COBOD

BOD2

SPECIFICATIONS

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CONTENT

3D CONSTRUCTION PRINTING OVERVIEW

3D Construction Printing (3DCP) was initiated in the late 1990s with the very first attempts to extrude concrete from a computer controlled robot. Since then, a vast development has occurred and in 2014 the world saw the first commercial 3D printed building.

Currently, the amount of interest and research has exploded around the world, with a wide range of traditional construction industry putting efforts and investment into 3D printing for the construction. Most of the major universities now have on-going research projects, challenging the boundaries and expanding the global knowledge about this field. By 2020, a total of 29 houses are estimated to have been built by 3D printing technology world-wide. And the number will likely increase fast in the next years.

Dominating types of 3D construction printers

While there are many ways to use 3D printing technologies for construction, two specific methods are currently dominating the industry:

- Gantry-type 3D printers mainly used for larger construction and on site
- Robotic arm 3D printers mainly used for smaller, more complex components

Robotic arm 3D printer

Gantry type 3D printer

The gantry type printers can have 4 Z axis (as seen in the picture above) or 2 Z axis mounted on rails. The gantry printer operates in 3 dimensions, with the print head moving back and forth on the X-axis (from side to side on the picture), which is the first direction. The x-axis moves along the y-axis (in and out of the picture), which is the second direction. The y-axis (holding the x-axis) moves up and down on the Z-Axis columns, which is the third direction. The gantry principle allows the printer to access any position within the print envelope and gives complete freedom of movement within the reach of the printer, also known as the printable area. Within the printable area an entire building can be printed with only one set up of the printer, and no need to move and calibrate the printer while constructing the building.

The robotic arm printer works different than that, typically with additional movements. The downside is that the robotic arm printer can only print in essence what is in front of it and with a width of the print of 1-1.5 meter. Also, small prints like that require fast curing of the concrete, typically leading to much higher cost than that of normal concrete. Larger prints than the single elements require moving the robotic arm and calibrating the system at the new location, which can be time consuming taking from hours to days for each movement.

While there are some similarities between the two methods, they can best be used for different applications, and with different strengths and weaknesses, outlined in the table below. The most characteristic difference being, that a robotic arm typically has a very small reach, and thus will only print smaller modules / parts/ elements of the whole building and will typically do it off-site, while the gantry system can reach much larger distances, and print entire buildings on site.

	Gantry	**Robotic arm**
Optimal/typical location	On site	Off site
Volume printed	High	Low
Market drivers	Costs and free forms	Free forms and special needs from customers
Promise to industry	Entire buildings on site High productivity, repeatable quality	Single, complex elements of site High agility, complex geometry
Competitors in current market	General contractors (low skill)	Specialized contractors (high skill)

Both technologies extrude concrete or mortar in layers, and the entire structure is built from the bottom and upwards, placing layer upon layer of concrete in a pattern decided by the 3D model input.

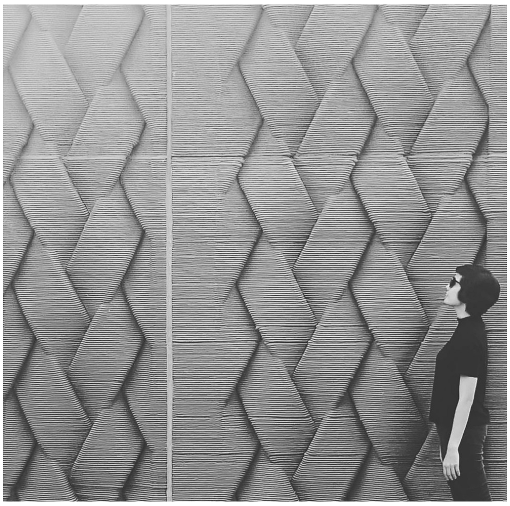
CONSTRUCTION WITH 3D CONSTRUCTION PRINTERS

Any technology has its optimal use and preferred shapes to build from. Historically, buildings have been shaped from the availability of its contemporary building methods. In ancient Rome, all structures were "compression only" structures with large arches to distribute the forces. This was the main method for many years in concrete, until the reinforced concrete was invented. This technology enabled concrete to have internal tensile strength, and the building methods of today were developed, i.e. the slab / column structures that are commonly used today in most parts of the world.

