy steps that shouldn’t take more than a couple of minutes to com-
plete.

Analysis
As a first step, single or large amounts of 3D models can be
loaded into RAPCAM for analysis. Having users work in their
own favorite CAD packages we support the industry-wide
standard STEP file format as well as others. To quickly re-
spond to either clients or colleagues about the validity of their
3D model, the geometry is first checked on its format, model
type and size.
Results from this analysis can be quickly returned to provide
designers and engineers with the information they need to
improve or change their models.

Configuration
As the core of any 3D printing application the object is sliced.
The 3D model can be configured with horizontal or dynamic
slicing, offsets types, layer height and -width, concrete type,
spiral modes, transitions and many more. This module can
also show you whether your print contains inclined parts that
might be challenging to print. You can also get great 3D visual-
izations of the printed element to send to your client.

Simulation
The sliced object that was configured in Product Setup can
now be assigned to the right machine and production posi-
tion. As clients can run multiple printers, including both ro-
botic arms, gantries and combinations, the printing process
can be accurately checked in a 3D simulation including colli-
sion detection to make sure there are no errors to be expect-
ed. For that purpose, custom hardware including end-effec-
tors, external axes, pumps and mixers can all be integrated
into the simulation.

Immediately after simulation, an instruction set can be gen-
erated into the machine-specific format, whether it’s a Sinu-
merik, ABB or Kuka controller or a generic GCode. Machine
feedback can be logged for quality control purposes and read
back to be included in the task details.
Showcase
The power of RAPCAM’s underlying technology can be witnessed at Bruil Prefab Printing in Veenendaal, the Netherlands. As our client Bruil started three years ago with a fixed robotic arm and is now running a highly customized version of RAPCAM to control a built-to-purpose 3D Concrete Printer based on a Kuka K120 R3900 and a 34m linear track.

The project that is launching Bruil’s efforts in 3D Concrete Printing into the spotlight is the renovation of two 1970’s apartment buildings in Den Helder (detailed report in CPT 1/2020). The project, designed by Kokon Architecten, uses 3DPCP for its aesthetically pleasing features on the outside of the building. These are non-load bearing elements that appear Gaudiesque. The project contains 125 custom designed elements for a total of 1200 printed elements; an engineering feat never shown before.

Being in control
Concrete printers and mortars are under rapid development and the quality of a print is extremely dependent on how these two are combined. The specific limitations and possibilities that arise from this combination has to continuously adapt.

The ability to assign specific workflows and permissions to users can be used to reflect any companies chain of command and reduce mistakes. To make sure that users can work within the continuously changing boundaries, RAP Technologies allows administrators to add or change limits on layer height and -width, overhang, printing speed or output for materials and tools. In this way, settings used for testing and acceptance can later be released for production.
To get started with your own materials and tools, RAP Technologies provides its setup service free-of-charge for machine-builders, equipment- or concrete manufacturers and end-users that require support for their machinery or material in RAPCAM Concrete, even if they are the only one using it.

**Outlook**
The incredible progress being made in all aspects of the 3DCP ecosystem provides a continuously demand for new features. For its second release planned for fall 2020, RAPCAM Concrete will include more advanced features aimed at eliminating failed, deformed or collapsed prints and increasing the possibilities of printers including: material open-time analysis, adaptive layer height, dynamic printing speed and, if all goes well, support for FEA analysis based on non-linear material properties.
PRODUCTION & APPLICATION

3D CONCRETE PRINTING WITH AN INDUSTRIAL ROBOTIC ARM

Next step towards digital project implementation

Besix Group, founded in 1909, is a leading Belgian company, mainly active in the construction, real estate development and concession sector. Over the years, the group has experienced enormous growth and has gained a great deal of know-how and experience. Among other things, this has ensured that the company has evolved from a valued construction partner to a company that can offer a complete service package.