Roman architecture

Completely new possibilities with 3DCP

Now, with 3D printing, entirely new methods of how to build houses have been developed. Not only does 3D printing allow for significantly less use of labor, but it is also possible to handle a much larger variation in geometries, giving the architects a bigger palette of geometries to use in their projects. Furthermore, 3D printing allows for the selective placing of material exactly where it is needed to optimize structures, minimize waste and the impact on the environment and climate. The possibilities are many, and several methods have already been tested.



3DCP geometry

Building permits and local building codes

When a 3D printed building project is initiated, the first thing to do is to investigate the local regulatory environment. Normally any planned building above a certain minimum size requires a building permit and such will only be given to the extent, that the local building code is followed in the planned 3D printed project. Thus, the 3D printed building must follow local building code, but as this code varies between regions and countries, in advance it cannot be stated how this should be done. Instead it is important to discuss the building method as early as possible in the process with representatives from regulatory parties and local structural engineers. Here you should remember that the printer is just a tool. The tool can be used for different construction methods. In other words, the tool does not dictate that a certain construction method should be used. COBOD is also always ready to advice you in the process of determining how the printer should be used to live up to the building code.

The 3D printer and other equipment do not require obtaining a building permit

It is important to recognize that it is not the printer or any other equipment for that matter, that require a building permit. It is the planned building when using the printer or any other equipment, that requires a permission. The 3D printers are not different from any other construction equipment in this respect. The printer is just a tool helping to construct a building, and like other tools require no building permit as such.

Earthquake and hurricane resistance

Similar arguments can be used for determining the 3D printer's ability to deliver buildings that are earthquake and hurricane resistant. As the printer is just a tool, making a building that can be permitted as earthquake and hurricane resistant is a matter of determining the requirements, and use the printer in such a way, that this can be delivered.

It is possible to find methods for all regions be it earthquake, hurricane proof or the cold climate of Scandinavia, the important thing is, to find a method that can be approved by the local authorities.

The BOD building, first 3D printed building in Europe

Load bearing walls or not

Load bearing walls/structures can be 3D printed, provided the specific material used for printing is approved locally. In cases where the material is not yet locally approved, an often-used method is to print hollow columns inside the printed walls, that are then cast with regular, approved, concrete with reinforcement to satisfy the regulations.

Reinforcement

It is also possible to print with fibers, to improve the static capabilities of the printed walls. Fibers can be PP, glass, steel, or any other mineral fiber available, as long as it is soft enough or small enough to pass through the pumping and extrusion system without clogging. Similarly, 3D printing can easily be combined with conventional reinforcement methods.

Cast column with reinforcement

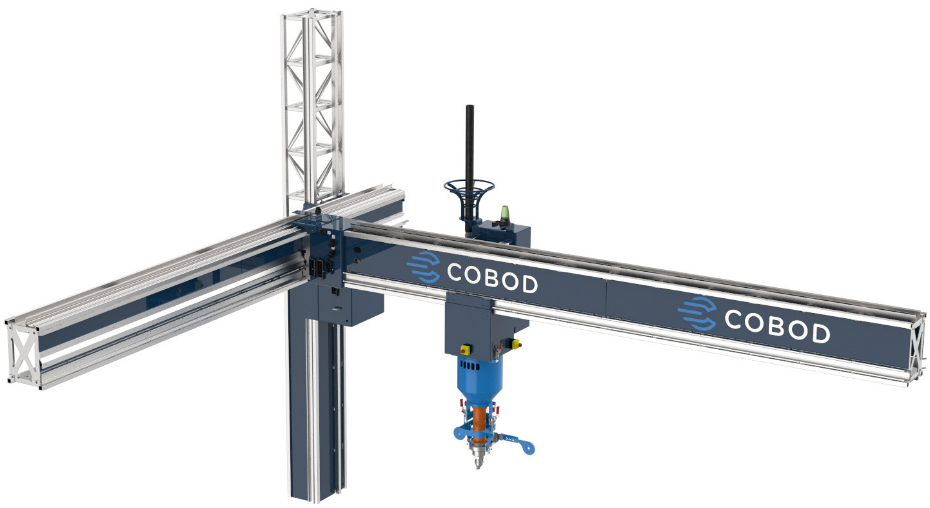
BOD2 OVERVIEW

The BOD2 3D Construction Printer is a gantry type printer and is designed to enable the on-site printing of a wide range of projects, including entire buildings with several floors. With its modular design, it can be scaled up and down to everything from small concrete precast components, to on site printing of houses, to larger office buildings, museums, schools, warehouses etc. in up to 3 stories (G+2).