This allows Besix Group to take on any project, whatever its size, including financing, design, construction and maintenance. The last few years, the company has focused on diversifying its activities, both geographically and across sectors. This has been made possible thanks to a strong organizational policy and some acquisitions and participations. Meanwhile, Besix Group is active in 25 countries on 5 continents. It can certainly be stated that Besix Group is a company of which the last has not yet been seen or heard. Their motto is therefore „To excel in creating sustainable solutions for a better world”.

Technological progress in the construction sector thanks to 3D concrete printing

The construction sector has always been very close to Besix Group’s heart, which is why it is the company’s core business. In recent years, the construction sector has been catching up strongly in terms of digitization and innovative tools. This technological progress is mainly in the design and engineering of buildings and constructions. With 3D concrete printing, Besix Group is taking the next step towards digital project implementation.

Besix Group first models all elements itself via the 3D software Revit and Grasshopper. This software will then drive the Kuka KR120 R3900 robot. This robot is equipped with a nozzle for 3D concrete printing.

More possibilities thanks to 3D concrete printing

This Besix Group 3D concrete printing application greatly increases the design freedom in the engineering phase, automatically presenting a wider range of possible solutions to customers. As a result, customers are no longer bound to standard designs. Because the model is printed in 3D with a Kuka robot, it is also possible to always create the same product with less waste and this at a much higher speed. This also increases Besix Group’s production capacity and all off this in a much safer, controlled working environment.

Innovation through Partnership

Besix Group is therefore more than satisfied with their choice to use a Kuka KR120 R3900 robot for this application. Because 3D concrete printing with an industrial robot arm was something new for them too, it was important to find a reliable partner who was willing to think along with them. Kuka and Besix Group took a close look at the application and discussed the possible steps in this process.

Thanks to this intensive qualitative collaboration, Besix Group succeeded in developing and implementing a successful, innovative robot application. Due to the great success of 3D concrete printing with a Kuka robot, Besix Group is even thinking of expanding their production facility in Dubai or a similar setup in Belgium or the Netherlands.
More possibilities thanks to 3D concrete printing

KUKA
www.kuka.com

BESIX
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3D PRINTED STAIR MOLDS

Reach new design heights

Aectual Stairs converts conventional concrete formwork techniques into works of art. The 3D printed stair molds can take virtually any shape and are 100% sustainable.
Aectual Stairs converts conventional concrete formwork techniques into works of art.
Aectual Stairs are produced in several types of concrete, with help of the unique 3D printed formwork technology. 3D printing enables unprecedented designs. Soft chamfers, patterns, ornaments, or logos can all be easily integrated into the formwork and thus into the final concrete stairs.

**Break free from conventional formwork**
Aectual’s unique 3D printed formwork is made from recyclable bioplastic. After use it can simply be shredded and directly re-printed into new formworks. This brings unequalled design possibilities, and faster and cheaper production that’s much less wasteful than conventional production methods. Also, with help of the design & engineering software Aectual can optimize the shape of the stairs and reduce the amount of concrete needed.

**Sustainable materials**
Aectual stairs are made of conventional concrete with steel reinforcement, and ranges in colours from white to dark grey. Different finishes are possible, as well as Ultra High-Performance Concrete stairs, which don’t require reinforcement and can be up to 6 cm thin.

**From unique design to engineered product in an instance**
Aectual design software combines parametric design-, engineering- and digital manufacturing constraints. This enables a fast and smooth design & build process and guarantees safe and certified production.

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Contour Crafting is a mega-scale fabrication process that enables additive fabrication of large-scale objects directly from computer models. CC simultaneously uses computer-controlled extrusion and troweling to achieve smooth and accurate free-form surfaces. CC has been enabled by many unique technologies in robotics, material delivery, and control systems that have been created over the course of a few decades. The CC concept was first proposed by Behrokh Khoshnevis at the University of Southern California in 1997, and years later it initiated the field of construction 3D printing. In 2017, Contour Crafting Corporation (CC Corp) was founded to commercialize this technology using the investment from the Umdasch Group Ventures. CC Corp is the first funded start-up in this domain with a mission to commercialize the revolutionary CC technology as well as other innovative technologies. CC Corp technologies use specially designed robotic systems to quickly construct structures using data from CAD models. While there are numerous applications for these technologies, CC Corp is initially focusing on transforming and revolutionizing house construction.

In CC, computer control is used to take advantage of extrusion and the superior surface forming capability of troweling to create smooth and accurate, planar and free-form surfaces. It provides architects the flexibility to design organic curved surfaces as easily as traditional rectangular shapes (Figure 1). With the level of automation possible by the CC technology, orders of magnitude in time savings are anticipated, compared to conventional construction methods.

Currently, almost all of the activities in the field of construction 3D printing is limited to the building shell construction. In this article, the CC technology is described as a platform technology which has shown great potential to be used in various domains. In the following sections, several important applications of this technology and the relevant implementation details are discussed.
Currently, almost all of the activities in the field of construction 3D printing is limited to single-unit one-story buildings. However, with the advancement of the technology and addressing the regulatory barriers, a wide range of buildings could be 3D printed. Figure 2 presents three variations of the CC technology which are designed to build detached houses, multi-story buildings, and multi-unit large structures.

Another major limitation with the current construction 3D printing systems is related to the fact that only the construction of the building shell (walls) is automated by these systems, while other activities are performed by traditional manual approaches. Considering the fact that building shell construction cost is typically less than half of the total construction cost, this is a major shortcoming which should be addressed in the future generations of the construction 3D printing systems. In the following paragraphs, perspectives and implementation details for automation of other major construction tasks using the CC technology are provided.

Once the CC robotic infrastructure is in place several robotic manipulators may be added to eventually achieve total automation of building construction. Considering major achievements and advances in manufacturing using robotics, the total automation of building construction seems possible. Today many complex products are accurately produced by robotic systems in fully automated manner. Buildings are relatively simpler with respect to geometry and required accuracy. The layer-wise fabrication paradigm used by Contour Crafting should now allow the realization of automation of total building construction.

Behrokh Khoshnevis is the president and CEO of Contour Crafting Corporation and the Louise L. Dunn Distinguished Professor of Engineering at the University of Southern California. He is a member of the National Academy of Engineering and a Fellow of the National Academy of Inventors.

Ali Kazemian is a senior R&D engineer at Contour Crafting Corporation with six years of experience in construction 3D printing. He received his PhD from the University of Southern California, where his research was focused on developing real-time quality monitoring measures for construction 3D printing using innovative techniques such as computer vision.

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Figure 2: Different scenarios for automated building construction using CC technology
Automated tiling of floors and walls

Tiling of floors and walls may be automated by robotically delivering and spreading grout and other material for adhesion of tiles to floor, as shown in Figure 3. Another robotics arm can then pick the tiles from a stack and accurately place them over the area treated with the adhesive material. Often 60% of the time in manual tiling could be spent on alignment. With a robotic infrastructure in place alignment could be done quickly and accurately.

Automated plumbing

The Contour Crafting process is able to build utility conduits within walls. This makes automated plumbing possible. In this arrangement, after fabrication of a certain number of wall layers, a segment of copper (or other material) pipe may be attached onto the lower segment already installed inside the conduit. The robotics system, shown on the left side of Figure 4, delivers the new pipe segment and has a heater element (shown in red) in the form of a ring. The inside (or outside) rim of each pipe segment may be pretreated with a layer of solder. The heater ring heats the connection area, melts the solder, and once the alignment is made, bonds the two pipe segments. Other universal passive (requiring no active opening or closing) robotic gripper and heater mechanism designs used for various plumbing components are also shown in the figure. Note that PVC plumbing is also possible in which adhesives may be used for pipe connections.