Modular printer – require the size you need

The BOD2 modularity is a function of 2.5 meter modules, as shown in the picture below. Vertically, 4 modules are the maximum and 6 modules wide, while there are no limitations in the length.

The printer will be delivered with assembled and connected modules according to the ordered size.



Rendering of all 3 axis of a gantry printer (BOD2)

Minimum and maximum size of printer

	Width (X-axis) *Printing area*	Length (Y-axis) *Printing Area*	Height (Z-axis) *Printing Area*
Minimum size	2 meter (2.5 meter)	2 meter (2.5 meter)	0.6 meter (2.5 meter)
Maximum size	14.5 meter (15 meter)	No limit	8.1 meter (10 meter) + height of any concrete installation feet used (page 10)

Cost effective construction – 2 operators

The BOD2 can be operated by a team of just two operators, one for the laptop controlling the printer and one for assuring materials supply, and various smaller tasks during printing.

Besides from printing of the walls, the printer can also be used to mark locations on the building site. For example, the printer can mark where installations should come out of the floor or walls, such that the electricians and plumbers can be shown precisely, where they should put installations.
During printing the operators can assure that the walls have been prepared for the later insertion of electrical sockets, plumbing, wires etc.

High speed and material output possible leading to minimal time to print the building

The BOD 2 printer is designed to be able to move the print head with a maximum speed of 1000mm/second – 1m/s.

Presently (2020) the maximum realized speed for longer periods of printing is 400-500 mm/s.

Depending on the complexity of the print, the materials printed with and the mixer/pump used a larger or smaller part of the speed can be utilized.

If a nozzle of 5 cm width and 2 cm layer height is used, at 400 mm/s speed, the printer will be extruding up to 1.4 m3 of mortar/concrete per hour equivalent to 3 tons. 3 tons also corresponds to printing 14 m2 of a double wall section (inner and outer wall) per hour. A 100 m2 house has approximately 200 m2 of wall sections, which the printer at that speed can do in 14-15 hours printing time, to which preparation and cleaning time must be added.

Choice of print widths and heights; print nozzles and flaps

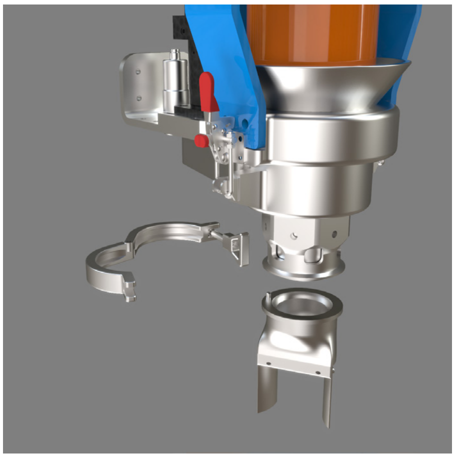
3D printed plastic nozzles can be used as print nozzles, while we recommend using metal nozzles for larger prints.

Using 3D printed plastic nozzles allows for experimentation with nozzle designs to optimize the flow of concrete and to change the size of the nozzle in minutes. The nozzles can be printed with plastic polymer printers costing a maximum of 1,500 euro. COBOD is normally using PET-G plastic for the 3D printed nozzles.

Because the nozzles are 3D printed, it is easy to try out new designs and produce nozzles for different layer heights or widths. Nozzle are exchanged and fastened to the printhead using a triclamp.

While PET-G is durable enough to run some trials and small projects, in production cases, it is recommended to use steel nozzles. COBOD will supply drawings for the specific nozzle size required if you want to produce them locally, or a specific size nozzle in metal can be bought alongside the BOD2 system.

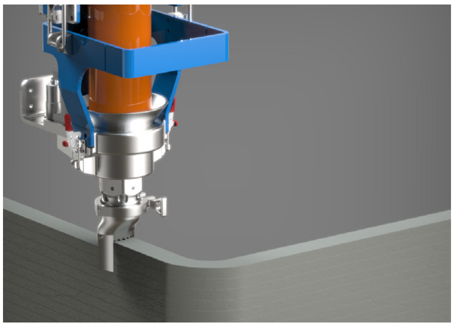
Flaps can be mounted on the nozzles which in combination with the tangential control allow for smooth printed walls.
Flaps can be produced by any material but are normally made from stainless steel (cuts outs from various pipes), which are then added to the side of the nozzles. The angle with which you connect the flaps will determine how visible the lines between each printed layer will be. Ie if you incline them a bit inwards the lines will be very visible with a sharp edge between each layer, while the line will be far less visible if the flaps are mounted straight down or a tilted a bit away from the nozzle.