Automated electrical and communication line wiring

A modular approach similar to industrial bus-bars may be used for automating electrical and communication line wiring in the course of the CC process. The modules, as shown in Figure 5, have conductive segments for power and communication lines, and inter-connect modularly. All modules may be robotically fed and connected. A simple robotic gripper on manipulator attached to a CC machine can perform the task of grabbing the component and connecting it to the component already placed within the conduit. The automated construction system properly positions these modules behind the corresponding openings on the walls. The only manual part of the process is inserting fixtures into the automatically constructed network.
Automated imbedding of sensors and computational devices

Construction materials such as smart concrete may be used in the CC process in certain segments of the building. Such materials demonstrate varying resistance under stress conditions. Also, discrete sensors may be densely placed by a robotic arm at pre-specified locations inside any type of construction material (e.g., conventional concrete). These sensors can be useful for in-process feedback for construction process control, and in completed structure as means for inspection and for creation of smart structures that sense various variables such as temperature, humidity, stress, vibration, etc.

Automated insulation, finish work and painting

Insulation as well as finish work such as plastering of walls may be achieved by using a hybrid CC nozzle that concurrently delivers multiple materials such as concrete, polyurethane, and plaster. After walls are constructed a conventional spray-painting robotic manipulator driven by the same CC machine may paint each room according to desired specifications. The painting mechanism may be a simple spray nozzle, or a large inkjet printer head (such as those used for printing large billboards).

Infrastructure

Many types of infrastructure elements may be automatically built with the CC technology. For example, a variation of CC technology for autonomous construction of tall concrete towers has been proposed, which applies to wind turbine towers, bridge pylons, water towers, silos, chimneys, etc. The method employs a set of coordinated vertically climbing robots that carry a special Contour Crafting nozzle assembly and motion control system and a special method of cementitious material delivery system. Implications for wind turbine towers is further elaborated in the following paragraphs.

Currently wind turbine towers are constructed using hollow steel segments that are produced at factories, transported to the site at great cost, and assembled using special cranes and specialized crew. The task is very hazardous as it is performed at high elevation often under strong wind condition and in tight work envelope involving risks of falling, getting cut between heavy steel segments and being hit by the crane or its load or accessories. Given the current method of tower construction, the tower is the most expensive part of the entire wind turbine assembly.

The large steel sections of the tower have to be transported from the factory to the wind farm for installation. They are often classified as wide load which require special transportation considerations. Furthermore, there is currently a strong motivation to build taller towers that can reach stronger wind elevations. However, the current method of tower construction is limited because it is expensive to build cranes that can reach higher than the current maximum height (85 to 100 meters). In addition, taller towers require large base segments that will be hard to transport (width limitation of available roads, height limits imposed by overpasses, etc.) Furthermore, large cranes will require wider roads at the wind farm. Currently the cost of road construction especially at hilly wind farms is very significant (about $30M for a wind farm having about 100 installations).

The alternative tower construction method based on the CC technology is motivated by the aforementioned high costs associated with steel segment fabrication, transportation, gigantic cranes, labor needed for assembly, and road construction.

Contour Crafting approach is based on using concrete and automatically constructing towers by means of: a) robotic system that can climb the tower as it is being constructed by a novel construction module, b) the construction module based on Contour Crafting (a large-scale 3D printing system), and c) a novel material delivery system. The robotic system keeps the construction module that it carries well aligned in such a way that the final tower ends up having near-perfect geometry and orientation with respect to the horizon. A small-scale version of the system has been constructed and the feasibility of the concept has been proven. Future plans of CC Corp include the development of full-scale CC tower builders. The major advantages of the new approach are:

- Fully autonomous operation
- Usage of concrete that eliminates factory work on steel segments and difficult transportation
- Safe operation due to elimination of human tasks at risky elevations and windy condition
- Low cost of transportation
- Possibility of building much taller towers

Figure 6: CC technology for automated wind turbine tower construction
Space Applications
The ability to fabricate extraterrestrial habitats, laboratories or manufacturing facilities is the key element for long-term human survival on the Moon or Mars. Contour Crafting technology has the potential to build safe, reliable, and affordable lunar and Martian structures, habitats, laboratories, and other facilities before the arrival of human beings. Special CC construction systems are being developed that exploit in situ resources and can utilize, for example, lunar regolith as construction material. These structures can include integrated radiation shielding, plumbing, electrical, and sensor networks.