Triclamp for changing and fixing nozzles

Tangential control – smooth walls

As an additional feature and separate option to be purchased with the printer itself, the BOD2 can be equipped with a tangential controlled nozzle (hardware and software) which will always that the print nozzle is turned to follow the direction of the print. See the price list for prices.



Tangential control

The tangential control facilitates the use of flaps, that removes excess material from the side of the walls and provides a much smoother surface on the finished wall. This reduces the amount of work and material needed for plastering and painting, and greatly increases the aesthetics of the wall.

Installation: quick when using concrete installation feet

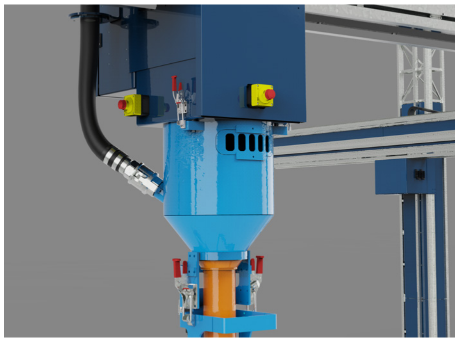
The BOD 2 printer can be installed in one of two ways. The columns of the Z-axis are either bolted to the ground or mounted on four concrete installation feet, which are placed on the foundation or ground. This also raises the printer about a meter over the floor, increasing the maximum height the printer can print (see page 8). The four concrete installation feet are not standard delivered with the printer, as it makes more sense to have these made locally where the printer will be operative. COBOD can deliver the files for producing the feet.

Concrete feet installation

For moving the printer, a forklift needs to be present, and this should be used to demount the X, and Y axis and move each axis as one part, so 7 parts total. With just 2-3 people, the printer can easily be disassembled into and moved with a truck. When using concrete feet, the installation at a new site can typically be done in 4-6 hours, while the demounting takes 2-3 hours.

Materials hopper above printhead – start and stop printing at any time/point

The BOD2 is equipped with a material hopper (with an extruder inside) above the nozzle, which enables accurate control of the extrusion of materials, including the possibility to start and stop prints at any point – a possibility that virtually no robotic arm printers have. To stop the material flow and start again after a while is needed while printing openings for doors and windows. The extrusion speed is synchronized to the printing speed, which makes it easy for the operator to adjust speed and acceleration of the printer without having to worry about material flow.



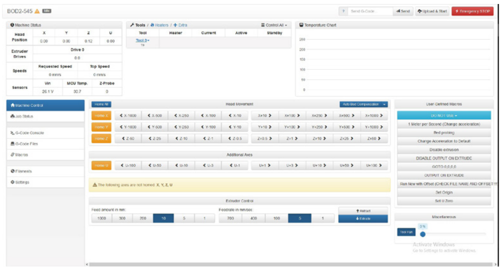
Material hopper

Automatic feeding of materials from the pump to the hopper

The material hopper is equipped with a material level sensor, and can be digitally connected to the pump and mixer (both are extra options to be acquired, see the pricelist) if delivered by COBOD whereby the whole feeding of materials to the printer is digital and automatically controlled. Hereby, the flow of materials to the printhead can occur without the involvement of the operators.
Material is fed to the hopper on the print head via a concrete hose (typical size of ø50 mm), which is connected to the pump and mixing system.

Preinstalled software controllable from the internet

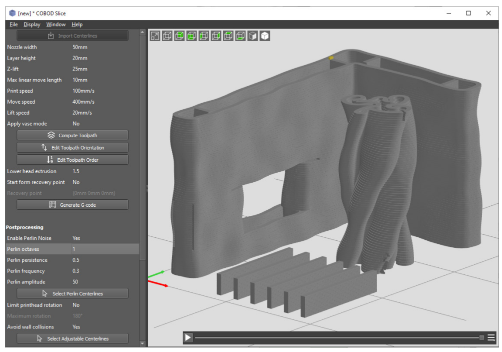
The printer comes with preinstalled software interface, accessible with Wi-Fi or ethernet, and can be controlled by any device with a browser and Wi-Fi/ ethernet connection like notebooks, tablets, smart phones etc.