A major limitation for lunar and Martian construction is the availability of resources, as conventional concrete constituents (aggregate, cement and water) are either hard to obtain or hard to manufacture using in situ resources on these celestial bodies; water is very scarce resource and also cement production requires a very significant amount of processing and energy consumption. To address this issue, a research project was carried out in the Contour Crafting lab which was supported by a Phase II NASA Innovative Advanced Concept (NIAC) program. In this project, sulfur concrete was investigated as an alternative for water-based concrete. Sulfur concrete has numerous terrestrial applications and is potentially an
ideal construction material for planetary construction, especially on Mars which has an abundance of sulfur and a temperature range that sulfur concrete structures can withstand. Its availability, high strength and durability properties make it a very attractive construction material. The developed CC process which includes preheating and mixing the sulfur and aggregate at 150°C is presented in Figure 8.

It should be mentioned that there are other CC Corp’s technologies to be used along with the CC technology, in order to realize the automated construction of extraterrestrial habitats and infrastructure for future colonization. For instance, Selective Separation Sintering (SSS) is a new 3D printing process which won the first place in the NASA In-Situ Materials Challenge. While CC is an extrusion-based 3D printing process suitable for construction of large-scale monolithic structures, SSS is a powder-based method ideal for building smaller-scale objects such as interlocking tiles and bricks, as well as a large array of functional objects such as metallic parts. SSS is the only powder-based process that can effectively work in zero gravity condition and as such it is ideal for use in the International Space Station for fabrication of spare parts and tools.

Summary
The Contour Crafting technology was conceptualized in 1997, and years later it initiated the fast-growing field of construction 3D printing. CC is a platform technology with great potential to be used in many application areas beyond building shell construction. In this article, several major application domains for the CC technology, namely, fully automated building construction, infrastructure development, and space applications were discussed. Experimental research studies and demonstration projects have already proved the feasibility of some of these novel applications of the CC technology.
3D PRINTED CUSTOM BLOCK PAVEMENT AND OBJECTS

New approach
Suppliers of building materials are working on construction printing technologies to protect and boost their sales of premixed material. A small startup from Austria is taking an opposing way – pushing hard to lower the cost of 3D printed items by offering an alternative to premixed printing material.

Printstones was founded in 2017, and – after 3 years of development – is now in the process of entering the market. The startup focuses on the development of fully-automated 3D printing processes for concrete and other cementitious materials.

Stationary 3D-printers (printing cells) based on industrial robots are offered as complete solutions. The reach of such printing systems can be between one and four meters leading to a maximum building size of around 2 x 5 m depending on the shape of the object. Extrusion of the cementitious material occurs at around 30 cm per second, whereas the extrusion volume depends on the selected extrusion diameter and ranges from 0.6 kg to 6 kg per minute.

The application of such a concrete printing system allows the customizable, just-in-time production of various concrete objects. “It doesn’t make sense for mass-production - but it does
3D printed paving stones
for mass-customization and smaller quantity product lines”, says Dr. Hengl, one of the founders of Printstones. “We offer complete solutions including hardware, software and printing material.” The systems also include fully automated material mixing and dosing units, which allow easy adjustment of recipes towards local materials. This is a new approach, opposing the more common ready-mix material solutions. The current printable product range is still under exploration and includes paving blocks, border stones, concrete plates, molds, facade panels, counters, free-form objects, stairs and furniture for public spaces. New product ideas keep coming in from existing customers and new partners every day.

The young company is also pushing into mobile on-site solutions. “Basically, it is an off-site printing cell mounted onto a tracked vehicle and enhanced with an autonomous navigation technology”, says Dr. Hengl. “In a first on-site test, we were able to print a paving area - by feeding the system with a 3D-model and corresponding environmental data”.

The compact design of their first mobile version is a key feature, allowing the vehicle to fit into elevators and through door frames. Furthermore, the use of tracks was chosen over a wheeled platform due to the higher stability and its ability to simply move up and down stairs.

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Robots are increasingly used in the construction process, from sketching an idea to moulding it. ABB robots have been instrumental in the completion of many projects. Let’s take a closer look at the contribution of ABB technology to 3D printing of buildings and the production of non-standard concrete moulds.