Software interface

COBOD Slice converts architect files to printable files automatically

The BOD2 runs on Gcode, an industry standard for CNC, 3D printers and machining equipment for many years. The Gcode is made by COBOD Slice (COBOD's own software), which comes with the machine. COBOD Slice accepts 3D model input from any CAD / BIM software suite and prepares it automatically for 3D printing and generate the Gcode. This means that you can design the building/work with your preferred BIM or CAD software during the project planning phase, and then export from it to COBOD Slice. Hereafter the printing process can be simulated, and material usage and printing time can be estimated to plan the printing of the project efficiently.

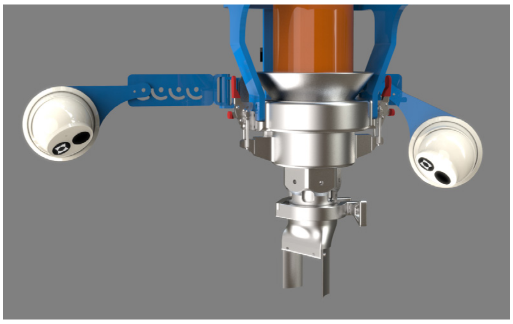


COBOD Slice

Follow the printing via 2 on board web cameras

The BOD2 has two webcams mounted above the printhead. Both are aimed at the currently printed layer, such that the operator has a full overview of the printing process, even when printing higher walls and far away from where the print operator is located.

The cameras work as a quality assurance tool, such that the operator can verify printing quality and record video if needed.



Live camera setup

CE certified and made by the highest quality materials according to IP67

The BOD2 printer is CE certified and built from an exceptionally durable steel truss framework, that ensures the robustness to accommodate rough handling on and between sites, as well as guarantee safety of the workers and operators during the construction process.
IP67 means that the printer safely can be operated in rainy and dusty conditions.

Manuals, instruction, and training

The BOD 2 printer comes with a manual, that explains how to operate the system and perform daily tasks. The manual is plus 50 pages long and describes in detail how the printer is operated and maintained.

COBOD provides on-site installation, training, and operation assistance as an extra option, see the pricelist. When supplying such COBOD will instruct the customer in how to assemble, disassemble and use the printer. We will also assist with doing test wall prints. The on-site training and installation usually ends with printing of a test wall.

More training can be acquired as needed, see the pricelist.

BOD2 SPECIFICATIONS

Max priting length:	No limit
Max printing width:	14.6 m
Max printing height:	8.1 m + height of concrete feet on to which the printer can be mounted
Max printing speed:	Up to 1000 mm/s (1 meter/s)
Layer height:	5-30 mm
Layer width:	30-300 mm
Movement system:	Servo
Material flow:	Up to 3,6 m3/hour at 1000 mm/s speed (for a 5cm wide and 2 cm height print)
Max aggregate size:	10 mm
Printer setup time:	4-6 hours
Printer takedown time:	2-3 hours
Manning:	2 operators
Connection:	Wifi or LAN
Interface:	Web client (through browsers like Chrome or Safari)
Slicer software:	COBOD Slice (Windows, MacOS), Third party slicers
Power supply:	32 A, 400 V, 3 phase

OTHER EQUIPMENT TO BE USED WITH BOD2

As an option (see the price list), the BOD 2 can be delivered with a silo for holding the printable material and a mixer/ pump for feeding the materials to the printer and the hoses for the same. These products are not made by COBOD and can also be purchased elsewhere. For ready mix dry mix materials, we recommend M-tec Duomix Connect, as shown here. For mixing of own concrete on site, we recommend using a COBOD mini batch plant and piston concrete pump. Please ask for additional information if you are interested in these solutions.

M-Tec Mixer/pump

When COBOD supplies the whole materials supply system next to the printer as turnkey supply, being the silo and mixer/pump, the mixer/pump can be placed under the silo whereby dry material from the silo are automatically send to the mixer as needed. The mixer/pump then adds water and mixes the concrete to always keep the pump filled. The pump and flow of materials to the printer is controlled by the printer itself.
The hopper of the printhead can contain a smaller amount of materials (20-30kg). The printer continuously measures the content of the hopper and when the hopper is near empty, the printer engages the pump. The system is monitoring the amount of material in the mixer and will automatically open the valve on the silo to re-fill dry material into the mixer as needed.