Bringing 3D printing to construction

Digital design tools have been at the centre of building design for decades, but construction itself has stubbornly remained a manual process. In 2018, Arup and CLS Architetti proved that a combination of 3D printing robotics could change all that.

ABB robots were used to ensure that the architects’ work was accurately reproduced in concrete. The flexibility of the software of robots allowed architects, engineers and other professionals to collaborate and solve problems in real-time. The big challenge was developing a concrete mix that could keep up with the superhuman speed of the 3D printer and dry in record time. The project’s material experts were able to handle this. Although concrete is a naturally sustainable building material, the real advantage was how little waste was generated during 3D construction. The accuracy of the printing process ensured that every centimetre of material was used. Given that 32% of today’s waste is generated in construction, this alone is a major improvement.
This project showed how new technologies and creative thinking can solve long-term challenges.

**Rethinking the construction industry**

Bladerunner is a multi-stakeholder collaboration project in Denmark that wants to revolutionize the construction industry by facilitating the production of organic moulds at comparable price levels to those of standard moulds. The new technology offers a serious alternative to the existing ones as it allows to create something different from monotonous concrete structures.

Bladerunner uses expanded polystyrene (EPS) for rapid production of non-standard concrete moulds. In Denmark and elsewhere, the number of architectural designs with advanced geometry is growing rapidly in the construction industry, so there is a demand for technologies that can improve the design of architects without increasing the construction budget.

Bladerunner also aims to promote the flexibility of concrete production, as each element can be easily adapted to different shapes, sizes and materials with the help of a modular software system and robots. Flexibility also facilitates on-site production, including cutting jigs directly on site.

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Icon, the construction technologies company, announced it has completed a series of 3D printed homes as part of its continued partnership with Mobile Loaves & Fishes (MLF), the Austin non-profit widely known for its compassionate service to the area's homeless community.

The 400 square foot homes, 3D printed with Icon's Vulcan II printer, feature one bedroom, one bath, a full kitchen, living room and a large porch with sweeping sunset views. The series of 3D printed homes will soon be a place for the formerly homeless to call home at Community First! Village, one of the most innovative communities in the world.

"Icon at its heart is innovation for a better future," said Jason Ballard, co-founder and CEO of Icon. "We're going to have to take some risks if we want a better world for ourselves, and the team at Mobile Loaves & Fishes shares a similar vision in their efforts to empower the community around them into a lifestyle of service with the homeless. We need a radical rethinking in the way that we approach solving vexing issues in our society like homelessness. At the end of the day, this is all about people and the dignity of human beings."

"The promise of Icon's 3D printing technology is really exciting, and what better place to start putting it to use than in one of the country's most innovative neighborhoods designed to serve men and women who have experienced the trauma of homelessness," said Alan Graham, founder and CEO of Mobile Loaves & Fishes. "Vulnerable populations like the homeless are never among the first to access leading-edge anything, but now here
The homes feature one bedroom, one bath, a full kitchen, living room and large porch and are located at Community First! Village in Austin, TX.

in Austin, Texas they’re among the first in line who will be living in some of the most unique homes ever built—and we think that’s a beautiful thing.”

The series of 3D printed homes by Icon are located in Phase II of the northeast Austin development, bringing the entire property to 51 total acres. When Phase II is completed and at full capacity, Community First! will have an estimated 480 formerly homeless individuals living in the Village — which represents about 40 percent of Austin’s chronically homeless population.

The 3D printed homes for the homeless were funded by MLF and its supporters, in particular Cielo Property Group, who commissioned one of Icon’s printers to be dedicated to the city of Austin to address affordable housing issues.

With architecture designs created by Logan Architecture and finishings by Franklin Alan, the series of 3D printed homes feature multiple home designs that were printed simultaneously, three at a time, to further increase speed and reduce cost. The first set of homes are now complete, with the first individuals to ever live in 3D printed homes in the U.S.