3DCP MATERIALS

The materials for 3D printing, mortar, or concrete, are many and varied.

General requirements for 3D printable materials

The BOD2 3D printer can work with any material that satisfies some basic requirements:

- Material can be pumped through a long hose (up to the length of the building to be printed + 10 meters) – materials are "pumpable"
- Material can be extruded, but are still stiff enough to support its own weight and has zero slump when being printed – materials are "printable
- Setting time of the material is fast enough after a few minutes such that it can carry the subsequent layers printed upon it – materials are "buildable"

Layer time and build-up time

One of the key factors, when deciding for a material for a project, is to know the so called "layer time" as well as the build-up time.

The layer time refers to the exact time it takes to print 1 layer of the building. If the layer time is fast, you need a fast setting material. If it is slow, you need a slower setting material.

The build-up time refers to the vertical build rate of the building in meter / hour. For faster build-up times, you also need a faster setting material.

The layer time is depending on:
- The size of the building (the length of one layer of print)
- The speed with which the printing occurs.

The build-up time dependings on:
- The size of the building
- The speed with which the printing occurs
- The chosen layer height

All three factors can be controlled in the software of the BOD2 printer and are key to getting a successful and stable print.

Ready mix dry mix mortars or real concrete and consequences for the pump and mixer needed

More and more manufacturers like Heidelberg/Italcementi, Laticrete, Lafarge, Siam Cement etc. are offering ready mix dry mix mortars for 3DCP in various parts of the world. Materials are typically supplied in 25 kg bags, where all the necessary elements are in and water just has to be added to make the 3D printable concrete. The maximum particle size is normally below 4 mm (hence it is more correctly described as a mortar not concrete).
As the cement is already mixed with the necessary sand and gravel aggregates all moisture has to be driven out of the aggregates prior to that the materials are mixed together and put into the bags, as if the moisture I still in there the process of making and curing of the concrete starts while in the bag. Pre-drying is a costly process and as a consequence these dry mix materials are expensive on a per ton or per m3 basis. For smaller prints, this will usually not be a big issue, but for larger prints and multiple buildings this will be a challenge. On the other hand, the ready-mix dry mix mortars are very easy and convenient to use.

The alternative is to make a 3D printable real concrete with a max particle size of 8-10 mm. The cement, sand and gravel and other ingredients are mixed together on site (where the moisture in aggregates has not been driven out first), which can be done with more manual equipment or via automatic mini batching plants, which COBOD also offers. This process is more complex than relying on ready mix dry mix mortars, but the cost is also a fraction of the cost of the alternative materials. We recommend making real concrete for any larger prints.
When real concrete is used, the M-tec mixer/pump suitable for the mortars will generally not be suitable, and a real concrete piston pump will be necessary. COBOD also supplies such. Other pumps, like pumps from for instance Putzmeister can also be used, but the whole materials delivery process is then more difficult to automate and make digital, than when COBOD is delivering all equipment as a turnkey supply.

Open source – locally sourced concrete

BOD2 is open source as for materials, which means that COBOD will not force you into using any material supplied by COBOD.

The BOD2 can handle any mortar and concrete fulfilling the above-mentioned criteria.

Concrete is very versatile by nature and can be adjusted to fit almost any weather condition and specification.

This feature becomes important when a local material is to be developed.

Due to cost of such, concrete is only very rarely shipped over longer distances, and thus in most places in the world, it is significantly better and cheaper to develop local recipes based on materials that can be supplied through the local infrastructure, then to use materials from far away.

This is why COBOD is constantly working alongside a long list of material suppliers around the world to develop and test materials suitable for the local climate. If you are in an area where no one has been 3D printing in concrete, we will initiate a dialog with your local material suppliers in order for them to supply materials for 3DCP, and we will work with you to help with finding the right recipe/mix of the concrete based on the local available materials

Example of recipe

An example of a 3DCP recipe can be found below.
This recipe was used when COBOD printed the first building in Europe in 2017, The BOD building. Although Denmark is a high cost country for materials, and we at the time were only a small unexperienced buyer of the needed materials, the cost was “only” around 80 euro/t (100 USD/t).

This recipe is a relatively slow setting material, as the printing speed in 2017 was less than 1/4 of what it is today with the new BOD2. The layer time was 15 minutes during most of the printing process, and thus, no accelerators or VMAs was needed. With smaller buildings, it might be necessary to add accelerators and VMAs in the mixture to control the stiffness and setting time more precisely.

The compression strength of this specific recipe was tested at 52MPa (6,500 PSI), mainly due to the relatively high cement content. In this specific project, 23% of the material was replaced with crushed, recycled tiles, which added to the flow capabilities in the system and proved that recycled materials can be used in 3DCP. However, this can easily be replaced with regular gravel of similar grain size.

Material	Quantity [ton]	Price DKK	Price EUR	Percentages by weight
Cement	6.12 ton	10,374 DKK	1,391 EUR	32 %
0-2mm sand	3.50 ton	595 DKK	80 EUR	18 %
0-4mm gravel (0-8mm)	3.50 ton	637 DKK	85 EUR	18 %
0-4mm recycled roofing tiles (0-8mm)	4.38 ton	525 DKK	70 EUR	23 %
Water	1.66 ton	62 DKK	8 EUR	9 %
Glenium sky 631 (superplasticizer)	0.04 ton	191 DKK	26 EUR	~0 %
Crackstop fibers	0.02 ton	1,038 DKK	139 EUR	~0 %
Total	**19.22 ton**	**13,422 DKK**	**1,799 EUR**	**100 %**

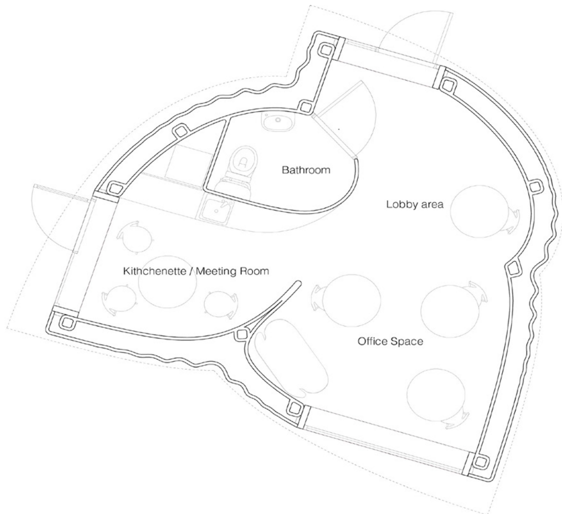
As for reinforcements and fibers, both were used when the BOD building was printed in 2017. So-called crackstop fibers were an integral part of our mixture and as part of the building 3D printed columns were printed, where reinforcement rebars were added and then they were casted in normal concrete.

COBOD

REFERENCE PROJECTS

The BOD building

The BOD, short for Building On Demand, was a project that demonstrated how 3D printing technology could be applied in the traditional construction industry in Europe. It was the first 3D printed building to be approved by the strict EU building codes in the even stricter Danish version of it with excessive insulation demands etc.



Floor plan of the BOD building

The BOD building illustrates the economic and architectural advantages of 3D construction printing. With traditional building techniques, any shape that is organic or not straight is a challenge, technically as
well as with respect to costs. The BOD does not contain any straight walls, the only straight elements being the windows and doors. Even when making the foundation, a non-straight shape provides expensive and difficult challenges when using the traditional methods. That is why we 3D printed parts of the foundation of the BOD building as well. You can visit the BOD building since it is close to our offices in Copenhagen.

You can see a time-lapse of the printing here:
https://www.youtube.com/watch?v=aZHsaaG7nTM
And a video of the finished building here:
https://www.youtube.com/watch?v=SJikUuWOT0M

As this was our first project, we made many mistakes and have improved our technology and skills considerably since this print


The BOD building, printed by COBOD in 2017 in Copenhagen, Denmark

3DPO building, Belgium

KampC printed the first onsite two-story building in Europe, using COBODs BOD2 model version 4-4-4 construction printer. It is a two-story building eight meters high and with 90 square meters of floor space in Westerlo, Belgium.

Other buildings that were printed around the world only have one floor. In many cases, the components were printed in a factory and were assembled on-site. KampC, however, printed the entire building envelope in one piece on-site.

You can see a time-lapse of the printing here:
https://www.youtube.com/watch?v=px-rVEfxrwUw

3DPO building, printed by Kamp C in 2019-20, in Westerlo, Belgium

Not yet officially announced Middle East Villa

Done in late 2019, this building was the first outside EU made by COBOD technology. The building is yet to be made know to the public (delayed because of the COVID virus disturbance).

Not yet officially announced Middle East villa printed in 2019