DEN Property Group sponsored the interior design completion of the homes allowing Icon and MLF to provide furnishings, decor and artwork to create a wonderful place for these individuals to call home. Designer, Claire Zinnecker, continued to work alongside Icon to create beautiful interiors for this series of 3D printed homes receiving input from the future residents.
Icon’s 3D printing construction process, which makes use of robotics, automated material handling, advanced software, and a proprietary concrete, Lavacrete, offers a new way to quickly build homes that are both resilient and beautiful in a price range significantly below comparable conventional approaches.

3D-printed homes for families in Mexico

Icon is currently underway delivering resilient, dignified 3D printed homes in Mexico alongside nonprofit partner, New Story. The resilient, 500 sq ft homes were each 3D printed in around 24 hours of print time across several days, and feature final construction build out by Échale, New Story’s nonprofit partner in Mexico.

Vulcano II

The Vulcano II is ICON’s first commercially available construction printer. Designed specifically to produce resilient single-story buildings faster, more affordably, and with more design freedom. It has expanded the footprint of Icon’s printing capability to approximately 2,000 square feet. It has an adjustable width (to accommodate different slab sizes) and is transported in Icon’s custom trailer with no assembly required. The Vulcano II features intuitive tablet-based controls, remote monitoring and support, onboard LED lighting for printing at night or during low-light conditions, and a custom software suite ensuring set-up, operations, and maintenance are as simple and straightforward as possible.
The built-to-last homes located in Tabasco, Mexico will be granted to local families currently living in extreme poverty and makeshift, unsafe shelter. The community of 3D-printed homes will contain 50 homes in total.

The 3D printed homes feature two bedrooms, a living room, kitchen and bath. Co-designed with feedback from the families who will live in them, the homes have been created to meet the specific needs of the community. Resting within a seismic zone, the community and its homes were engineered above the standard safety requirements including robust foundations to ensure the homes will last for generations.

Through partnership with the local government, the 3D printed community is to be part of a larger community plan for the overall municipal area. The families will have access to green spaces, parks, community amenities, and basic utilities through this master plan provided by the local government.

www.iconbuild.com
In the face of the Corona epidemic, Yingchuang Building Technique (Shanghai) CO., LTD. (Winsun) donated 3D printed, smart isolation houses to designated hospitals to relieve the medical pressure and assist with effective crisis management.

To fight against the current epidemic, following a month of innovation, research and development, Winsun launched 3D printed anti-epidemic prefabricated buildings, including smart temperature measuring disinfection checkpoints, intelligent temperature measuring disinfection bus stops, and negative pressure isolation houses. Each of the prefabricated buildings is integrated into one single unit and can be put into operation after hoisting.

3D printed smart temperature measuring disinfection check
The 3D printed smart temperature measuring disinfection check is applicable to densely populated areas, such as hospitals, communities, office buildings, supermarkets, schools, and heavy-traffic areas. It is equipped with several features, including face recognition, attendance management, temperature measurement, spray disinfection, ultraviolet sterilization, and alarm activation, all of which work in a safe, effective and intelligent way. Therefore, the unit can significantly reduce the risk of infection of staff who work on the frontline of the fight against the Corona virus.

3D printed intelligent temperature measuring disinfection bus stop
The 3D printed intelligent temperature measuring disinfection bus stop, derived from the Winsun 3D printed smart bus stop, has a zero-discharge public toilet and epidemic prevention products selling area, and it is also equipped with face recognition, temperature measurement, spray disinfection, ultraviolet sterilization, and alarm activation. If the temperature measured is abnormal, the alarm will be activated, thus reducing the risk of infection. With application of big data technology, health records of citizens can be established and monitored.

3D printed isolation house
The Winsun 3D printed isolation house is designed and manufactured in accordance with novel Corona virus isolation requirements. It is equipped with a negative pressure device, monitoring facilities, temperature measurement, ultraviolet sterilization, air purification, and other AI (artificial intelligence) devices. Therefore, the situation of isolated patients can be monitored in real time, and the information can be fed back to the attending physician. This saves time in the medical treatment of patients. The individual isolation house is suitable for home isolation and medical staff resting facilities. Multiple isolation houses can be connected to form larger units, which for example may be required in hospitals and other medical facilities.

Case studies

3D PRINTED ISOLATION HOUSES

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3D printed disinfection check units

3D printed isolation house

3D printed bus stop

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LIVE 3D CONSTRUCTION PRINTING OF A SMALL HOUSE

In front of thousands of visitors

During the international Bautec construction exhibition in Berlin with over 30,000 visitors from more than 40 countries Cobod and Peri demonstrated the productivity of the Bod2 3D construction printer from Cobod by live 3D printing 64 m² of walls of a small house every day of the show. Each day visitors could live witness the Bod2 3D construction printer create the walls of a small house. The demonstration showed the way towards printing the walls of a normal size house in less than 24 hours.
Henrik Lund-Nielsen, CEO of Cobod explained: “With this showcase of live 3D construction printing we wanted to demonstrate, that our Bod2 printer technology is ready for the market, as it has the quality, speed, robustness and stability to perform hour after hour, day after day and with incredible productivity beating the conventional construction methods. We set out to print 4 small houses in 4 days and we achieved almost that. Each of the first 3 days we printed a small house, but the last day on request of the exhibition we chose to print a couple of their logos in large scale and consequently could only print half a house.”
The Bod2 printer from Cobod has a modular build and can be extended in any direction with modules of 2.5 m, to a maximum of 15 m in the width and 10 m in the height. In the length the printer can be as long as desired. For Bautec Cobod brought a relatively small Bod2 printer measuring 5 x 5 x 5m, smaller than any of the seven Bod2 printers, that Cobod has sold since the Bod2 began shipping in January last year. The Bod2 could print with a speed of 100 cm/s, but materials and pumping equipment limitations have meant that the maximum speed so far has been 40 cm/s.

Tilmann Auch, Cobod product development engineer, commented: “We would of course have liked to bring an even bigger 3D construction printer, but printing live during the exhibition meant some limitations. Consequently, we could only print a very small one-bedroom house of approx. 4 x 4 m. Also, as for speed, we have had to restrict ourselves. During Bautec we only printed with 25 cm/s. This is due to the EU machine and robotics directive, which requires a safety fence around the printer, if we were to print faster. We surely did not want to put a fence up at the exhibition, as it would block the visitors’ possibility to see the printer in action too much.”

Even with the relatively limited speed of 25 cm/s, Cobod and Peri managed daily to 3D print a house with approx. 64 m² of walls in total, during the 8 hours opening time of the exhibition. Dr. Fabian Meyer-Brötz, head of 3D printing at Peri Group commented: “During Bautec we proved in front of all visitors, that we with a minimal crew could 3D print an average of 8 m² of walls per hour, and the walls were not even straight, as a good deal of them were curvy. It is important to note that these freeform capabilities are not only relevant for architectural purposes but allow for the integration of functionality in the walls and hence enable smarter building designs. We are not aware of any other technology, which can produce such results. This is why we from Peri believe this technology is ready for the market, and we are pleased to bring it to the German speaking countries of Europe and continue the development in partnership with Cobod.”
Cobod and Peri are very keen on not just emphasizing the freeform possibilities of 3D construction printing, but always also focus on the competitiveness of the technology in terms of productivity and labor cost. Henrik Lund-Nielsen explained: “Overall we managed what we set out to do and the results speak for themselves: With our technology our customers will be significantly more productive than users with conventional construction equipment and methods. Although we had to lower the speed in the exhibition area, we still managed to print 8 m² per hour. Going forward we aim to reach 20 m² of walls per hour by printing with 40 cm/s and use more powerful pumps. With such productivity the walls of a building with a floor plan of 150 m² could be printed in less than 24 hours. No other technology can produce such results.”

New extrusion system in the printhead leading to much smoother printing.

Fabian Meyer-Brötz, head of 3D printing at Peri, and his team showcasing the end result for the printing on February 19, 2020.
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